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Discomfort Glare for Pedestrians
Can Any Model Get Us in the Ballpark?

Joint Biennial CNC-CIE, CIE-USNC & CORM Conference

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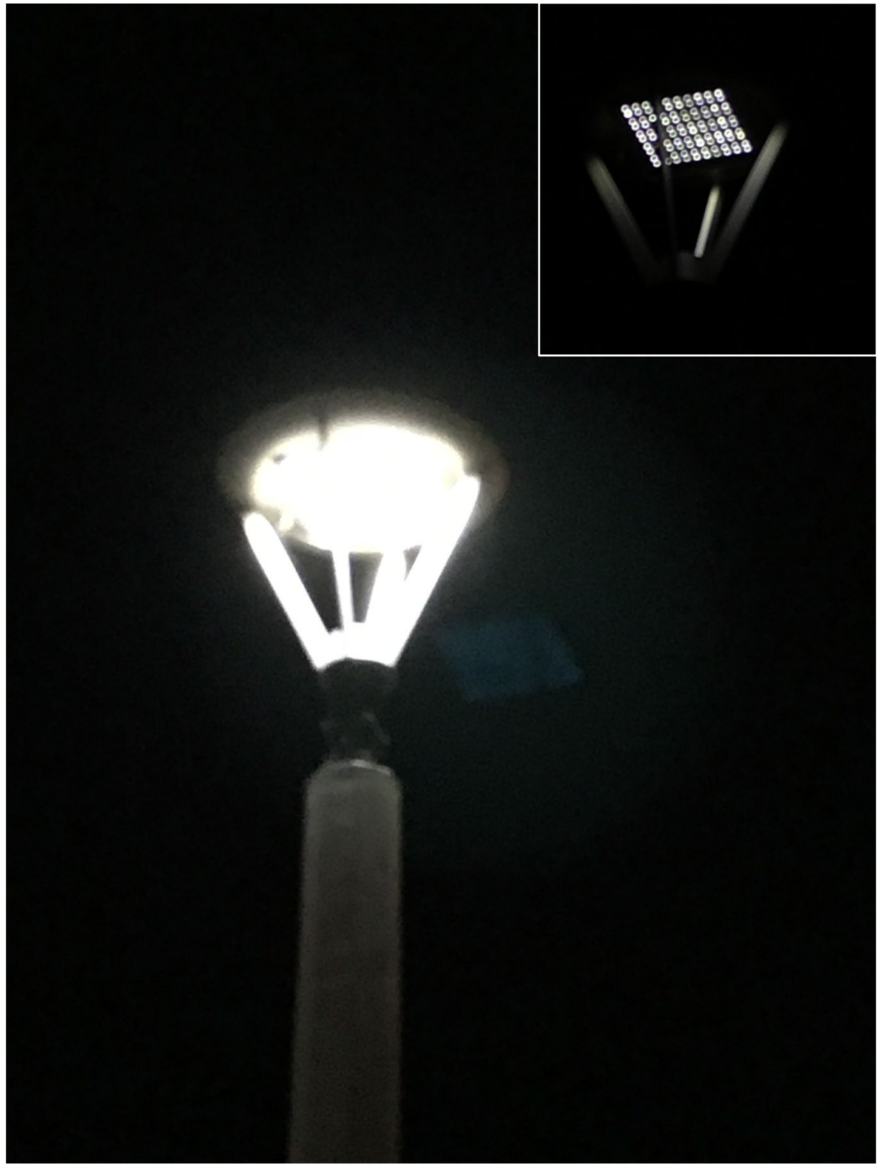
Discomfort from Glare



Challenges with existing models

- Most discomfort glare models include the ratio between the luminance of source (L_{avg}) and background (L_b).
  - L_{avg} can be difficult to measure.
  - Background areas can include different surfaces with widely different luminance levels.

- How do illuminance-based models compare to luminance-based models?

