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# INTEGRATING RESEARCH ON SAFETY PERCEPTIONS UNDER PARKING LOT ILLUMINATION

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# INTEGRATING RESEARCH ON SAFETY PERCEPTIONS UNDER PARKING LOT ILLUMINATION

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## Abstract

Parking lot lighting should meet multiple objectives. One important design objective is that parking lot lighting should provide a sense of personal safety and security. This objective has been the focus of studies from the Lighting Research Center since the 1990s, which involved research on lighting characteristics such as the average illuminance, the spectral power distribution of the light source, and the uniformity of illumination across the parking lot surface. Building upon this body of research, a recent study is described in which the interactions among these factors, not only their isolated impacts, on subjective perceptions of safety and security are assessed. The research efforts described here demonstrate how light level, spectrum and uniformity combine to affect perceptions of safety in parking lot users. Importantly, specifications of lighting based on these criteria would permit substantial reductions in energy use and light pollution in outdoor lighting while meeting users' needs.

*Keywords*: Safety and Security, Visual Performance, Exterior Lighting

## 1 Introduction

According to the North American recommended practice for parking lot lighting (IES, 2018), lighting in these facilities should support the safe movement of vehicles and pedestrians while also enhancing perceptions of personal safety and security. Many prior studies and evaluations involving parking lot lighting have focused on visibility for the safety of pedestrians and drivers (e.g., Box, 1981; Monahan, 1995). Slips, trips and falls make up nearly three-quarters of all liability claims in parking facilities (Monahan, 1995). Ensuring that pedestrians can detect potential tripping hazards has been investigated through several studies. Fotios and colleagues (Fotios and Cheal, 2009, 2013; Uttley et al., 2017) found in several studies that the illuminance required for detection of a potential obstacle on the ground plateaued at a horizontal illuminance of 2 lux, a finding reinforced by Bullough (2010) using a visual performance analysis (Figure 1).

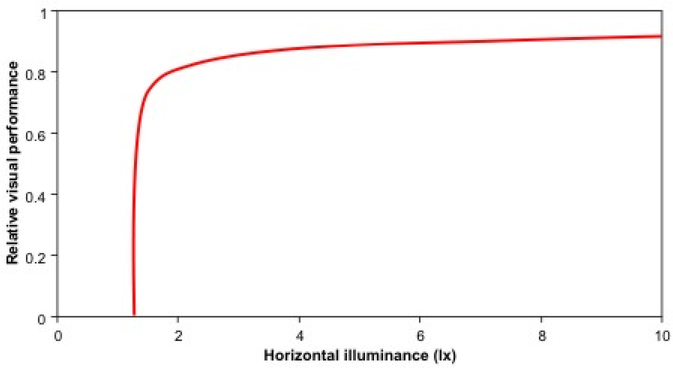


**Figure 1 – Relative Visual Performance (RVP) as a Function of Horizontal Illuminance for Detecting a Tripping Hazard by a 60-Year-Old Observer (Bullough, 2010); Note Saturation Above 2 lux**

Minimum light levels sufficient for adequate visual performance, however, do not necessarily guarantee that pedestrians will feel safe and secure when using a parking lot. In research carried out in preparation for the ground-breaking *Outdoor Lighting Pattern Book* (Leslie and Rodgers, 1996), Leslie (1998) and Boyce et al. (2000) reported that observers who visited several different parking lots did not reach substantial agreement that the lighting was a good example of security lighting until the average horizontal illuminance reached 30 to 50 lux, values much higher than those required for tripping hazard visibility, even if the illuminance in Figure 1 is considered a minimum value and those in Figure 2 are average values – for example, a previous edition of the North American recommended practice for parking lot lighting (IES, 1998) suggests that a minimum illuminance of 2 lux can often be achieved by specifying an average illuminance of 10 lux.

