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Predicting discomfort glare from outdoor lighting installations

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In addition to sky glow and light trespass, discomfort glare from outdoor lighting installations is a growing concern to the public. A series of experimental investigations was performed to assess the relative impacts of light source photometric characteristics on subjective ratings of discomfort glare. The results converge, demonstrating the influence of light source illuminance, surround illuminance and ambient illuminance on subjective judgements of discomfort glare. A simple model relating these photometric quantities is proposed for making predictions of discomfort glare from outdoor lighting installations. This model can be readily incorporated into existing frameworks for evaluating light pollution as well as into lighting calculation software.

1. Introduction

Outdoor lighting involves the use of high-lumen sources, in the context of relatively dark surrounding environments. In addition to the potential of outdoor lighting to contribute to sky glow and light trespass, high-lumen sources can also create *discomfort glare*, the sensation of annoyance or even pain that is experienced when viewing a very bright light source.[1] In the present paper, we describe a series of experimental investigations from the laboratory and from the field to investigate discomfort glare. The results of these investigations converge to a simple quantitative model for predicting discomfort glare from outdoor lighting installations. Inputs to this model are based on illuminance and therefore predictions of discomfort glare can be incorporated into existing lighting calculation software and can be readily verified in the field. Using the methods described here, discomfort glare complements the sky glow and light trespass assessments of night-time light pollution using the outdoor site-lighting performance (OSP) method.[2,3]

2. Background

Light levels for outdoor lighting installations are one or more orders of magnitude lower than experienced during the daytime and indoors. For example, headlamps on vehicles produce at most a few lux at the eyes of oncoming drivers, creating sometimes objectionable levels of glare at night when ambient light levels are usually under 1 lx;[4] during the daytime, when the sky can produce thousands of lux at drivers' eyes, the same few lux from headlamps produce no glare at all. For example, the U.S. National Highway Traffic Safety Administration has received thousands of complaints about night-time headlamp glare,[5] describing discomfort and annoyance experienced from headlamps while driving at night. The phenomenon of *discomfort glare* is separate from that of *disability glare*,[1] which is the degree to which visibility of objects is reduced in the presence of a bright light via scattered light in the eye.[6] Disability glare is well understood and relatively straightforward

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to predict; discomfort glare has been notoriously intractable.

A number of studies have explored the factors that influence discomfort glare, and in particular, whether the illuminance from[7–11] or the luminance of[12–15] a light source is the primary determinant of discomfort glare. One published study in an automotive headlamp context[16] has suggested both, that discomfort glare is illuminance-driven for very small sources and luminance-driven for large sources. The extent to which either illuminance or luminance influences discomfort glare is important in the context of predicting discomfort glare from an outdoor lighting installation. This question is particularly important when using photometrically accurate lighting design software based on flux transfer, where illuminance is much more simple and straightforward to calculate than luminance.

Some predictive models for discomfort glare exist; one of the most widely used to assess glare from automotive headlamps was developed by Schmidt-Clausen and Bindels.[8] Using the illuminance from a light source at the eye, the luminance of the background surrounding the light source, and the angle from the line of sight to the light source, Schmidt-Clausen and Bindels[8] developed equations to predict the degree of discomfort along the De Boer[17] subjective rating scale. This nine-point discomfort glare scale is complemented by parallel word descriptors:

9	just noticeable glare
8	
7	satisfactory
6	
5	just permissible
4	
3	disturbing
2	
1	unbearable

Research using the De Boer scale,[17] like all subjective rating research, is prone to potential difficulties. Certainly, individual interpretations of the nine-point scale could differ, resulting in inconsistencies.[18] In addition, the range of conditions that are viewed in a given experiment can also affect ratings; Lulla and Bennett[14] showed light sources to two groups of people with different ranges of intensities (the maximum intensity seen by one group was higher than that for the other group). The glare ratings from the group with the more limited range were on average lower (indicating more discomfort) at the highest intensity than the ratings from the other group to the same intensity. This ‘range effect’ is a tendency for subjects to use as much of the rating scale as possible in the context of the experimental conditions. As another example of experimental context, Bullough et al.[10] asked subjects to respond to high- and low-reflectance targets in the presence of glare, and subjects consistently reported experiencing more discomfort from the same light source when they were responding to targets of lower reflectance (i.e. more difficult to see); similar findings have been published by Sivak et al.[19] and by Theeuwes et al.[20] Despite all of these difficulties, using ratings such as the De Boer[17] scale is recognised presently as the best and most reliable method for measuring discomfort glare. Taking into account the factors outlined above, the results of studies using the De Boer scale are reasonably consistent, and models such as that developed by Schmidt-Clausen and Bindels[8] can and have been used in the context of vehicle lighting as a good measure of discomfort glare.[21]

Notwithstanding the aforementioned issues with subjective ratings in general[18] and therefore, a model for predicting them, a difficulty with using the model from Schmidt-Clausen and Bindels[8] is that in many situations, the background luminance surrounding a light source is not a single, uniform value. The presence of buildings and other structures having multiple surface reflectances in any outdoor lighting installation complicates the selection of a single value for the background luminance. Another issue is that the model from Schmidt-Clausen and Bindels[8] requires the user to specify an angle from the line of sight at which the light source is located (since discomfort is reduced as this angle increases), but if an observer is looking more or less directly at a luminaire, the angle becomes zero, and the model, which contains the value for this angle in a denominator term, grows to infinity. For applications such as driving, in which a driver is expected to maintain visual contact along one's own lane ahead, and when oncoming headlamps are likely to appear at least one lane away, this model form is not problematic. However, if one wishes to predict discomfort experienced by a person looking directly at a luminaire while walking past a car park, for example, the model from Schmidt-Clausen and Bindels[8] would not be expected to be useful because it would predict infinite discomfort glare for any directly viewed source, regardless of its illuminance or luminance.

