



University Transportation Research Center - Region 2

Final Report



Leveraging Brightness from Transportation Lighting Systems through Light Source Color: Implications for Energy Use and Safety for Traffic and Pedestrians



Performing Organization: Rensselaer Polytechnic Institute

November 2013



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University Transportation Research Center - Region 2

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The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

Research

The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the most responsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally. Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council, New York State Department of Transportation, and the New York State Energy and Research Development Authority and others, all while enhancing the center's theme.

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The modern professional must combine the technical skills of engineering and planning with knowledge of economics, environmental science, management, finance, and law as well as negotiation skills, psychology and sociology. And, she/he must be computer literate, wired to the web, and knowledgeable about advances in information technology. UTRC's education and training efforts provide a multidisciplinary program of course work and experiential learning to train students and provide advanced training or retraining of practitioners to plan and manage regional transportation systems. UTRC must meet the need to educate the undergraduate and graduate student with a foundation of transportation fundamentals that allows for solving complex problems in a world much more dynamic than even a decade ago. Simultaneously, the demand for continuing education is growing – either because of professional license requirements or because the workplace demands it – and provides the opportunity to combine State of Practice education with tailored ways of delivering content.

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16. Abstract Roadway transportation lighting is installed for multiple reasons including traffic safety and pedestrian security. Judgments of pedestrian safety and security along roadways are not strictly correlated to specified light levels, but the color of the light source influences pedestrians' judgments as well. In general, the brighter a roadway location appears, the safer and more secure it is judged as being. Most roads are illuminated using "yellowish" high pressure sodium lamps, but light sources such as light emitting diodes (LEDs) are increasingly being considered as alternative light sources for roadway lighting, and these produce a "white" light appearance. Roads illuminated by "white" light sources are consistently judged as brighter, and as a consequence safer and more secure, than roads illuminated by "yellowish" sodium lamps, even when they are lighted to the same level. The present laboratory study used lighting varying in color in order to help understand the mechanisms underlying brightness perception. Better understanding of these mechanisms can lead to recommendations for lighting that could allow engineers to design roadway lighting for equal brightness and therefore, equivalent perceptions of safety and security by pedestrians, possibly while reducing energy use.			
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ABSTRACT

Roadway transportation lighting is installed for multiple reasons including traffic safety and pedestrian security. Judgments of pedestrian safety and security along roadways are not strictly correlated to specified light levels, but the color of the light source influences pedestrians' judgments as well. In general, the brighter a roadway location appears, the safer and more secure it is judged as being. Most roads are illuminated using "yellowish" high pressure sodium lamps, but light sources such as light emitting diodes (LEDs) are increasingly being considered as alternative light sources for roadway lighting, and these produce a "white" light appearance. Roads illuminated by "white" light sources are consistently judged as brighter, and as a consequence safer and more secure, than roads illuminated by "yellowish" sodium lamps, even when they are lighted to the same level. The present laboratory study used lighting varying in color in order to help understand the mechanisms underlying brightness perception. Better understanding of these mechanisms can lead to recommendations for lighting that could allow engineers to design roadway lighting for equal brightness and therefore, equivalent perceptions of safety and security by pedestrians, possibly while reducing energy use.

1. INTRODUCTION

Roadway lighting specifications (IES, 2000) are made in terms of *illuminance*, the amount of light falling on a surface, or *luminance*, the amount and density of light leaving a surface toward a particular direction. Illuminance and luminance quantities are based on a specific type of visual response that takes into account the response of the eye's photoreceptors very near the line of sight (referred to as *photopic* sensitivity), but does not take into account the response of the eye's photoreceptors in the visual periphery. An example of a visual response that takes the visual periphery into account is the judgment of the overall *brightness* of a scene such as a roadway. *Brightness* is defined as the perception that an object or scene *appears* to be emitting or reflecting more or less light (Rea, 2000). Overall, the perceived brightness of a roadway scene, for example, will tend to be somewhat related to the luminance of the roadway, but the relationship is not perfect. The visual periphery is relatively more sensitive to "blue" (short-wavelength) light (Rea et al., 2011), so that two identical roadways illuminated by two light sources to the same *photopic luminance* will not necessarily look equally bright. The light source that produces more "blue" light output will result in a scene that appears brighter than one with less "blue" output. In other words, for a light source with relatively little "blue" output and one with more "blue" output, the same level of perceived brightness can be achieved using a lower light level with the latter light source, compared to the former.