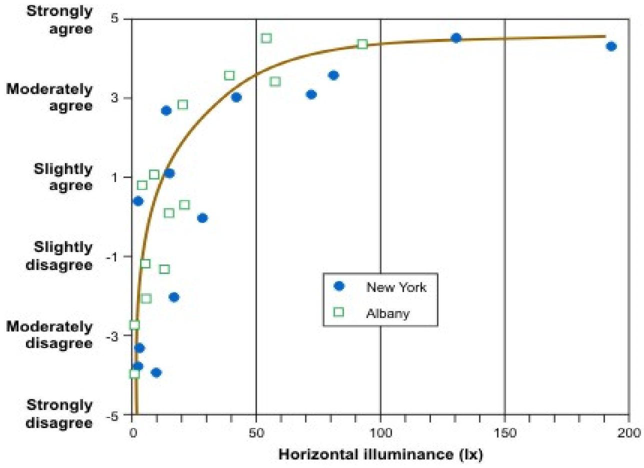


**Figure 2 – Agreement with the Statement "This is a Good Example of Security Lighting," as a Function of Horizontal Illuminance in Urban Parking Lots (Leslie, 1998; Boyce et al., 2000)**

Perceptions of personal safety and security appear to be strongly correlated with the perceived brightness of an outdoor location such as a parking lot or street. Rea et al. (2009) asked observers to rate the overall scene brightness and their perceptions of personal safety for streets illuminated to different light levels and by different light sources, finding very similar trends for both questions (i.e., under higher light levels and "whiter" light, scenes were judged as brighter and safer). In that study, perceptions of brightness and personal safety under high pressure sodium (HPS) illumination were lower than those under metal halide (MH) illumination, even when matched for the same average illuminance (Rea et al., 2009), suggesting that spectral distribution as well as light levels can impact perceived safety.

In addition to minimum light levels (previously recommended to be 2 lux and currently recommended to be 5 lux), North American recommendations (IES, 2018) specify upper limits on the maximum-to-minimum (max:min) ratio for the illuminance in the parking lot of 15:1. According to these recommendations (IES, 2018) the max:min illuminance ratio upper limit is specified to ensure that an observer standing in the brightest portion of a parking lot can see within the darkest portion of the lot. Little empirical research has been published on the impacts of parking lot or road illumination uniformity on perceptions of safety, however; Kimura et al. (2014) found that more uniform illumination in a tunnel contributed to increased perceived brightness, which should in turn (Rea et al., 2009) influence perceptions of safety.

In the section that follows, research studies primarily from the Lighting Research Center are briefly described with regard to how their findings implicate each of the three factors mentioned previously (average illuminance, spectral distribution, and uniformity of illumination). These studies culminated in a study to assess the combined impacts of these factors on perceived safety, the results of which can assist specifiers in choosing lighting configurations that maximize perceptions of safety while minimizing collateral effects of outdoor lighting including energy usage and light pollution.

## 2 Research Review

### 2.1 Light Level

Perhaps it is obvious that the amount of light, often characterized by the average horizontal illuminance, should influence perceptions of safety under parking lot illumination. Numerous studies have established that improvements of outdoor lighting resulting in increased light levels tend to result in decreased fear of crime (e.g., Tien et al., 1977; Painter, 1994; Nair and Dutton, 1994). The precise nature of the quantitative relationship between average illuminance and such perceptions, however, was not fully understood until this question was investigated in a series of field studies carried out by Boyce et al. (2000).

In those studies, Boyce et al. (2000) asked observers to visit different parking lots in urban and suburban locations at night and to rate the perceived quality of the lighting for security. What they found was that observers' ratings indeed increased as a function of increasing light level (see Figure 2, for urban parking lots), but the trend was not linear. Rather, as the average parking lot illuminance increased, the ratings began to exhibit a plateau. Similar findings have been noted subsequently by Bhagavathula and Gibbons (2019). Interestingly, Boyce et al. (2000) found that ratings for urban parking lots were slightly, but consistently, lower (Figure 3) than for suburban parking lots lighted to the same average illuminance.

