



Perception of discomfort glare in relation to the CIE Unified Glare Rating scale (UGR) and the impact of ambient light on both UGR and Subjective Glare Indexes (SGIs)

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ABSTRACT

The Unified Glare Rating (UGR) method defined by the International Commission on Illumination is practically the only one used for evaluation of discomfort glare in the lighting design process. However, it is unclear if this method aligns with subjective discomfort glare measures using subjective glare indexes (SGIs). We compared calculated UGR values with commonly used subjective discomfort glare scales across five common office lighting systems. In a controlled laboratory setting with three studies, fifty-nine participants evaluated the degree of perceived discomfort from the selected lighting systems. The findings indicate that classical SGIs were not consistent with UGR values and individual factors (age, sex and emotional state) can influence the discomfort sensitivity. Furthermore, the findings provide new insights into how ambient light levels and viewing direction affect both calculated discomfort glare and perceived discomfort glare. Collectively, these findings deepen the understanding of discomfort glare and underscore the need to refine glare evaluation methods, with direct implications for office lighting design and standards.

1. Introduction

Glare from daylight and lighting can cause visual discomfort, headache, nausea and pain in, or around, the eyes [1]. In office environments, glare is a common issue experienced from lighting systems, causing distractions [2], migraine [3], psychological stress [4], and reducing visual performance [5]. The regulations on Energy Performance of Buildings Directive (EPBD) from the European Commission of Regulation [6] promotes using LED systems while emphasizing the importance of good lighting properties without glare [7]. However, LED systems have raised concerns about glare, primarily due to their high luminance and the configuration of their light intensity distribution curve (LIDC) [8].

Discomfort glare is a type of glare induced by high luminance in the field of view, causing individuals to experience irritation or pain [9]. The definition of discomfort glare was given by the International

Commission on Illumination (CIE) as “glare that causes discomfort without necessarily impairing the vision of objects” [10]. There have been significant discussions regarding development of models to predict experienced glare from technical measurements [11] that had limited applicability and certain mathematical inconsistencies [12]. Current prediction models to evaluate glare and visual discomfort are mostly derived from physical measurements [5,13,14] and lack consensus on human perception of discomfort glare [15,16].

One of the most used prediction models for discomfort glare for electric lighting is the Unified Glare Rating (UGR [17];) that predicts discomfort glare based on the size and the position of a glare source (luminaire) relative to an observer's position, background luminance (adaptation), as well as luminance of the glare source. Currently, the UGR tabular method defined by the CIE [17–19] is practically the only one used for evaluation of glare in the lighting design process. However, the impact of ambient light is not fully considered in either the design

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process or the calculation for verification of discomfort glare when using the tabular method (UGR_L). Ambient light corresponds to ambient illuminance which now is introduced as a new lighting parameter in today's application standards [20,21]. The ambient illuminance is calculated through the formula below.

$$\bar{E}_{amb} = (\bar{E}_{wall1} + \bar{E}_{wall2} + \bar{E}_{wall3} + \bar{E}_{wall4} + \bar{E}_{ceiling}) / 5$$

where

$\bar{E}_{amb}$ is the mean ambient illuminance.

$\bar{E}_{wall1-4}$ is the average illuminance in the plane of the wall for walls one to four.

$\bar{E}_{ceiling}$ is the average illuminance in the plane of ceiling.

The floor area illuminance is excluded from the formula as its contribution to the ambient illuminance in working areas is low because the floor is generally obstructed, forms a very small part of the normal visual field, and has a low reflectance. For workspaces where ambient light is considered (e.g., offices), the mean ambient illuminance is recommended to be within the range of 200 lx to 500 lx.

The assessment of perceived discomfort glare involves subjective evaluation indexes that measure the potential glare experienced by individuals through observer ratings, referred to as subjective glare indexes (SGIs) [22]. On the other hand, the current knowledge gathered by using SGIs are not consistent over experimental studies [23]. The ambiguous response categories of the SGIs [22] and different numbers of response categories [23] contributes to this inconsistency. Moreover, exposure to previous lighting systems may influence individuals' evaluation of lighting systems presented later, a phenomenon known as the presentation order effect [24]. Lastly, individual factors such as emotional state, age, and sex may influence individuals' evaluations when rating perceived discomfort glare [25–27].

In summary, evaluations of current design standards and methods are important to promote a better lighting quality without glare but there seems to be no consensus yet on the current methods for perceived discomfort glare. To improve the understanding of perceived discomfort glare from commonly used LED lighting systems in office environments, this paper aimed to evaluate current discomfort glare methods by considering the potential influence of ambient light together with individual factors and presentation order.

1.1. Technical calculations of discomfort glare

The Unified Glare Ratings (UGR) scale was developed by the CIE to calculate and estimate discomfort glare in indoor environments [28]. The UGR considers luminance light source, solid angle of the luminous parts of each luminaire at the observer's eye together with positioning index. The CIE UGR_L values from the tabular method are calculated as a perceived value for individual positions to each luminaire using the CIE formula. The UGR tabular method is calculated as a perceived value for individual positions to each luminaire using the formula:

$$UGR = 8 \log \left[\frac{0.25}{L_b} \sum \left(\frac{L_i \omega_i}{\rho^2} \right) \right]$$

where L is the luminance of each luminaire in the direction of the observer's eye (cd/m^2), L_b is the background luminance (cd/m^2), calculated as $E_{ind}\pi^{-1}$, in which E_{ind} is the vertical indirect illuminance at the observer's eye, ω is the solid angle of the luminous parts of each luminaire at the observer's eye (steradian), p is the Guth position index for each individual luminaire which relates to its displacement from the line of sight, and Σ shows that the equation (shown above) includes all the fittings located within the area.

The formula above may be expressed in terms of apparent luminaire surface area, distance to a luminaire, intensity towards the observer, the position index and the indirect illuminance on the wall produced by a luminaire using the formula:

$$UGR = 8 \log \Sigma [(\pi I_{cy}^2) (4AD^2 p^2)^{-1}] - 8 \log E_{wid}$$

where I_{cy} is the luminous intensity of the source at the angles to the downward vertical γ and of azimuth C , appropriate to the eye position O of the observer and the viewing direction, C is $\tan^{-1} x_T y_R^{-1}$ = azimuth $\rightarrow \gamma = \cos^{-1} HD^{-1}$ = elevation, A is the projected luminous area of the source (m^2) from the observer position of $A_B HD^{-1} + A_S x_T D^{-1} + A_E y_R D^{-1}$ for a linear luminaire viewed endwise or $A_B HD^{-1} + A_S y_R D^{-1} + A_E x_T D^{-1}$ for a linear luminaire viewed crosswise, D is calculated as $(H^2 + x_T^2 + y_R^2)^{-0.5}$, and E_{wid} is the indirect component of the illuminance on the walls.

Application standards for indoor lighting set requirements and limits for discomfort glare in all indoor workplaces. The required limit of UGR_L values is given by the European Committee for Standardization (CEN) and International Organization for Standardization (ISO). CEN is currently the only recognised by European Parliament and Council of European Union [29] for the adoption of European Standards. In our study, we mainly investigated the UGR tabular method because lighting design standards require limits for discomfort glare based on the tabular method (UGR_L). Currently, the standards [20,21] consider lighting quality for many different indoor workplaces using a UGR_L scale from 16 to 28. For offices and classrooms, the required UGR_L value (R_{UGL}) is set to ≤ 19 .

As ambient illuminance was recently introduced in the standards for lighting of workplaces [20,21] there seems to be a need for a deeper understanding of how ambient lighting influences perceived discomfort glare. One such method of considering ambient illuminance is the Borderline between Comfort and Discomfort (BCD) calculation [30] that incorporates the Guth Position Index to evaluate the effects of lighting in the direct line of sight. While the CIE UGR_L tabular method is calculated as a perceived value for individual positions to each luminaire using the CIE formula, the BCD assesses discomfort glare by comparing the luminance of glare source to its immediate surroundings. In specific, the UGR_L tabular method calculates the discomfort glare from a specific luminaire in an application/room under specified conditions and is affected by background luminance, e.g. the vertical indirect illuminance at the observer's eye. On the other hand, the BCD considers the difference between the glare source and its surrounding e.g. the specific luminaire and its immediate background. The difference between the UGR and BCD based on the line of sight is shown in Fig. 1.

The BCD calculation [30] considers the luminance of glare source subtending 0.0011 (approx. 2° square) at a discomfort threshold (BCD) as a function the background luminance (light to which the eyes are adapted).

$$L_b = 302 F 0,44$$

where.

L_b is the moderate background luminance

F is the adaptation luminance

According to the recent lighting standard [21] workplaces, the background illuminance (ambient luminance) can be converted to background luminance (ambient illuminance) using the formula:

$$E_{amb} = L_{amb} \times [\pi / \rho^*] \quad \rho^* = 0.60$$

where.