For this reason, a series of experimental investigations of discomfort glare were conducted to better elucidate the relative influence of light source illuminance or luminance and of the photometric characteristics of the area surrounding a light source. An underlying objective of all of these experiments was to determine whether a model of discomfort glare might be developed that uses illuminance-based quantities. A model based on illuminance avoids the difficulties mentioned earlier regarding background complexity, and could facilitate incorporation of a calculation procedure into lighting calculation software that could in turn be used as part of an assessment of light pollution.

In most of the experiments, a single light source in the field of view was used for the glare evaluations. The final indoor experiment utilised a secondary light source to assess the independence of light source glare evaluations in a scene.

3. Methods

A series of field and laboratory experiments were conducted, each under different conditions, in order to investigate the relationship between photometric characteristics [e.g. light source illuminance (E_ℓ), light source luminance (L_ℓ), surround illuminance [E_s] and ambient illuminance (E_a)] of light sources (and their surrounds) and subjective ratings of discomfort. Six to eighteen subjects between the ages of 20 and 57 years participated in each experiment. In every experiment subjects were asked to look at the light source from a designated location and to rate the level of discomfort glare they experienced using the De Boer scale.[17] Tables 1–3 summarise the experimental conditions for each experiment.

To determine the light source illuminance (E_ℓ), the vertical illuminance from the light source in each experiment was measured (at a height of 1.5 m) at the subjects' viewing location using a baffle that blocked the light surrounding the source from reaching the illuminance meter. The light source luminance (L_ℓ) was measured at a distance from which the luminance meter aperture subtended as much of the source as possible without including any dark areas. With the light source switched off, the ambient illuminance (E_a) was estimated by measuring the vertical illuminance (at a height of 1.5 m) at the subjects' viewing location. With the light source switched on, the surround illuminance (E_s) was estimated by measuring the total vertical illuminance (at a height of 1.5 m) at the subjects' viewing location, and subtracting E_ℓ and E_a from this value.

Regarding the values for ambient illuminance (E_a) for the indoor experiments, comparisons of direct illuminance measurements from each test light source (measured using a

Table 1 Summary of experimental conditions and results (±standard error of the mean) for the outdoor experiments

Experiment type and no. of subjects	Light source illuminance (E_ℓ, lx)	Surround illuminance (E_s, lx)	Ambient illuminance (E_a, lx)	Light source luminance (L_ℓ, cd/m^2)	Viewing distance (m)	Mean De Boer rating (±s.e.m.)
Outdoor experiment 1 ($n=18$)	0.5	0.01	1.60	24 000	20	7.44 ± 0.25
	2.8	0.01	1.60	78 000	20	3.83 ± 0.32
	8.7	0.01	1.60	196 000	20	2.33 ± 0.27
	2.2	0.01	1.40	26 000	10	7.22 ± 0.24
	11.8	0.01	1.40	82 000	10	3.06 ± 0.25
	34.8	0.01	1.40	196 000	10	1.61 ± 0.16
Outdoor experiment 2 ($n=8$)	0.1	0.01	0.01	66 650	3	7.50 ± 0.64
	3.5	0.01	0.01	15 750	3	4.00 ± 0.81
	9.9	0.01	0.01	54 300	3	4.00 ± 0.53
	12.4	0.01	0.01	49 540	3	3.50 ± 0.57
	12.7	0.01	0.01	66 650	3	3.07 ± 0.54
	20.1	0.01	0.01	15 750	3	2.88 ± 0.62
	23.0	0.01	0.01	15 750	3	2.25 ± 0.48
	29.5	0.01	0.01	15 750	3	3.00 ± 0.40
	65.9	0.01	0.01	66 650	3	2.38 ± 0.28
	80.1	0.01	0.01	49 540	3	2.00 ± 0.29
	85.8	0.01	0.01	66 650	3	2.25 ± 0.27
	111.3	0.01	0.01	66 650	3	2.13 ± 0.37
Outdoor experiment 3 ($n=14$)	1.7	0.05	0.10	5300	9	5.93 ± 0.43
	6.6	0.06	0.10	20 500	9	3.64 ± 0.37
	1.7	0.11	0.10	5300	9	7.07 ± 0.41
	6.6	0.28	0.10	20 500	9	4.57 ± 0.56

baffle that only permitted a direct view of the source) with the total illuminance (without the baffle present) revealed that on average, the room surfaces did contribute a small amount (~0.3%) to the total illuminance at the observers' eyes during the experiments. These amounts were proportional to the direct illuminances from the test light source, and are listed in Table 2 and in Table 3 (for the indoor conditions in the indoor/outdoor experiment). In the outdoor experiments, conducted in large open areas, inter-reflected light from the test light source did not contribute measurably to the ambient illuminance.

The experiments were conducted in the following chronological order:

- Outdoor experiment 1
- Indoor experiment 1
- Outdoor experiment 2
- Indoor experiment 2
- Indoor experiment 3
- Indoor experiment 4
- Indoor experiment 5
- Outdoor experiment 3
- Indoor/outdoor experiment
- Indoor experiment 6

This section discusses the outdoor experiments, followed by a description of the indoor experiments and the indoor/outdoor experiment.

