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COMFORT VIEW ZONE: MEASURING DISCOMFORT GLARE

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Abstract

Measuring discomfort glare is a notoriously difficult task. Many physiological measures (like pupil response) and psychophysical measures (like subjective rating scales) have been proposed. Two important complicating factors are the large individual variability in glare sensitivity and the strong influence of the observer's gaze direction. Instead of attempting to fixate the gaze direction, we propose a method where respondents are free to determine the range of comfortable viewing directions: the "comfort view zone". This range is individual and depends on the context of the experiment. Variations in lighting conditions will then lead to relative individual variations in the comfort view zone, which is used as a measure of discomfort glare. Pilot tests in outdoor and indoor lighting setups shows promising results: the measure is sensitive to modest variations in light output, and to variations in luminance distribution of the glare source.

Keywords: Discomfort glare, Methodology, Viewing direction, Position index, Outdoor lighting, Indoor lighting, Glare source uniformity

1 Introduction: measuring discomfort glare and the sensitivity to gaze direction

Discomfort glare, a significant issue in both indoor and outdoor lighting environments, has been the subject of extensive research (e.g.: CIE, 1983, CIE, 1995, CIE, 2019, CIE, 2021, Boyce, 2003, Luckiesh and Guth, 1949, Vos, 2003, Takase and Hara, 2021, Fotios and Kent, 2020, Tyukhova, 2024, Vissenberg, 2023). The primary methodologies to measure discomfort glare involve subjective psychophysical assessments and objective physiological measures, each with their own advantages and limitations.

The most common approach involves subjective rating scales, like the De Boer scale (ranging from "unnoticeable" to "intolerable"). This method relies on human perception, providing valuable insights into subjective experiences. However, it is known that people may interpret the subjective scale labels differently, and that the results are often biased by the experimental design (Fotios and Kent, 2020). This severely limits the comparison of results obtained in different studies and makes the method less suitable for universal applicability.

Physiological methods aim to quantify discomfort glare objectively by measuring the body's response to glare stimuli. Techniques include pupil size monitoring, eye movement tracking, and electroencephalography (EEG) to detect brain activity related to discomfort (for a review, see, e.g. Tyukhova, 2024). These methods offer objective data, bypassing the biases inherent in subjective scales. However, they require specialized equipment, which limits their practicality in real-world settings or large-scale studies. Furthermore, a single physiological measure may not cover all situations since the underlying mechanisms of discomfort glare remain unknown.

For another type of glare, disability glare, the underlying mechanism is known to be scattering of light in the eye (Vos, 2003). The dependence of disability glare on e.g. glare source properties, observer age, iris colour, or the deviation angle θ between glare source and gaze direction could be determined by measurements of light scatter profiles inside the eye. For instance, the veiling luminance that diminishes the contrast of the object to be observed decreases according to ~$1/\theta^2$, known as the Stiles-Holladay equation.

The dependence of discomfort glare on the position of the glare source in the observer's field of view was determined in a psychophysical experiment by Luckiesh and Guth, 1949. They found that the BCD (boundary between comfort and discomfort) luminance of a test source is lowest in foveal view and increases with increasing eccentricity. The Guth position index, the multiplication factor for the BCD luminance as a function of position in the visual field, is used in the Unified Glare Rating (UGR, see CIE, 1995) as well as in several other discomfort glare measures (Tyukhova, 2024). The Luckiesh and Guth experiment showed large individual variations in BCD value up to a factor 10, due to individual variations in glare sensitivity. Takase and Hara (2021) reported BCD luminance values for 5 observers with a similarly large individual spread, but a much steeper increase in BCD value close to foveal view. This may be due to the different experimental setup, and/or related to the fact that the 5 observers in this test were very skilled at keeping a fixed gaze on the target.