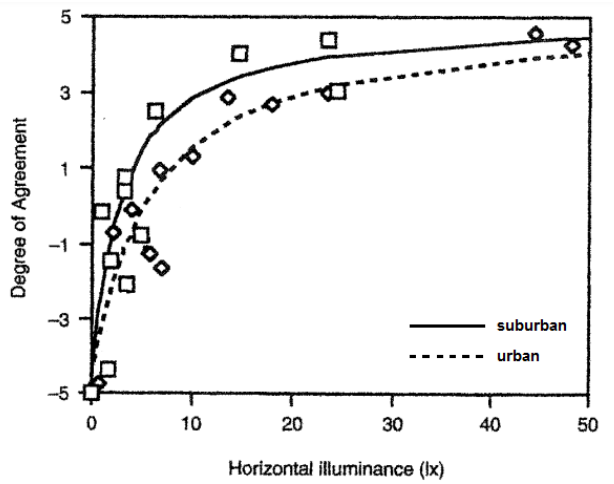


**Figure 3 – Agreement that Parking Lot Lighting is Good Security Lighting (Boyce et al., 2000) as a Function of Horizontal Illuminance for Suburban and Urban Parking Lots (Scale: -5, Strongly Disagree to +5, Strongly Agree)**

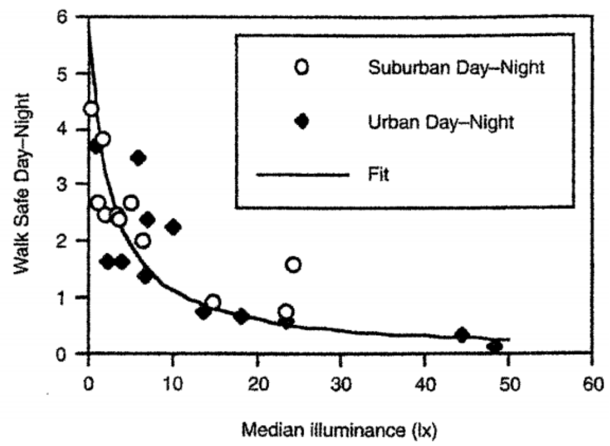


**Figure 4 – Difference Between Daytime and Nighttime Ratings of How Safe People Would Feel Walking Alone to Their Car in Urban and Suburban Parking Lots Illuminated to Different Light Levels (Boyce et al., 2000)**

The results in Figure 3 imply that urban parking lot night never feel as safe to an observer as a parking lot in a suburban (or rural) location, regardless of the lighting. To investigate this notion, Boyce et al. (2000) compared how safe people would feel if they had to walk to their car alone in each parking lot based on visits to the lots during both the daytime and the nighttime, The difference in the rating between these two questions was taken to be a measure of the impact of lighting, independent of each parking lot's location. As illustrated in Figure 4, these differences, when plotted as a function of the median illuminance in the parking lot, did not exhibit systematic differences between urban and suburban locations, confirming that lighting alone does not guarantee perceived security, but the asymptotic effect of lighting was similar for different locations. Fotios et al. (2018) showed similar trends in the difference between daytime and nighttime ratings.

## 2.2 Spectral Distribution

For at least several decades, as light sources used for outdoor lighting have evolved, it has been apparent that perceptions about the brightness of streets, parking lots and other outdoor locations illuminated by these sources differ, even when they are illuminated to the same average light level (Ferguson and Stevens, 1956; Rea, 1996; Fotios and Cheal, 2007). As previously mentioned, perceptions of scene brightness are relevant because scene brightness is correlated with perceptions of personal safety and security (Rea et al., 2009). The aforementioned studies have all found that light sources producing a greater proportion of short-wavelength light result in greater perceived scene brightness than those with less short-wavelength output, when matched for photopic illuminance.