3.1 Outdoor experiment 1

The main objective of the first outdoor experiment was to provide some initial normative data to relate various lighting conditions (illuminances and luminances) to subjective responses using the De Boer rating scale.[17]

Subjects viewed a metal halide (100 W) rectangular floodlight luminaire (wall pack) that was positioned adjacent to the brick building that houses the Lighting Research Center (LRC), at a height of 1.5 m and directed outward toward a paved parking lot. The luminaire could be tilted to one of three angles (10° above horizontal, 37° below

Table 2 Summary of experimental conditions and results (±standard error of the mean) for the indoor experiments

Experiment type and no. of subjects	Light source illuminance (E_ℓ, lx)	Surround illuminance (E_s, lx)	Ambient illuminance (E_a, lx)	Light source luminance (L_ℓ, cd/m^2)	Secondary light source illuminance (lx)	Secondary light source luminance (cd/m^2)	Secondary light source position (°)	Viewing distance (m)	Mean De Boer rating (±s.e.m.)
Indoor experiment 1 ($n=9$)	0.1	0.01	0.01	66 650	n/a	n/a	n/a	3	6.56 ± 0.65
	3.5	0.01	0.01	15 750	n/a	n/a	n/a	3	5.00 ± 0.50
	9.9	0.01	0.03	54 300	n/a	n/a	n/a	3	3.89 ± 0.35
	12.4	0.01	0.04	49 540	n/a	n/a	n/a	3	4.22 ± 0.55
	12.7	0.01	0.04	66 650	n/a	n/a	n/a	3	3.17 ± 0.35
	20.1	0.01	0.06	15 750	n/a	n/a	n/a	3	4.44 ± 0.47
	23.0	0.01	0.07	15 750	n/a	n/a	n/a	3	3.78 ± 0.52
	29.5	0.01	0.09	15 750	n/a	n/a	n/a	3	4.33 ± 0.53
	65.9	0.01	0.20	66 650	n/a	n/a	n/a	3	1.78 ± 0.39
	80.1	0.01	0.24	49 540	n/a	n/a	n/a	3	2.11 ± 0.45
	85.8	0.01	0.26	66 650	n/a	n/a	n/a	3	2.11 ± 0.39
	111.3	0.01	0.33	66 650	n/a	n/a	n/a	3	2.22 ± 0.43
Indoor experiment 2 ($n=6$)	5.2	0.01	0.02	15 750	n/a	n/a	n/a	3	3.33 ± 0.56
	13.9	0.01	0.04	53 400	n/a	n/a	n/a	3	2.92 ± 0.52
	14.1	0.01	0.04	15 750	n/a	n/a	n/a	3	3.50 ± 0.50
	37.0	0.01	0.11	53 400	n/a	n/a	n/a	3	2.33 ± 0.49
	5.2	0.23	0.02	15 750	n/a	n/a	n/a	3	4.00 ± 0.45
	13.9	0.23	0.04	53 400	n/a	n/a	n/a	3	3.17 ± 0.54
	14.1	0.23	0.04	15 750	n/a	n/a	n/a	3	2.67 ± 0.49
	37.0	0.23	0.11	53 400	n/a	n/a	n/a	3	2.33 ± 0.33
Indoor experiment 3 ($n=8$)	2.0	0.01	0.01	15 750	n/a	n/a	n/a	5	4.50 ± 0.27
	5.0	0.01	0.02	15 750	n/a	n/a	n/a	5	3.38 ± 0.56
	5.0	0.01	0.02	53 400	n/a	n/a	n/a	5	3.13 ± 0.35
	14.0	0.01	0.04	53 400	n/a	n/a	n/a	5	2.63 ± 0.38
	5.2	0.01	0.02	15 750	n/a	n/a	n/a	3	3.00 ± 0.46
	13.9	0.01	0.04	53 400	n/a	n/a	n/a	3	2.00 ± 0.42
	14.1	0.01	0.04	15 750	n/a	n/a	n/a	3	2.50 ± 0.46
	37.0	0.01	0.11	53 400	n/a	n/a	n/a	3	1.75 ± 0.16
Indoor experiment 4 ($n=8$)	2.0	0.01	0.01	15 750	n/a	n/a	n/a	5	4.00 ± 0.44
	5.0	0.01	0.02	53 400	n/a	n/a	n/a	5	2.94 ± 0.37
	5.2	0.01	0.02	15 750	n/a	n/a	n/a	3	3.19 ± 0.44
	13.9	0.01	0.04	53 400	n/a	n/a	n/a	3	2.19 ± 0.28
Indoor experiment 5 ($n=8$)	5.0	0.08	0.02	53 400	n/a	n/a	n/a	5	3.38 ± 0.42
	2.0	0.16	0.01	15 750	n/a	n/a	n/a	5	4.63 ± 0.71
	5.0	0.16	0.02	53 400	n/a	n/a	n/a	5	3.25 ± 0.75
	5.2	0.23	0.02	15 750	n/a	n/a	n/a	3	4.00 ± 0.53
	13.9	0.23	0.04	53 400	n/a	n/a	n/a	3	2.75 ± 0.62
	5.2	0.40	0.03	15 750	n/a	n/a	n/a	3	4.13 ± 0.77
Indoor experiment 6 ($n=12$)	1.5	0.01	0.01	8 000	n/a	n/a	n/a	3	5.38 ± 0.49
	5.0	0.01	0.02	28 000	n/a	n/a	n/a	3	3.00 ± 0.37
	1.5	0.01	0.01	8 000	0.6	8 000	9	3	6.00 ± 0.49
	1.5	0.01	0.01	8 000	0.6	8 000	27	3	5.83 ± 0.41
	1.5	0.01	0.01	8 000	1.5	8 000	9	3	5.42 ± 0.43
	1.5	0.01	0.01	8 000	1.5	8 000	27	3	5.83 ± 0.34
	1.5	0.01	0.01	8 000	3.0	8 000	9	3	5.08 ± 0.47
	1.5	0.01	0.01	8 000	3.0	8 000	27	3	5.83 ± 0.24
	5.0	0.01	0.02	28 000	2.0	28 000	9	3	3.25 ± 0.39
	5.0	0.01	0.02	28 000	2.0	28 000	27	3	3.25 ± 0.45
	5.0	0.01	0.03	28 000	5.0	28 000	9	3	2.92 ± 0.48
	5.0	0.01	0.03	28 000	5.0	28 000	27	3	2.92 ± 0.38
	5.0	0.01	0.05	28 000	10.0	28 000	9	3	2.83 ± 0.46
	5.0	0.01	0.05	28 000	10.0	28 000	27	3	2.92 ± 0.40