ρ is the reflection factor of the background surface of the room

1.2. Subjective discomfort glare indexes (SGIs)

Perceived discomfort glare has been widely studied through experiments using subjective discomfort glare indexes (SGIs), with research dating back several decades. For instance, the De Boer scale [31] is one of the most common scales used to evaluate the perceived discomfort glare by assessing the magnitude of discomfort experiences using odd numbers. The scale is widely used to evaluate glare from indoor electric lighting [32–35]. The original De Boer scale [31] is a nine-point scale:

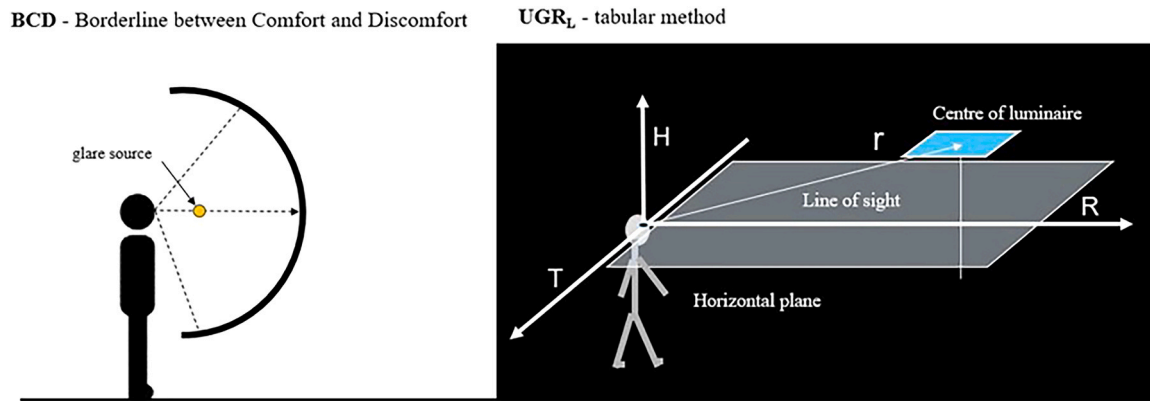


Fig. 1. Difference between BCD and UGR predictions regarding participants' viewing direction.

1 = unbearable, 3 = disturbing, 5 = just admissible, 7 = satisfactory, 9 = unnoticeable. This scale has been previously tested with various answer alternatives.

Another commonly used scale is the Hopkinson's glare sensation scale [36] that rates subjective discomfort glare using four criteria: just not perceptible, satisfactory, just uncomfortable, just intolerable. In 1970, the nine-point version of the Hopkinson scale was created by using the following criteria: intolerable, just intolerable, uncomfortable, just comfortable, unacceptable, just acceptable, perceptible, just perceptible, and imperceptible [37]. Previous studies used different answer options as a four-point scale [38], five-point scale [39], and seven-point scale [40]. Each option in the nine-point Hopkinson scale was paired with a corresponding UGR value previously [37,41]. Table 1 shows the relationship between UGR values and the answer options from the Hopkinson scale based on previous literatures. In addition, the De Boer scale has been included in the table. Apart from these two classical subjective scales, Suk [42] recently assessed perceived glare from LED systems using descriptions of lighting conditions in a controlled office environment. The questions were based on general light level, satisfaction, comfort and discomfort experience while undertaking experimental tasks. These questions differed from classical methods by enabling participants to describe their perception of lighting characteristics and discomfort sensation instead of just evaluating the degree of discomfort glare.

1.3. Individual factors on perceived discomfort glare

Given that perceived discomfort glare is assessed subjectively, individual factors can significantly influence its perception. Previous studies

Table 1
UGR values according to Hopkinson's glare sensation scale based on previous literatures [37,41] and the De Boer scale.

Index values for the answer options	De Boer scale	Hopkinson's glare sensation scale	UGR values
1	Unbearable	Intolerable	34
2		Just intolerable	31
3	Disturbing	Uncomfortable	28
4		Just uncomfortable	25
5	Just acceptable	Unacceptable	22
6		Just acceptable	19
7	Satisfactory	Perceptible	16
8		Just perceptible	13
9	Unnoticeable	Imperceptible	10

Note: International lighting standards [21] recommend maximum UGR values tailored to different environments. For industrial spaces, UGR limits set up to around UGR 28, whereas for office lighting the recommended maximum UGR is typically around UGR 16–20 to ensure visual comfort and minimize glare.

on individual factors focused on biological characteristics (e.g. age and sex) but the findings were not consistent. For instance, it was found that females are more sensitive to discomfort glare compared to males [26] but other studies failed to detect such sex-based differences in discomfort glare sensitivity [27,43–45]. Even though Bennett [46] argued that older people are more sensitive to discomfort from bright lighting systems than younger people, Wolska and Sawicki [37] found that younger people (up to 35 years) are more sensitive to discomfort glare compared to older people (more than 50 years). In addition, several studies failed to indicate age-related differences on discomfort glare [43,47].

Perceived discomfort glare can be influenced not only biological characteristics but also psychological factors, such as negative and positive emotional state [25]. However, the relationship between emotional state and discomfort glare sensitivity remains inconclusive in the existing literature. For instance, Altomonte et al [48], found that participants with a positive emotional state experienced slightly higher discomfort glare, whereas Osterhaus [49] found no significant relationship between emotional state and perceived discomfort glare.

1.4. Objectives of the study

The objectives of our study are to investigate:

- whether perceived discomfort glare from commonly used lighting systems in workplaces align with the International and European standards (i.e. UGR method).
- whether increased room brightness and ambient lighting influence perceived discomfort glare.
- whether individual factors (age, sex, and emotional state) influence subjective perceptions of discomfort glare.

The hypotheses are as follows:

H_1 : There is an association between calculated values of predicted discomfort glare (UGR) and perceived discomfort glare using subjective glare indexes (SGIs).

H_2 : Individual factors (age, sex, and emotional state) influence the evaluation of perception of discomfort glare.

1.5. Description of the study design

This article presents three studies conducted with repeated and non-repeated design experiments in Sweden to evaluate perceived discomfort glare from five commonly used office lighting systems (LSs). Fig. 2 illustrates the experimental design across studies one, two, and three together with calculated predicted discomfort glare values (UGR_L) for each lighting system. The lighting systems (LSs) in each study were selected based on UGR_L values. A total of 60 participants took part in the studies where one person decided to be excluded from the analyses.

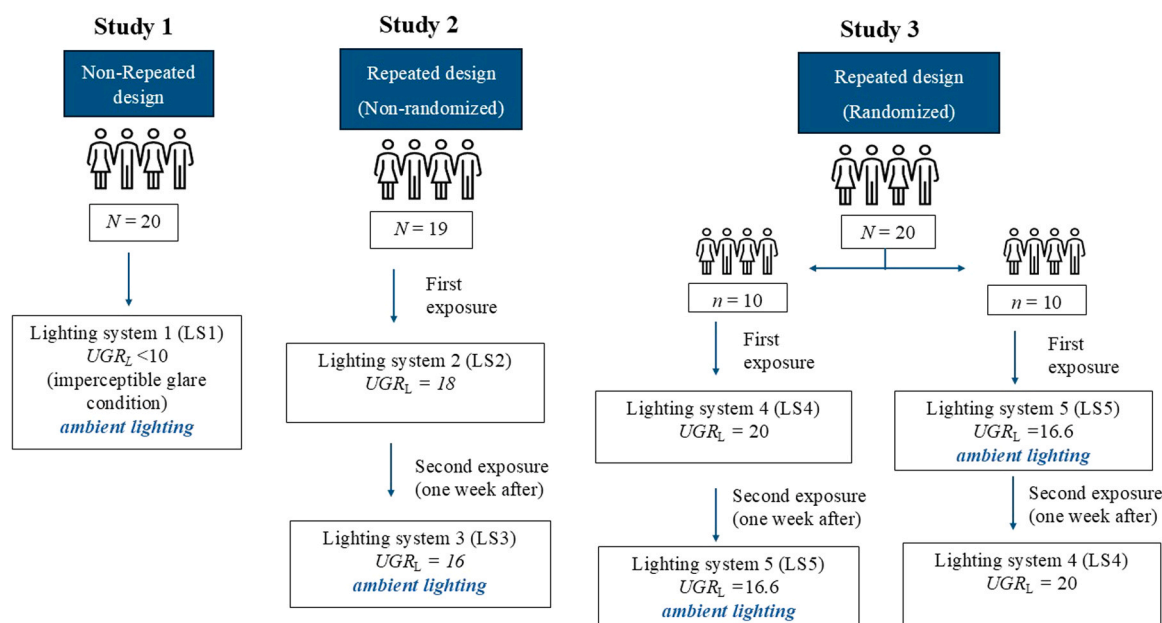


Fig. 2. A visual description of the experimental design describing studies one, two and three and calculated predicted discomfort glare values (UGR_L) for the lighting systems.