The framework for a model of spectral sensitivity for scene brightness was developed through several initial laboratory studies (Rea et al., 2011) and refined through subsequent studies (Rea et al., 2016; Besenecker et al., 2016; Besenecker and Bullough, 2017) and through analyses of independently published data sets (Fotios and Cheal, 2011; Zele et al., 2018; Bullough, 2015, 2018). In summary, the spectral sensitivity for scene brightness appears to be influenced by short-wavelength (S) cones through the blue-yellow colour opponent channel, as well as by melanopsin in the intrinsically-photosensitive retinal ganglion cells; the influence of both of these channels also appears to increase with increasing radiance. Rea (2013) published a provisional spectral sensitivity function that approximates the modelled spectral sensitivity for light levels used outdoors (e.g., 1 to 25 lux).

This function was used to spectrally weight the spectral distributions of three sources [HPS, MH and light emitting diode (LED)] used to light three different parking lots on a college campus in Seattle, WA (Rea et al., 2017). The average photopic illuminances in those lots differed (HPS: 46 lux, MH: 6 lux; LED: 15 lux). Observers visited each lot and were asked to rate how safe they would feel walking in the parking lot. When plotted as a function of photopic illuminance the agreement between the average ratings and light levels was relatively poor ($r^2$=0.22) but when plotted against irradiances weighted by the spectral sensitivity proposed by Rea (2013), termed "brightness illuminance," the agreement was very high (see Figure 5).

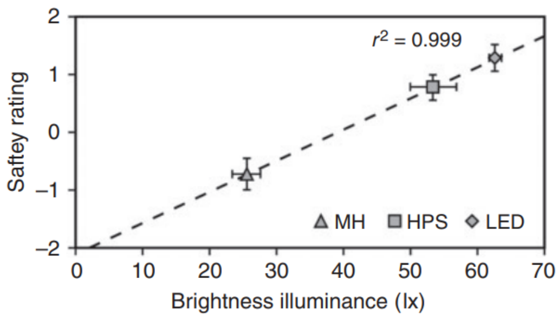


**Figure 5 – Ratings of Perceived Safety in Three Different Parking Lots (Rea et al., 2017) as a Function of Scene Brightness-Based Quantities (Scale: -2, Very Unsafe to +2, Very Safe)**

This very high level of agreement between ratings of perceived safety and brightness-based quantities in Figure 5 is empirical evidence for the role of short-wavelength photoreceptors in perceptions of safety and security from parking lot lighting.

## 2.3 Uniformity of Illumination

As stated above, the impacts of uniformity of outdoor illumination have not been extensively studied, although lighting recommendations (e.g., IES, 2018) include limits on the uniformity ratio for parking lot lighting. Because of anecdotal observations that LED outdoor lighting systems might be able to produce more uniform illumination (with lower max:min ratios) and because LEDs tend to have small source sizes that in principle, are conducive to the design of efficient optical systems that could produce uniform illumination, Narendran et al. (2016) conducted a study to assess whether, as suggested by Kimura et al. (2014), more uniform lighting could increase perceptions of scene brightness and hence safety and security, than more non-uniform lighting.

In their study, Narendran et al. (2016) set up a parking lot with two pole configurations and dimmable LED luminaires that each could generate a wide range of average photopic illuminances on the parking lot surface, with two nominal max:min ratios ("standard": approximately 10:1 and "improved": approximately 3:1, although the higher max:min ratio could range up to 20:1 or higher depending upon the average illuminance). Observers in the study viewed each combination of average illuminance and uniformity ratio and rated their perceptions of safety and security. Figure 6 shows the average safety ratings as a function of average illuminance, for each uniformity condition.