This finding is important to transportation applications, especially when pedestrian use is important, because perceptions of safety and security by pedestrians of roadway environments are strongly related to perceptions of brightness of the same environments (Rea et al., 2009). In other words, it may be possible to use lower measured light levels along roadways when pedestrians' perceptions of safety and security are critical, when using light sources that produce higher amounts of "blue" light output compared to sources that produce little "blue" output. This has implications for energy efficiency, especially when considering that the most common light source used to illuminate roadways in the U.S. is the high pressure sodium (HPS) lamp, which produces a "yellowish-white" color with relatively little "blue" (short-wavelength) energy (Navigant, 2012).

There are several photoreceptors in the human eye that might account for the increased sensitivity to "blue" light in the visual periphery: short-wavelength cones (responding maximally to "blue" light with a wavelength near 450 nanometers [nm]) and rods (responding maximally to "blue-green" light with a wavelength near 500 nm), and as recently discovered, intrinsically-photoreceptive retinal ganglion cells (ipRGCs), which respond maximally to "blue" light with a wavelength near 480 nm. In comparison, the visible spectrum spans wavelengths between 400 nm ("violet" light) and 700 nm ("red" light). The ipRGC cells in the eye carry signals from rods and cones to the visual centers of the brain, but it was recently discovered that some of these ganglion cells respond directly to light because they contain a photopigment, known as melanopsin, which generates electrical signals when exposed to light, especially "blue" light (Dacey et al., 2005).

The purpose of the present study is to provide information about the possible mechanisms underlying scene brightness perception when viewing scenes such as illuminated

roadways. The techniques used and results generated are based on an area of research known as *visual psychophysics*, which is not a traditional area of research in transportation science and engineering, and which carries its own vocabulary and terminology. However, because pedestrians use visual information, such as brightness perception, to judge the safety and security of environments such as roadways, using visual psychophysics to develop new metrics for roadway lighting can provide a way to "tune" the color or spectral properties of lighting to balance one of the benefits of roadway lighting (increased perceptions of safety and security) against the costs (electrical energy and lighting system maintenance costs).

2. BACKGROUND

Photometric specifications for light levels for most lighting applications, including roadway lighting, are most often characterized by the *photopic* luminous efficiency function, $V(\lambda)$, which represents the spectral (or color) sensitivity of the eye to light. More specifically, $V(\lambda)$ represents the sensitivity of the eye near the visual line of sight. Luminous quantities such as illuminance or luminous intensity are implicitly based on this function, which represents the spectral sensitivity of the long- (L) and middle-wavelength (M) cone photoreceptors in the central (foveal) portion of the retina (CIE, 1978). A second function, known as the *scotopic* luminous efficiency function, $V'(\lambda)$, represents the spectral sensitivity of the rod photoreceptors located throughout the retina, excluding a rod-free area in the fovea. The light levels at which rods are the sole photoreceptor class that contributes to vision are so low, however, that the scotopic function has little if any applicability to lighting practice, even at night (CIE, 1978).

Recently, the Commission Internationale de l'Éclairage (CIE, 2010) recommended a unified system of luminous efficiency functions, applicable to luminances between 0.005 and 5 cd/m^2 , which are linear combinations of the photopic and scotopic luminous efficiency functions, and which represent a combination of sensitivity from cones and rods in the peripheral visual field of the eye. The light level range at which this system is applied corresponds to many levels specified for roadway lighting at night (IES, 1999, 2000). This system approximates the human eye's retinal spectral sensitivity outside the rod-free (foveal) region, when both rods and cones contribute to vision for tasks such as detection of peripheral objects (Rea et al., 2004).

Another visual response that is relevant to transportation lighting is the perception of scene brightness of a lighted roadway. Rea et al. (2009) showed that brightness perceptions of real-world street scenes lighted with different spectra were highly correlated with perceptions of safety and security under those conditions. Higher scene brightness perception was associated with a greater sense of security.

Ferguson and Stevens (1956) noted that brightness perception differed under low pressure sodium (LPS), a light source producing a saturated "yellow" color appearance, and mercury vapor (MV) illumination, MV producing "white" light. Rea (1996) reported brightness differences between lighting from high pressure sodium (HPS) lamps, which produce "yellowish-white" light, and metal halide (MH) lamps, which produce "white" light, throughout a range of common outdoor light levels. Fotios and Cheal (2007) compared a number of practical outdoor light sources. In all of these studies, it was found that "white" light sources produced higher levels of scene brightness than "yellowish" sources such as sodium vapor lamps.