- There is a lack of independent analysis using multiple data sets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cie
International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

TECHNICAL REPORT

Discomfort Glare in Road Lighting and Vehicle Lighting

CIE 243:2021
UDC: 628.931
628.987
612.84
Descriptor: Electrical lighting design
Evaluation of lighting installations
Vision

GCM
Luckiesh and Guth's model
Bennet CBE
Vos model
Bullough et al. 2011 model
European method
Lehnert model
Alferdinck model
Voelker model
…

Luminance-based models

$$L_{avg}$$

$$Pet50 = \frac{{L_{avg}}^{1.6} \times \omega^{0.8}}{L_b}$$

$$Lin14 = 3.45 - log_{10}\left(\frac{\left(L_{avg} \times \omega\right)^{2.21}}{{L_b}^{1.02} \times \theta^{1.62}}\right)$$

Illuminance-based models

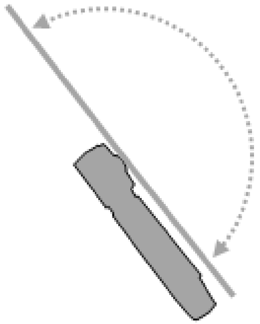
$$E_d$$

$$Sch74 = 5 - 2\log_{10}\frac{E_d}{0.003 \times \left(1 + \sqrt{\frac{L_b}{0.04}}\right) \times \theta^{0.46}}$$

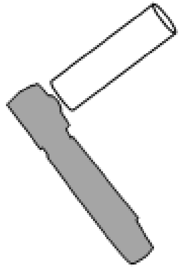
$$Lin15 = 7.09 - log_{10}\left(\frac{{E_d}^{2.21}}{{E_a}^{1.02} \times \theta^{1.62}}\right)$$