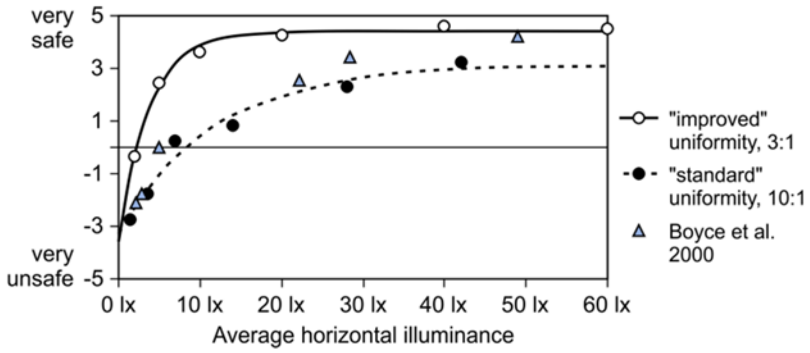


**Figure 6 – Safety Ratings for Two Levels of Uniformity as a Function of Average Illuminance (Narendran et al., 2016); Also Shown are Data from Boyce et al. (2000)**

Also shown in Figure 6 are safety rating data from Boyce et al. (2000); presumably the pre-LED installations viewed by participants in the study by Boyce et al. has standard uniformity, and indeed, the ratings for this uniformity condition match well between Narendran et al. (2016) and Boyce et al. (2000). When the max:min uniformity ratio is lower, the safety ratings are significantly higher even for the same average illuminance, and an asymptotic level of safety is reached at a lower average illuminance. These data clearly indicate the effect of illumination uniformity on perceived safety under parking lot illumination.

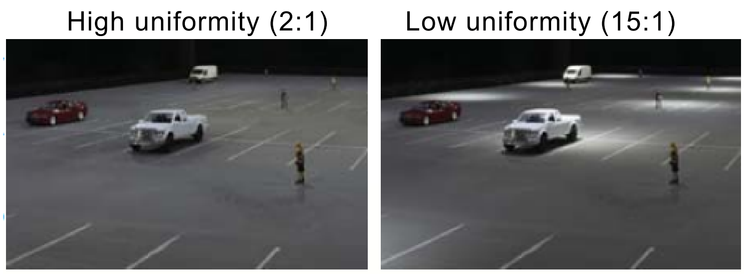


**Figure 7 – Photographs of the Scale Model Parking Lot; Left: Very Uniform Lighting with a Low Max:Min Uniformity Ratio, Right: Less Uniform Lighting with a High Max:Min Uniformity Ratio**

## 2.4 Combined Impacts

In order to establish the effects of light level, spectral distribution and uniformity on perceptions of safety in parking lot lighting, these lighting characteristics were usually studied in isolation, or in limited combinations [e.g., illuminance and uniformity by Narendran et al. (2016)] while holding others constant (e.g., spectral distribution). In order to provide a comprehensive tool to assist specifiers in trading off the impacts all three factors described in this paper, a laboratory study was conducted at the LRC, using a specially constructed and calibrated lighting system.

A scale model (1:48, corresponding to O scale) of a parking lot (Figure 7) was constructed from a gray-painted board (1.2 by 2.4 m) over which were suspended 15 equally-spaced LED luminaires equipped with an array of four closely spaced LEDs, two with a correlated colour temperature (CCT) of 2850 K and two with a CCT of 5800 K, and equipped with a narrow spot lens and a wide diffuse lens for each CCT. By controlling the current to each LED, the overall average illuminance on the scale model surface could be precisely set. In addition, it was possible to produce illumination with a range of max:min uniformity ratios from 2:1 to 60:1, and with any CCT between 2850 and 5800 K by adjusting the proportion of output to each CCT. The model was populated with several scale-model vehicles and people, as shown in Figure 7.

Four average illuminances of 2.5, 5, 10 and 20 lux; three max:min uniformity ratios of 2:1, 6:1 and 15:1; and three CCTs of 2850, 3870 and 5800 K were used, so that there was a total of 36 combinations of these factors. The conditions were presented to observers in randomized order while they sat at one corner of the lot facing the opposite corner, with their eye height adjusted to the scale of the model. Observers rated the perceived safety from the lighting, if they were to walk across the parking lot alone. Figure 8 shows, for each average illuminance, the impacts of the max:min uniformity ratio on the mean safety ratings, and Figure 9 shows the impacts of the spectral distribution (i.e., CCT) at each illuminance.