Using side-by-side scale model scenes of a lighted parking lot containing buildings, trees and colored cars, Rea et al. (2011) conducted an initial laboratory experiment in which they systematically adjusted the amount of short-wavelength ("blue") light from the illumination in each scene, using HPS and MH sources as the baseline conditions, and under two horizontal (photopic) illuminances (2 lx and 20 lx). Scenes with higher amounts of

short-wavelength spectral content were systematically judged as brighter overall, even though this was not necessarily the case for specific objects in the scenes such as the individually-colored cars (Bullough et al., 2011). The brightness judgment data from Rea et al. (2011) were consistent with previously published brightness data from Weale (1953) and data from Wooten et al. (1975) using an increment threshold task (Figure 1), the latter of which exhibited a strong short-wavelength lobe in spectral sensitivity that was largest for the highest light adaptation levels used in that study (Figure 1). In other words, sensitivity to "blue" light (the lobes of increased height between 400 and 500 nm in Figure 1) was increased for higher light levels.

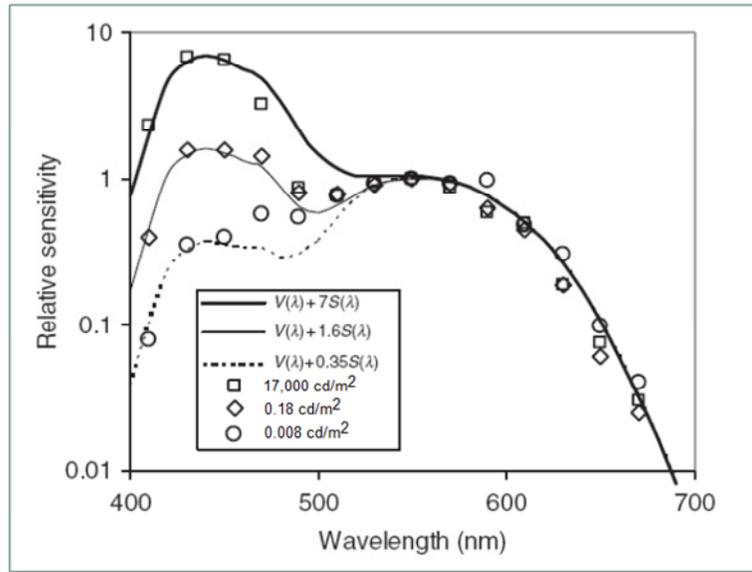


Figure 1. Spectral sensitivity data from Wooten et al. (1975) for three light adaptation levels (17,000 cd/m², 0.18 cd/m² and 0.008 cd/m²).

The data from Rea et al. (2011) exhibited increased short-wavelength sensitivity (relative to the photopic luminous efficiency function) for brightness. In addition, short-wavelength sensitivity was higher for higher adaptation levels. Comparing adaptation data from Haig (1941) and increment detection data from Graham and Kemp (1938) to the spectral sensitivity functions from Wooten et al. (1975), Rea et al. (2011) identified a robust relationship between the adaptation luminance and the gain in short-wavelength sensitivity. This gain was parsimoniously modeled using a luminous efficiency function, $B(\lambda)$, defined as an additive combination of functions as follows (Rea et al., 2011):

$$B(\lambda) = V(\lambda) + gS(\lambda) \tag{1}$$

In Equation 1, $S(\lambda)$ is the spectral sensitivity of the short-wavelength (S) cone (Smith and Pokorny, 1975), and $V(\lambda)$ is the photopic luminous efficiency function used conventionally to define light.

Based on the data from Rea et al. (2011), Wooten et al. (1975), Haig (1941) and from Graham and Kemp (1941), the value of g was approximately 1.5 at an illuminance of 2 lx

and approximately 2.5 at 20 lx. The model was validated in a subsequent follow-up experiment using similar scenes and different light sources. Consistent with these results, Hamm (2011) found that the relative brightness difference between a roadway scene illuminated by a halogen lamp and a roadway scene illuminated by a light emitting diode (LED) source increased as a function of light level. This increase in short-wavelength gain might also be manifested in the Bezold-Brücke effect (Wyszecki and Stiles, 1982), in which the blue-yellow opponent channel increases in significance to color vision as light levels increase. The model was also validated when colored objects within the roadway scenes, such as scale model cars, were absent (Bullough et al., 2011), demonstrating that the color of specific objects in the scenes did not influence the overall scene brightness. This finding was consistent with Fotios and Cheal (2011a), and suggests that color rendering plays little role in scene brightness perception. Figure 2 shows the percentage of times each light source was chosen at 2 lx, and at 20 lx, for the respective value of g at each level. Goodness-of-fit values (R^2 in Figure 2) were high (>0.8).

