What to measure and report in studies of discomfort from glare for pedestrian applications

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Short title: Measurement and reporting guidelines

Abstract

In outdoor environments after dark, pedestrians may experience discomfort from glare caused by lighting. Several models to predict discomfort glare have been proposed or extended for pedestrian applications; these models use different luminous and geometrical quantities to predict discomfort. Consistent measurements and reporting in discomfort glare studies are important for identifying best performing models; however, previous studies proposing a new model tended to only report the performance of the new model and its quantities. This practice makes it difficult to evaluate how a new model performs compared to other existing models. To promote more consistent and complete reporting, this research note proposes measuring and reporting all relevant quantities that are used in existing models. This can make it easier for researchers to use a study dataset to compare the performance of several models or to combine datasets from several studies to address between-study variance.

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1. Introduction

Discomfort from glare can be defined as a sensation of annoyance or pain without necessarily impairing one's vision or visual performance.[1] In outdoor spaces after dark, pedestrians may experience discomfort from luminaires mounted at different heights, including those specifically installed to illuminate pedestrian walkways. A pedestrian's gaze scans the general environment to perform different tasks above and below eye level, such as detecting trip hazards and identifying an approaching person's face and gestures.[2,3] As a result of this flexibility in gaze direction, pedestrians may be able to resolve the luminance distribution in the aperture, such as bright spots from an LED array. Compared to drivers, pedestrian's movement speed is lower, which limits the applicability of some models developed for drivers such as the Glare Control Mark that considers the number of luminaires per kilometer.[4]

Previous studies have proposed several models that relate lighting conditions to subjective ratings. Only a few models were developed specifically for pedestrian applications, including the models by Bullough *et al.*,[5,6] Lin *et al.*,[7] Tashiro *et al.*,[8] Kohko *et al.*,[9] and CEN R_{GI}.[10] Other models that might be relevant for pedestrian application include Unified Glare Rating small-source extension (UGRs),[11] Bennett Cumulative Brightness Evaluation (CBE),[4] Petherbridge and Hopkinson,[12] Schmidt-Clausen and Bindels,[13] and CIE R'_{UG} model.[14] Evaluating the performance of these models and their applicability to pedestrian applications remains an active area of research and discussion such as in the IES Discomfort Glare in Outdoor Nighttime Environments committee.

Unfortunately, studies of discomfort from glare document only the measurements relevant to the specific model being tested. For example, some studies did not report average luminance of the source (L_{avg}),[15,16] background luminance (L_b),[9] or source size.[5] Uncommon quantities used in newer models are unlikely to be reported because such quantities might be used only in one or few models, such as maximum luminance (L_{max}) used in the model proposed by Bullough *et al.* in 2011. Differences in reported quantities across different studies limit the ability to independently reanalyze datasets underlying published studies to evaluate all potential models. These differences make it only possible to compare the performance of a model based on one study to the performance of another model based on another study. For example, comparing the performance of UGRs from one study to the performance of the Bullough *et al.* 2008 model from another study.[17,5] This can be problematic due to the range of lighting conditions and differences in experimental methods.

Current inconsistency in measuring and reporting quantities in glare experiments is hindering the process of reaching consensus. Different researchers utilizing consistent measurements and reporting would enable the identification of best-performing models to predict discomfort from glare. In this research note, we recommend a common set of quantities to measure and report in studies of discomfort from glare for pedestrian applications. The goal is to encourage more comprehensive within-study comparisons of several models and allow researchers to use datasets from several studies to evaluate multiple models, addressing between-study variance. More robust reporting of stimulus conditions will also make past data more valuable as new models are proposed in the future. The scope of this work does not include overall best practices for research conduct and statistical analysis, which are discussed in other recent studies.[18,19]

Existing models of discomfort from glare use different terms to describe the stimulus, as summarized in Table 1. While there are overlaps between models (*i.e.,* the same quantity is used in several models), there are also quantities unique to just one model.

Table 1: A matrix showing the different quantities used in discomfort from glare models. Cells with the letter *y* indicate that a model uses the corresponding quantity.