Study one was designed as a controlled condition to establish a baseline reference for assessing the relationship between self-reported perceived discomfort glare and calculated UGR values. In study one, non-repeated measures design was used with twenty participants including lighting system one (LS1). LS1 included no visible glare from luminaires in the visual field of view and the estimated calculated UGR tabular values for LS1 according to the CIE formula reached lower values than specified in the UGR_L scale (10–34). Studies two and three were designed as repeated measures and participants were asked to visit the laboratory again one week after the first lighting system was assessed. Study two was conducted with twenty other participants (with one-drop out) using lighting systems two and three (LS2–LS3). Lighting system three (LS3) provided ambient lighting and had a lower calculated predicted discomfort glare (UGR_L) than lighting system two (LS2). Study three was conducted with another twenty participants using lighting systems four and five (LS4–LS5). Lighting system five (LS5) provided ambient lighting and had lower calculated predicted discomfort glare (UGR_L) than lighting system four (LS4). Additionally, in study three, an influence of the presentation order of the lighting system was tested as a design-rigor check. Half of the participants first evaluated LS5 and the other half of the participants first evaluated LS4.

2. Methods and materials

2.1. Participants

Participants who lived in southern Sweden and aged between 20 and 76 years old were recruited using poster advertisements and posts in social media groups based in this area. People who wanted to participate in the study contacted the responsible person of the study using e-mail or telephone. To ensure a variety of ages in the study, the recruitment was based on age groups between 20–35, 36–55, and 56–76 years old. The data collection took place at Lund University between October 2022 and March 2023. The participants received compensation amounting to 500 SEK after the completion of their experiments.

The study was approved by the Swedish Ethical Board (Dnr 2021–05071) and carried out in accordance with the Swedish Ethical Review Authorities' guidelines around requirements for information, consent and confidentiality. Information about the aim of the study was

presented to the participants before their visit. Written informed consent was obtained from all participants before inclusion. A detailed description of the participants is shown in Table 2.

2.2. Description of the test room and lighting systems

The experiments were carried out in a test room with a six-metre long front wall, four-metre wide side walls, and a 2.70-metre-high ceiling. The room did not receive any natural light. The walls in the room were painted in grey (Natural Colour System code S 2000-N) with 60 % light reflection. The gloss number of the walls was under 5. The walls did not contain any decorations. The experiments included visual tasks that required participants to read words and numbers from the visual charts to ensure that their eyes were adapted to the selected lighting system. The visual charts consisted of six words and nine distinct numbers displayed in matrix boxes, using Calibri Bold font at size 50. The charts were presented on A4-sized paper (21.0 cm × 29.7 cm) with a grey background and displayed on the front, right and left walls. An example of the visual chart with numbers is shown in Appendix A. An example of the instructions for the visual tasks is shown in Appendix B.

The surface of the office table was a light oak with a reflectance rate of 31 %. The ceiling was white (Natural Colour System code S 0500-N) with an 80 % reflectance rate. The participants' sitting position was

Table 2

Descriptive information about the participants included in the analysis.

	Lighting system	Type of experimental design	Number of participants	Sex	Age range (M, SD)
Study 1	LS1	Non-repeated	20 participants	12 female, 8 male	21–73 years (M = 45, SD = 21)
Study 2	LS2 and LS3	Repeated	19 participants	9 female, 10 male	22–69 years (M = 45, SD = 16)
Study 3	LS4 and LS5	Repeated	20 participants	14 female, 6 male	20–76 years (M = 45, SD = 18)

3.25 m from the front wall and in the middle between the side walls. The height of the participants' eye level was 1.20 m.

Descriptions of all lighting systems and luminaires used in the experiments are shown in Table 3. Directions towards the luminaires (i.e. grid points indicated by the letter "G") as well as the luminaires' positions used for calculation using the CIE formula for each lighting system are shown in Figs. 3–5. The luminaires' positions and light distribution from all lighting systems (LSs) are shown in Figs. 6 and 7. Pictures of the test room as viewed by the observer for all lighting systems (LS1–LS5) are shown in Figs. 8–10.

2.3. Materials

2.3.1. Light measurements

Illuminance meter Hagner E4-X and luminance meter Konica Minolta CL-70F were used to measure lighting characteristics of the test room and waiting room. These instruments were continuously calibrated and checked if the similar instruments were showing the same value.

2.3.2. Information about individual factors

Information regarding participants' age, sex, and eye colour was self-reported.

2.3.3. Psychological factors influencing subjective evaluations

Swedish translation of a self-reported 20-item questionnaire [50] Positive and Negative Affect Scale (PANAS) by Watson [51] was used to measure positive and negative emotional states. The questionnaire included a statement: "Please indicate the extent to which you have felt this way over the past week". Answering options for each item were presented with a 5-point Likert scale from 1 (not at all) to 5 (too much). Participants filled in the PANAS scale before and during the experiments.

2.3.4. Subjective discomfort glare indexes (SGIs)

To assess subjective discomfort glare, the questionnaire items (i.e., SGIs) and response options from previously published studies were translated into Swedish and employed in the experiments.

Classical SGIs: The degree of perceived discomfort glare was

Table 3
Luminaires used in the lighting system.

Lighting system (LS)	Information of the lighting systems LED luminaire type	Note
LS1	Localised lighting - Direct/indirect suspended LED luminaire + ambient lighting by a wall washer. LS1 = Fagerhult, 29475-402 DTI type 2 Beta Opti LS5 = Ateljé Lyktan PLAIN- 2002028/ 32-402	Suspended 2.1 m Recessed, CCT 4000 K, CRI 80
LS2	General lighting- Direct, ceiling mounted LED luminaires with opal diffusor. LS2 = Fagerhult, 56133-402 - Pozzo Scale Opal	Ceiling mounted, CCT 4000 K, CRI 80
LS3	General lighting- Direct/indirect, suspended LED luminaires with opal diffusor. LS3 = Fagerhult, 56133-402 - Pozzo Scale Opal	Suspended 2.2 m, CCT 4000 K, CRI 80
LS4	General lighting - Direct, recessed downlights LS4 = Fagerhult, 77446-402 - EVO	Recessed downlight, CCT 4000 K, CRI 80
LS5	General lighting - Direct, recessed downlights + ambient lighting by wall washers. LS4 = Fagerhult, 77446-402 - EVO LS5 = Ateljé Lyktan, PLAIN-2002028/ 32-402	Recessed downlight, CCT 4000 K, CRI 80 Recessed wall washer, CCT 4000 K, CRI 80

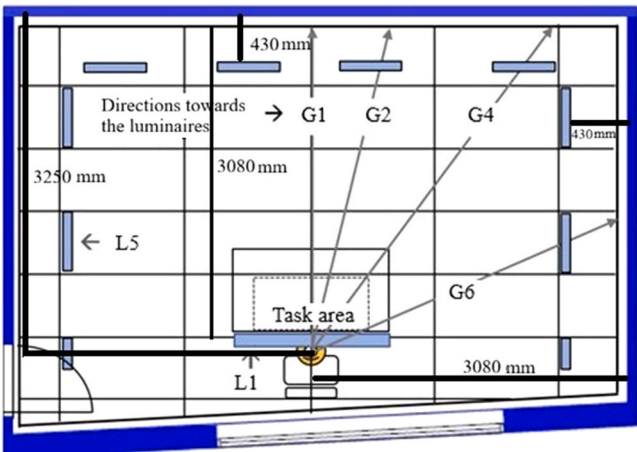


Fig. 3. The luminaires' positions and directions towards the luminaires for Lighting System 1 (direct and indirect and wall washers) in study one.

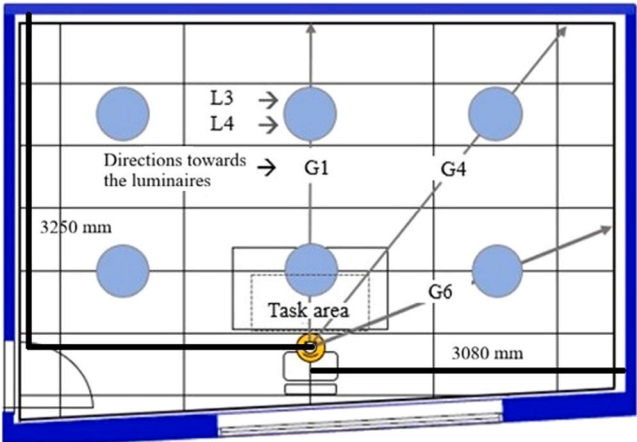


Fig. 4. The luminaires' positions and directions towards the luminaires for Lighting System 2 (direct lighting only) and Lighting system 3 (direct and indirect lighting) in study two.

ascertained using the nine-item scale by De Boer [31] and Hopkinson [36]. The answer options for the De Boer scale were: 1 (unbearable), 2, 3 (disturbing), 4, 5 (just acceptable), 6, 7 (satisfactory), 8, 9 (unnoticeable). The answer options for the Hopkinson scale were: 1 (intolerable), 2 (just intolerable), 3 (uncomfortable), 4 (just uncomfortable), 5 (unacceptable), 6 (just acceptable), 7 (perceptible), 8 (just perceptible), 9 (imperceptible).

Perceived lighting conditions: The descriptions of perceived lighting conditions were asked using four questions by Suk [42]. The questions and answer options were given as stated below.

1. How do you rate the general light level inside the office for the purpose of reading and typing? From too dark to too bright.
2. How satisfied were you with the lighting condition? From very dissatisfied to very satisfied.
3. How comfortable were you with the lighting condition? From very uncomfortable to very comfortable.
4. If you experienced visual discomfort while reading and typing, how would you rate the problem? Intolerable, Disturbing, Perceptible, Imperceptible.

