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Impacts of average illuminance, spectral distribution, and uniformity on brightness and safety perceptions under parking lot lighting

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In addition to supporting visibility, parking lot lighting should enable people to feel safe and secure while they are walking through a parking lot at night. Previously published research has indicated that perceptions of safety and security under outdoor illumination are correlated with perceptions of scene brightness, which in turn are influenced by the light level in the lot, by the spectral distribution of the illumination, and the uniformity of illumination. However, the interactions and interplay among these factors are not well understood. To address this knowledge gap, two laboratory experiments were conducted using a scale model parking lot scene and a controllable light-emitting diode (LED) lighting system that allowed parametric variations in light level, spectrum and uniformity. From the results, a mathematical model of overall brightness and safety perceptions was developed to predict how different lighting configurations are perceived. The model can be used to help specifiers select lighting systems for parking lot illumination that meet the objectives of reinforcing sensations of personal safety while balancing energy use and cost concerns.

1. Introduction

Outdoor lighting installations, such as those for parking lots, should provide adequate visibility of pedestrians and drivers, and should help convey a sense of personal security to those walking through or about to walk through the lot at night.[1,2] While meeting these objectives, outdoor parking lot illumination should also minimise negative consequences including wasted electrical energy and light pollution. Fortunately, providing adequate visibility for drivers does not necessarily require high light levels, because vehicle speeds are low, headlights are used, and driving lanes are often well marked.[3] Identifying potential tripping hazards by pedestrians also does not require very high illuminances.[4–7]

A number of studies have been performed to identify factors that contribute to the sense of personal safety and security by people in outdoor lighting installations. These include:

- Average illuminance
- Spectral power distribution
- Uniformity of illumination

Regarding the average illuminance, Boyce *et al.*[1] determined that nighttime safety perceptions relative to those during daytime were improved as the average illuminance in lighted parking lots increased, but with relatively smaller improvements as the light level increased above 20 to 30 lx. The light sources

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in the parking lots assessed by Boyce *et al.*[1] were primarily high pressure sodium (HPS) and metal halide (MH) lamps. Bhagavathula and Gibbons[8] reported that as the average illuminance in a parking lot increased from 2 lx to 10 lx, perceptions of safety, comfort and visibility did not improve substantially. Regarding the spectral distribution, Rea *et al.*[2] found for outdoor lighting installations that perceptions of personal security were correlated ($r^2 = 0.80$, $n = 28$, $p < 0.05$) with perceptions of overall scene brightness (e.g. the perception of luminosity coming from all of the light sources and surfaces within an illuminated setting) and that 'white' light sources (e.g. MH) resulted in brighter- and safer-appearing scenes than 'yellow' sources (e.g. HPS), even for the same average (photopic) illuminance. These findings were extended in a series of laboratory and analytical studies that identified a spectral sensitivity model that predicted the relative scene brightness of a lighting installation.[9,10] Consistent with these findings, Bhagavathula and Gibbons[8] reported improved perceptions of safety, comfort and visibility in a parking lot illuminated by a 5000 K light-emitting diode (LED) source compared to a 3000 K LED source or to HPS illumination. Based on the modeling from Rea *et al.*[9] and Bullough *et al.*,[10] scene brightness appears to be strongly affected by participation from the short-wavelength (S) cones, with the result that for nighttime light levels (approximately between 1 and 25 lx), the spectral sensitivity for scene brightness, $B_2(\lambda)$, can be modeled[11] by

$$B_2(\lambda) = V(\lambda) + 2S(\lambda) \quad (1)$$

where $V(\lambda)$ is the photopic luminous efficiency function, and $S(\lambda)$ is a luminous efficiency function based on the spectral sensitivity of S cones.[12] The subscript '2' in the term $B_2(\lambda)$ refers to the coefficient in front of the $S(\lambda)$ term in the equation. This spectral sensitivity model (Figure 1) was found in a field study of parking lots, lighted by different light sources (i.e. HPS, MH or LED sources) and to different average illuminances (6 to 46 lx), to rectify judgments of perceived safety by visitors to the parking lots.[13] When using light sources with greater short-wavelength output, lower (photopic) illuminances can be used to achieve the same level of perceived safety than with light sources having less short-wavelength output.

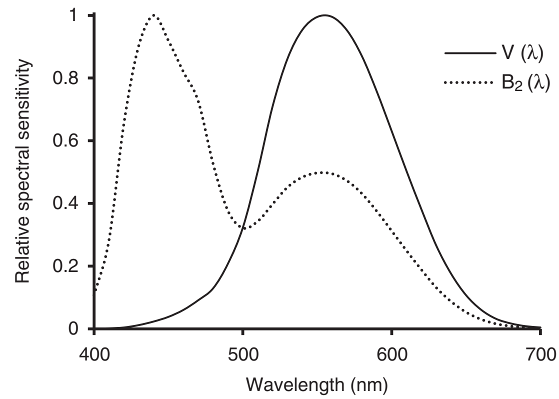

Figure 1 Modeled spectral sensitivity for scene brightness[9,10] at outdoor lighting levels [$B_2(\lambda)$],[11] and the photopic luminous efficiency function [$V(\lambda)$]. Both functions are scaled to a peak value of 1

Regarding the uniformity of outdoor illumination, a few studies have specifically looked at the impact of uniformity on perceptions of outdoor lighting installations. In the field studies by Boyce *et al.*[1] and by Rea *et al.*,[13] the uniformities of the installations that were evaluated were representative of North American lighting practices[14] (which use the ratio between the maximum and minimum horizontal illuminance to define uniformity, rather than the ratio between the average and minimum illuminance) with maximum:minimum illuminances of 10:1 or 20:1 being typical,[14] but uniformity was not explicitly studied by those researchers. Kimura *et al.*[15] reported that more uniform distributions of light could result in lighted tunnels being perceived as brighter than installations with higher average light levels but less uniformity. Nasar and Bokharaei[16] reported that observers preferred outdoor lighted scenes that were illuminated more uniformly, and Fotios *et al.*[17] found larger differences between daytime and nighttime safety ratings for street lighting installations under more non-uniform nighttime lighting.