horizontal and 62° below horizontal). Changing the tilt angle had the effect of changing the projected area of the luminaire and the illuminance from the luminaire at the eyes of subjects standing in front of the luminaire. The area immediately surrounding the luminaire (i.e. the wall behind the luminaire) was dark (surround illuminance

Table 3 Summary of experimental conditions and results (±standard error of the mean) for the indoor/outdoor experiment

Experiment type and no. of subjects	Light source illuminance (E_ℓ, lx)	Surround illuminance (E_s, lx)	Ambient illuminance (E_a, lx)	Light source luminance (L_ℓ, cd/m^2)	Viewing distance (m)	Mean De Boer rating (±s.e.m.)
Indoor/outdoor experiment ($n=14$, $n=10$)	1.7	0.11	0.10 (outdoor)	5 300	9	6.29 ± 0.49
	6.6	0.28	0.10 (outdoor)	20 500	9	4.64 ± 0.46
	2.0	0.16	0.01 (indoor)	15 750	5	3.79 ± 0.35
	5.0	0.16	0.02 (indoor)	53 400	5	2.64 ± 0.37
	1.7	0.11	0.01 (indoor)	5 300	9	5.70 ± 0.45
	6.6	0.28	0.02 (indoor)	20 500	9	3.30 ± 0.37

of approximately 0.01 lx), although there were several luminaires switched on in adjacent properties located at large peripheral angles that resulted in vertical illuminances of 1.4 lx and 1.6 lx at subjects' eyes, when they were standing at distances of 10 m and 20 m from the luminaire, respectively. Table 1 summarises the photometric characteristics and viewing distances in this experiment.

The tilt angles and viewing distances were ordered randomly for each subject to minimise order effects, and subjects provided De Boer[17] ratings under every condition. Both experimental sessions were completed in approximately 10 min.

3.2 Outdoor experiment 2

Outdoor experiment 2 was conducted to investigate the relative impact of illuminance from and luminance of a light source on subjective ratings of discomfort glare. The light source in this experiment consisted of a metal halide (250 W) floodlight luminaire inside an enclosure. The front of the enclosure was covered with a diffuser; two sideways 'V' panels (Figure 1) could slide back and forth to create a diamond-shaped, fairly uniform luminous source of variable size. (While the source was not perfectly uniform, variations in luminance were small enough that the average luminance did not increase or decrease by more than 20% for different aperture sizes.) Neutral density filters were used to produce a range of light source luminances and corneal illuminances.

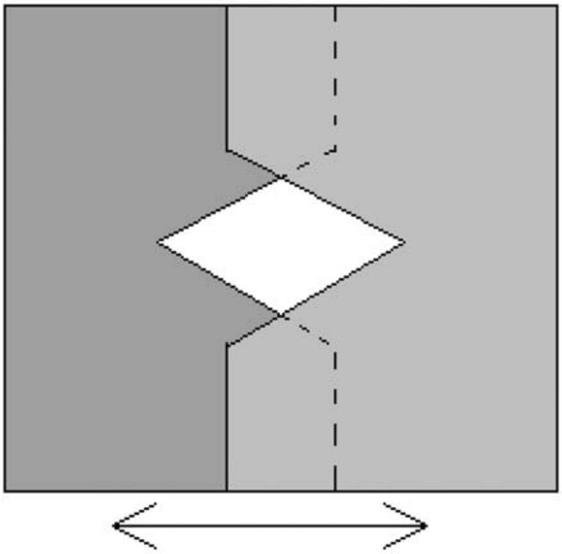

Figure 1 Sketch of front panel of adjustable-size glare source apparatus used in the several experiments. The two panels could slide to create glare source apertures of various sizes

The light source was positioned, as in outdoor experiment 1, 1.5 m above the ground. This experiment took place outside the building housing the LRC. Subjects stood 3 m in front of the light source, viewed every condition (listed in Table 1) in a randomised order, and provided discomfort glare ratings using the De Boer scale.[17] The ambient illuminance for this experiment (0.01 lx) was lower than for outdoor experiment 1 because the viewing location for this experiment (3 m from the light source) was close to the unlighted façade of the building, blocking light from adjacent properties from reaching subjects' eyes.