$$DG = \log(E_d + E_i) + 0.6\, log\left(\frac{E_d}{E_i}\right) - 0.5\log(E_a)$$

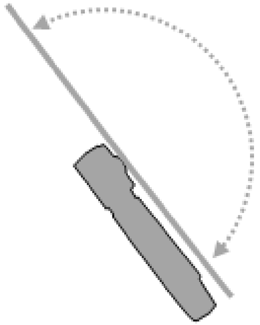
$$Bul08 = 6.6 - 6.4\log DG$$



1. Measure total illuminance at the eye (E_t)

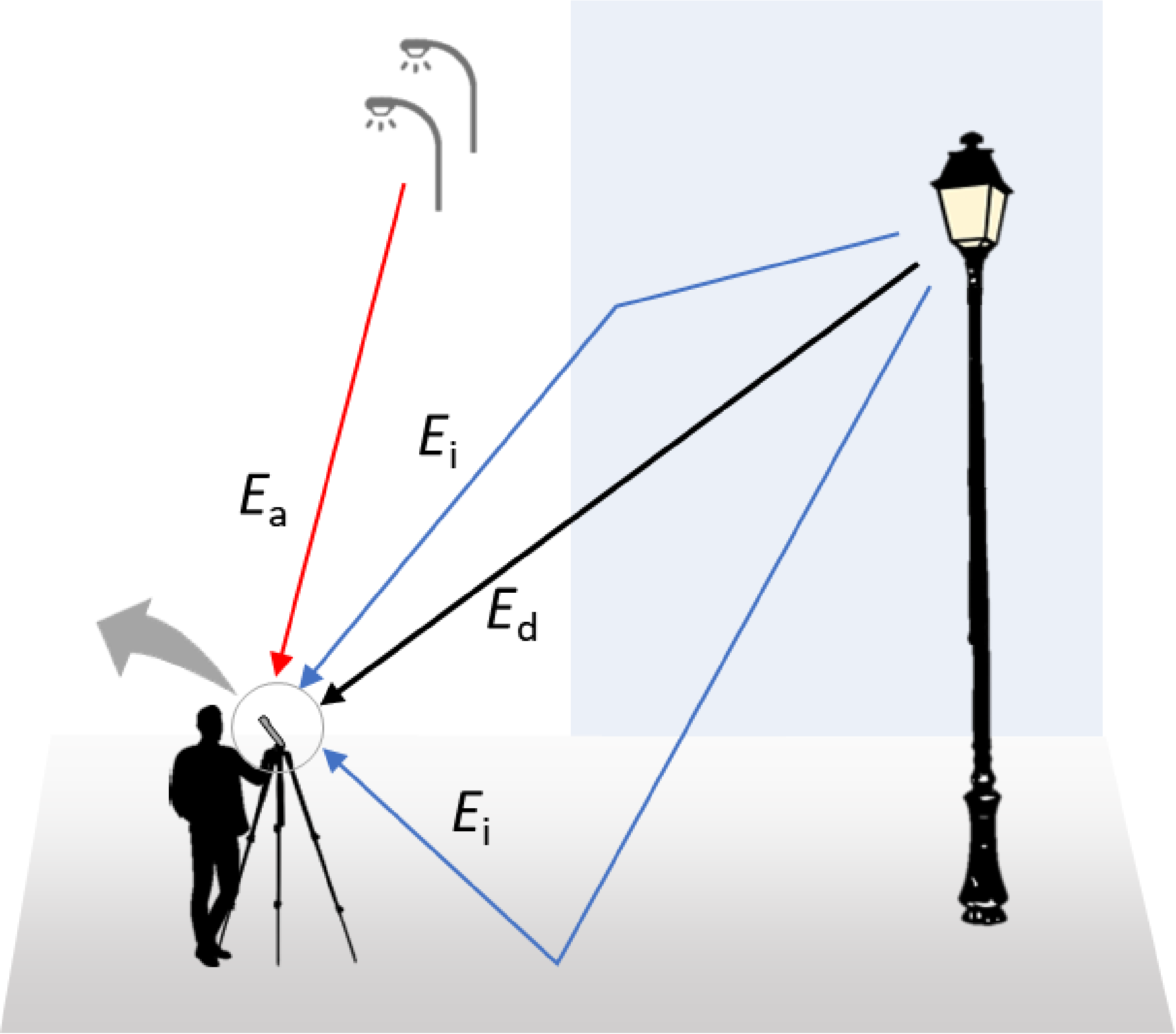


2. Use a tube to block light from surrounding areas and measure E_d



3. Measure E_a while source is switched off

4. Subtract E_d and E_a from E_t to calculate E_i.



Review of model performance reported in previous studies

Model	Reported performance in model development study	Tyukhova and Waters 2018	Villa et al. 2017†
Pet50	Not reported	-	-
Sch74	Not reported	r=0.79§	rho=0.75§
Bul08	R^2=0.70§	r=0.86§ for predictions from Bul08 and Bul11	-
Bul11	Not reported	r=0.86§ for predictions from Bul08 and Bul11	-
Lin14	r=0.87§ for 3000K source; r ≥0.95§ for 5000K and 6500K sources	-	rho=0.37§
Lin15	R^2=0.96** for young subjects, R^2=0.88** for seniors	-	rho=0.75§

† The values reported for Villa *et al.* are for conditions with one glare source, using the 'static' procedure, with the area surrounding target as background area ('disk zone').
A correlation coefficient Pearson's r or Spearman's rho of 0.3-0.5 is moderate, and a coefficient >0.5 is large.
R^2 ≥0.26 is a large effect.
A dash (-) denotes that model performance was not studied.
** denotes significance at 1% level (p<0.01).
§ denotes that the p-value was not reported.
n refers to the number of observations in each study, this being the combination of participant sample and number of scenes evaluated.

Review of model performance reported in previous studies

Model	Villa et al. 2017†	Kohko et al. 2015	Sivak et al. 1999	Bullough et al. 2008‡
E_d	rho=0.72§	R^2=0.70§ for central; R^2=0.53§ for peripheral viewing	R^2=0.99**	R^2= 0.93§ (exp 2), 0.73§ (exp 5), and 0.45§ (in/out exp)
L_{avg}	rho=0.74§	R^2=0.80§, 0.81§ for central and peripheral viewing	-	R^2= 0.02§ (exp 2)

† The values reported for Villa *et al.* are for conditions with one glare source, using the 'static' procedure, and L_{avg} being measured luminance of the LED.
A Spearman rho correlation coefficient >0.5 is large.
The goodness of fit R^2 ≥0.26 is considered a large effect.
A dash (-) denotes that model performance was not studied.
§ denotes that the p-value was not reported. n refers to the number of observations in each study.
‡ exp refers to the experiment number in Bullough *et al.* study.