Narendran *et al.*[18] carried out a field study in which a parking lot was illuminated to different average illuminances with nominal uniformity ratios of 3:1 or 10:1 (as defined by the Illuminating Engineering Society[14]), using LED luminaires with a correlated colour temperature (CCT) of 4300 K. The actual measured uniformity ratios in the parking lot used for this study under the less-uniform lighting installation that was used ranged from about 10:1 to 20:1 (or higher in some cases). Ratings of personal safety were substantially higher when the illumination was more uniform, even for the same average illuminance.

While the published literature clearly indicates that light level, spectral distribution and uniformity of illumination all impact perceptions of brightness and hence personal safety, the combined impacts of all three of these factors have not, to date, been investigated. The purpose of the present study was to identify how these factors interact to influence perceptions of safety in parking lot lighting installations. Two laboratory experiments were performed, subsequently denoted as Experiment 1 and Experiment 2. Both experiments used the same experimental apparatus.

2. Experimental apparatus

A scale model (O scale, approximately 1:45) parking lot was constructed in the Robert Levin Photometric Laboratory at the Lighting Research Center. The surface of the model was a flat plywood board 1.2 by 2.4 m in dimension, simulating a parking lot approximately 50×100 m in size. The board was painted matte gray ($\rho = 0.15$), similar in reflectance to weathered asphalt.[19] White paint was used to apply parking lot striping as illustrated in Figure 2. Black plastic fencing simulating wrought iron was mounted along a long and short edge of the plywood sheet. Six scale-model vehicles (four passenger cars, a pickup truck and a delivery van) were located in parking spaces throughout the lot, and 10 scale-model people were distributed throughout the lot.

A 3×5 array of 15 luminaires was suspended at a height of 0.4 m above the plywood sheet. Each luminaire (Figure 3) consisted of four LEDs; two with a CCT of 2850 K and two with a CCT of 5800 K. When mixed in equal photopic proportion, the

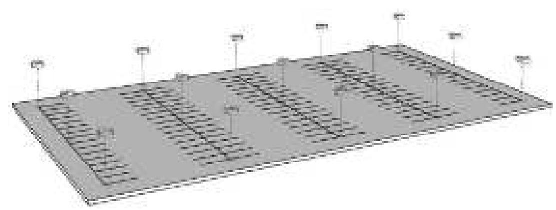

Figure 2 Perspective view of the scale model parking lot. The observer's viewing location was from the corner at the lower left. Also shown are the locations of the LED luminaires used to illuminate the scene

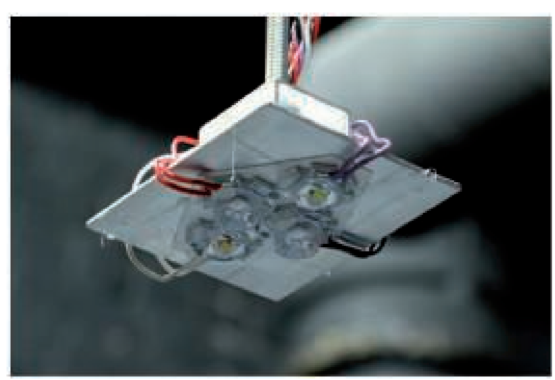

Figure 3 Photograph of an LED luminaire used to illuminate the parking lot scene

resulting illumination had a CCT of 3870 K. Spectral distributions from each CCT are shown in Figure 4, and colorimetric data for each condition are listed in Table 1. Two LEDs in each module (differing in CCT) were fitted with a lens providing a broad, Type V ('flood') distribution and two were fitted with a lens having a narrow ('spot') distribution. As indicated in Figure 2, the luminaire locations were designed to be directly over the parking spaces in locations that would logically correspond to a parking lot pole lighting layout, but no scale-model poles were used.

At one corner of the parking lot (opposite the sides with the black fence), a plastic-covered foam chin rest was mounted onto the plywood sheet. A rectangular baffle of black foam core material with a window 18 cm high and 25 cm wide was placed so that someone sitting at the corner of the plywood sheet with their chin on the chin rest would be able to look through the window at the parking lot scene. In this configuration, the observer's eyes were at approximately the same height as a scale-model person's eyes would be (approximately 3.5 cm above the simulated pavement), and a direct view of the overhead luminaires was blocked.

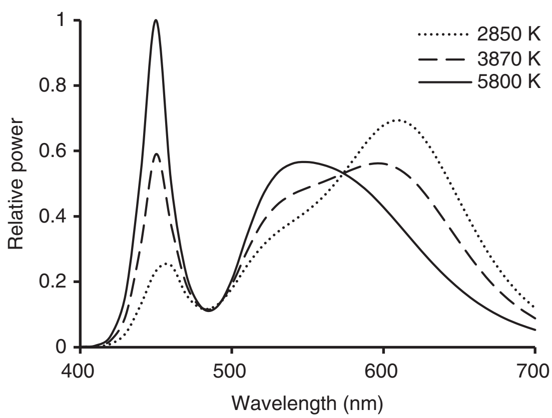

Figure 4 Spectral power distributions for each of the correlated colour temperatures used in the experiments, scaled to equal light output

Horizontal illuminance measurements were made on a 10-cm grid along the entire parking lot surface, with all 15 LEDs for each individual LED/lens combination switched on, in order to determine the average illuminance and the maximum:minimum illuminance uniformity values for each combination. With the flood lens for each LED CCT, the maximum:minimum uniformity was 2:1 (with a minimum:average illuminance ratio of 0.59); with the spot lens, the uniformity was 60:1 (with a minimum:average illuminance ratio of 0.10).