When answering the last question by Suk [42], some participants stated that they did not experience any visual discomfort and were instructed to choose the "imperceptible" option.

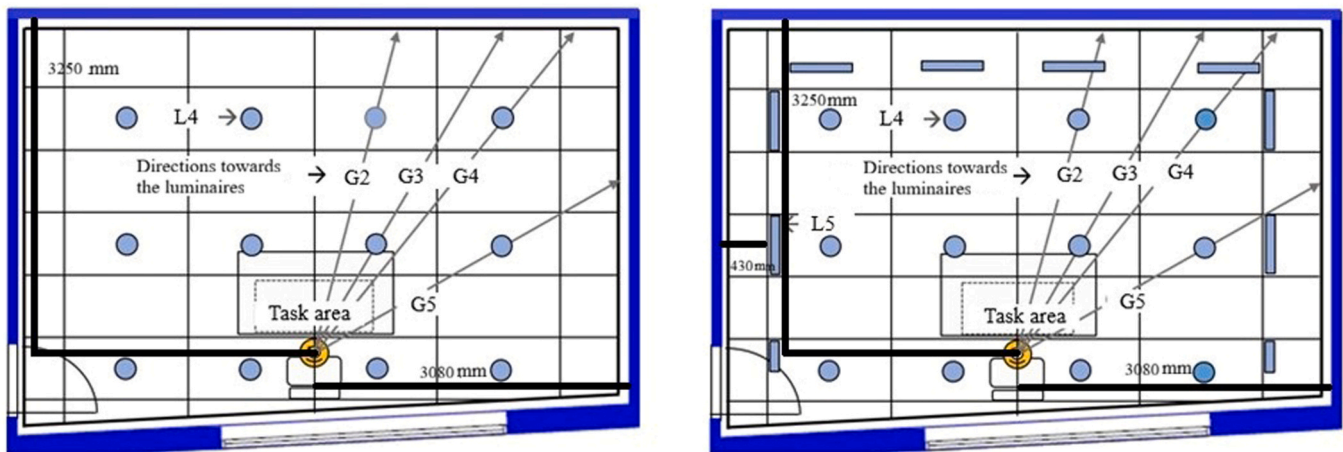


Fig. 5. The luminaires' positions and directions towards the luminaires for Lighting System 4 (as shown left, downlights) and Lighting system 5 (as shown right, downlights and wall washers) in study three.

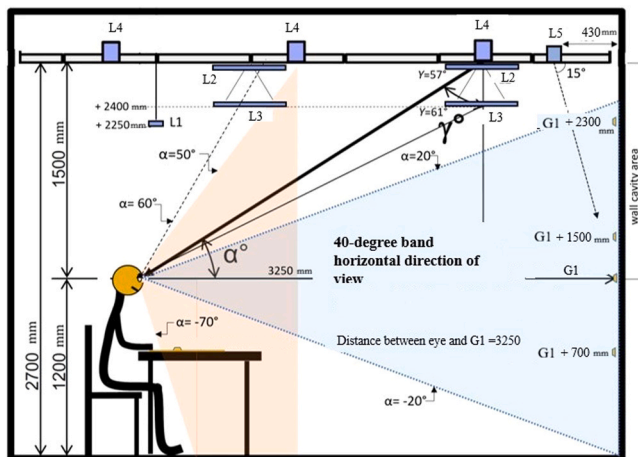


Fig. 6. Cross section of the test room – observers' visual field of view and luminaires' positions.

In addition, participants were asked to rate the brightness of the luminaires using a six-item scale by Geerdinck et al. [33]. During data collection, we observed that participants tended to look directly at the luminaires when responding. This behaviour introduced ambiguity in interpreting their answers, as it was unclear which luminaire each participant was focusing on. Therefore, the question was discarded during the data analysis.

2.4. Experimental procedure

Participants were randomly assigned to one of three experimental groups according to their age: 20–35 years, 36–55 years, or 56–76 years. For each lighting system, half of the participants took part in experiments during the morning and the other half during the afternoon. In study two and three, participant's second visit was scheduled for the same time, but on a date one week later. Before the experiments, participants were asked not to consume nicotine and caffeine and received an information consent form which included a description of the laboratory procedure and the aim of the study. Before meeting the participants, the luminaires of the selected lighting system were switched on, and the illuminance and luminance values re-checked. The luminaires

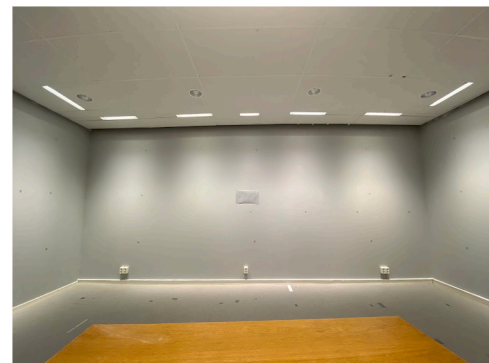


Fig. 8. Picture of the test room for Lighting System 1 as viewed by the participants in study one.

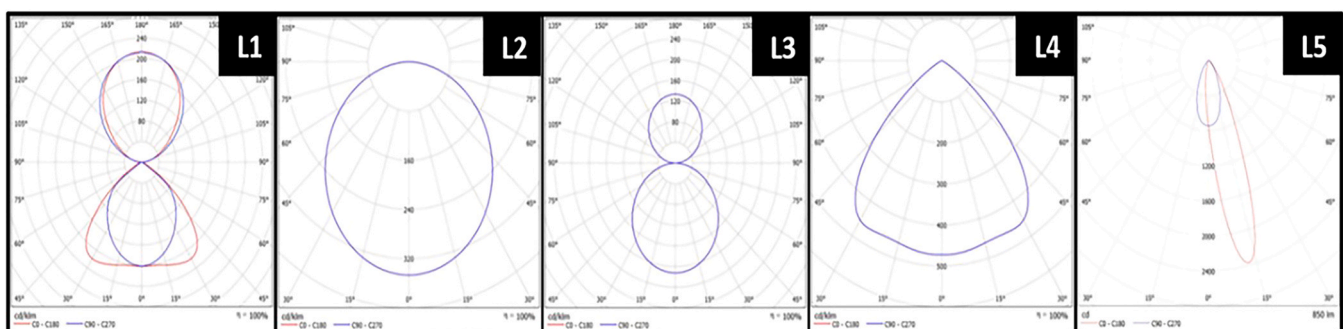


Fig. 7. Light distribution from luminaires for all lighting systems in the study (cd/klm).



Fig. 9. Pictures of the test room for Lighting System 2 (left) and Lighting System 3 (right) as viewed by the participants in study two.



Fig. 10. Pictures of the test room for Lighting System 4 (left) and Lighting System 5 (right) as viewed by the participants in study three.

were used consistently throughout the entire procedure without any adjustments. Detailed information about the experimental procedure is shown in Table 4.

First, participants were welcomed to the waiting room which was lit with a light providing 500 lux at the task area. Participants received information about the aim of the study and their right to cancel their participation at any time. Then participants received information about the discomfort glare, which was provided as follows: “*glare occurs when a part of the interior is significantly lighter than the room's luminosity in general*”. After that, participants were asked to fill in the form which comprised questions about their individual characteristics. After filling in the form, they had an eye vision test. The whole procedure in the waiting room took around 20–30 min. For the second visit in studies two and three, the procedure in the waiting room was shortened to twenty minutes, since the participants' basic information had already been collected during their first visit.

After the welcoming session, all participants were shown to the test room which was designed as an office with a desk and chair. Participants were asked to sit on the chair in the designated area and not to stand up during the procedure. Before evaluating the lighting systems, participants completed both visual tasks and attention tasks, presented in a paper-and-pen format. The attention tasks included the Digit Symbol Test [54] and the Trail Making Test [53,55] which required participants to read instructions on a sheet of paper, find missing symbols and connect numbers on the sheet. The visual tasks included reading numbers and words attached to the walls and writing them on a sheet of paper. The entire procedure took a maximum of one and a half hours.

2.5. Statistical analysis

A priori sample size estimations were conducted using R package “pwrss” to estimate the minimum required sample sizes. For the repeated measures designs (study two and three) the estimated minimum size was $n = 9$ for calculated for Analysis of Variance (ANOVA)

with a statistical power ($1 - \beta$) of 0.80, an alpha of 0.05 and estimated medium effect size (eta squared) of 0.25 [52]. Similarly, the minimum sample size for the analysis of participants' emotional state in each group was estimated to $n = 17$ calculated for independent sample t -test with a statistical power ($1 - \beta$) of 0.80 [52], an alpha of 0.05, mean difference of one score and a standard deviation of one [50].

During the data entry, one missing value was detected in one PANAS item which was assigned the mean value of the item. The questions by Suk were presented to the participants without numbering options and the numbers related to specific answering options were added during the analyses. The range was selected as minimum (1) (e.g. too dark, very dissatisfied, very uncomfortable) to maximum (7) (e.g. too bright, very satisfied, very comfortable). The last (fourth) question by Suk had four answer options, numbered from (1) intolerable to (4) imperceptible.