	Quantities used in models												
Discomfort from glare models relevant for pedestrian applications	L_{avg} (cd/m^2)	I (cd)	E_d (lx)	L_{max} (cd/m^2)	k	L_b (cd/m^2)	E_i (lx)	E_a (lx)	R (m)	ω (sr)	θ (°)	p	A_p (m^2)
Petherbridge and Hopkinson	y	-	-	-	-	y	-	-	-	y	-	-	-
Schmidt-Clausen and Bindels	-	-	y	-	-	y	-	-	-	-	y	-	-
Bennett CBE	y	-	-	-	-	y	-	-	-	y	y	-	-
UGRs	-	y	-	-	-	y	-	-	y	-	-	y	-
Bullough *et al.* 2008	-	-	y	-	-	-	y	y	-	-	-	-	-
Bullough *et al.* 2011	-	-	y	y	-	-	y	y	-	-	-	-	-
Lin *et al.* 2014	y	-	-	-	-	y	-	-	-	y	y	-	-
Lin *et al.* 2015	-	-	y	-	-	-	-	y	-	-	y	-	-
CEN R_{GI}	-	y	-	-	-	-	-	-	-	-	-	-	y
CIE R'_{UG}	y	-	-	-	y	y	-	-	-	y	-	y	-

L_{avg}: average source luminance
I: source intensity toward the eye
E_d: direct illuminance at the eye from source
L_{max}: maximum source luminance
k: uniformity correction
L_b: background luminance
E_i: indirect illuminance
E_a: ambient illuminance
R: distance of source from eye
ω: source solid angle
θ: eccentricity of the source
p: the Guth position index
A_p: projected area of source

Lin *et al.* (2014 model),[7] Petherbridge and Hopkinson,[12] and Bennett's CBE model use L_{avg} to describe source luminance.[4] In these models, higher L_{avg} is related to more discomfort. On the other hand, for small sources with a projected luminous area smaller than 0.005 m^2, Paul and Einhorn (1999) found the luminous intensity (I) to be more predictive of discomfort from glare than L_{avg}, making the UGRs model more appropriate. More recently, the UGRs model was extended to outdoor lighting applications by Tyukhova and Waters.[17] Maximum luminous intensity limits are included in CIE 115:2010 for pedestrian and low-speed traffic areas.[20] On the other hand, the European standard 13201 recommends the R_{GI} model for pedestrian applications, using both luminous intensity and projected luminous area (A_p).[10]

Other models such as those by Schmidt-Clausen and Bindels and Bullough *et al.* 2008 use direct illuminance at the eye from the source (E_d).[13,5] Bullough *et al.* proposed the use of E_d and L_{max} for sources subtending more than 0.3° in visual size.[6,15] The inclusion of L_{max} might help differentiate between sources that cause the same E_d but differ in their luminance distribution and uniformity. Figure 1 shows luminaires with different luminance distributions and the corresponding context of each luminaire.

To predict discomfort from non-uniform sources, Tashiro *et al.* and Kohko *et al.* proposed models that include a weighted luminance term called effective luminance (L_{eff}).[8,9] Using a luminance map of the glare source where each pixel represents a luminance measurement, the weighting scheme predicts higher discomfort from glare as pixel luminance increases. Recently, CIE 232:2019 (Discomfort Caused by Glare from Luminaires with a Non-Uniform Source Luminance) proposed the use of the R'_{UG} model that includes a uniformity correction factor (k) to address glare from non-uniform sources.[14]