3.3 Outdoor experiment 3

Outdoor experiment 3 was conducted to investigate the impact of illuminance from the area surrounding a luminaire on discomfort glare. The light sources in this experiment were two identical yard light luminaires containing mercury vapour lamps (175 W; see Figure 2). This experiment was conducted at night-time on the roof of the building housing the LRC. Subjects viewed the luminaires one at a time (while the other was covered in dark fabric). The luminaires were located 9 m away and mounted 3 m above the roof level. Directly behind one of the luminaires was a 1 m (high) × 2 m (wide) fabric-covered board ($\rho = 0.6$). These sources were seen in the context of an urban sky and unlighted foliage as illustrated in Figure 2. Each luminaire was always viewed through two 20 cm (high) × 30 cm (wide) apertures. One aperture was clear while the other contained a 25% transmittance neutral density filter; this allowed the resulting luminance of the light source to be changed. Subjects viewed every lighting condition (listed in Table 1) in a randomised order and provided discomfort glare ratings using the De Boer scale.[17]

Figure 2 Yard light luminaires and different surrounding conditions used in outdoor experiment 3

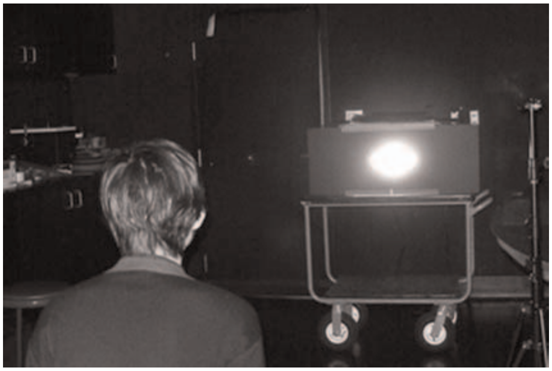

Figure 3 Photograph of experimental setup for all indoor experiments

3.4 Indoor experiment 1

Indoor experiment 1 was conducted using the same apparatus (Figure 3) and lighting conditions as outdoor experiment 2. In addition to investigating the relative impact of light source illuminance and luminance on discomfort glare, the same conditions were used in these two experiments to determine whether their results would be similar, thus permitting data from indoor and outdoor experiments to be compared. Subjects viewed and rated every lighting condition (Table 2) from a distance of 3 m in a randomised order in the Levin Photometric Laboratory at the LRC, which contains black painted surfaces and black furnishings. No lighting other than the light source under study was switched on during this experiment.

3.5 Indoor experiment 2

Indoor experiment 2 was conducted to assess the impact of surround illuminance on discomfort glare. The same apparatus as used in indoor experiment 1 was employed, with combinations of halogen floodlight lamps and neutral density filters to illuminate the black wall behind the light source to produce an illuminance of approximately 0.01 lx or 0.23 lx.

The light source size was changed by adjusting the separation between the front panels, and the light source luminance was adjusted using neutral density filters. Subjects viewed every lighting condition (listed in Table 2) from a viewing distance of 3 m, in a randomised order, and provided discomfort glare ratings using the De Boer scale.[17]

3.6 Indoor experiments 3 and 4

Indoor experiments 3 and 4 were conducted to assess the effects of light source size and viewing distance on discomfort glare. The same apparatus as in the previous indoor experiments was used, with a surround illuminance of approximately 0.01 lx; the light source was viewed from 3 m and from 5 m, and several sizes and light source luminances were used to create a range of illuminances at subjects' eyes. Some of the conditions at the shorter distance produced the same illuminances as other conditions at the longer distance. Subjects viewed each condition (listed in Table 2) in a randomised order and provided subjective ratings of discomfort glare using the De Boer scale.[17]

3.7 Indoor experiment 5

Indoor experiment 5 was conducted with the objective of identifying the relationships between light source illuminance and illuminance from the area surrounding the light source on visual discomfort. The same apparatus as in previous laboratory studies was used with the surrounding illumination provided by halogen floodlight lamps, filtered as needed to provide different amounts of surrounding illumination. Subjects made observations from two distances and provided subjective ratings of discomfort glare using the De Boer scale[17] for every condition, viewed in a randomised order.

3.8 Indoor experiment 6

Indoor experiment 6 was conducted using two versions of the apparatus used in the previous indoor experiments to permit two light sources in the field of view. One (the primary light source) was located 3 m in front of the subjects' seating location and the other (the secondary light source) was located either 9° or 27° to the right of the primary source. Peripheral angles of less than 9° were not studied; Schmidt-Clausen and Bindels[8] demonstrated that when light sources are close together, their impact on discomfort glare is additive (i.e. the combination of luminaires can be treated as a single luminaire). The illuminance from (and luminance of) each source and the location of the secondary source were adjusted as in Table 2, and the conditions were presented to, and rated by, subjects in a randomised order.

3.9 Indoor/outdoor experiment

An objective of the indoor/outdoor experiment was to determine to what extent ambient urban night-time illuminances might influence subjective ratings of discomfort. The adjustable diamond-shaped light source was used in the black-painted Levin photometry laboratory, and the mercury vapour yard light luminaires were used on the roof of the LRC building; these conditions were observed in a randomised order by 14 subjects, who provided subjective ratings of discomfort using the De Boer scale.[17] Shortly afterward, the mercury vapour luminaires were brought indoors into the photometry laboratory, and ten of the same subjects viewed and rated these conditions. The photometric characteristics of all conditions in this experiment are listed in Table 3.

4. Results and discussion

The mean subjective ratings (and standard errors of the mean) for every condition in each experiment are listed in Tables 1–3, alongside the description of the lighting conditions for each experiment.