Measurements were made for a range of drive currents ranging between zero light output and an average illuminance exceeding 20 lx from each LED/lens combination. From these measurement data, it was possible to identify drive currents for all four LED/lens combinations in the array that would provide a calibrated distribution on the parking lot surface with any average illuminance up to 20 lx, any maximum:minimum uniformity between 2:1 and 60:1, and any CCT between 2850 and 5800 K. Although the LED/spot lens combinations of each CCTs were about 1.5 cm apart in each luminaire (Figure 3), the mounting height of 0.4 m ensured that their distributions were superimposed on the

Table 1 Colorimetric data for each CCT condition in the study

Correlated colour temperature (K)	Chromaticity (*x*,*y*)	Colour rendering index (CRI)	Gamut area index (GAI)	Scotopic/ Photopic ratio
2850	0.450, 0.412	84	48	1.27
3870	0.387, 0.383	81	71	1.58
5800	0.325, 0.354	71	78	1.93

pavement surface without color striations from each CCT. The LED/flood lens combinations of each CCT were about 2.5 cm apart, but mixing was not problematic because of the much wider distributions of the lenses for these combinations.

3. Procedure: Experiment 1

The lighting conditions used for Experiment 1 were combinations of average illuminance, illuminance uniformity and CCT indicated below:

- Average illuminance: 2.5, 5, 10 or 20 lx
- Maximum:minimum uniformity ratio: 2:1, 6:1 or 15:1 (corresponding to minimum:average illuminance ratios of 0.59, 0.50 and 0.31, respectively)
- CCT: 2850 K, 3870 K, 5800 K

The combination of four average illuminances, three uniformity values and three CCTs resulted in 36 conditions. A maximum uniformity ratio of 15:1 was used because this is the largest value permitted in North American recommendations for parking lot lighting.[14] The CCT of 3870 K was achieved by providing an equal amount of illumination from the 2850 K and 5800 K LEDs in each luminaire. For illustrative purposes, Figure 5 shows the appearance of 2850 K CCT illumination with a maximum:minimum uniformity ratio of 2:1, and the 5800 K illumination with a uniformity ratio of 15:1. The photographs in Figure 5 were taken from slightly above the participants' eye height to make the illumination on the parking lot surface easier to see.

A total of 16 people [12 males, 4 females; average age 37 years, standard deviation (s.d.) 13 years, range 24–62 years], participated in Experiment 1. Similar or smaller sample sizes have been used in several previous experiments involving perceptions of brightness and/or safety in illuminated environments.[18,20,21] After signing a consent form

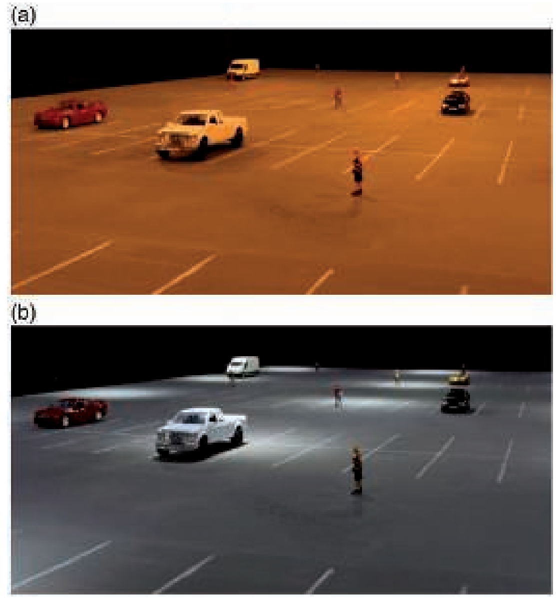

Figure 5 (a) View of parking lot under uniform (2:1 maximum : minimum uniformity ratio), 2850 K illumination. (b) View of parking lot under non-uniform (15:1 uniformity ratio), 5800 K illumination

approved by Rensselaer's Institutional Review Board (IRB), participants were screened for normal colour vision using a set of Ishihara colour plates and brought to the laboratory where their seat was adjusted to proper height for the chin rest, and where they were given instructions for the experiment. Participants were first shown a reference lighting condition (average illuminance 10 lx, maximum:minimum uniformity of 6:1, and a CCT of 3870 K). The overall brightness of the lighted parking lot scene under this condition was defined to have a magnitude of 10. All 36 lighting conditions were shown in a randomised order for each participant. After every six trials, the reference condition was repeated as a reminder of a brightness magnitude of 10.

For each experimental trial, the participant was asked to judge the overall brightness of the lighted parking lot scene relative to the reference condition (e.g. if the scene appeared to be half as bright as the reference condition, it would be rated as a 5; if it appeared twice as bright it would be rated as a 20). This method has been used successfully in other studies of brightness judgments.[22,23] Participants were instructed to rate the overall brightness of the scene and not that of any specific objects or parts of the parking lot scene.

After making the brightness judgment rating, participants were asked to judge their own sense of personal safety, if they were walking through this parking lot alone at night. Safety ratings were given on a scale of +2, to −2, defined as follows:

- +2: very safe
- +1: somewhat safe
- 0: neither safe nor unsafe
- −1: somewhat unsafe
- −2: very unsafe

4. Results: Experiment 1

Table 2 lists the mean brightness and safety ratings and standard errors of the mean (s.e.m.) for each combination of average illuminance, uniformity ratio and CCT. To assess the possible influence of the safety rating scale having an odd number of responses, mean safety ratings when the 'zero' (neither safe nor unsafe) responses were omitted were compared to the means of all ratings. The two sets of values were strongly correlated ($r^2 = 0.99$, $n = 36$, $p < 0.05$) with a slope of 1.08 and a y-intercept of intercept of −0.04, suggesting relatively little influence of the rating scale.