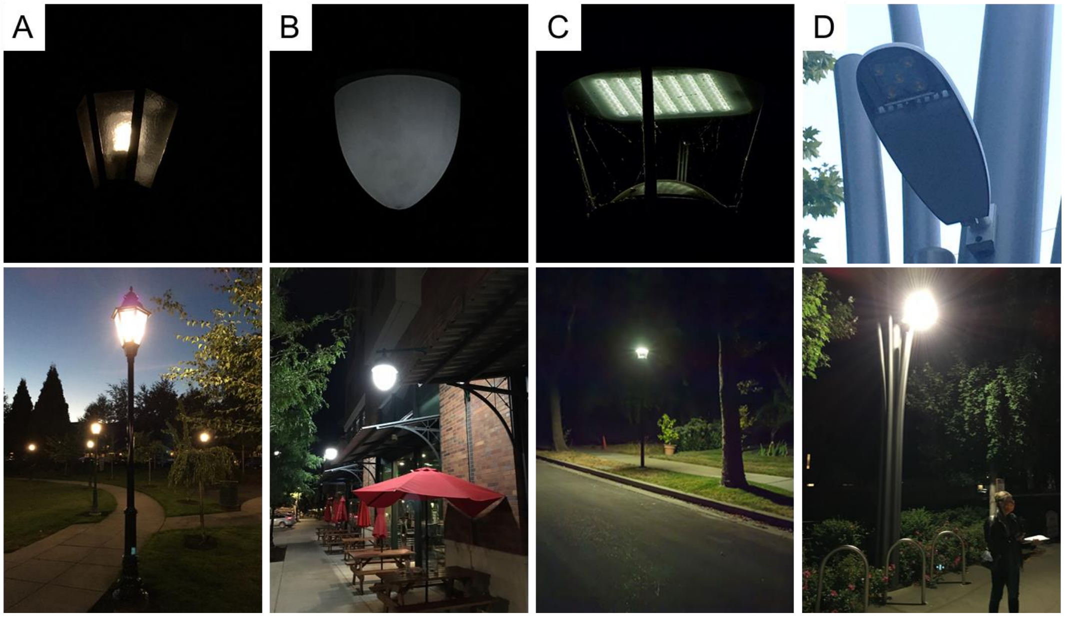

Figure 1: Examples of outdoor luminaires with different aperture geometry, diffusion, and background areas. The top row shows close-up images of the luminaires that are shown within their contexts in the bottom row.

Background areas can affect discomfort from glare; a higher source to background contrast being associated with higher discomfort.[7,8] Different models use different variables to express this. For example, Lin *et al.* (2014 model) uses the ratio between L_{avg} and L_b,[7] UGRs uses the ratio between luminous intensity and L_b,[11] and Schmidt-Clausen and Bindels model uses the ratio between E_d and L_b.[13] The model by Bullough *et al.* uses the contrast between E_d and indirect illuminance from source (E_i).[5,15] E_i quantifies light from the glare source that is reflected from buildings, pavement, and other surrounding surfaces. Their decision to use E_i was to account for realistic situations with non-uniform backgrounds that can include buildings, dark sky, and trees (Figure 1/ bottom row). As a result, models based on a singular background luminance value might not provide robust predictions. Another term in their model, E_a, represents light from other lighting installations. Higher E_i and E_a values reduce the magnitude of predicted discomfort.

Geometrical properties of source and viewing condition can affect discomfort from glare.[12] These include the distance of the observer from the source (R), the visual size (*i.e.,* solid angle of the glare source [ω]), and its location within the field of view described using Guth's position index (p) and eccentricity (θ).[21] Eccentricity refers to the angular displacement of the source from the point of fixation regardless of the direction (Figure 2). Generally, the closer the source to the point of fixation, the larger the discomfort from glare.[13,21] A few models, such as Bullough *et al.* (2008 model),[5] do not include a term for source location—the experiments used to derive this model were conducted with participants directly viewing the source.

We recommend that all quantities listed in Table 1 be measured and reported in future studies of discomfort from glare for pedestrian applications. While this article focuses on models and quantities most relevant to pedestrians, studies examining other applications such as drivers and interior lighting likely face similar challenges related to the consistency of reported quantities, and hence may benefit from developing similar guidelines.

The following sections discuss the reporting of photometric quantities, geometric properties, subjective ratings, and experimental settings and procedures. These items may be included in the main text of a journal article or supplemental materials.

2. Recommendations for measuring and reporting the lighting stimulus

Typically, only L_{avg} and L_{b} have been measured and reported. L_{max} may be important for sources with a visual angle larger than 0.3° and are non-uniform.[15] Reporting L_{max} will allow for further investigation of its role when examining discomfort from uniform and non-uniform sources.

The measured luminance value is influenced by the capture angle of the instrument and the encompassed area of the luminaire surface. If a spot luminance meter is used, L_{avg} can be measured when the measurement area (typically a circle) is just filled by the luminaire aperture. To measure $L_{\mathrm{max},}$ some luminance meters have a “peak” setting that allows the experimenter to scan across the aperture multiple times, and the meter will display the maximum value measured while the trigger button is pressed. However, these measurements depend on the viewing distance and optics; the measuring circle can be a small area encompassing one LED, a larger area that includes most of the aperture, or an area so large that it includes the background (Figure 2). Thus, repeatability can be an issue.

Alternatively, Imaging Luminance Measuring Devices (ILMDs) can be used to collect luminance maps which can be processed to calculate L_{avg}, L_{b}, L_{max}, and effective luminance (L_{eff}) to take non-uniformity into account. These luminance maps can also be helpful to test model performance using different background and source area boundaries, such as L_{avg} of the LED or the whole luminaire.[22] Guidelines for collecting and analyzing luminance maps have been discussed by others.[14,23–26] A question that warrants further investigation: Are ILMDs a viable way for collecting scene luminances and converting them into illuminances at the eye on the assumption that outdoor surfaces are Lambertian?