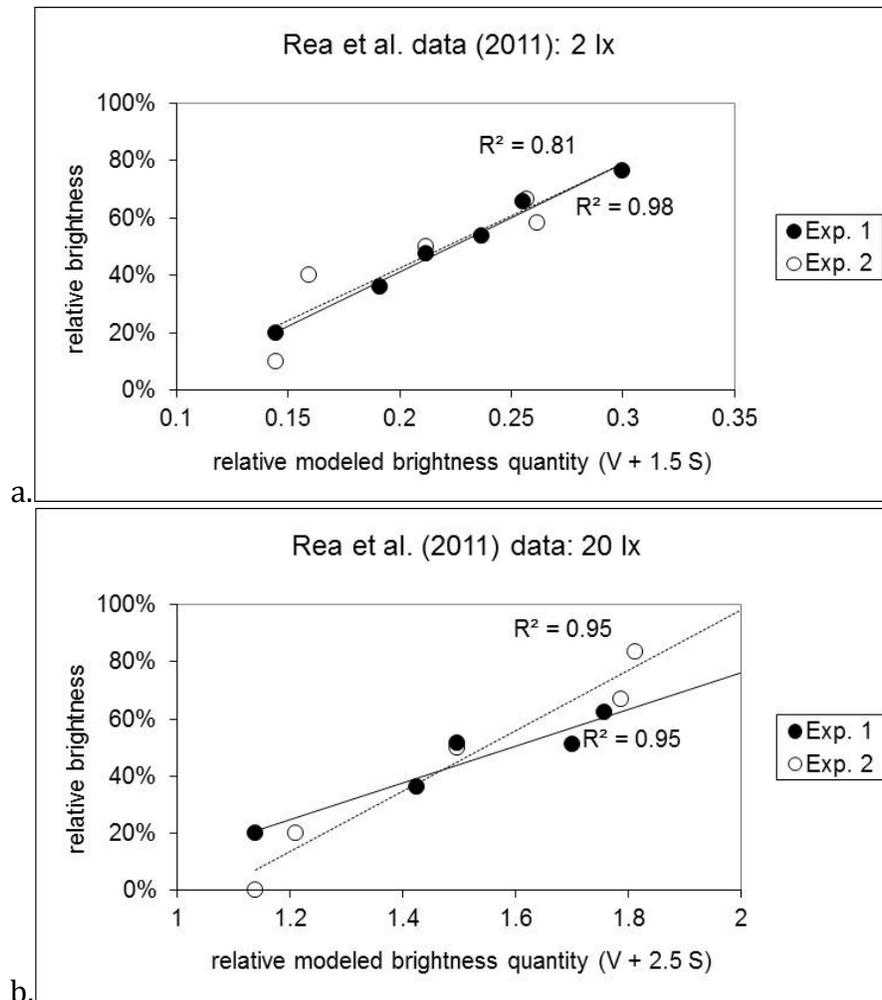


Figure 2. Brightness judgment percentages for the light sources used by Rea et al. (2011) in their experiments (a: 2 lx, b: 20 lx), as a function of the predicted brightness quantities from Equation 1. Experiment 1 is the initial experiment by Rea et al. (2011) and Experiment 2 is their follow-up experiment.

Equation 1 (Rea et al., 2011) was put forth as a provisional model because the light source spectra they used in their experiments did not have sufficient leverage to test whether other spectral mechanisms (e.g., rods or ipRGCs) might also contribute to brightness under the conditions they used. Rea et al. (2011) reasoned that rods probably played little role in brightness perception under these conditions because of observations that color perception (mediated by cones) was robust even under 2 lx, as well as a number of findings in previously published literature [summarized by Rea et al. (2004)] that showed only negligible participation from rods in brightness perception at 0.1 cd/m^2 , which was near the lowest level used by Rea et al. (2011), and even less rod participation at higher levels.

The inclusion of the MV source in the study by Rea et al. (2011), which produced relatively large S-cone stimulation, but relatively low rod or ipRGC stimulation, also provided an empirical basis that much of the increased short-wavelength sensitivity for scene brightness perception had to be due to a mechanism shorter than the peak sensitivity wavelengths for rods (507 nm) or for ipRGCs (~480 nm). More recently, Brown et al. (2012) measured the relative brightness of large fields having similar chromaticities and luminances but differing in their stimulation of ipRGCs. They found that brightness perception was enhanced for stimuli having greater ipRGC stimulation, consistent with a role of melanopsin in brightness perception not incorporated into the provisional model from Rea et al. (2011; Equation 1).

As mentioned previously, the CIE (2010) unified system of mesopic photometry was not intended to be applied to brightness perception but rather to the detection of objects in the visual periphery at nominally mesopic (i.e., nighttime) light levels. Still, since brightness perception exhibits scotopic spectral sensitivity at very low light levels, and exhibits spectral sensitivity based on cone responses at higher levels [although not with the same sensitivity as implied by $V(\lambda)$], it is not unreasonable to wonder whether the CIE (2010) unified system might have utility for predicting scene brightness under nighttime viewing conditions.