The decrease of the glare effect with increasing eccentricity is much less steep for discomfort glare (Guth position index) than for disability glare (Stiles-Holladay). Exceptions to this rule are e.g. discomfort glare formulas related to outdoor sports lighting, car headlights, or road lighting (see e.g. the review by Tyukhova, 2024). These show a steep variation in glare sensitivity for source positions close to the fovea, resembling that of the Stiles-Holladay law. This suggests that for some outdoor lighting conditions (dark ambient lighting conditions, small sources) the halo caused by light scattering in the eye influences the discomfort or at least the suggestion of discomfort. In indoor electric lighting, the background lighting is generally at a high level. Such halos are then almost never observed and therefore do not contribute to discomfort.

Despite the influence of individual sensitivity or contextual parameters, discomfort generally increases when the glare source is closer to the observer’s gaze direction. Most glare methods try to eliminate this influence by forcing an unnatural fixed gaze direction. Instead, we propose to use the gaze direction itself to measure the BCD: the “comfort view zone” is the range of viewing directions for which the glare source is deemed comfortable. The degree of comfort relates to the size of this comfort view zone, which remains individual and context dependent. Discomfort glare can now be measured for different conditions by considering the relative change in comfort view zone per individual.

The benefits of this new approach are:

- variations of discomfort glare with gaze direction are no longer a disturbing factor,
- respondents are not forced to fixate the gaze in a direction that is very uncomfortable,
- respondents are free to use their own individual judgment of “just uncomfortable” glare, since only relative deviations in gaze direction are used.

This “comfort view zone” method was tested in a glare experiment in a simulated outdoor setting. This experiment demonstrates that the method is sensitive enough to distinguish small variations in discomfort (caused by 30% variations in glare source flux) with a small group of observers (10).

Furthermore, the comfort view zone method was applied in two small-scale experiments to address two issues linked to discomfort glare and gaze direction:

- the point source approximation (regularly used in outdoor lighting glare models that use the source intensity or eye illuminance, without taking into account the glare source size, see CIE, 2021)
- the uniform source approximation (used by most other discomfort glare models, see CIE, 2019 and 2021).

The visibility of glare source details strongly depends on the position of the source in the visual field. Typically, in both indoor and outdoor lighting the gaze direction is assumed to be either horizontal or below the horizon and the glare source is in the periphery of the visual field. In that case the detailed luminance distribution is often not visible in indoor lighting situations (see Annex A1 of CIE 2019). At the longer viewing distances that are customary in outdoor lighting, the peripheral resolution is even insufficient to discern the overall size of the glare source and it may be considered as a point source. When people look around freely, they might see more details of the source and these assumptions are then no longer valid. These assumptions are tested by two pilot tests in which the luminance of the glare source is varied in a simulated outdoor setting and in an indoor setting.

2 Experiments

Three experiments were conducted, two in an outdoor setting, and one in an office setting. The first experiment tested the sensitivity of the new comfort view zone method for measuring (dis)comfort perception of an outdoor luminaire in a simulated outdoor environment. In this experiment only the intensity of the luminaire was varied to see how this affects the range of comfortable viewing directions.

In the second experiment in a similar outdoor setting both the intensity and the luminance of the glare source was varied, the latter by using a diffuser foil in front to the glare source. The effect of the diffuser on the intensity in the direction of the observer was cancelled out by calibrating the luminaire flux such that the illuminance at the observer's eye stays the same.

In the third experiment in an office setting, both intensity and glare source uniformity were varied by comparing a uniform office lighting panel to highly non-uniform experimental office lighting luminaire. As in experiment 2, the luminaire light output was calibrated such that the eye illuminance was the same.

2.1 Participants

In the first experiment, 10 participants (5 males, 5 females, aged 24-54 years) were recruited from employees and students. Inclusion criteria were normal or corrected-to-normal vision and no history of ocular disease. In the second experiment, 9 participants were recruited (5 M, 4 F, aged 24-54 years), and in the third experiment 7 participants were recruited (5 M, 2 F, aged 28-58 years), following the same inclusion criteria as in the first experiment.