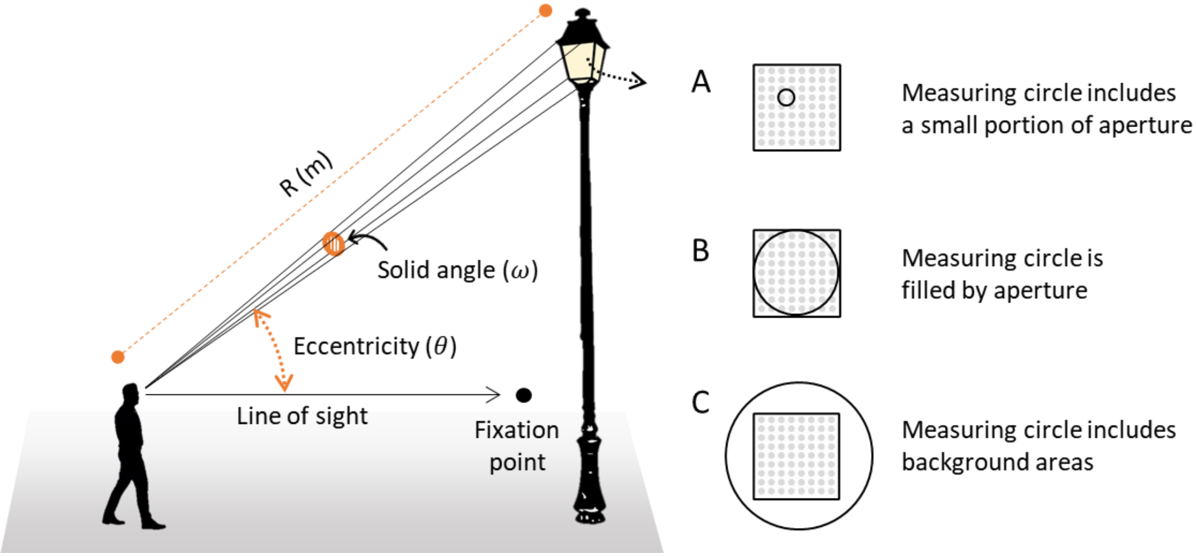

Figure 2: Geometric properties of a light source (left graph), and spot luminance measurements (panels A, B, and C). A captures average luminance primarily from an individual LED, B captures the average of an area with a representative mix of LEDs and non-lighted area, and the C configuration includes background areas in the measurement of average luminance, diluting the luminance contribution from the LED array.

L_b has been defined differently in past studies, including a 30° circular area surrounding the target,[22] a 20° circular area,[27] a rectangular area that included road surfaces and targets,[22] and a rectangular area surrounding the source and fixation point.[8] Given that there is no consensus on the definition of background areas, it is important to clearly describe the size and shape of background areas measured.

Direct (E_d), indirect (E_i), and ambient illuminance (E_a) are measured at the eye. They have been shown to affect ratings of discomfort from glare.[5] Measuring and reporting these quantities would enable further assessments of the following models: Bullough *et al.* models,[5,15] Lin *et al.* (2015 model),[16] and Schmidt-Clausen and Bindels.[13]

To measure E_d at the eye looking toward the light source, Tyukhova and Waters used a tube to measure E_d, but noted the difficulty in aligning the tube with the glare source.[27] A more practical approach is to measure total illuminance at the eye (E_t) and then use a baffle to block direct light from source,[27] which will measure the total of E_i and E_a (Figure 3). Subtracting E_i and E_a from E_t yields E_d, the direct illuminance from the light source alone (Equation 1). To measure E_a, the source should be turned off, which may not be possible in field studies. Alternatively, a value of 20, 2, 0.2, and 0.02 lx can be assumed for a very commercial urban, urban, suburban, and rural district, respectively, as suggested by Bullough *et al.* and as defined by the environmental zones of the CIE.[5,28] To measure E_d, E_i and E_a when not looking directly at the source, the same procedure can be used, but the calculated E_d has to be cosine-weighted to account for source eccentricity. Future studies exploring best measurement techniques for E_d, E_i, and E_a for use in laboratory and field settings would be valuable.