Fotios and Cheal (2011b) compared several light sources including HPS, MH, fluorescent and light emitting diode (LED) sources when used to illuminate a test box to 5 lx. The LED source in their study was not a phosphor-converted white LED but rather, used a mixture of green and red LED illumination producing a yellowish-green color appearance. Fotios and Cheal (2011b) conducted an initial brightness judgment experiment (Experiment 1) in which subjects judged which of two adjacent scenes were brighter, as well as a follow-up experiment (Experiment 2) in which the light level from one source was adjusted to match the brightness from another.

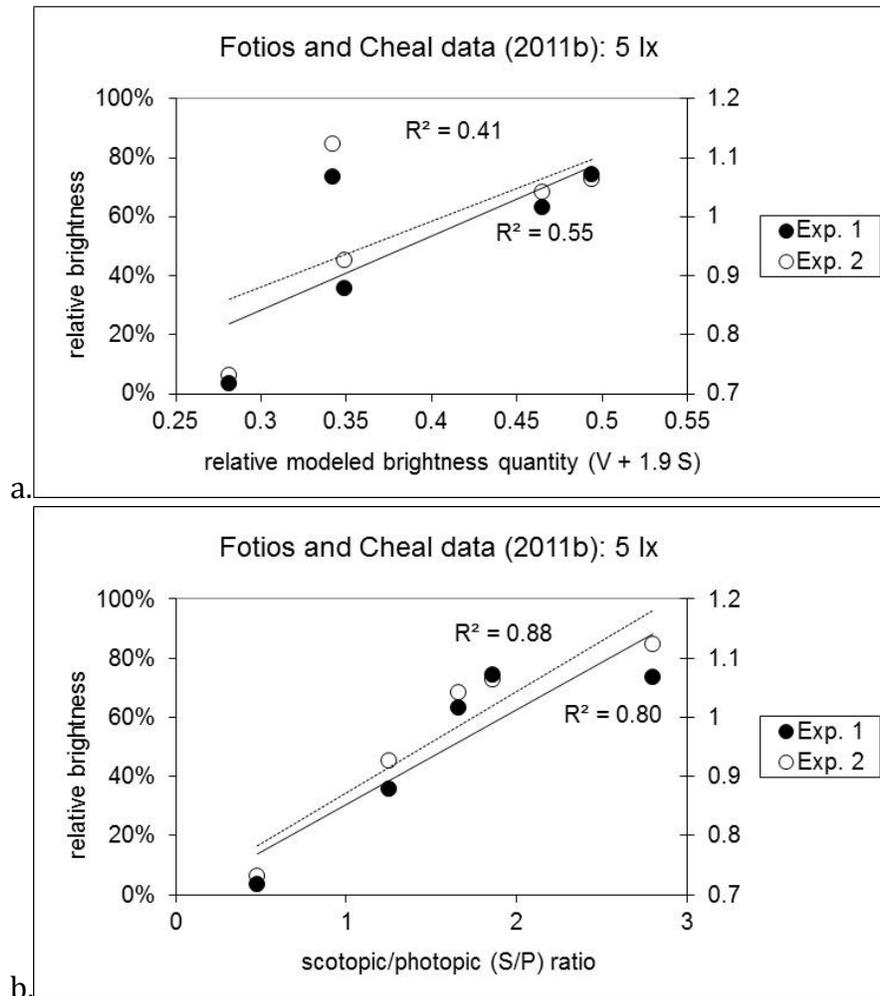


Figure 3. Brightness data from Fotios and Cheal (2011b) as a function of (a) Equation 1, and (b) the scotopic/photopic ratios of the sources in their study. Experiment 1 is their brightness judgment experiment, and Experiment 2 is their brightness matching study.

Fotios and Cheal (2011b) noted that their measured brightness data were not strongly correlated with a brightness model such as that based on Equation 1 (Rea et al., 2011). At 5 lx, the value of g in Equation 1 would be predicted to be 1.9. Figure 3a shows the goodness of fit between the data from the two experiments (either the percentage of times a condition was judged brighter or the reciprocal of the illuminance ratio at matched brightness) by Fotios and Cheal (2011b) as a function of quantities based on the provisional model in Equation 1. The goodness of fit value is moderate but the provisional model substantially underestimates the brightness of the same condition in each experiment, the yellowish-green LED condition, which produces relatively little short-wavelength output yet was judged as one of the brighter sources in the study.