Statistical analyses were carried out using IBM SPSS version 28.0. The descriptive statistics were used to evaluate SGIs and different UGR values of each lighting system. Kolmogorov-Smirnov and Shapiro-Wilkson tests indicated non-normal distribution for the SGIs ($p < 0.001$). Therefore, non-parametric statistical tests were used to evaluate the hypotheses. To analyse the concurrent validity of the participants' answers using classical SGIs, Spearman's correlation test was used. To compare SGIs in different lighting conditions in repeated measures (study two and three), Friedman's ANOVA using post-hoc analysis with Wilcoxon signed-rank tests were used. To analyse a possible influence of presentation order in study three and individual factors (age and sex) on perceived discomfort glare using SGIs, Mann Whitney U test was used. When analysing participants' age, participants were grouped as either younger (47 years or younger) or older (48 years or older) as this resulted in equal number of participants in each group based on cumulative percentages in the repeated design group. To analyse possible impact of emotional state on perceived discomfort glare using SGIs, Spearman's correlation test was used.

Table 4
Experimental procedure of the study.

	Time (min)	Operation
Before the experiment	- 40	Lights switched on
	- 35	Luminance and illuminance values of the luminaires for the chosen lighting system were re-checked
	- 30	A participant entered the waiting room
	- 29	Brief introduction to the experiment was given to the participant
	- 25	Information about individual factors (e.g. age, gender, medication, eye conditions) and psychological factors (i.e. emotional state) using PANAS [51] were asked to the participant
During the experiment	- 5	The participant entered the test room
	0	Experiment began
	3	Attention task one using Trail Making Test (TMT) [52] was performed by the participant
	8	Visual task one was performed by the participant
	10	Break
	13	Self-report of psychological state (PANAS) [51] was asked to the participant
	18	Attention task two using Digit Symbol Test (DST) [53] was performed by the participant
	21	Break
	23	Questions about behavioural intention to use the lighting systems were asked to the participant
	28	Visual task two was performed by the participant
	31	De Boer scale [31] was asked to the participant
	36	Visual task three was performed by the participant
	39	Hopkinson scale [37] was asked to the participant
	42	Break
	47	Visual task four was performed by the participant
	50	A question on brightness of the luminaires [33] was asked to the participant
	55	Visual task five was performed by the participant
	58	Questions on perceived lighting conditions [43] were asked to the participant
After the experiment	62	Debriefing - feedback from the participant was gathered

2.6. Design-rigor check for presentation order

Analyses of possible influence of presentation order for study three including LS4 and LS5 showed no significant differences using the

classical SGIs (De Boer and the Hopkinson scales) for participants. For the De Boer scale, participants who evaluated LS4 ($Mdn = 21$) and LS5 ($Mdn = 20$) stated no difference, $U = 193$, $z = -0.21$, $p = 0.84$, $r = -0.01$. For the Hopkinson scale, participants who evaluated LS4 ($Mdn = 21$) and LS5 ($Mdn = 20$) stated no difference, $U = 183$, $z = -0.47$, $p = 0.64$, $r = -0.02$.

3. Results

The results are presented in the following order: i) light and energy measurements for all lighting systems, ii) descriptive statistics of subjective glare indexes (SGIs) for each lighting system, along with predicted UGR tabular and observer values, and validity assessments of classical SGIs iii) analyses examining the impact of ambient lighting conditions on SGI values across repeated measures, and iv) analyses of individual factors across three studies.

3.1. Technical measurements of light and energy

The observer and tabular values for each lighting system (LS1–LS5) were calculated in the study. A summary of light and energy measurements are shown in Table 5. The current lighting design standards [20, 21] set limits for the average value across the whole space according to the tabular value (UGR_L) but not according to the observer value (UGR_{obs}) calculated from the CIE formula [17,19]. Since LS1 was localized lighting system, the UGR_L value in LS1 was estimated based on the formula. The calculated observer values (UGR_{obs}) and tabular values (UGR_L) for each lighting system were shown in Table 5. $\bar{E}_h$ corresponds to mean horizontal illuminance whereas $\bar{E}_v$ is the vertical illuminance. $\bar{E}_h$, Task Area ($\bar{E}_h$) in lux was calculated at a desk height of 0.75 metres, whereas $\bar{E}_h$, Floor Level was calculated at a height of 0.85 metres. The ambient light for illuminance ($\bar{E}_{amb}$) and luminance (L_{amb} (cd/m²)) values were calculated for each lighting system based on the formula shown in 1.1. Technical calculations of discomfort glare. Average luminaire luminance from the angle between 65 and 85 ° and luminaire luminance in participants' position are shown in the table.

3.2. Descriptive statistics and validity assessments

The descriptive information on calculated values and subjective

Table 5
Lighting and energy measurement for the different lighting systems.

Summary Light Measurements	LS1	LS2	LS3	LS4	LS5
Illuminance Distribution					
$\bar{E}_h$, Task Area (lux) H = 0.75 m	524	530	545	524	526
$\bar{E}_h$, Floor Level (lux) H = 0.85 m	326	510	535	410	516
$\bar{E}_h$, Ceiling (lux)	141	148	410	83	160
$\bar{E}_v$, Walls (lux)	305	326	324	170	313
$\bar{E}_v$, Eye	229	257	371	225	280
$\bar{E}_{amb}$ (lux)	272	290	341	153	282
$\bar{E}_{amb}$ (lux) ceiling excluded	305	326	324	170	313
$\bar{E}_z$, Observer (lux)	213	331	370	226	259
Luminance Distribution					
L_h , Task Area (cd/m ²)	52	73	72	54	58
L_h , Floor Level (cd/m ²)	35	56	54	34	54
L_h , Ceiling (cd/m ²)	43	48	109	31	49
L_v , Walls (cd/m ²)	57	64	59	34	61
L_{amb} (cd/m ²)	54	60	69	33	58
Patch Luminance (cd/m ²) (minimum–maximum values)	190–205	4490–4880	4490–4880	900–3500	600–3300
L average luminaire luminance (cd/m ² / $y = 65-85^\circ$)	1712	4032	2709	1978	1586
L luminaire luminance in Participants' position (cd/m ²)	Not Available	4200 (57°)	2750 (61°)	7000 (57°)	5500 (57°)
Discomfort Glare (calculated values)					
UGR_L , RuG_L	Not Available	18.0	16.0	20.0	16.6
UGR_{obs} , RuG_{obs} , observers' position	8	18.1	16.6	20.6	16.8
Energy used for lighting					
Installed specific power (w/m ²)	7	6.0	6.0	4.4	9.5

evaluations of discomfort glare for each lighting system is shown in Table 6. In study one, the calculated discomfort glare of LS1 showed imperceptible glare ($UGR_{obs} < 10$), based on the adapted semantic scale of Hopkins (via UGR values) as given by Sawicki and Wolska [37]. However, participants rated discomfort glare of LS1 as *perceptible* using the Hopkins [36] scale and *just acceptable* using the De Boer [31] scale. The second-best lighting condition according to the tabular method was LS3 in study two with a calculated glare value (UGR_L) of 16. By considering De Boer and Hopkins scales, participants evaluated LS3 more positively than the other lighting system (LS2), with median values on both scales indicating *satisfactory* or *just perceptible* glare. By contrast, in study three, when evaluating LS4 and LS5, participants' discomfort glare ratings on both scales showed no difference. The median values of visual comfort question by Suk [42] in study two and three indicated higher visual comfort in lighting systems where the lower calculated perceived discomfort glare was presented. Among all lighting systems, participants exposed to LS3 exhibited highest satisfaction, visual comfort, and lowest visual discomfort using the questions by Suk [42]. The validity assessments of participants' ratings for De Boer [31] and Hopkins [36] scales across all three studies showed strong significant correlations ($r > 0.80$, $p < 0.001$) indicating that participants rated their perception of discomfort glare in a similar manner using two different scales in same lighting conditions.

3.3. Analyses of SGIs across different UGR values within repeated measures

The findings indicated that there were no significant differences ($p > 0.05$) in classical SGIs using De Boer and Hopkins scales across repeated measures (study two and three) despite variations in UGR values under different lighting systems. Even though the calculated discomfort glare value (UGR_L) was lowered in LS3 ($UGR_L = 16$) than LS2 ($UGR_L = 18$) due to ambient lighting, this difference was not significantly visible for participants when using De Boer and Hopkins scales. The non-significant difference using De Boer scale between LS2 ($Mdn = 5$) and LS3 ($Mdn = 7$) was $z = 1.54$, $p = 0.13$, $d = -0.53$ and using Hopkins scale between LS2 ($Mdn = 6$) and LS3 ($Mdn = 8$) was

$z = 1.19$, $p = 0.24$, $d = -0.43$. Similar finding was observed between LS5 and LS4. LS5 had ambient lighting with lowered calculated discomfort glare value of $UGR_L = 17$ than LS4 ($UGR_L = 20$). The non-significant difference using De Boer scale between LS4 ($Mdn = 6.5$) and LS5 ($Mdn = 6.5$) was $z = 0.10$, $p = 0.92$, $d = -0.04$ and using Hopkins scale between LS4 ($Mdn = 7.50$) and LS5 ($Mdn = 7$) was $z = -0.32$, $p = 0.75$, $d = 0.08$.