2.2 Setup and stimuli

The experimental set-up for experiments 1 and 2 is shown in Figure 1 (a schematic representation of the set-up, a picture taken from an observer's position, and a sketch of the dimensions). An outdoor luminaire was mounted at a height representative for urban outdoor lighting: a typical street lighting luminaire containing 6x6 lensed LEDs behind a glass cover. The luminaire flux was adjusted to vary eye illuminance at the observer's position. This was the only variable in this experiment with the goal to test the method.

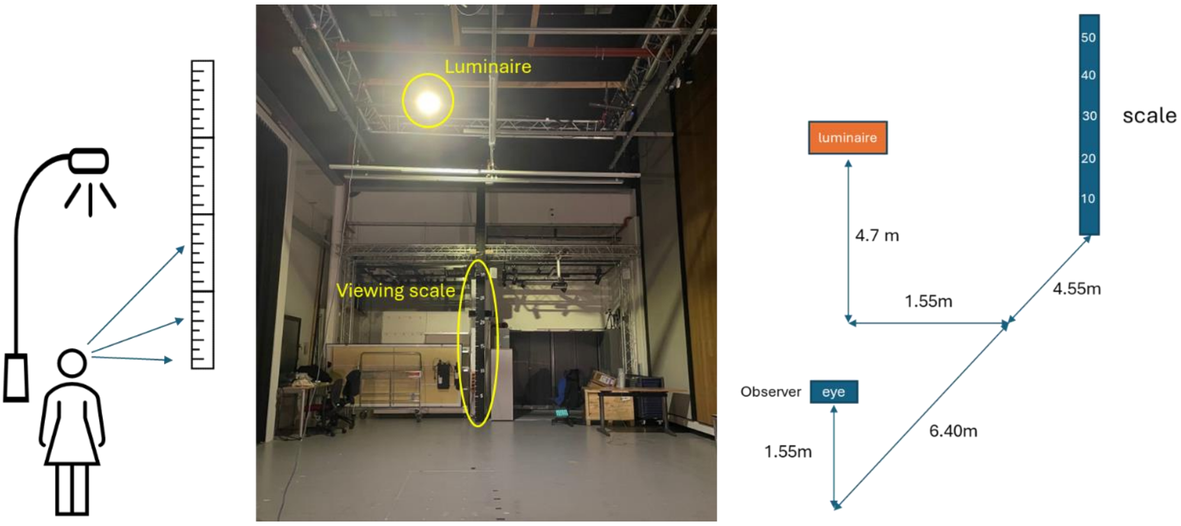

Figure 1 – Experimental setup (schematic representation, photograph and sketch of dimensions) showing the position of the light source and of the viewing scale.

The observer was instructed to look at a vertically positioned scale at 10,95 m distance right in front of the observer: a viewing direction along a hypothetical street direction. The luminaire was placed at 6,4 m distance along the "street" direction, 1,55 m to the left of this line and 4,7 m above the floor. In this setup, the Guth position index is 2,7 when the observer looks straight ahead (at scale position 15,5 dm above the floor). When looking slightly up, to e.g. scale position 30 dm, the Guth position index reduces to 2,0, which indicates a stronger glare effect. When looking slightly down, at position 0 dm on the scale, the Guth position index increases to 3,9, which indicates lower glare. As a result, 0,6 m displacement of the gaze along the scale corresponds with ~1 point difference in Unified Glare Rating (UGR), a just noticeable difference (CIE, 1995). Given the outdoor lighting setting, sensitivity to gaze direction may be even stronger (CIE, 2021, Tyukhova, 2024).

Three lighting conditions were used, resulting in 7 lx, 10 lx and 13 lx, measured at eye position. Eye illuminance higher than the middle value (10 lx) is known, from experience, to lead to discomfort glare in street lighting. The variation of 30% in luminaire flux is expected to cause a just noticeable difference in discomfort glare (1 UGR point). Ambient lighting (by two luminaires behind the observer) contributed ~1 lx to the eye illuminance, which is typical for outdoor lighting conditions. Each light level condition was repeated 5 times in random order. A break of 20 sec was used in between each stimulus presentation.