In general, subjective ratings of discomfort glare are more closely related to illuminance at the cornea produced by the light source than to light source luminance. For example, the data from outdoor experiment 2 revealed many intransitivities between light source luminance (L_ℓ) and discomfort glare ratings (Figure 4; $r^2 = 0.02$); the results were more consistent with light source illuminance (E_ℓ; $r^2 = 0.93$). This is consistent with findings from Lewin[15] who measured how objectionable several light sources were that had different luminances and sizes. An analysis of Lewin's data showed that ratings of 'objectionableness' were more closely correlated with corneal illuminance than with source luminance.

Although light source illuminance (E_ℓ) appears to better than source luminance (L_ℓ) for predicting ratings of discomfort glare, additional terms also need to be considered, as shown by the data from indoor experiment 5 (Figure 5). As with luminance, light source illuminance alone is not directly related to discomfort glare ratings. Because previous studies[8,11] indicate that the luminous characteristics of the area surrounding a light source influences discomfort glare, indoor experiment 5 and outdoor experiment 3 were conducted to develop and then validate a quantitative relationship between discomfort glare ratings and light source illuminance (E_ℓ) and surround illuminance (E_s).

In outdoor experiment 3, indoor experiment 5 and the indoor/outdoor experiment, the illuminance from the area surrounding the light source was adjusted to create different ratios of light source illuminance and the surround illuminance (E_ℓ/E_s), the hypothesis being that as this ratio increases, discomfort glare ratings should also increase. However, since the total illuminance at the eye should still be a factor related to discomfort, the total corneal illuminance ($E_\ell + E_s$) was also hypothesised to be related to discomfort. Finally, building on the premise that discomfort glare in a high ambient lighting environment (e.g. an urban city centre) should be reduced relative to a low ambient lighting environment (e.g. an isolated rural area), even if the illuminance at the eye and the illuminance from the surround are the same, discomfort glare ratings are expected to be negatively correlated with ambient illuminance (E_a) in the indoor/outdoor experiment, particularly since the results of this experiment were not strongly correlated with the light source illuminance (Figure 6).

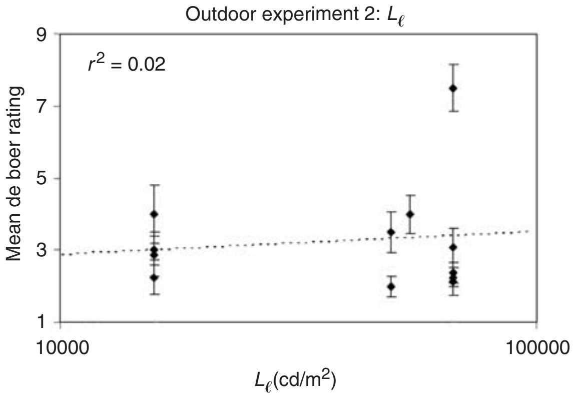

Figure 4 Mean discomfort ratings (±standard error of the mean) for outdoor experiment 2 plotted as a function of light source luminance (L_ℓ)

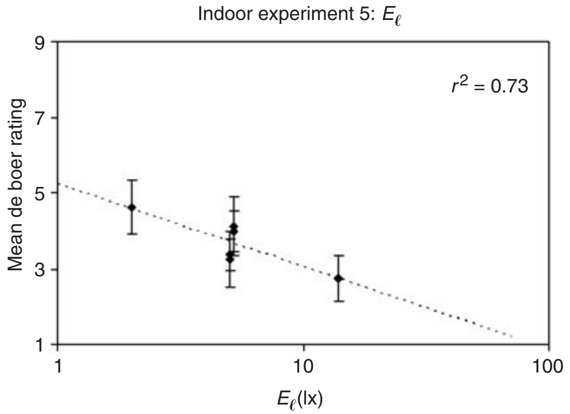

Figure 5 Mean discomfort ratings (±standard error of the mean) for indoor experiment 5 plotted as a function of light source illuminance (E_ℓ). The conditions at the middle illuminance values had different surround illuminances (E_s) and resulted in different ratings

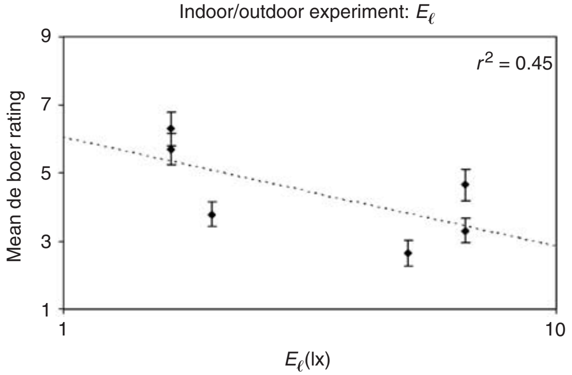

Figure 6 Mean discomfort ratings (±standard error of the mean) from the indoor/outdoor experiment, plotted as a function of light source illuminance (E_ℓ)

Indoor experiment 6 was conducted to test whether the presence of a secondary light source would affect discomfort ratings while viewing a primary source. A within-subjects analysis of variance (ANOVA) of these data revealed that subjective ratings of discomfort glare were not reliably affected by the presence of a secondary source, its illuminance, or its position. Only the characteristics of the primary light source (with surround and ambient illuminance held constant) had a statistically reliable ($p < 0.05$) effect on discomfort glare ratings. When evaluating discomfort glare experienced from a particular luminaire in the field of view, the presence of another luminaire can be ignored if it is sufficiently far from the luminaire being evaluated (more than a few degrees).[8]