Table 2 Mean and standard error of the mean (s.e.m) brightness and safety ratings for each condition in Experiment 1

Average Illuminance (lx)	Uniformity	CCT (K)	Brightness Rating		Safety Rating	
			Mean	s.e.m.	Mean	s.e.m.
2.5	2:1	2850	4.88	0.57	−0.40	0.27
2.5	2:1	3870	5.13	0.56	−0.33	0.23
2.5	2:1	5800	5.09	0.56	−0.39	0.24
2.5	6:1	2850	3.69	0.44	−0.88	0.21
2.5	6:1	3870	5.13	0.48	−0.64	0.19
2.5	6:1	5800	4.09	0.39	−0.64	0.23
2.5	15:1	2850	3.31	0.46	−1.44	0.16
2.5	15:1	3870	4.31	0.51	−1.08	0.13
2.5	15:1	5800	4.25	0.42	−1.17	0.24
5	2:1	2850	7.94	0.38	0.60	0.22
5	2:1	3870	8.78	0.69	0.94	0.17
5	2:1	5800	10.59	1.27	1.00	0.26
5	6:1	2850	7.19	0.40	0.21	0.19
5	6:1	3870	7.50	0.52	0.35	0.21
5	6:1	5800	8.13	0.42	0.38	0.21
5	15:1	2850	5.44	0.40	−0.67	0.15
5	15:1	3870	5.69	0.55	−0.62	0.21
5	15:1	5800	6.25	0.46	−0.51	0.19
10	2:1	2850	14.25	1.20	1.56	0.15
10	2:1	3870	14.06	1.21	1.63	0.15
10	2:1	5800	20.63	5.42	1.72	0.11
10	6:1	2850	10.56	0.53	0.96	0.20
10	6:1	3870	11.25	1.04	1.20	0.15
10	6:1	5800	11.50	0.49	1.33	0.14
10	15:1	2850	8.28	0.51	−0.08	0.21
10	15:1	3870	7.91	0.42	0.00	0.23
10	15:1	5800	8.41	0.43	0.34	0.16
20	2:1	2850	20.25	2.44	1.96	0.04
20	2:1	3870	19.88	2.04	1.96	0.04
20	2:1	5800	24.31	3.25	1.97	0.03
20	6:1	2850	16.44	2.01	1.61	0.12
20	6:1	3870	14.38	1.24	1.61	0.11
20	6:1	5800	21.06	3.40	1.88	0.08
20	15:1	2850	12.31	1.92	0.73	0.24
20	15:1	3870	12.38	0.73	1.09	0.17
20	15:1	5800	14.31	1.59	1.18	0.19

Repeated-measures analyses of variance (ANOVAs) were performed on the brightness magnitudes and safety ratings, to identify statistically significant effects. For each of the 36 experimental conditions (4 average illuminances × 3 uniformity ratios × 3 CCTs), Anderson-Darling normality tests were conducted on the brightness and safety ratings to assess suitability for ANOVAs. For both ratings, the majority of ratings were consistent with a normal distribution ($p > 0.05$ in 26 of 36 cases for brightness and in 24 of 36 cases for safety). Since most of the data were distributed normally, and since non-normality has negligible effects on the F statistic used in the ANOVA (and similar effects on nonparametric tests),[24,25] ANOVAs were used to evaluate the statistical significance of trends in the data for both Experiment 1 and Experiment 2.

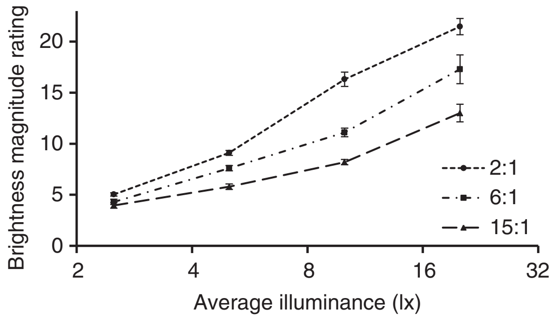

Figure 6 Mean brightness magnitude ratings (+/− standard error of the mean) for each combination of average illuminance and uniformity ratio in Experiment 1, collapsing across correlated colour temperature for each data point

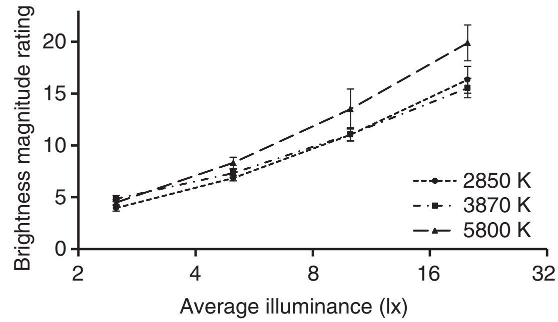

Figure 7 Mean brightness magnitude ratings (+/− standard error of the mean) for each combination of average illuminance and correlated colour temperature in Experiment 1, collapsing across uniformity ratio for each data point

The ANOVA for the brightness magnitude data revealed statistically significant main effects of average illuminance ($F_{3,45} = 44.9$, $p < 0.05$), uniformity ratio ($F_{2,30} = 23.1$, $p < 0.05$) and CCT ($F_{2,30} = 7.67$, $p < 0.05$). Mean brightness magnitudes increased with increasing average illuminance, with decreasing uniformity ratio, and with increasing CCT. Figure 6 shows the statistically significant ($F_{6,90} = 6.27$, $p < 0.05$) interaction between average illuminance and uniformity on brightness magnitudes, and Figure 7 shows the (non-significant) interaction between illuminance and CCT. In Figure 6, differences among the uniformity ratios were largest at an average illuminance of 20 lx and smallest at 2.5 lx. A similar trend is shown in Figure 7, although the differences between 2850 K and 3870 K were negligible. No other two-way interactions, nor the three-way interaction among all factors, were statistically significant.