Fotios and Cheal (2011b) recommended that scene brightness of lighted outdoor streets be predicted by the CIE (2010) unified system of photometry, based on the finding that their brightness judgment data were more strongly correlated with the scotopic/photopic (S/P)

ratios of the sources used in their study (Figure 3b). The S/P ratio puts light sources producing equal illuminances in proper rank order regarding their relative effectiveness for peripheral detection at mesopic light levels, according to the CIE (2010) unified photometry system.

The recommendation to use the CIE (2010) unified photometry system for predictions of scene brightness under roadway lighting is problematic for several reasons. First, the brightness judgment data from the follow-up experiment by Rea et al. (2011) were only moderately correlated with the S/P ratio. Second, the CIE (2010) unified photometry system exhibits a shift in spectral sensitivity toward shorter wavelengths as the light level is decreased, not as it is increased. The published data from Weale (1953), Wooten et al. (1975), Hamm (2011) and Rea et al. (2011), as well as recent data from Bullough et al. (2014), all point toward a spectral sensitivity shift in the opposite direction. Third, Fotios and Gado (2005) has found scene differences between different spectra even when the light levels were well above the upper limit of the mesopic range value (5 cd/m^2) applicable to the CIE (2010) unified photometry system; the CIE (2010) system would predict no differences between light sources differing in spectral content at these light levels. Fourth, as pointed out by Rea et al. (2004), rod contributions to brightness perception [which are modeled by CIE (2010)] seem to be negligible at or above a light level of 0.1 cd/m^2 . Fifth, Brown et al. (2012) demonstrated that ipRGCs likely contribute to brightness perception at light levels ($>300 \text{ cd/m}^2$) where rod contribution should be practically nonexistent.

Rejecting the notion, therefore, that the CIE (2010) unified system of mesopic photometry can provide meaningful insight into perceptions of brightness, and considering the hypothesis that melanopsin could play a role in brightness perception (Brown et al., 2012), the provisional model in Equation 1 could be modified by the inclusion of a term to represent input from mRGCs into this response. One strictly empirical model, also offered provisionally, is shown in Equation 2:

$$B_2(\lambda) = V(\lambda) + 0.5\text{Mel}(\lambda) + g_2S(\lambda) \quad (2)$$

In Equation 2, $\text{Mel}(\lambda)$ is a luminous efficiency function based on an opsin photopigment having a peak spectral sensitivity at 480 nm. $V(\lambda)$ and $S(\lambda)$ are defined as in Equation 1. The value of g_2 is determined similarly as g in Equation 1, but reduced by 40% to empirically adjust the overall short-wavelength sensitivity based on optimizing the goodness of fit to the brightness data published by Rea et al. (2011) and by Fotios and Cheal (2011b). At 2 lx, $g_2=0.9$, at 5 lx, $g_2=1.1$ and at 20 lx, $g_2=1.5$. The coefficient of 0.5 used with the $\text{Mel}(\lambda)$ term was also based on empirical goodness of fit analyses.