Since previous studies[8,11,22] have shown that discomfort glare ratings are related logarithmically to intensity, it was postulated that a quantitative model of discomfort glare using illuminance would contain the terms: $\log(E_\ell + E_s)$, $\log(E_\ell/E_s)$ and $\log(E_a)$. The most parsimonious model combining these terms for predictions of discomfort glare (DG) would be an algebraic combination of the terms above with the appropriate arithmetic signs. Since the relative contribution of each factor is not known, coefficients (a, b and c) in front of each term were identified to provide the best fit between the model:

$$\begin{aligned}\mathrm{DG} = a\ \log(E_\ell + E_\mathrm{s})\\ + b\ \log(E_\ell/E_\mathrm{s}) - c\ \log(E_\mathrm{a})\end{aligned} \tag{1}$$

Fixing the value of a at 1.0, the values of b and c resulting in the best fit of the data from all of the experiments to the model equation were determined through iterative trial and error to be 0.6 and 0.5, respectively.

As examples, Figure 4 shows that the ratings from outdoor experiment 2 were poorly ($r^2 = 0.02$) related to light source luminance (L_ℓ), but as shown in Figure 7(a), the combination of terms in the model results in a much higher goodness-of-fit value ($r^2 = 0.93$). (This r^2 value is the same with or without E_a and E_s being considered, because the surround and ambient illuminances were constant in this experiment.) Likewise, when the data from indoor experiment 5 (Figure 5) were plotted as a function of the model in Equation (1) [Figure 7(b)], the goodness-of-fit value (r^2) increased from 0.73 to 0.91. Finally, consider the results of the indoor/outdoor experiment (Figure 6). Some of the conditions resulted in identical values of E_ℓ from the source and E_s from the area surrounding the source, but resulted in different subjective ratings of discomfort. Once the model transformed the values based on different ambient conditions (E_a) in the two experimental locations, there was improved agreement (r^2 increased from 0.45 to 0.72) between the model predictions and the measured subjective ratings [Figure 7(c)].

The ambient illuminance (E_a) term certainly affected discomfort glare ratings. However, this term is the least well understood, and more research is justified. For the purposes of predicting discomfort glare responses, and until more research is available, it can be estimated in one of several ways. Obviously it is best to measure E_a directly, but often E_a is a

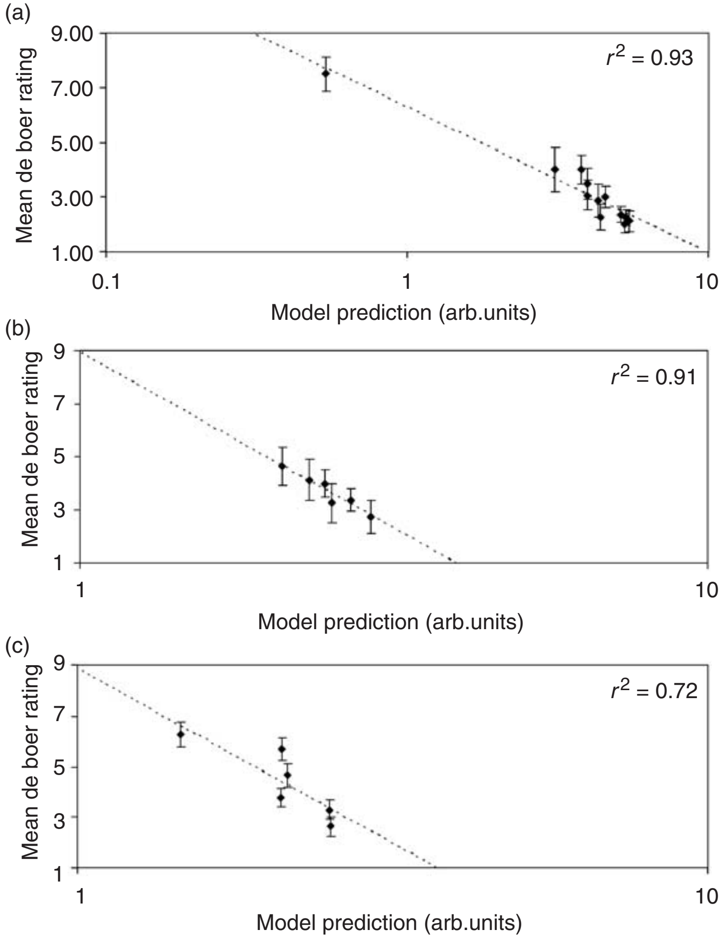

Figure 7 Mean discomfort ratings (±standard error of the mean) from (a) outdoor experiment 2, (b) indoor experiment 5 and (c) the indoor/outdoor experiment, plotted as a function of the model values from Equation (1)

low, uncertain value when using commonly available illuminance meters. If an installation is located within a particular lighting environmental zone (e.g. as described by the CIE[23]), an E_a value corresponding to that for the environmental zone could be assumed. Alternatively, if the installation is very large, the average illuminance on the vertical plane containing the property boundary could be used as a rough estimate of the ambient illuminance (E_a). When very dark surroundings are assumed outdoors, minimum surround and ambient illuminances of 0.02 lx, corresponding to one-fifth the illuminance provided by moonlight,[24] are suggested. Li et al.[25] conducted ambient lighting measurements in urban and residential areas, and based on those measurements, ambient illuminance values of 0.2 lx, 2 lx and 20 lx are suggested for locations corresponding to suburban districts, urban districts and very commercial urban districts (e.g. central Shanghai or London), respectively.