The ANOVA for the perceived safety rating data revealed statistically significant main effects of average illuminance ($F_{3,45} = 139$, $p < 0.05$), uniformity ratio ($F_{2,30} = 57.8$, $p < 0.05$) and CCT ($F_{2,30} = 7.19$, $p < 0.05$). As with the brightness magnitude judgments, safety ratings increased with increasing average illuminance, with decreasing uniformity ratio, and with increasing CCT. There was also a statistically significant two-way interaction between average illuminance and uniformity ratio ($F_{6,90} = 4.23$, $p < 0.05$; see Figure 8) such that differences among the uniformity ratios were smallest at the lowest and highest average illuminances. None of the other two-way interactions, nor the three-way interaction among all factors, was statistically significant. Figure 9 shows the non-significant interaction between illuminance and CCT on the mean safety ratings.

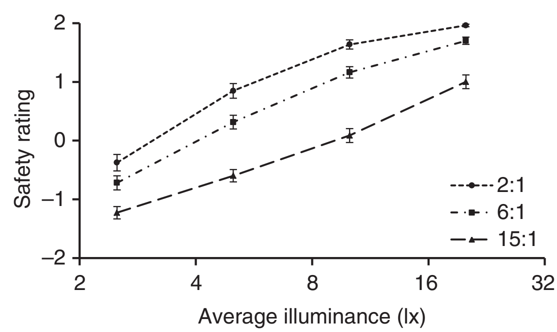

Figure 8 Mean safety rating (+/− standard error of the mean) for each combination of average illuminance and uniformity ratio in Experiment 1, collapsing across correlated colour temperature for each data point

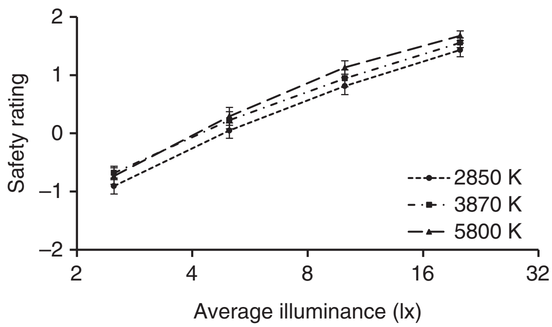

Figure 9 Mean safety rating (+/− standard error of the mean) for each combination of average illuminance and correlated colour temperature in Experiment 1, collapsing across uniformity for each data point

5. Procedure: Experiment 2

The primary purpose of Experiment 2 was to increase the resolution of the illuminance and uniformity values used in the study to help in understanding how illuminances and uniformity ratios intermediate to the ones used in Experiment 1 would influence brightness and safety perceptions. In addition, since organisations such as the American Medical Association (AMA) have made calls to avoid outdoor illumination with high (>4000 K) CCTs,[26] only the lower two CCTs used in Experiment 1 were investigated. Therefore, combinations of the following factors were used in Experiment 2:

- Average illuminance: 6.7, 10 or 15 lx
- Maximum:minimum uniformity: 3.3:1, 5:1 or 7.5:1 (corresponding to minimum:average illuminance ratios of 0.59, 0.53 and 0.47 respectively)
- CCT: 2850 K or 3870 K

The same reference condition (average illuminance 10 lx, maximum:minimum uniformity 6:1 and CCT of 3870 K) was used in Experiment 2 so that the brightness magnitude judgments in both experiments could be compared. This reference condition was shown at the start of the experiment, and after every six trials, with the definition of having an overall brightness magnitude of 10. Participants in Experiment 2 (11 males and 5 females, average age 40 years, s.d. 11 years, range 23 to 60 years) viewed all 18 experimental conditions in a random order for each participant, making brightness and safety judgments as in Experiment 1.

Table 3 Mean and standard error of the mean (s.e.m.) brightness and safety ratings for each condition in Experiment 2

Average Illuminance (lx)	Uniformity	CCT (K)	Brightness Rating		Safety Rating	
			Mean	s.e.m.	Mean	s.e.m.
6.67	3.3	2850	8.77	0.80	0.92	0.31
6.67	3.3	3870	9.84	1.13	0.90	0.26
6.67	5	2850	7.83	0.11	0.65	0.26
6.67	5	3870	7.77	0.45	0.86	0.26
6.67	7.5	2850	6.79	−0.13	0.57	0.31
6.67	7.5	3870	6.63	−0.13	0.61	0.35
10	3.3	2850	11.16	1.17	0.83	0.21
10	3.3	3870	11.97	1.52	0.80	0.13
10	5	2850	10.38	0.79	0.95	0.29
10	5	3870	9.63	1.29	0.47	0.12
10	7.5	2850	8.69	0.48	0.68	0.28
10	7.5	3870	8.89	0.79	0.31	0.30
15	3.3	2850	13.19	1.63	0.90	0.20
15	3.3	3870	14.72	1.88	1.09	0.09
15	5	2850	11.72	1.13	0.87	0.22
15	5	3870	14.50	1.83	0.88	0.09
15	7.5	2850	11.25	1.38	0.83	0.15
15	7.5	3870	11.75	1.44	0.60	0.14

6. Results: Experiment 2

Table 3 lists the mean brightness and safety ratings and s.e.m. for each combination of average illuminance, uniformity ratio and CCT. The mean safety ratings when the 'zero' (neither safe nor unsafe) responses were omitted were compared to the means of all ratings. The two sets of values were strongly correlated ($r^2 = 0.95$, $n = 18$, $p < 0.05$) with a slope of 0.98 and a y-intercept of intercept of 0.11, suggesting relatively little influence of the odd number of rating scale values.

Repeated-measures ANOVAs were performed on the brightness magnitudes and safety ratings from Experiment 2, to identify statistically significant effects. The mean ratings of brightness and safety appear to be slightly lower for Experiment 2 than for similar conditions in Experiment 1. Some participants from Experiment 1 also participated in Experiment 2, and differences in the responses between the sample groups, or in the different ranges of lighting conditions, might have influenced the difference in average rating values between experiments.