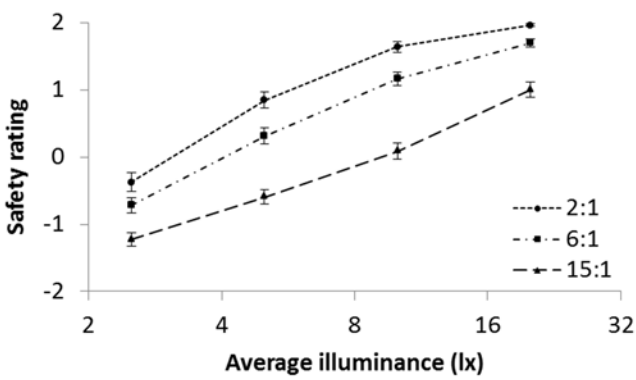


**Figure 8 – Safety Ratings (Scale: -2, Very Unsafe to +2, Very Safe) as a Function of Illuminance for Each Max:Min Uniformity Ratio, Collapsing Across All CCTs**

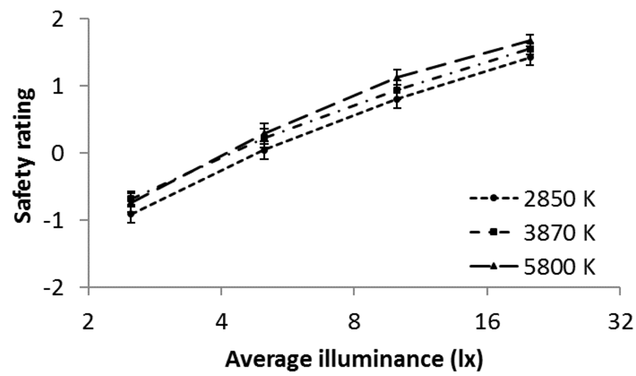


**Figure 9 – Safety Ratings as a Function of Illuminance for Each CCT, Collapsing Across all Max:Min Uniformity Ratios**

The impacts of all three factors (average illuminance, max:min uniformity ratio, and CCT) are evident from Figures 8 and 9. The effect of CCT illustrated in Figure 9 could be combined with illuminance by using the same spectral sensitivity function for scene brightness proposed by Rea (2013) and used by Rea et al. (2017) in their field study. The illuminances for each CCT (2850, 3870 and 5800 K) were multiplied by 1.36, 1.65 and 1.98, respectively, to determine the brightness based quantities. This resulted in excellent fits between the safety rating data and brightness-based quantities ("brightness illuminance") for each uniformity ratio. Figure 10 illustrates this goodness of fit for the lowest (2:1) and highest (15:1) max:min uniformity ratios in the study, demonstrating how all three factors can be combined to predict perceptions of safety under parking lot lighting, at least for the range of average illuminances (2 to 20 lux), CCT (2850 to 5800 K) and max:min uniformity ratios (2:1 to 15:1) used in this study.