$$E_d = E_t - (E_i + E_a) \tag{1}$$

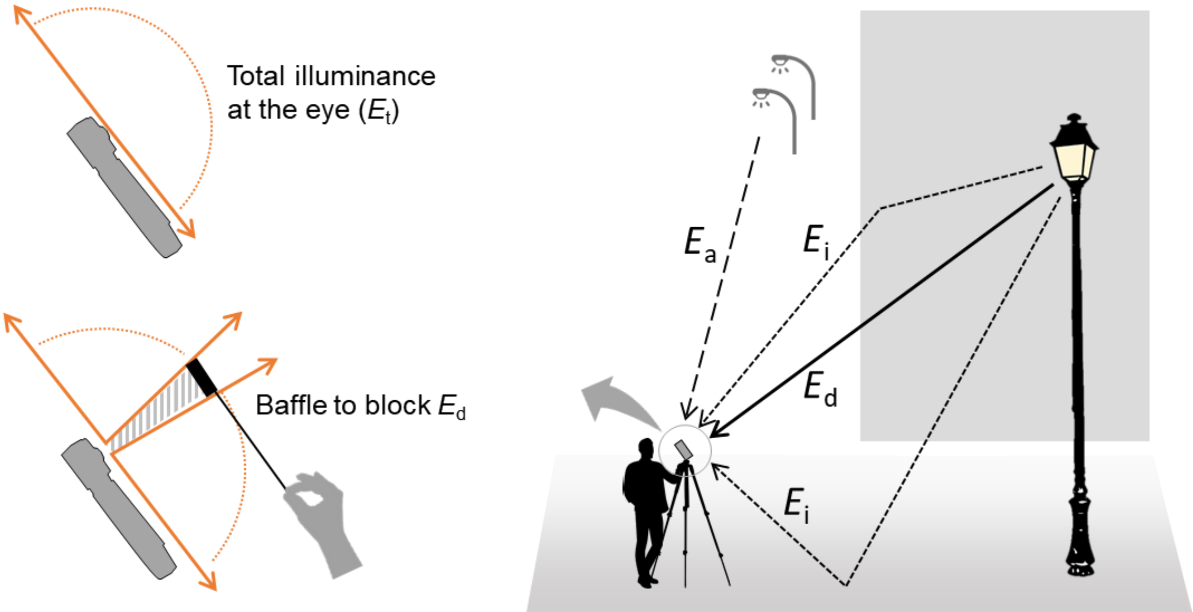

Figure 3: The schematic diagram on the right shows direct illuminance at the eye from source (E_d), indirect illuminance (E_i), and ambient illuminance (E_a). The two graphs on the left show the measurement of total illuminance and the use of a baffle to block E_d.

Luminous intensity is needed to calculate UGRs, R_{GI}, and to check compliance with maximum luminous intensity recommendations (CIE 115:2010).[20] Equation 2 can be used to calculate luminous intensity.[1] In this equation, θ refers to the angle between the line of sight and the direction of incident light. This equation is intended for situations where R is at least five times the maximum dimension of the light source, which likely applies in most pedestrian applications.

$$I = \frac{E_d \times R^2}{cos\theta} \tag{2}$$

Most models of discomfort from glare incorporate a variable that describes source position such as the eccentricity of the luminaire's aperture from the line of sight, the Guth position index,[21] and/ or the distance of the source from the eye (Figure 2). Reporting the fixation point, the mounting height of the source, and the horizontal distance between the participant and the source is helpful for understanding the exact position of participants.

Most models of discomfort from glare address source size as a solid angle in steradians or projected area. The solid angle is the source's projected area, modified by the viewing distance. Both solid angle and projected area are difficult to measure in the field, and even more challenging if the luminaire has a dropped lens or non-planar light-emitting area. If the luminaire's geometry and dimensions are known, the solid angle can be calculated using Equation 3, where A_p is the projected area of the luminaire.[29] The projected area is needed to determine whether it is considered a small source and can be used in the R_{GI} model. Describing source size in plane angles is not recommended given that it only conveys the size of the source in one direction.

$$\omega = \frac{A_p}{R^2} \tag{3}$$

3. Recommendations for reporting participant ratings

The mean of ratings from all participants for a certain experimental condition has commonly been used in outdoor studies to conduct regression and correlation analyses.[5,22] Studies may report mean ratings in a table in the manuscript, but because mean ratings might mask uncertainty in discomfort from glare responses,[30] we strongly recommend authors report individual ratings in supplemental materials per journal format.