In the second experiment, the same simulated outdoor setting was used as in experiment 1, with the same positions of observer, luminaire and viewing scale. In this experiment, the luminaire was an experimental prototype consisting of a single line of lensed LEDs. The variable parameters in this experiment were the eye illuminance at the observer's position and the presence of a diffuser foil to cover the row of lensed LEDs. To minimize the effect of the diffuser on the intensity distribution, a holographic elliptical diffuser with limited scattering angles (1°x15°, Brightview E-0115-PE07-S) was used, bent in a cylinder shape over the line of LEDs. The diffuser did not make the source appearance fully uniform (individual light sources were still distinguishable when looking straight at the luminaire), but did reduce the peak luminance by a factor of ~3 by increasing the area of the bright dots. This subtle variation in luminance is not likely to be observed in peripheral view of an observer that is looking straight along the street direction, but it makes a big difference when one looks straight at the luminaire. In this experiment, the observers were allowed to look up and down along the scale to test the effect of luminance reduction (at constant intensity) in case the gaze is not fixed. The luminous flux of the luminaire was adjusted to have the same eye illuminance at the observer's position with or without diffuser: 7 lx, 10 lx and 13 lx.

In the third experiment an office setting was used. Observers were seated (eye height 1,2 m) on one side of an office, while two office luminaire panels (both approximately 60 cm by 60 cm) were mounted next to each other on the ceiling on the opposite side of the office, at 2,60 m height. Two observer positions were used: at the first position, 3 m in front of the luminaires, the luminaires are located at 25° above the horizon, while at the second position, 1,4 m in front of the luminaires, the luminaires are 45° above the horizon. The viewing scale was mounted on the wall behind the luminaires, right in between the two adjacent test luminaires. The test luminaire on the left was a standard office lighting panel with a uniform luminance distribution over the full surface area of the panel. The test luminaire on the right was an experimental office luminaire consisting of about 200 small LED clusters with separate optical elements, which resulted in a highly non-uniform luminance distribution over the luminaire surface. The high contrast of this non-uniform luminance distribution is clearly uncomfortable to people who look straight at the luminaire. On the other hand, according to CIE 232 (2019) this type of fine-grained non-uniformity would not lead to any UGR penalty, i.e. the discomfort glare should be comparable to that of the uniform luminaire for an observer with a fixed horizontal gaze direction. In this small pilot test, the observers were allowed to look up and down along the scale to test the effect of non-uniformity of glare source luminance when the gaze is not fixed. The luminaire flux of the experimental luminaire was adjusted to give the same vertical illuminance at the observer's eye as the standard office panel at 100% output and at 70% output. The ambient lighting was provided by the regular office lighting installation at horizontal illuminance levels on the desk between 500 lx and 700 lx.

2.3 Procedure

In the outdoor setting, participants were seated 10,95 m from the viewing scale on a stool with adjustable height, such that eye height was at 1,55 m. They were instructed never to look directly into the luminaire, to avoid overexposure and after images. Then they were instructed to look at the scale and answer one question: “At what height on the scale (viewing direction) the glare from the luminaire starts to become uncomfortable?”. The observer was free to start at the bottom of the scale and look up until the light becomes uncomfortable or start from the top and look down until the light becomes comfortable or try both. The higher the observer could look without experiencing discomfort, the larger the comfort view zone.

In the indoor setting, participants were seated at a desk straight in front of the scale and the two luminaires. Because the scale ends at the luminaire, the participants sometimes looked directly into the luminaires. Because of the much lower brightness contrast in the indoor lighting setting, this did not lead to overexposure or adaptation issues. Aside from this aspect, instructions were the same as for the outdoor experiments.

2.4 Results and discussion

Experiment 1: Testing the sensitivity of the method.

Figure 2 shows the gaze positions of all 10 participants for all settings. The whole scale appears to be used by the participants. On average, participants rate toward the middle of the scale, which is usually a consequence of the test setup itself. The spread in individual BCD gaze positions for the different stimuli is about 10 dm on the scale. This is roughly in agreement with the estimated spread of 2x6 dm associated with the applied intensity variation of +/- 30%.