Method

Literature search

Inclusion criteria

- written in English and published in a peer-reviewed journal
- addressed discomfort glare from one light source
- measured and reported E_d, E_i, E_a, and L_{max}
- presented experimental conditions in a randomized or counterbalanced order
- used a static viewing procedure

Search results

- Data from four previous studies were included:
  - Villa et al. 2017 → V17 dataset
  - Sweater-Hickcox et al. 2013 → S13 dataset
  - Tyukhova and Waters 2018 → T18 dataset
  - Tashiro et al. 2015 → T15

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

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In outdoor environments after dark, pedestrians may experience discomfort from glare caused by lighting. Several models to predict discomfort from 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 studies of discomfort from glare 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.

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 considering 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] Petherbridge and Hopkinson,[12] Schmidt-Clausen and Bindels,[13] and the 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, most studies of discomfort from glare document only the measurements relevant

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	Dataset			
	V17 (from Villa *et al.* 2017)	**S13** (Sweater-Hickcox et al. 2013)	**T18** (Tyukhova and Waters 2018)	**T15** (Tashiro et al. 2015)
Number of participants	33	10; 8; 6	47	8; 12; 19; 11
Number of observations	1056	108	1692	4410
L_{avg} (cd/m^2)	11,000-152,000	401-1041†	20,477-766,440	1.56-177,617
L_b (cd/m^2)	0.034-0.237	0	0.037-1.156	0.1; 1; 10
Eccentricity (°)	23 - 62	0	0; 10	8.5
Source size (sr)	0.00044-0.00823	0.00096; 0.00383	0.00001; 0.0001	0.0001-0.0081
Source size (°)	1.36-5.87	2; 4	0.2; 0.65	0.65-5.82

- Villa, C., Bremond, R., Saint-Jacques, E., 2017. Assessment of pedestrian discomfort glare from urban LED lighting. Light. Res. Technol. 49, 147–172.
- Sweater-Hickcox, K., Narendran, N., Bullough, J.D., Freyssinier, J.P., 2013. Effect of different coloured luminous surrounds on LED discomfort glare perception. Light. Res. Technol. 45, 464–475
- Tyukhova, Y., Waters, C.E., 2018. Discomfort Glare from Small, High-Luminance Light Sources When Viewed against a Dark Surround. LEUKOS - J. Illum. Eng. Soc. North Am. 14, 215–230.
- Tashiro T, Kawanobe S, Kimura-Minoda T, Kohko S, Ishikawa T and Ayama M. Discomfort glare for white LED light sources with different spatial arrangements. Lighting Research and Technology 2015; 47: 316–337.