Studies may utilize different scales to elicit discomfort from glare ratings. Understanding the scale is important to inform analyses by other researchers. Differences in responses might be due to the use of different scales, labels, translations, and/ or instructions. Therefore, we recommend reporting the wording and language of the questionnaire, rating scale, the scale presentation method, and any descriptions, translations, or definitions provided to participants. Stating that a study used the "de Boer scale" is likely insufficient information, given that there were multiple iterations of the scale ascribed to that name.[31,32] For example, the point '9' on this scale corresponded to 'just noticeable' in one study and 'unnoticeable' in another study.[33,22]

4. Recommendations for reporting ancillary information

To explore effects of source luminance uniformity on glare ratings, we recommend that authors report L_{eff} and effective solid angle (ω_{eff}) for each viewing position,[14] which are needed to calculate the uniformity correction parameter (k) in CIE R'_{UG} model (Equation 4). L_{eff} represents average luminance of pixels with luminance greater than 500 cd/m^2, and ω_{eff} describes the solid angle of those pixels, requiring luminance maps from ILMDs.[26] It is recommended to follow resolution recommendations outlined in CIE 232:2019 to ensure that small sources are properly represented. Uniformity metrics based on two points like Max:Min are not recommended because they can be very sensitive to small changes in luminance map area or resolution.

$$k^2 = \frac{{L_{eff}}^2\ \omega_{eff}}{{L_{avg}}^2\ \omega} \tag{4}$$

The spectral power distribution (SPD) of the glare source likely affects responses to discomfort from glare.[34–36] However, reporting the source Correlated Colour Temperature (CCT) alone is insufficient because CCT may not accurately represent variations in SPD; hence visual differences can be perceived between two sources with the same CCT.[37] Therefore, in addition to reporting CCT, it is recommended to include a graph of light source SPDs and provide the SPDs in tabular format as supplemental material. The tabulated SPD data will allow future researchers to compute new quantities or explore different weighting as did Sweater-Hickcox *et al.*.[35] Given that it can be difficult to obtain SPDs from manufacturers, it is recommended to measure luminaire SPDs on site using a spectrophotometer.

Describe the experimental setting with daytime and nighttime photos of the setup, as well as photos of the luminaire. This information can clarify the lighting conditions experienced by participants. If the experiment was conducted in an uncontrolled environment, report environmental conditions such as ambient temperature, noise level, air speed, and other characteristics that might prove distracting or could compound the participant’s discomfort. Bullough *et al.* noted that wind might cause eye dryness which can affect ratings of discomfort from glare.[5] Additionally, we recommend authors describe any wet or rainy conditions that can affect the reflectance of outdoor surfaces, especially when making assumptions of Lambertian reflectance to convert luminance measurements from ILMDs to illuminance.

Report the sample size, age groups, and visual condition of participants which will help future researchers evaluate their potential effects on discomfort from glare, as raised by Lin *et al.*.[16] Report the number of participants that had normal, corrected to normal, and uncorrected vision, as well as those that had eye diseases or disabilities. Accounting for age and vision conditions may help explain variability in responses between participants.

Given difficulties in luminance measurements and the use of different measurement procedures, it is helpful to state the instruments used for lighting measurement and calibration status for the range of illuminance, SPD, and luminance values.

5. Conclusion

Multiple models of discomfort from glare have been proposed for pedestrian applications, each of which uses different terms. These models are under active consideration by researchers and lighting standards organizations. More thorough reporting of the lighting stimulus, viewing conditions, dependent measures, and procedures can help the industry reach a consensus on a model for predicting discomfort from glare for pedestrians in outdoor nighttime environments. This work provided a list of items that we recommend researchers measure and report in order to maximize the value of the collected data. Open-access publication of study datasets is highly encouraged to allow independent analysis of existing or new models by other researchers. The availability of datasets would also allow researchers to utilize various statistical tests for model evaluation. A wide-data format can be used where rows represent different experimental conditions and the columns represent different variables and participant ratings from each participant. Table 2 shows a summary of the recommendations. Some of the items are based on existing models of discomfort from glare; hence, new quantities may be added to this list in the future.

Table 2: A summary of recommended quantities and information to be reported in discomfort glare studies for pedestrian application.

Lighting stimulus	• Average and maximum luminance of the source • Background luminance • Direct, indirect, and ambient illuminance at the eye • Luminous intensity • Source position in terms of eccentricity, Guth position index, and distance from the eye • Source solid angle and projected area
Participant’s ratings	• Individual ratings of discomfort glare
Ancillary information	• Uniformity correction parameter • Source CCT and spectral power distribution • Research setting description: a photo or a sketch and ambient environmental conditions • Participant characteristics: sample size, age groups, and visual condition • Instruments, their calibration status, and measurement procedure

Conflict of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship and/or publication of this paper.

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