The ANOVA for the brightness magnitude data revealed statistically significant main effects of average illuminance ($F_{2,30} = 69.1$, $p < 0.05$) and uniformity ratio ($F_{2,30} = 22.9$, $p < 0.05$), as in Experiment 1. Although the average brightness magnitude judgment for the 3870 K CCT was higher than for the 2850 K CCT, there was not a statistically significant main effect of CCT. There was, however, a statistically significant interaction between the average illuminance and the CCT ($F_{2,30} = 3.40$, $p < 0.05$; see Figure 10); the difference between the CCTs increased as the average illuminance increased. None of the other two-way interactions, nor the three-way interaction among all factors, were statistically significant. Figure 11 illustrates the non-significant interaction between the average illuminance and uniformity ratio.

The ANOVA for the perceived safety ratings showed statistically significant main effects of average illuminance ($F_{2,30} = 43.5$, $p < 0.05$), uniformity ratio ($F_{2,30} = 30.4$, $p < 0.05$) and CCT ($F_{1,15} = 6.26$, $p < 0.05$), all following the same trends as in Experiment 1. None of the two-way interactions, nor the three-way interaction among all factors, were statistically significant. Figures 12 and 13 illustrate the non-significant interactions between average illuminance, and CCT and uniformity ratio, respectively.

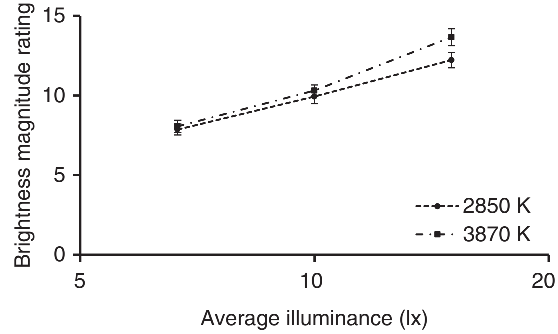

Figure 10 Mean brightness magnitude rating (+/– standard error of the mean) for each combination of average illuminance and correlated colour temperature in Experiment 2, collapsing across uniformity for each data point

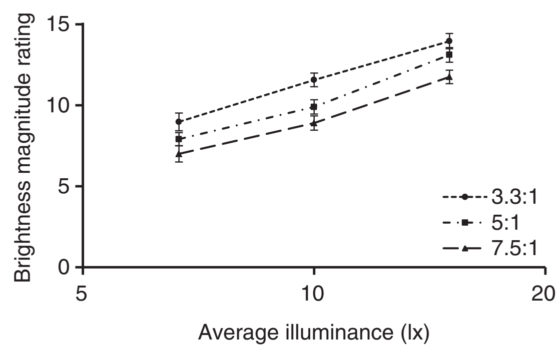

Figure 11 Mean brightness magnitude rating (+/– standard error of the mean) for each combination of average illuminance and uniformity ratio in Experiment 2, collapsing across correlated colour temperature for each data point

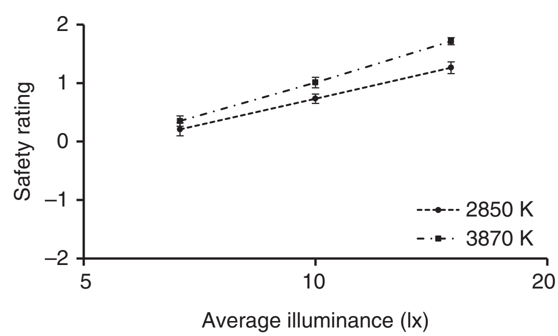

Figure 12 Mean safety rating (+/– standard error of the mean) for each combination of average illuminance and correlated colour temperature in Experiment 2, collapsing across uniformity for each data point

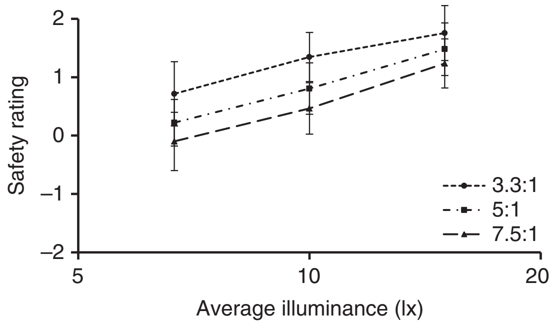

Figure 13 Mean safety rating (+/− standard error of the mean) for each combination of average illuminance and uniformity ratio in Experiment 2, collapsing across correlated colour temperature for each data point

7. Discussion

Overall, the results from both experiments confirm the previously reported impacts of average illuminance, illuminance uniformity, and CCT on both brightness magnitude judgments and ratings of personal safety. Further, the results describe, for the first time, how these factors interact in the ways they affect judgments of brightness and personal safety. In order to understand the practical implications of these findings, several further analyses were undertaken.

7.1 Combining Illuminance and CCT

Light source CCT is a limited characterisation of the spectral distribution of that source. While the present results suggest that light sources with higher CCTs (within the range used in this study) will result in brighter-appearing scenes than those with lower CCTs, CCT is not directly related to a likely mechanism underlying scene brightness perception at these levels,[9–11] namely participation from S cones (see Figure 1). Indeed, light sources with the same CCT can have very different colour appearance.[27] To address this, the spectral sensitivity model described in equation (1) was used to derive the brightness illuminance quantities (B_2-lx) as described by Rea *et al.*[28] for each combination of average illuminance and CCT in each experiment. For each LED CCT, the resulting multipliers relating brightness-illuminance quantities (in B_2-lx) to photopic illuminances are as follows:

- 2850 K CCT: 1.36
- 3870 K CCT: 1.65
- 5800 K CCT: 1.98

For these LEDs, the relationship between the CCT (in K) and the multiplier that can be used to estimate the brightness illuminance (in B_2-lx) for CCTs between 2850 and 5800 K, is given by the following best-fitting ($r^2 = 0.998$) logarithmic function

$$\text{Brightness illuminance multiplier} = 2\log C - 5.55 \tag{2}$$

where C is the CCT in K. Using the brightness magnitude rating data as an example, two multiple regression models were developed to predict the magnitude ratings as a function of:

Model 1: average illuminance, illuminance uniformity, and CCT
Model 2: average brightness illuminance and CCT

According to Model 1, the brightness magnitude ratings are predicted by the following equation

$$\text{Brightness magnitude rating} = 13.6\log E - 5.82\log U + 8.42\log C - 27.8 \tag{3}$$

where E is the average illuminance (in lx), U is the maximum:minimum uniformity ratio, and C is the CCT (in K). The coefficient of determination (r^2) for this model is 0.86.

For Model 2, the magnitude ratings are predicted by

$$\text{Brightness magnitude rating} = 18.0\ \log B - 5.82\ \log U - 2.9 \quad (4)$$

where B is the average brightness illuminance (in B_2-lx) and U is the maximum:minimum uniformity ratio. The coefficient of determination for Model 2 ($r^2 = 0.83$) is similar to that for Model 1. The predicted brightness magnitude ratings based on Model 1 are correlated with those based on Model 2 ($r^2 = 0.86$, $n = 54$, $p < 0.05$), which suggests that the two factors of average (photopic) illuminance and CCT can be collapsed into a single factor, average brightness illuminance, in B_2-lx. This suggests that the spectral sensitivity for scene brightness perception likely underlying perceptions of safety is influenced largely by short-wavelength input. (Although the scotopic/photopic ratios in Table 1 increase with increasing CCT, previous studies have shown that rod participation probably plays a negligible role in scene brightness at the light levels used in the present study.[9,29])

7.2 Modeling brightness illuminance and uniformity impacts on perceived safety

Having a valid spectral sensitivity function for scene brightness perception as illustrated in the previous section, means that data for different CCTs from Experiments 1 and 2 can be combined and characterised by the average brightness illuminance (in B_2-lx) rather than by average (photopic) illuminance (in lx) and by CCT. This makes it possible to develop predictions of safety ratings for each maximum:minimum uniformity value in the study. These predictions used a sigmoid function of the form

$$\text{Safety rating} = 2 - 4/[1 + (B/c)^d] \quad (5)$$

where B is the brightness illuminance (in B_2-lx) and (lowercase) c and d are free parameters adjusted to provide the best-fitting sigmoid curve to the mean safety ratings. For illustration, Figure 14 shows the best-fitting ($r^2 = 0.97$) sigmoid for the safety ratings when the maximum:minimum uniformity ratio was 2:1, where $c = 5$ and $d = 1.86$. Similar goodness-of-fit values ($r^2 > 0.95$) were found for each uniformity value. The best-fitting values of c increased systematically as the uniformity ratio increased, according to the best-fitting ($r^2 = 0.87$) linear relationship:

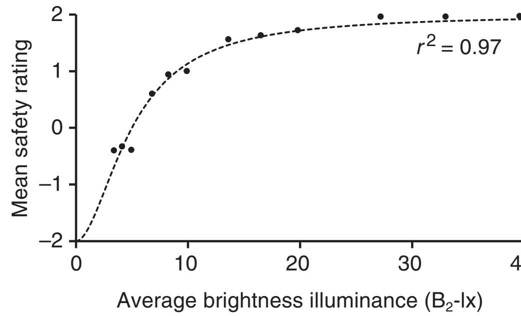

Figure 14 Mean safety ratings for the 2:1 maximum: minimum uniformity conditions in Experiment 1 as a function of the average brightness illuminance (in B_2-lx). Also shown is the best-fitting sigmoid function to the data

$$c = 0.67U + 4.49 \quad (6)$$

where U is the maximum:minimum uniformity ratio, but the values of d fluctuated around a central value, averaging 1.75. Substituting equation (6) for c and using a constant value of 1.75 for d in equation (5), Figure 15 shows the predicted safety ratings for each uniformity value in the study.

Thus, equation (5), using the value of c from equation (6) and a value for d of 1.75, provides a basis for identifying combinations of light level, spectral distribution, and maximum:minimum uniformity that will elicit a particular perception of personal safety. If LED sources are to be used and only the CCT is known (and if it is between 2850 and

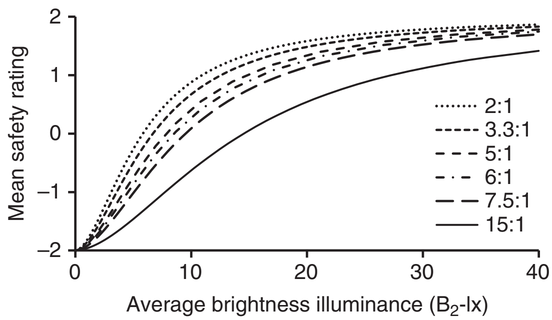

Figure 15 Sigmoid functions for each maximum: minimum uniformity ratio, plotted as a function of average brightness illuminance (in B_2-lx)

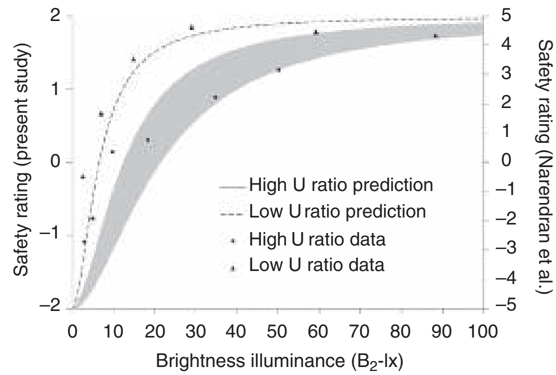

Figure 16 Mean safety ratings from the study by Narendran *et al.*,[18] plotted alongside predicted safety ratings for the two nominal uniformity (U) ratios used in that study (low and high), as a function of the average brightness illuminance (in B_2-lx)

5800 K), it is also possible to use equation (5) in conjunction with the product of the average illuminance and the multiplier in equation (2) to estimate the brightness illuminance quantity.