The following section presents the findings on participants' perceived lighting conditions as measured by the questions from Suk (2019) in relation to calculated UGR values across repeated measures.

3.3.1. Perceived light level

Fig. 11 shows the mean values of each lighting system for the degree of perceived light level at a 95 % confidence interval. Analyses of the degree of perceived light level of the lighting systems showed difference in study two for LS2 ($UGR_L = 18$) and LS3 ($UGR_L = 16$), $\chi^2(1) = 5.4$,

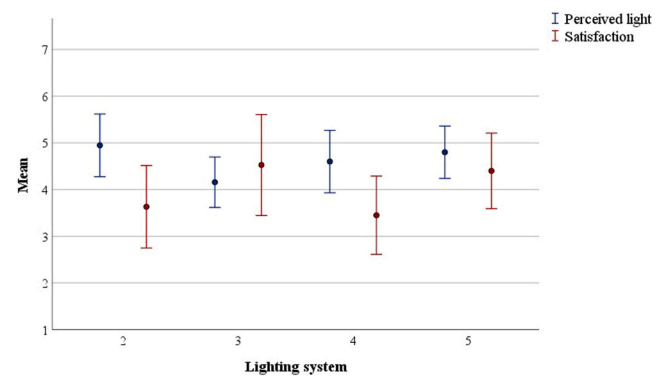


Fig. 11. The dots represent the mean values of the numerical values for the perceived light level and satisfaction for each lighting system. The whiskers represent the 95 % confidence intervals for the mean values. The response options for perceived light ranged from (1) too dark to (7) too bright. The response options for satisfaction ranged from (1) very uncomfortable to (7) very comfortable.

Table 6

Calculated UGR values vs. subjective evaluated values of discomfort glare. Higher numerical values in subjective evaluations indicate lower perceived glare and lower UGR values indicate less glare.

Lighting system	Viewing direction horizontal	UGR_{obs} observers' position	UGR_L tabular method	De Boer (Range 1–9) mean/ median (SD)	Hopkinson (Range 1–9) mean/ median (SD)	Suk ¹ (perceived light level) (Range 1–7) mean/ median (SD)	Suk ² (satisfaction) (Range 1–7) mean/ median (SD)	Suk ³ (visual comfort) (Range 1–7) mean/ median (SD)	Suk ⁴ (visual discomfort) (Range 1–4) mean/ median (SD)
LS1	G1 (N/A)	< 10	< 10	5.6 / 5.5 (2.2)	6.0 / 7.0 (2.2)	4.6 / 5.0 (1.3)	4.0 / 4.5 (1.6)	4.0 / 3.5 (1.8)	3.1 / 3.0 (0.9)
LS2	G2 (L2)	18.1	18	5.2 / 5.0 (2.3)	5.8 / 6.0 (2.3)	5.0 / 5.0 (1.4)	3.6 / 3.0 (1.8)	3.6 / 3.0 (1.6)	2.8 / 3.0 (0.8)
LS3	G4 (L2) G6 (L2) G2 (L3)	18.1 17.8 16.5	16	6.42 / 7 (2.2)	6.7 / 8.0 (2.1)	4.2 / 4.0 (1.1)	4.5 / 6.0 (2.2)	4.7 / 6.0 (2.1)	2.2 / 4.0 (0.9)
LS4	G4 (L3) G6 (L3) G2 (L4)	15.5 16.6 20.6	20	5.7 / 6.5 (3.0)	6.5 / 7.5 (2.7)	4.6 / 4.0 (1.4)	3.5/3.0 (1.8)	3.5/3.0 (1.9)	2.9 / 3.0 (0.9)
LS5	G3 (L4) G4 (L4) G5 (L4) G2 (L4)	20.4 20.3 20.1 16.8	17	5.8 / 6.5 (2.3)	6.30 / 7.0 (2.5)	4.8 / 4.5 (1.2)	4.4 / 4.5 (1.7)	4.4 / 4.0 (1.7)	3.3 / 3.5 (0.9)
	G3 (L4) G4 (L4) G5 (L4)	16.7 16.5 16.4							

Note: Higher numerical values for responses to the question from Suk⁴ indicate lower discomfort.

$p = 0.02$, $d = 0.64$. Even though participants reported slightly higher level of brightness from LS2 ($Mdn = 5$) than LS3 ($Mdn = 4$), further analysis failed to indicate the difference, $z = -1.90$, $p = 0.57$. There was no significant difference between participants in study three who evaluated LS4 and LS5, $\chi^2(1) = 0.09$, $p = 0.76$, $d = -0.15$.

3.3.2. Satisfaction

Fig. 11 shows the mean values of each lighting system based on participants' perceived satisfaction. Analyses of the degree of satisfaction between the lighting systems showed no significant difference in study two between LS2 and LS3, $\chi^2(1) = 1.5$, $p = 0.23$, $d = -0.45$, as well as in study three between LS4 and LS5, $\chi^2(1) = 3.3$, $p = 0.07$, $d = -0.51$.

3.3.3. Visual comfort

Fig. 12 shows the mean values of the visual comfort levels for each lighting system. Analyses of the degree of visual comfort between the lighting systems showed that the participants in study two stated slightly higher comfort when evaluating LS3 ($Mdn = 6$) compared to LS2 ($Mdn = 3$), $z = -1.73$, $p = 0.08$, $d = -0.59$. This pattern was observed by the other participants in study three who evaluated LS5 ($Mdn = 4$) and LS4 ($Mdn = 3$), $z = -1.81$, $p = 0.07$, $d = -0.50$. However, the difference was not significant for LS2 and LS3, $\chi^2(1) = 3.8$, $p = 0.05$, and for LS4 and LS5, $\chi^2(1) = 2.9$, $p = 0.09$.

3.3.4. Visual discomfort

Fig. 12 shows the mean values of the perceived discomfort levels for each lighting system. Analyses of the degree of visual discomfort between the lighting systems showed that participants experienced slightly higher comfort in study two when evaluating LS3 ($Mdn = 4$) compared to LS2 ($Mdn = 3$), but this difference was not significant, $\chi^2(1) = 3.3$, $p = 0.07$, $d = 0.70$. This pattern was observed among the other participants in study three who evaluated LS5 ($Mdn = 3.5$) compared to LS4 ($Mdn = 3$), $\chi^2(1) = 3.8$, $p = 0.05$, $d = -0.44$.

3.4. Individual factors influencing perceived discomfort glare (H_2)

3.4.1. Age

No significant differences of perceived discomfort glare using classical SGIs among the age groups were found in all three studies. However perceived light level among younger (20–47 years) and older age (48–76 years) group varied in study two that included LS2 and LS3. For LS2, the older group reported a higher brightness ($Mdn = 12.5$) than the younger group ($Mdn = 7.2$), $U = 20$, $z = -2.1$, $p = 0.04$, $r = -0.11$. For LS3, the older group also reported a higher brightness ($Mdn =$

12.3) than the younger group ($Mdn = 7.4$), $U = 22$, $z = -2.0$, $p = 0.04$, $r = -0.11$.

3.4.2. Sex

A significant difference in perceived discomfort glare using classical SGIs was found between sexes in study two that included LS2 and LS3. For LS2, the male participants reported less glare than the female participants using the De Boer scale (male $Mdn = 13.0$, female $Mdn = 6.7$), $U = 15.00$, $z = -2.54$, $p = 0.01$, $r = -0.58$ and the Hopkins scale (male $Mdn = 12.6$, female $Mdn = 7.2$), $U = 19.50$, $z = -2.13$, $p = 0.03$, $r = -0.49$. In addition, for LS3, the male participants reported less brightness than the female participants (male $Mdn = 6.7$, female $Mdn = 13.7$), $U = 12.00$, $z = -2.93$, $p = 0.00$, $r = 0.67$. However, no significant difference was found between the sexes in study one (for LS1) and study three (for LS4 and LS5).

3.4.3. Emotional state

A significant association between perceived lighting conditions and reported having a positive/negative emotional state was found in study one including LS1. For this lighting system, participants who reported a positive emotional state indicated less discomfort glare using the Hopkins scale [36], $r(18) = 0.5$, $p = 0.02$, $r^2 = 1.0$, and higher satisfaction with the lighting system in response to the question by Suk (2019), $r(18) = 0.6$, $p = 0.01$, $r^2 = 1.8$. However, this pattern was not observed in study two (for LS3 and LS4) and three (for LS4 and LS5). Also, there was no significant association of perceived lighting conditions by Suk (2019) between participants reporting positive and negative emotional state across all studies.