The data for all of the experiments are plotted in Figure 8 as a function of the model value calculated using Equation (1). Figure 8 also shows the logarithmic equation that transforms the model prediction from Equation (1) (DG) to De Boer ratings (DB):

$$\mathrm{DB} = 6.6 - 6.4\ \log\ \mathrm{DG} \qquad (2)$$

The goodness-of-fit (r^2) between the model predictions and the overall set of data created by combining all experiments in Figure 8 is 0.70. This value is lower than the goodness-of-fit values for individual experiments in Figures 7(a), (b) and (c) (0.93, 0.91, and 0.72, respectively), and is probably indicative of different methods and subjects employed in the various experiments. For example, the range of conditions in each experiment varied among experiments, and indeed, the slope of the best fitting function in Figure 7(a) (with a larger range of conditions) is lower than those of the functions in Figures 7(b) and (c) (with smaller ranges of conditions). This finding is consistent with expectations based on the range effect.[14] The simple, theoretical, model presented here clearly does not account for all of the factors contributing to differences among all of the experiments. It is worth noting that *post hoc* multiple regression models using linear and logarithmic terms corresponding to E_ℓ, E_s and E_a did not result in improved fits over the model in Equation (1).

Additional terms such as the degree of luminance uniformity of the background surrounding a light source, the type of objects visible in the field of view, or even outdoor wind conditions (which could result in drier eyes of observers) that might impact subjective ratings of visual discomfort, might provide an improved goodness-of-fit. Developing a model incorporating these factors would be complex and of little incremental utility, because the present simple model accounts for most of the variability already. Nonetheless, the factors listed above might have important influences on discomfort glare in specific applications.

An important factor not considered in the present experiments is the influence of spectral

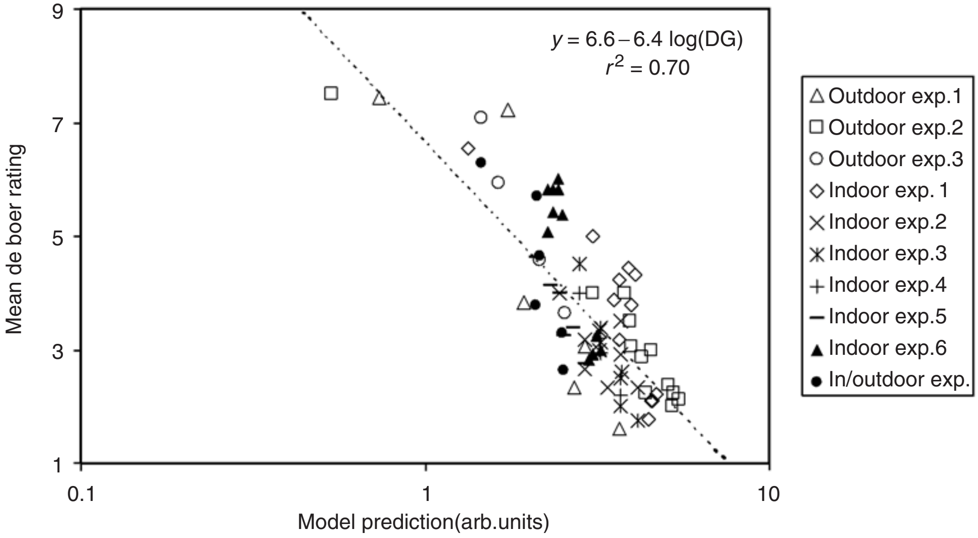

Figure 8 Results of all experiments, plotted as a function of the model values calculated from Equation (1)

power distribution on discomfort glare. 'Yellow' light sources such as high pressure sodium lamps would be expected to produce less discomfort glare for the same measured illuminance than 'white' light sources such as the metal halide and mercury vapour lamps used in the present study,[9–11,17] but the model does not presently address this effect.

Since the simple model introduced here has a reasonable basis in theory and still predicts the data from the present experiments as well or better than a *post hoc* empirical regression model, it is proposed as a useful starting point for modelling discomfort glare in outdoor lighting installations. Subsequent work should be undertaken to validate and refine the model. In particular, the part of the visual scene that contributes to the surround illuminance (E_s) is defined loosely in the present study as the area more or less surrounding the light source of interest, a more precise specification of the solid angular extent of the surround, as opposed to the ambient environment, would be a beneficial extension.

5. Conclusions

The results of the experiments summarised in this paper demonstrate that, under the range of conditions tested, discomfort glare for a lighting application can be predicted by a combination of illuminance values associated with the application. Clearly, neither source luminance nor corneal illuminance from the light source alone provide satisfactory predictions of discomfort glare; surround illuminance and ambient illuminance also affect discomfort glare ratings.

The model proposed here for predicting discomfort glare is simple, is predictive for many scenarios, can be readily incorporated into conventional application software, and predictions can be validated using straightforward techniques and instrumentation. Although the model is simple, it appears to be the best available method of predicting discomfort glare from light sources used in a wide range of outdoor lighting installations and possible viewing conditions.

Acknowledgements

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Discussion

Comment 1:

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I would like the authors' views on a topic that goes beyond the results from this well-run project. In a recent study on glare from display screens and from windows, we found that subjects' assessments of discomfort were affected by extent of their interest in the images displayed on the screens, and by the content of the view from windows. In particular we found that bright views of natural scenes were judged less uncomfortable that matched views of hard city environments.[1,2]