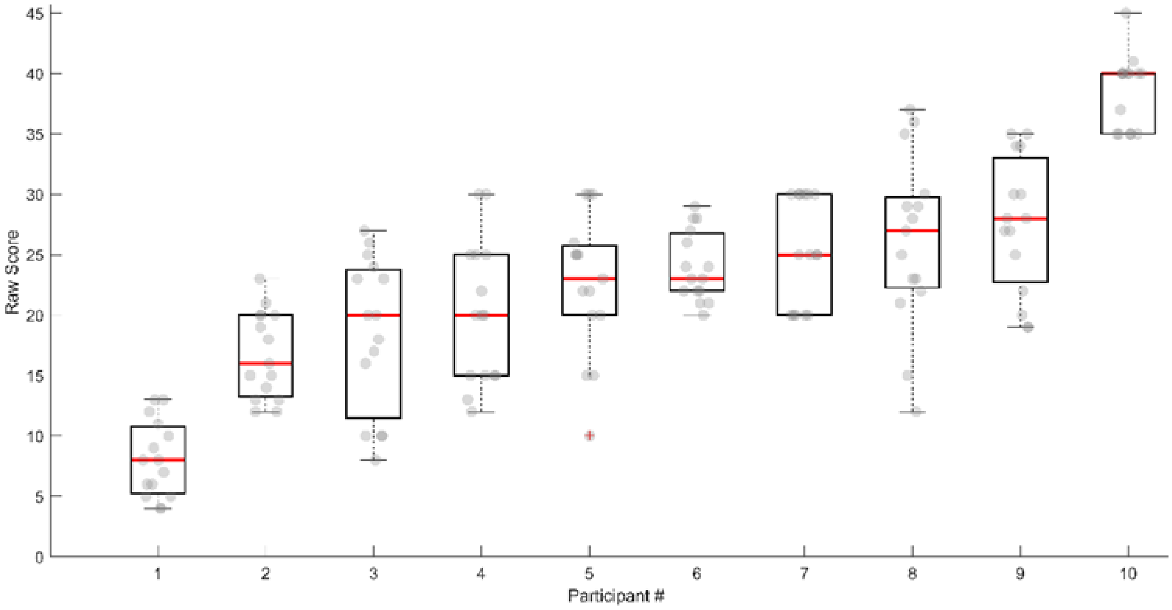

Figure 2 – Raw data of experiment 1: BCD gaze positions on the scale (in dm above the floor) for all luminaire settings (grey dots) for all 10 participants.

Figure 3 is based on the same data as figure 2, now with the three eye illuminance settings on the horizontal scale. To account for individual differences, the raw scores on the vertical scale were normalized using a z-score normalization. Specifically, for each participant, their mean score was subtracted from each individual score. This centred the data around zero for each participant, removing any bias in scale usage (e.g., consistently high or low ratings). The resulting values were then divided by the standard deviation of the scores for each participant. This normalization ensures that the relative variation in scores, rather than absolute differences in scale preferences, is emphasized, allowing for a consistent basis of comparison across participants.

An analysis of variance (ANOVA) revealed a statistically significant difference in scores across the three lighting conditions, F(2,147) = 50,1, p<0,001. Post-hoc comparisons using the Tukey HSD test indicated that the mean score for the 7 lx condition (M = 0,80, SD = 0,77) was significantly different from the 10 lx condition (M = -0,10, SD = 0,77, p < 0,001) and the 13 lx condition (M = -0,70, SD = 0,72, p < 0,001). Additionally, the mean score for the 10 lx condition was significantly different from the 13 lx condition (p < 0,001). In line with expectations, these results strongly suggest that the higher eye illuminance values are associated with the decreased scores (looking more away from the source).