4. Discussion

4.1. Subjective perception of discomfort glare in comparison to UGR values

The main aim of the paper was to investigate whether subjective discomfort glare experiences were in line with predicted discomfort glare calculations using UGR values. Although participants in repeated measures (study two and three) reported less perceived discomfort glare on De Boer [31] and Hopkins [36] scales for the lighting systems with lower UGR values than for the other lighting systems, the difference was not large enough to be statistically significant. Moreover, participants in study one rated perceived glare of LS1 as *perceptible* using the Hopkins scale while according to the predicted calculated UGR_L value of this lighting system resulted in as *imperceptible* discomfort glare [37]. This result can be explained in different ways. First, the classical SGIs ask a subject to rate discomfort glare experience, but the definition of glare is not clearly understood by people. Although the participants were informed at the beginning of each session about what glare is and how to evaluate it, it seems that the participants in study two interpreted it differently than intended. Instead of thinking of discomfort glare, they evaluated the relative room brightness. This was confirmed by the perceived brightness of the room question from Suk [42] in study two. The results showed that a lower perceived brightness of the room was reported when the UGR value decreased for LS3 ($UGR_L = 16.0$) in comparison to LS2 ($UGR_L = 18.0$). Second, despite the variations in calculated UGR values of the lighting systems in the repeated measures (study two and three), there were no reported visible differences of perceived discomfort glare. Although the studies compared the most commonly used office lighting systems, the difference in UGR units between them was only two, which may be too small for participants to visually notice. For instance, there were no greater predicted differences regarding UGR values between participants in study two who evaluated LS2 ($UGR_L = 18.0$) and LS3 ($UGR_L = 16.0$) and in study three who evaluated LS4 ($UGR_L = 20.0$) and LS5 ($UGR_L = 16.6$). This result reveals a gap in how lighting designers and the general public perceive discomfort glare, with the latter having a less comprehensive

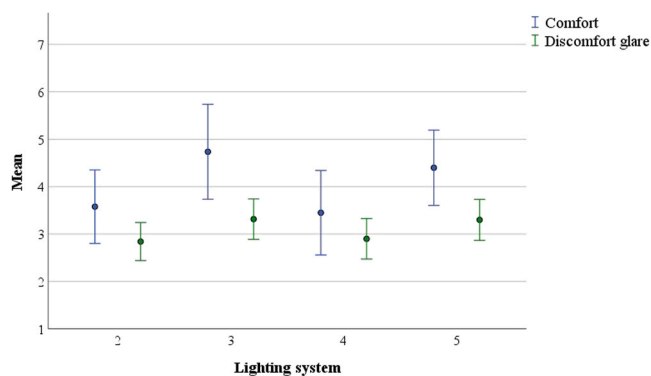


Fig. 12. The dots represent the mean values of the numerical values for visual comfort and discomfort glare experiences for each lighting system. The whiskers represent the 95 % confidence intervals for the mean values. The response options for visual comfort ranged from (1) very uncomfortable to (7) very comfortable. The response options for discomfort glare ranged from (1) intolerable to (4) imperceptible.

understanding of the phenomenon.

Apart from the findings for classical SGIs (the De Boer and Hopkinson scales), the descriptive statistics of the perceived lighting conditions by Suk [42] in repeated measures (study two and three) showed that higher degree of comfort and satisfaction were exhibited by participants in experiments where the lowest UGR values were presented (see Table 6). Similarly, responses to the visual discomfort question by Suk [42] indicated that lower degree of visual discomfort was exhibited by participants where the lower UGR values were presented. However, the differences between the responses in each study were not large enough to provide a significant difference. Considering the findings from visual comfort question by Suk [42], it is most likely that all participants in study two and three evaluated the perceived discomfort glare by directly looking at the luminaires and the ceiling area. The calculated differences in study two between LS2 and LS3 were visible by directly looking at the luminaires but the calculated differences in study three between the LS4 and LS5 could be noted by looking at the walls and not directly looking at the luminaires or ceiling. As all UGR values consider a horizontal viewing direction, our findings do not show similarities as expected for the predicted discomfort values of UGR since participants also considered luminaires and the ceiling area when evaluating lighting systems. Similarly, in a Danish study [56], 18 participants took part in a study about glare and were asked if the situation with wall washers was more or less glary than a situation without wall washers. The expected result was that wall washers should reduce the perceived discomfort glare. However, five participants experienced the opposite, and three did not see any difference.

In summary, our findings showed the challenges of asking participants to rate the degree of discomfort glare. As the need of new methods for assessing perceived discomfort glare while continuing the use of category ratings has been previously emphasized [23,57], we suggest that new assessments of perceived discomfort glare could better include the evaluation of perceived lighting conditions (i.e. satisfaction, comfort, discomfort) rather than relying solely on glare ratings. It is also important that future evaluations of perceived discomfort glare in indoor environments consider eye illuminance as a proxy for adaptation, similar to the Daylight Glare Probability metric [58]. Furthermore, similar to the studies on daylight discomfort glare [59], including an initial question on whether the participant is experiencing discomfort glare with binary response options (i.e., yes or no) before asking about the severity of the discomfort could be beneficial for evaluating self-reported perceived discomfort glare from LEDs.

4.2. Evaluations of predicted discomfort glare calculations

The evaluated lighting systems were all commonly used in different indoor lighting applications and, according to the European standard for indoor workplaces [20], the predicted discomfort glare value UGR_L should not exceed 19, for example in offices and classrooms in schools. LS1 was a localised lighting system with additional wall washers and had a UGR_{obs} below 10 thus should not have caused any discomfort glare. LS2 was a general lighting system with direct light with a UGR_L of 18 and thus fulfilled the required value of ≤ 19 . LS3 was equal to LS2 but with suspended luminaires having both direct and indirect lighting. Due to the indirect component, the calculated UGR_L value was reduced to 16 and should therefore have caused less discomfort glare. LS4 had downlights for general lighting with a UGR_L of 20 and thus exceeded the current mandated limit of 19 for offices and schools. LS5 was equal to LS4, but the system was equipped with additional wall washers. Due to the increased background luminance (ambient light), the UGR_L value was reduced to just below 17 and was expected to provide less discomfort glare.

Regarding the results from the UGR calculations of discomfort glare, there was a minor deviation between the CIE tabular method versus the CIE formula when taking the actual observer position into an account. The UGR_{obs} values from the CIE formula did not exceed more than 1 unit

versus the UGR_L values according to the CIE tabular method. This may be attributed to the fact that all participants evaluated the whole lighting system from the same location. According to the UGR tabular formula, all lighting systems except LS4 were below the required value of 19, whereas the predicted discomfort value of LS4 exceeded the limit by 1 unit. The single unit change did not make much difference in practice and therefore the threshold of discomfort glare was not visible by the participants.

In addition to the commonly used UGR method, all lighting systems were also evaluated using Borderline between Comfort and Discomfort (BCD) calculations [30], which consider the Guth Position Index to assess the effect of sensation in the line of sight. Fig. 13 shows the highest luminaire luminance and background luminance for the different lighting systems evaluated by the participants at specified viewing angles from the baseline within their normal field of view. According to the BCD graph, LS3 was the only system that clearly reached the comfort zone. The luminance values from luminaire types used in the different lighting systems are shown in Fig. 15 together with the participants' viewing angles towards the luminaire versus its background luminance.

In our study, the calculated UGR values show that LS1, LS2, LS3 and LS5 are below the perceived discomfort glare limits of 19 for offices and schools. This was due to the higher wall brightness which can be seen when the participants' viewing direction is horizontal towards the front wall (see Figs. 14 and 15). LS4 and LS5 had the highest level of perceived discomfort glare due to high luminance ratio between the luminaire and the immediate surrounding in the ceiling when participants' viewing direction is across the luminaire. Of all lighting systems, LS3 showed best comfort as it had the smallest luminance ratio between the luminaire and the immediate surrounding in the ceiling when the viewing direction is across the luminaire.

4.3. Possible factors influencing perceived discomfort glare

Findings indicated that individual factors (i.e. age, sex, and emotional state) were associated with perceived discomfort glare, though this association was not consistent across all studies. Regarding the differences between age groups, only study two revealed that older participants (ages 48–76) reported greater perceived brightness compared to younger participants (ages 20–47) which is in line with the findings of Bennett [46] that older people are more sensitive to discomfort from greater brightness. However, in all three studies, no age-related differences were found when participants rated their degree of discomfort glare through classical SGIs, consistent with previous findings including Saur [43] and Van Den Wymelenberg [47]. Regarding the differences between sexes, in study two, female

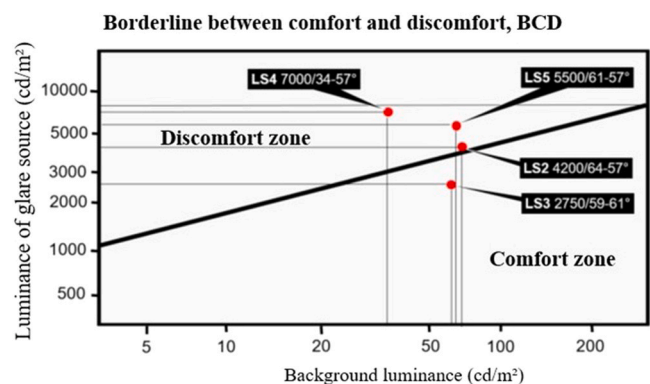


Fig. 13. The luminance of glare source subtending 0.0011 (approx. 2° square) at a discomfort threshold (BCD) as a function of the background luminance (light to which the eyes are adapted): moderate background luminance. $L_b = 302F^{0.44}$ (F = adaptation luminance).