Testing Model Performance

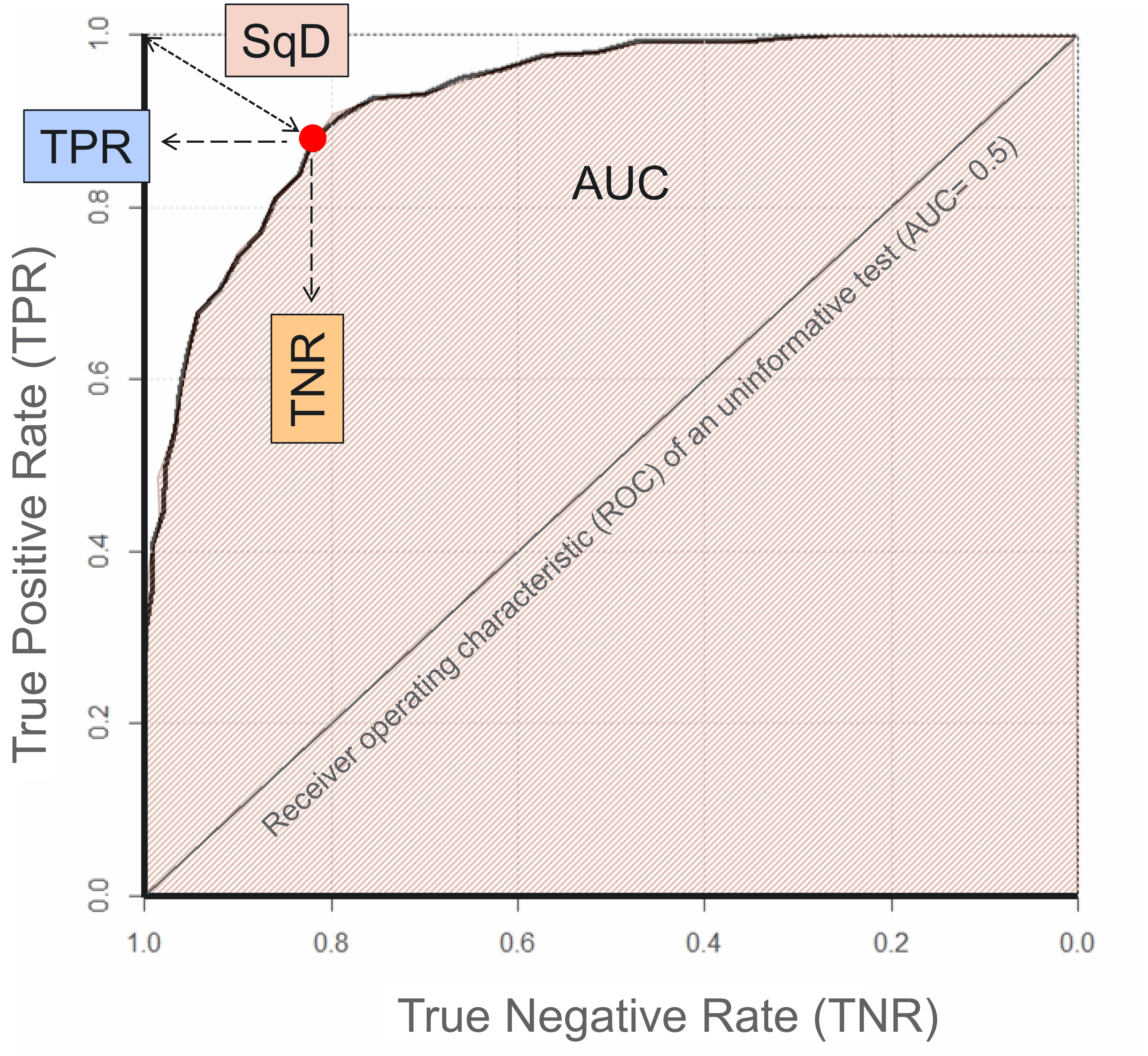
Ratings by subjects

9 (Unnoticeable)
8
7 (Satisfactory)
6
5 (Just admissible)
4
3 (Disturbing)
2
1 (Unbearable)