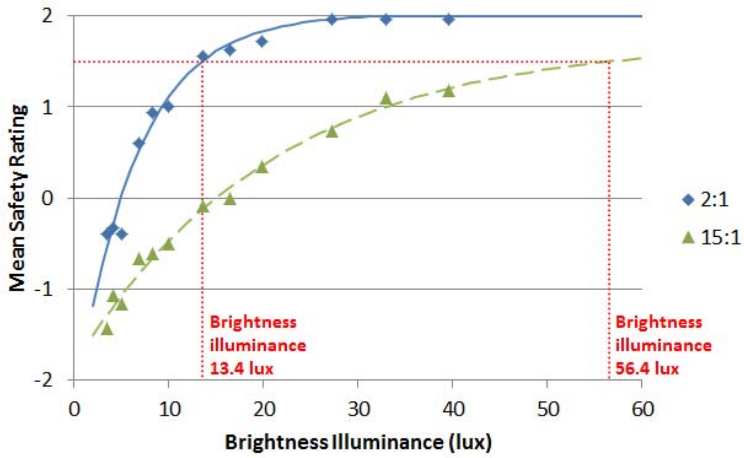


**Figure 10 – Safety Ratings for Two Max:Min Uniformity Ratios as a Function of Brightness Based Quantities**

## 3 Discussion

The series of research studies from the LRC that are described in this paper demonstrate how perceptions of safety under parking lot lighting are influenced by three important lighting-related factors: average illuminance (Boyce et al., 2000), spectral distribution (Rea et al., 2017) and uniformity of illumination (Narendran et al., 2016). Taken together, the studies summarized here provide the basis for realizing substantial energy savings, as much as 50%-75% from parking lot installations using HPS lamps, if LED installations producing “white” light and more uniform illumination is used, while maintaining equivalent perceptions of personal safety.

As shown using the curves in Figure 10, it is possible to estimate the brightness illuminances needed to achieve a mean safety rating criterion, such as +1.5 [corresponding to a high level of perceived safety (Rea et al., 2017)]. For the 2:1 uniformity ratio, a rating of +1.5 is achieved at a "brightness illuminance" of 13.4 lux; for the 15:1 ratio, the same rating requires a "brightness illuminance" of 56.4 lux. These values correspond to photopic illuminances for each CCT and max:min uniformity ratio as follows:

- 2850 K: 9.9 lux @ 2:1 max:min; 41.5 lux @ 15:1 max:min
- 3870 K: 8.2 lux @ 2:1 max:min; 34.2 lux @ 15:1 max:min
- 5800 K: 6.8 lux @ 2:1 max:min; 28.5 lux @ 15:1 max:min

Assuming luminous efficacies of 140, 145 and 150 lm/W for LED outdoor luminaires having CCTs of 2850, 3870 and 5800 K, respectively (DOE, 2017), the following assumptions are used for a parking lot scenario defined by Rea et al. (2015):

- Parking lot area: 18,562 $m^2$
- Pavement type: Asphalt
- Lateral distribution type: Type III
- Pole height: 13.7 m

For this scenario, the following power densities ($W/m^2$) are determined for the photopic illuminances listed above, to achieve a safety rating of +1.5:

- 2850 K: 0.22 $W/m^2$ @ 2:1 max:min; 0.91 $W/m^2$ @ 15:1 max:min

- 3870 K: 0.17 W/m$^2$ @ 2:1 max:min; 0.72 W/m$^2$ @ 15:1 max:min
- 5800 K: 0.14 W/m$^2$ @ 2:1 max:min; 0.58 W/m$^2$ @ 15:1 max:min

Of interest, meeting a minimum illuminance of 5 lux with a max:min uniformity ratio of 15:1 as recommended by IES (2018) would require an average photopic illuminance of 16 lux, but would not result in a +1.5 safety rating. Rather, the predicted safety ratings would be between 0 and +1 for each of the three CCTs listed above. The laboratory study described in this paper therefore provides a quantitative basis for evaluating parking lot lighting options to balance the perceived safety and security in parking lots against the energy use for lighting them. The findings suggest that uniformity could provide stronger leverage for realizing energy savings than spectrum, particularly once white light sources are being used. This point is often ignored in calls to use low-CCT sources for outdoor illumination (e.g., AMA, 2016).

One factor that might influence perceptions is the number of vehicles parked in the lot. Bullough et al. (2011) showed that there were few if any differences in perceived scene brightness between an empty lot and one with several vehicles in it. Whether this lack of difference would also translate to ratings of safety is unclear.

Finally, the results of this study, while consistent with previous field studies and holding promise for outcomes including not only energy reduction but also decreased light pollution (Rea et al., 2015), need to be validated in subsequent field research. Such field work is presently underway.

## 4 Acknowledgments

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