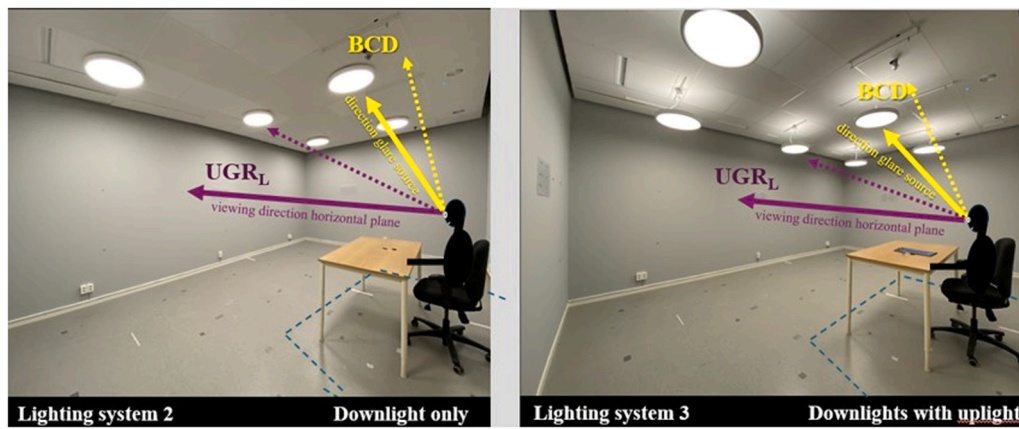


Fig. 14. Differences between UGR_L and BCD calculations for the viewing directions for LS2 and LS3.

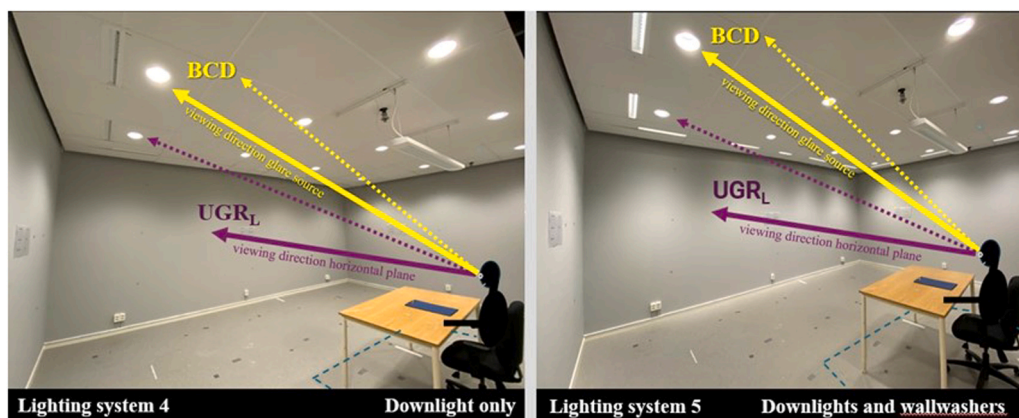


Fig. 15. Differences between UGR_L and BCD calculations for the viewing directions for LS4 and LS5.

participants reported greater sensitivity to discomfort glare and greater perceived brightness compared to the male participants. This results were in line with the findings of Marié et al [26], by showing the difference between sexes on perceived discomfort glare. Conversely, study three found no sex-related differences in perceived discomfort glare, consistent with earlier works by Kent et al [45], and Verriotto et al [27]. Concerning emotional state, only participants in study one exhibited a significant association between positive emotional state and less perceived discomfort glare by using the Hopkinson [36] scale and higher satisfaction with the lighting system in response to the question by Suk [42]. However, the other studies (study two and three) failed to replicate this finding. This result diverges from Osterhaus [49], who similarly found no significant impact of emotional state (negative vs. positive) on SGIs.

In summary, results from study two revealed that older participants were more sensitive to brightness when exposed to opal luminaires with UGR_L values of 18 (LS 2) and 16 (LS 3). Under the same lighting conditions, female participants reported greater sensitivity to discomfort and perceived brightness compared to male participants. However, this difference was not evident in study three, where only downlights (LS 4 with UGR_L 20) and downlights with wall washers (LS 5 with UGR_L 16.6) were used. Additionally, variations in emotional state, perceived discomfort, and satisfaction were only observed in the non-repeated experimental design of study one, where the UGR value indicated an imperceptible glare condition ($UGR_L < 10$). It therefore remains uncertain whether this finding was influenced by the experimental design or the lighting systems employed. Future research incorporating both repeated and non-repeated designs with identical lighting setups would help clarify this issue. Overall, to better understand how individual

factors contribute to perceived discomfort glare, further studies with larger sample sizes and a focus on specific demographic groups (such as older people) are strongly recommended.

4.4. Implications

This study contributes to the understanding of perceived discomfort glare and the individual factors affecting this phenomenon. The findings of the study contribute to the development of new SGIs by indicating the issue of solely asking participants to rate the degree of discomfort glare. The study also employed the Boundary Between Comfort and Discomfort (BCD) calculations to incorporate ambient illuminance into the assessment of perceived discomfort glare. Compared to the UGR method, BCD values more closely aligned with participants' reported comfort levels. We posit that emphasizing BCD calculations, rather than solely relying on UGR values, is crucial, as our findings suggest that participants focused on luminaires and ceiling areas rather than the horizontal plane when responding to SGIs. The BCD method could be further improved and used to improve the accuracy of predicting discomfort glare, potentially leading to the development of new methods.

4.5. Limitation and suggestions for future studies

Several factors may limit the generalizability of our findings. First, presentation order was controlled for participants who exposed to LS4 and LS5, but not for those exposed to LS2 and LS3. This was due to practical constraints: LS2 and LS3 were ceiling-mounted and required separate installation, which was not feasible within the data collection

timeframe. Accommodating these installations would have prolonged intervals between experimental sessions, increasing the risk of dropouts and thereby compromising the comparability of SGIs. However, in the group where order effects were controlled (i.e., LS4 vs. LS5), analysis revealed no significant order effect. Second, due to the design of the study, it was not possible to control whether participants looked above and behind where they sit during the breaks. Even though we tried to control participants' viewing directions through visual tasks, our results indicated that they evaluated lighting scenarios by directly looking at the luminaires and the ceiling area. Third, all participants were presented each of the subjective glare scales in the same order. This may create some anchor bias as wording options are different for each subjective glare scale [57]. Future studies could be carried out to evaluate the possible order effects caused by the order of the presented scales and response options. Fourth, the data were collected in Sweden, and pre-validated scales in Swedish language were limited. While pre-validated translations of the PANAS scale were used, no such validations were available for the SGIs, which were therefore translated by the authors. The translation of the SGIs may introduce a bias as the semantic meaning of words can vary between languages (see [23]). Fifth, the answer options for the classic glare scales (De Boer and Hopkins) were presented as numerical values from one to nine alongside descriptions, whereas questions by Suk included only category-based information (i.e. descriptions) without numerical values. This difference stems from the use of pre-validated scales. Future research comparing the possible effect of category-based versus number-based answer options on discomfort glare assessment would be beneficial. Sixth, to minimize bias arising from prior knowledge of discomfort glare, all participants were provided with a definition of discomfort glare before seeing the lighting systems. However, this may have introduced another bias, as participants might have focused on identifying discomfort glare when they saw the lighting system. Final, participants did not report high level of discomfort nor dissatisfaction. This might be related to central tendency bias in which participants might avoid choosing extreme ratings.

5. Conclusion

The results from the De Boer and Hopkins scales (as mentioned classical subjective glare indexes) were not in line with our expectations according to the predicted calculated (UGR) values. The reasons for this may be (1) the classical subjective glare indexes

were too advanced for participants to understand what glare is and evaluate the glare accordingly, and/or (2) the participants were not looking within the normal field of view as calculated from UGR method but rather considering the lighting systems in relation to ambient lighting. The descriptive statistics of visual comfort, discomfort, and satisfaction questions from Suk [42] in study two and three revealed that low-UGR conditions with ambient lighting were rated more positively than high-UGR conditions without ambient lighting; however, the magnitude of these differences did not achieve statistical significance. Our results showed that understanding of discomfort glare is varied, and may be influenced by individual factors such as age, sex, and emotional state with results showing inconsistency across the lighting systems. We believe that developing new methods for more accurately predicting perceived discomfort glare is essential for improving the correspondence between the UGR values and SGIs. Our study provides new insights of understanding subjective discomfort glare using three different scales as well as discussing relevant technical calculations of discomfort glare. The results could be used to design new subjective evaluations to provide a better understanding of discomfort glare.

CRedit authorship contribution statement

Klas Sjöberg: Writing – review & editing, Conceptualization. **Thorbjörn Laike:** Writing – review & editing, Writing – original draft,

Validation, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Tommy Govén:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Zeynep Ekim Olsson:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Madeleine Selvander:** Writing – review & editing, Methodology, Conceptualization.

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. Thorbjörn Laike reports financial support was provided by Swedish Energy Agency. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indenv.2026.100149.

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