Model Predictions

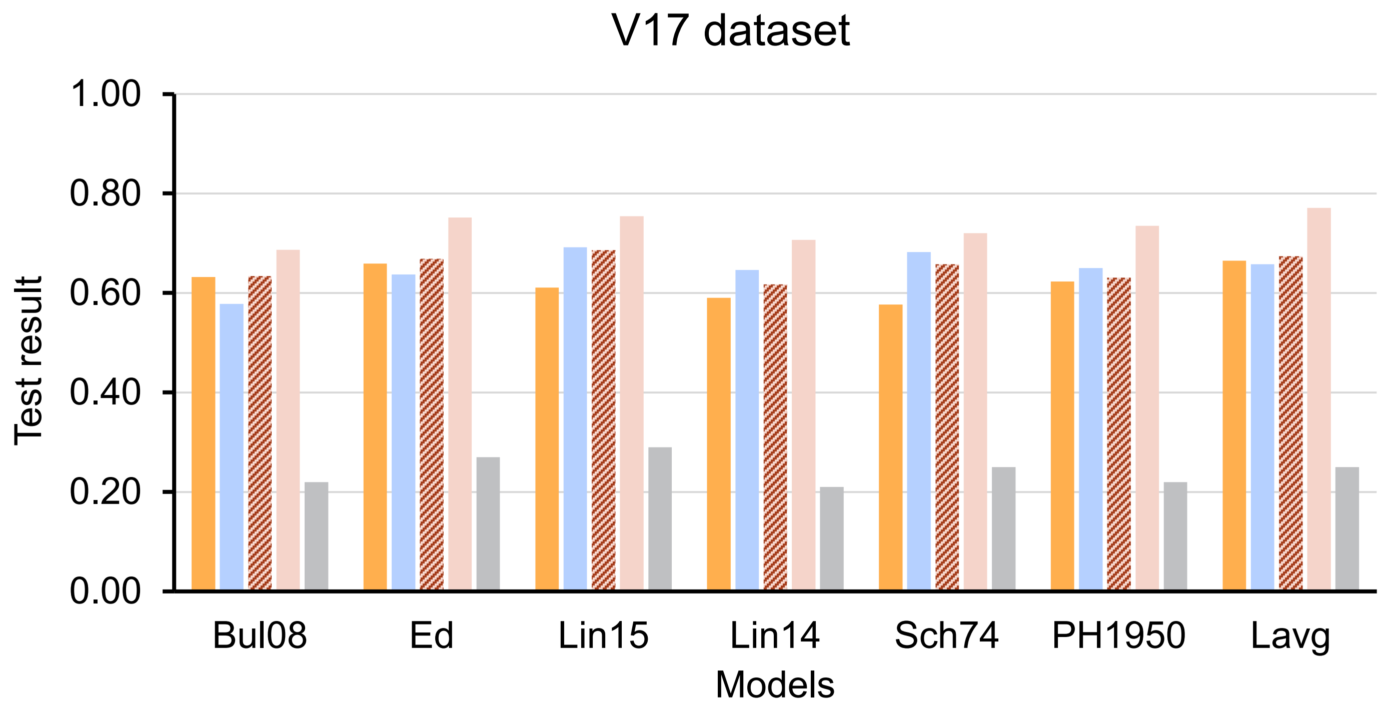
	Disturbing (positive)	Non-disturbing (negative)
≥5 : non-disturbing (negative)	False positive	True negative
<5 : disturbing (positive)	True positive	False negative