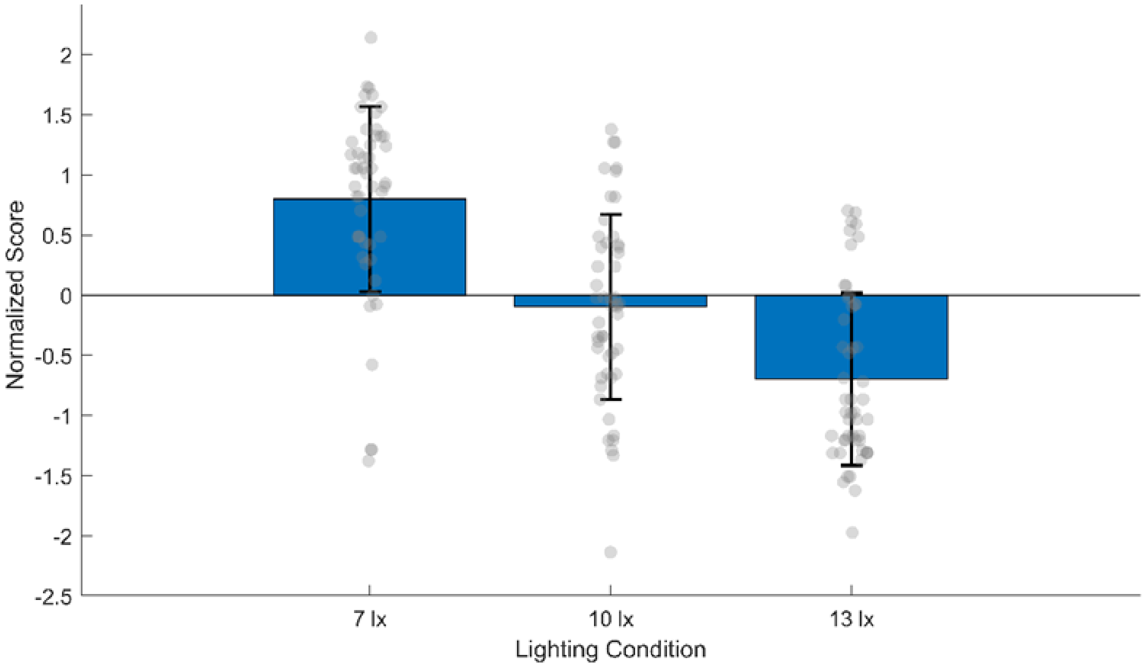

Figure 3 – Data of experiment 1, normalized to the individual average scale position and individual spread in scale positions, separately for the three eye illuminance values (lighting conditions).

Experiment 2: Testing the point source approximation in an outdoor setting

To account for inter-individual differences in how participants used the glare rating scale, raw scores were normalized (z-scored) per participant, in the same way as in experiment 1. A linear mixed-effects model (LMM) was fitted to the z-scored data using the model **zScore** ~ **Diffuser** * **LightLevel** + (1 **|** **Subject**). This model included fixed effects for **Diffuser** (with diffuser vs. without diffuser), **LightLevel** (7 lx, 10 lx, 13 lx), and their interaction, as well as a random intercept for each participant to account for repeated measurements.

The analysis revealed a significant main effect of **Diffuser**, F(1, 156) = 3,97, p =0,048, indicating that, across light levels, gaze directions on the scale were systematically higher (less discomfort glare) when the diffuser was present. There was also a highly significant main effect of **Light Level**, F(2, 156) = 18,82, p < 0,001, suggesting that glare perception increased as light level increased. The interaction between **Diffuser** and **LightLevel** was not significant, F(2, 156) = 1,43, p =0,24, indicating that the effect of the diffuser was consistent across light levels. Partial eta squared values, calculated from F-statistics, were $\eta^2_p = 0{,}025$ for **Diffuser** and $\eta^2_p = 0{,}194$ for **Light Level**.