7.3 Consistency with field evaluations

A potential limitation of the present study is that it was a laboratory study carried out using a scale model, and may not represent the judgments of observers in actual, real-world situations. For example, in the present study, a direct view of the light sources illuminating the simulated parking lot was blocked, whereas in real-world conditions this would not be the case. To address such limitations, comparisons were made with data from a recent field investigation.

As described in the introduction to this paper, Narendran *et al.*[18] measured the perceptions of individuals in a full-scale parking lot illuminated by 4300 K LEDs to varying average illuminances (between 1.5 and 52 lx) and with two maximum:minimum uniformity values (low – 3:1, or high: 10:1 to 20:1). As the spectral distribution for the LEDs used in the study by Narendran *et al.*[18] was not given, the brightness illuminance (B_2-lx) quantities in that study were estimated from the CCT using equation (2).

Figure 16 shows the data for the question asked by Narendran *et al.*[18] regarding the perception of safety of each lighting condition, using a scale of +5 (very safe) to −5 (very unsafe). This scale differs from the present study's safety rating scale, which ranged from +2 (very safe) to −2 (very unsafe), but it is assumed in Figure 16 that the rating values of each scale can be related to each other by a factor of 2.5 (5/2). Also shown in Figure 16 are the predicted safety ratings based on equation (5) for each lighting condition's average illuminance and maximum:minimum uniformity (for the higher nominal uniformity ratio conditions, a shaded region bounding the predictions for 10:1 and 20:1 is shown). Agreement between the data and predicted values in Figure 16 is reasonably good, suggesting that the participants in the present study were able to relate the lighting conditions they experienced in the laboratory to those that might be experienced in a full-scale, real-world parking lot installation.

In another field study,[8] ratings of safety for asphalt-paved parking lots began to plateau between 2 and 10 lx, which is lower than the illuminances at which safety ratings began to plateau in the present studies. The range of average illuminances used in that study differed from those in the present study (1 to 12.5 lx), and illumination was always relatively uniform with a maximum:minimum ratio of 5:1. These differences may explain the difference in plateaus for the safety ratings between the studies.

7.4 Energy implications

Rea *et al.*[13,28] discussed the energy use implications of incorporating the spectral sensitivity characteristics of scene brightness perception into parking lot lighting design, and Narendran *et al.*[18] discussed how more uniform illumination could result in energy use reductions while maintaining perceptions of safety and security. The modeling efforts described in the present study could allow energy use analyses to include the combined impacts of light level, spectral distribution and uniformity.

For example, consider a parking lot lighted by HPS (with a luminous efficacy of 80 lm/W and a B_2-lux to photopic illuminance multiplier of 1.15) to an average photopic illuminance of 15 lx and with a maximum:minimum uniformity ratio of 12:1. The predicted safety rating for this parking lot would be +0.5, based on the equations in the previous sections of this paper. If a specifier wished to compare the 2850 K and the 5800 K LED sources (assuming a luminous efficacy of 100 lm/W) used in the present study as alternatives for lighting this parking lot with the same uniformity ratio of 12:1, a safety rating of +0.5 could be achieved with the 2850 K LED source with an average illuminance of 12.7 lx (and a resulting energy use reduction of 32%), or with the 5800 K LED source with an average illuminance of 8.7 lx (and a resulting energy use reduction of 54%).

In comparison, if the LED sources were able to provide more uniform illumination with a lower maximum: minimum uniformity ratio of 3.5:1, the 2850 K LED source could be used with an average illuminance of 6.7 lx (resulting in 64% less energy use), and the 5800 K LED source could be used with an average illuminance of 4.6 lx (resulting in 75% less energy use), while maintaining the same safety rating of +0.5. If the specifier wished to achieve higher ratings of perceived safety, the following energy reductions from the HPS baseline could be achieved:

- +1.0 safety rating: 10.6 lx from the 2850 K LED (43% energy use reduction), or 7.3 lx from the 5800 K LED (61% energy use reduction)
- +1.5 safety rating: 16.6 lx from the 2850 K LED (11% energy use reduction), or 11.4 lx from the 5800 K LED (39% energy use reduction)

These analyses show that substantial energy savings can be achieved when perceived safety is a primary criterion for illumination in parking lots, by manipulating the spectral and especially the uniformity characteristics of the lighting system.

8. Conclusions

The results and analyses described here lay a foundation for predicting brightness-based perceptions of outdoor illumination as a function of average illuminance, spectral distribution, and uniformity characteristics. Increasing short-wavelength output to leverage spectral sensitivity for scene brightness perception, and improving uniformity distributions will both increase perceptions of safety, but when a white light source (e.g. LED) is chosen, the magnitude of the spectral effect is relatively small compared to the impact of more uniform illumination.[30] The influence of uniformity in supporting brightness and safety perceptions has heretofore largely been ignored in favor of an inordinate focus on spectrum.[26]

Importantly, the laboratory experiments in this study yielded results that were largely consistent with those from published field research.[1,8,13,18] They indicate that models of spectral sensitivity for scene brightness[9,10] in conjunction with analytical predictions of safety incorporating both uniformity and spectrally adjusted brightness quantities can be used to make reasonable predictions of perceived safety in parking lot lighting. Further efforts to test these predictions in *a priori* tests and not only in *post hoc* comparisons to published literature are underway. It is hoped that such model predictions will be successful in helping reduce energy use for outdoor lighting, a reduction that could also benefit the night sky.[28]

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