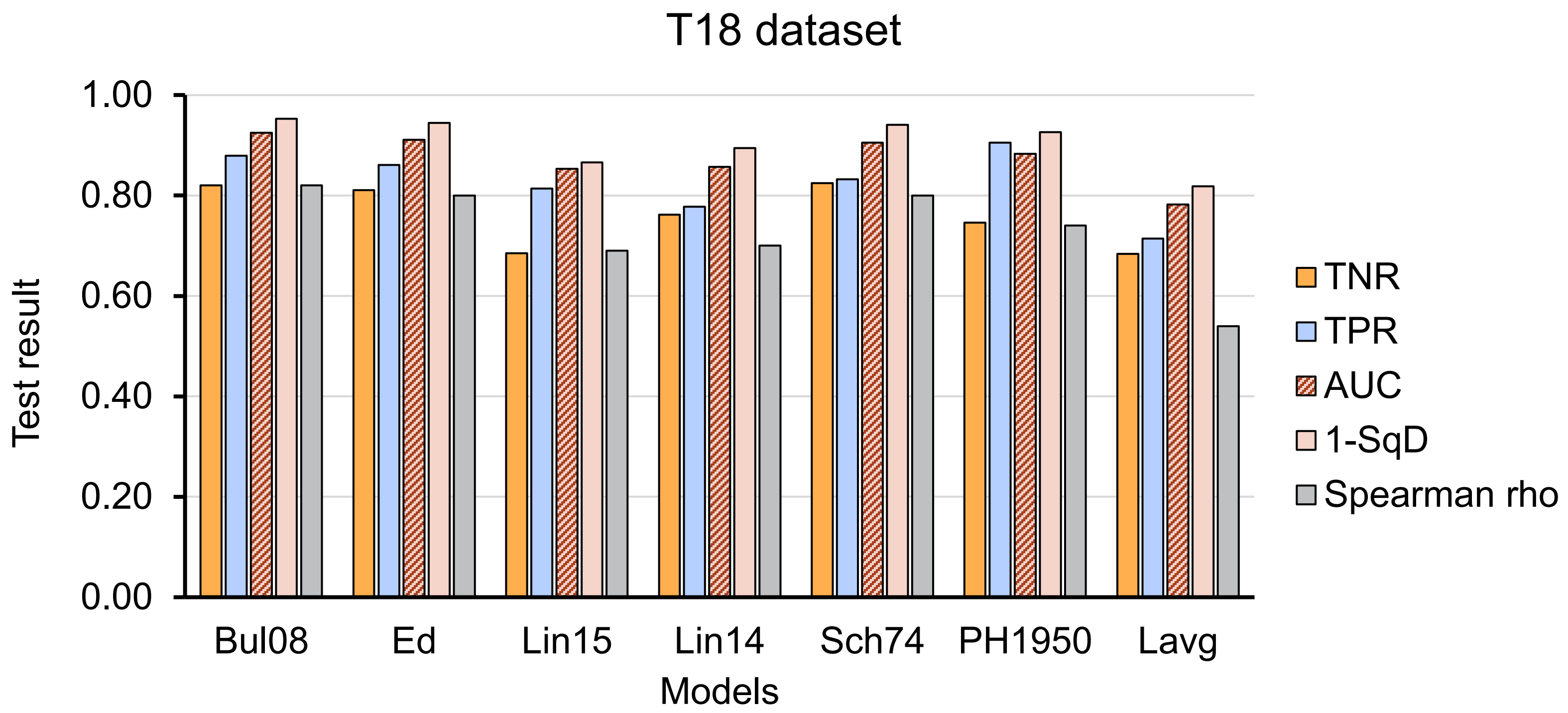
Diagnostic Tests



- Area under the curve (AUC)
  >0.6 sufficient
  >0.7 good
  >0.8 very good
  >0.9 excellent
- TPR and TNR
  Random result if <0.5
- 1 - Squared distance (SqD)
  Larger is better
- Spearman correlation coefficient (ρ)
  0-0.3 negligible
  0.3-0.5 low
  0.5-0.7 moderate
  0.7-0.9 high
  0.9-1 very high