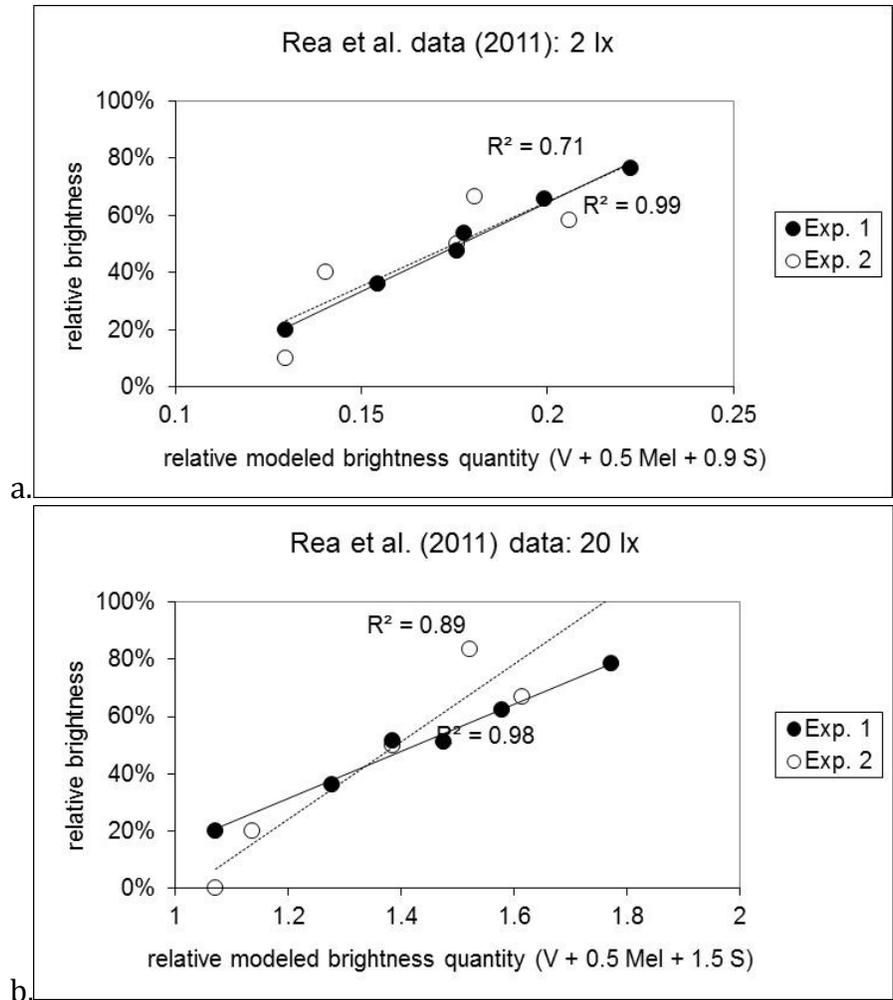


Figure 4. Brightness judgment percentages for the light sources used by Rea et al. (2011) in their experiments (a: 2 lx, b: 20 lx), as a function of the predicted brightness quantities from Equation 2.

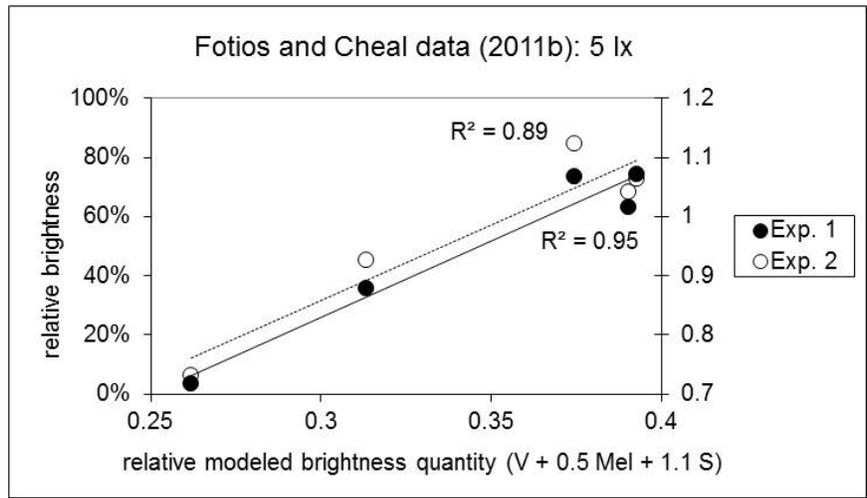


Figure 5. Brightness data from Fotios and Cheal (2011b) as a function of Equation 2.

Figure 4 shows the relationships between the revised provisional model quantities based on Equation 2 and the brightness judgment data from the experiments by Rea et al. (2011), and Figure 5 shows the data from Fotios and Cheal (2011b) plotted in a similar manner. Goodness of fit values are, in general, reasonably high (>0.7) for all sets of data.

Any model, to be useful, requires independent validation, and the provisional model in Equation 2 has not been validated experimentally. Indeed, the values of the coefficient for melanopsin sensitivity and for the short-wavelength gain were determined empirically based on goodness of fit values to previously published data. To provide further validation, a series of experiments was conducted.

3. METHODS

The laboratory study described in this chapter builds upon methods used by Rea et al. (2011) and by Fotios and Cheal (2011b), using a scale model box to provide a full field of view of a scene illuminated by various colors of light.

3.1. Apparatus

A 0.6-m cubical box with an open front was painted matte white (reflectance, 0.7) on the interior; the box could be illuminated from above by an array of indirect computer-controlled light emitting diode (LED) sources including the following:

- Blue (Cree XP-E, peak wavelength 468 nm, half-maximum bandwidth 24 nm)
- Green (Lumileds Luxeon I, peak wavelength 525 nm, half-maximum bandwidth 38 nm)
- Red (Cree XR-C, peak wavelength 625 nm, half-maximum bandwidth 15 nm)

Multiple LEDs could be switched on to produce combination SPDs by mixing; the white surfaces of the box produced very homogenous illumination with uniform color and light level. A calibrated light/color meter (Gigahertz-Optik) measured the illuminance and chromaticity of light at the center of the bottom surface of the box, and feedback from this instrument was used to maintain stable light output and chromaticity (within a 0.6-step MacAdam ellipse for each condition) through computer control, using a custom circuit designed to digitally control the output from each source with a 12-bit resolution.