Estimated marginal means (EMMs) from the model showed a clear progression in discomfort glare perception with increasing light levels, with lower z-scores observed at higher light levels. They also showed a higher discomfort glare perception (i.e. lower scores on the scale), with a luminaire with no diffuser (see Figure 4). Adding a diffuser resulted in an improvement in comfort view zone comparable to a 3 lx reduction on the eye. This demonstrates that spreading the luminance of the source improves comfort for the simulated outdoor urban lighting conditions of our test.

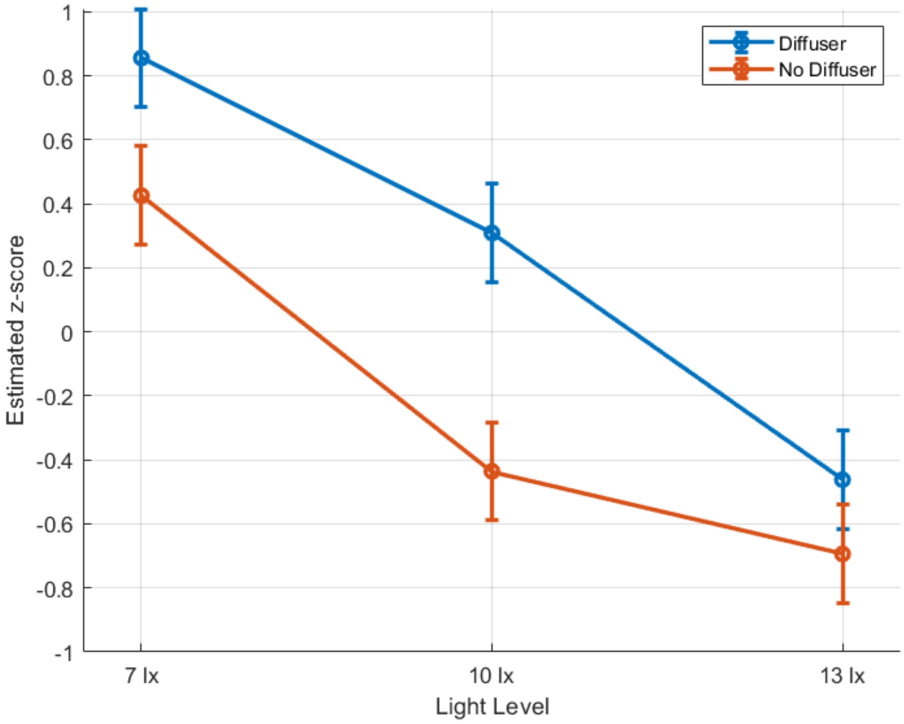

Figure 4 – Estimated Z-scores of experiment 2 (based on data normalized to the individual average scale position and individual spread in scale positions), separately for the three eye illuminance values (Light Level), for the glare source with diffuser (orange line) and without diffuser (blue line).

Experiment 3: Testing the uniform source approximation in an indoor setting

At the first observer position (3,0 m in front of the luminaires, luminaire 25° above horizontal line of sight) all 7 observers could look at all scale positions and even into the luminaires without experiencing discomfort. This is probably because the uniform reference office luminaire had a very low intensity in the direction of the eye.

At the second observer position (1,4 m in front of the luminaires, 45° above horizontal line of sight), the two youngest observers could still look into both luminaires without experiencing discomfort. The results shown in Figure 5 are based on the remaining 5 observers (3 M, 2 F, aged 40-58 years). A similar model was applied as in experiment 2: The analysis revealed a significant main effect of “spottiness” (non-uniformity), F(1, 16) = 5,28, p =0,035, indicating that gaze directions on the scale were systematically lower with the non-uniform luminaire. There was also a significant main effect of Light Level, F(1, 16) =0,08, p <0,03, suggesting that gaze positions on the scale decreased as light level increased. At this observer position, the comfort view zone of this “spotty” luminaire seems to be comparable to that of a uniform panel at ~30% lower light output. While this clearly shows an effect of luminance non-uniformity of discomfort glare, a larger size test would be required to quantify the effect. Furthermore, this conclusion does not take into account the fact that two observers did not experience a difference between the luminaires at the second position, and none of the 7 observers at the first observer position.