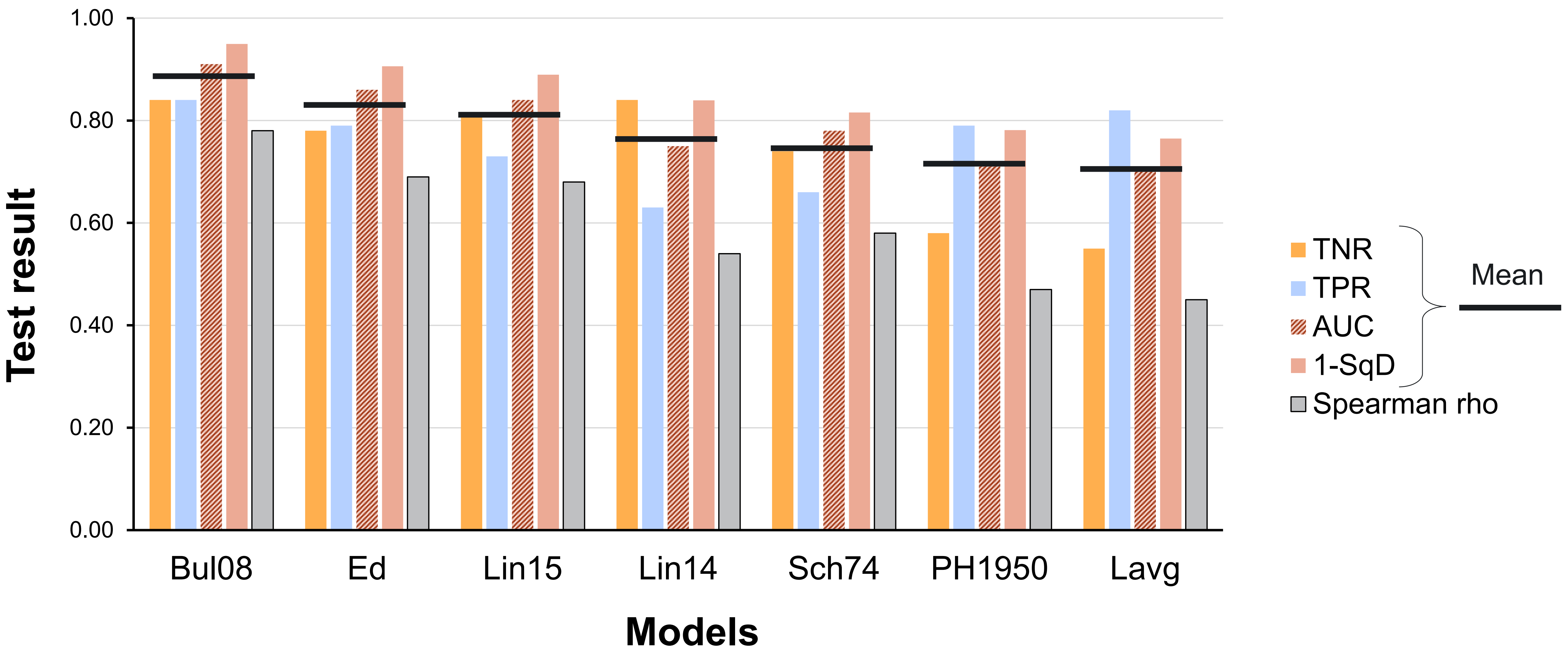
Results from individual data set





Mean of four diagnostic tests (TNR, TPR, AUC, 1-SqD) for the seven models using individual data sets. A higher mean value indicates a better performance.

Results from the combined data set



Test results for the seven models using the combined data set. A higher value indicates a better performance.

Conclusions

- Highest mean performance was for the model proposed by Bullough et al. (2008) followed by direct illuminance at the eye
- While the mean performance of direct illuminance at the eye is slightly lower than the model by Bullough et al. (2008), the former offers a simpler approach for design and installation practice
- Conclusions are specific to the range of lighting conditions in the combined data set

	Dataset			
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Source size (sr)	0.00044 - 0.00823	0.00096; 0.00383	0.00001; 0.0001	0.0001 - 0.0081

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Thank you

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Predicting discomfort from glare with pedestrian-scale lighting: A comparison of candidate models using four independent datasets

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After dark, pedestrians may experience discomfort from glare caused by outdoor lighting. While several models for measuring discomfort have been proposed, there is no consensus as to which model should be used. The performances of different models were investigated using datasets from four independent studies, comparing the degree of association between model predictions and subjective ratings, and the ability of a model to distinguish between discomfort and non-discomfort situations. The models tested are those proposed by Petherbridge and Hopkinson in 1950, Schmidt-Clausen and Bindels in 1974, Bullough *et al.* in 2008 and Lin *et al.* in 2014 and 2015. They also include two quantities: direct illuminance at the eye from the glare source and average source luminance. Of the models tested, the best performance was found using either the model proposed by Bullough *et al.* in 2008 or by direct illuminance at the eye.

1. Introduction

Glare arises when part of the visual field, a light source or a surface, is much brighter than the rest of the field. Two common visual impacts of glare are disability and discomfort, and these outcomes may persist individually or together. Disability from glare is a situation where the glare source impairs visibility or visual performance.[1,2] Discomfort from glare is a situation when the observer feels visual discomfort due to the glare source but does not necessarily experience a visual disability.[1,2] The induced discomfort can be described as a sensation of annoyance or pain from a glare source located within the field of view. The magnitude of discomfort is usually described on a scale ranging from barely noticeable to unbearable.

One aim of a lighting design is to minimize discomfort for pedestrians (and other road users) and to do so designers might refer to the quantitative recommendations of lighting guidance documents. For interior lighting, glare limits such as the Unified Glare Rating (UGR) are calculated based on the luminances of light sources and their background, the size subtended by each light source at the observer's eye and its position in the visual field: a UGR of 22 is the threshold

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