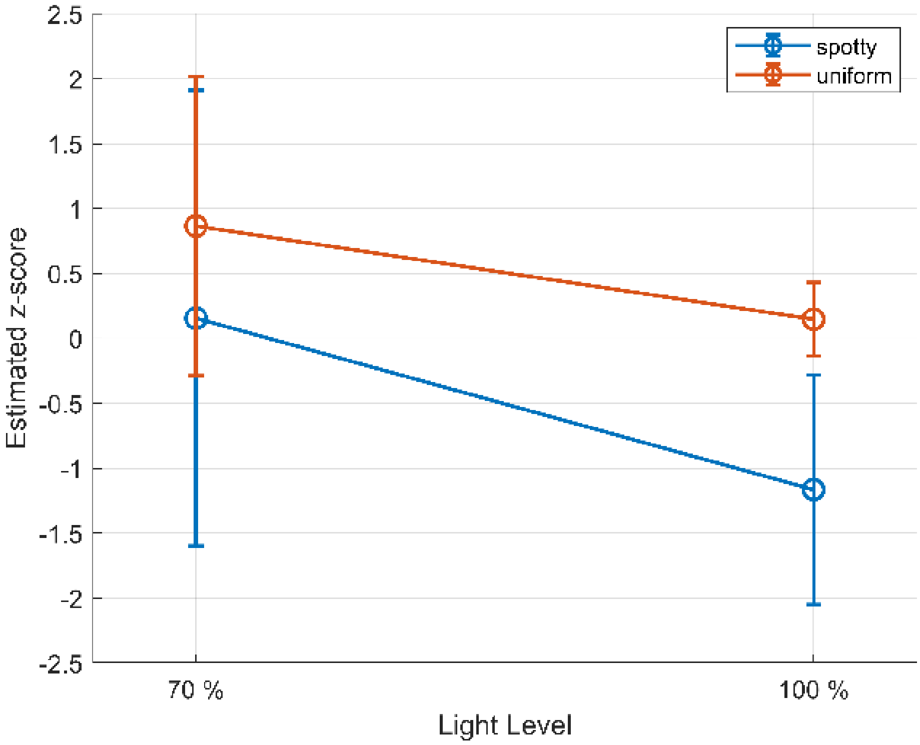

Figure 5 – Estimated Z-scores of experiment 3 (based on data normalized to the individual average scale position and individual spread in scale positions), separately for the two light output levels (Light Level), for the uniform office lighting panel (orange line) and for the non-uniform (spotty) experimental office luminaire (blue line)

The interaction between spottiness of the luminaire and LightLevel was not significant, F(2, 16) = 2,15, p =0,16, indicating that the effect of the spottiness was consistent across light levels.

3 Conclusion

We propose a new measurement method for discomfort glare based on a person’s individual variation in glare sensitivity to variations in gaze direction. We allow respondents to freely determine the range of viewing directions they consider to be comfortable: the “comfort view zone”. Relative variations in comfort view zone are used as a measure of discomfort glare. A pilot test on an outdoor lighting setup shows that the comfort view zone method works as expected (people look away more from stronger glare sources) and is sensitive enough to detect small variations in glare source intensity. This method was subsequently applied in a similar outdoor setting where we studied the effect of a diffusing window on an outdoor luminaire on discomfort glare. The test showed a significant effect of the presence of a diffuser, although the effect was relatively small. A similar small-scale experiment was performed in an indoor lighting setting, to test the influence of glare source uniformity in an office luminaire. The non-uniform luminance distribution in the luminaire resulted in a significantly higher degree of discomfort, but again the effect was relatively small. The conclusions related to the effect of luminance distribution of the glare source depend on the test conditions (glare source position relative to the observer, position of the viewing scale, degree of non-uniformity, etcetera) and should not be generalized. The experiments do consistently demonstrate the relevance and high sensitivity of the new comfort view zone method.

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