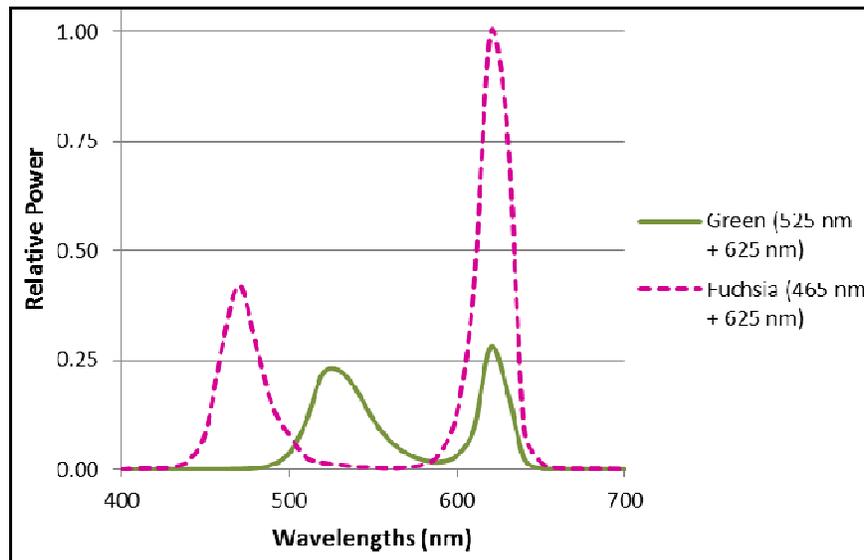


Figure 6. Normalized SPDs used in the experiments.

3.2. Lighting Conditions

In each of the experiments, two relative SPDs were used: one (denoted green) was created using a combination of green and red LEDs, and another (denoted fuchsia) was created

using a combination of blue and red LEDs. Figure 6 shows representative, normalized (to a peak value of 1) curves for each SPD. The SPDs were not selected because they are representative of illuminants used in outdoor applications; rather, they were selected to provide differentiation in spectral content below 500 nm in order to investigate the short-wavelength gain in spectral sensitivity predicted by the model from Rea et al. (2011) and the revised model described above. Colorimetric properties of the SPDs are as follows:

- Green SPD: chromaticity (x,y) coordinates (0.399, 0.573)
- Fuchsia SPD: chromaticity (x,y) coordinates (0.447, 0.229)

Two light level ranges were selected for the study, a low range with horizontal illuminances near 10 lx, and a high range with horizontal illuminances near 50 lx. Nominally, these corresponded to light levels near those recommended for roadway lighting (IES, 2000) for the low range, and light levels found in some urban plazas (Brons et al., 2008) for the high range.

For the lower range of light levels, the revised provisional model of spectral sensitivity based on Rea et al. (2011) and including a contribution from melanopsin would predict the green and fuchsia SPDs to produce equivalent scene brightness when the (photopic) illuminance from the green condition was 12 lx, and when the illuminance from the fuchsia condition was 6 lx. These illuminances were selected as the baseline conditions for the lower range of light levels used in the study. For the higher range of light levels, the revised provisional model would predict the two SPDs to produce equivalent brightness when the illuminance from the green SPD was 64 lx and when the illuminance from the fuchsia SPD was 30 lx.

For the low light level range, two experiments were performed with each of the two SPDs serving as the reference stimulus condition (either 12 lx from the green SPD, or 6 lx from the fuchsia SPD) and the other, test stimulus condition SPD was adjusted to produce predicted brightness values higher and lower than that of the control condition [interval steps averaged approximately 30% in magnitude, similar to intervals used by Bullough et al. (2007) and by Fotios and Cheal (2007, 2010) in previously published studies], as follows:

- Green SPD control condition (12 lx): Compared to fuchsia SPD test stimulus conditions at 2.5, 4, 6, 8 and 10 lx
- Fuchsia SPD control condition (6 lx): Compared to green SPD test stimulus conditions at 5, 8.5, 12, 16 and 24 lx

Conditions were selected similarly for the two experiments conducted under the high light level range:

- Green SPD control condition (67 lx): Compared to fuchsia SPD test stimulus conditions at 8, 19, 30, 47 and 60 lx
- Fuchsia SPD control condition (30 lx): Compared to green SPD test stimulus conditions at 16, 42, 67, 86 and 109 lx

3.3. Experimental Procedure

Twelve color-normal subjects between the age of 22 and 53 years participated in each experiment. After signing an Institutional Review Board (IRB) approved informed consent form, subjects were seated in front of the experimental test box. Each pair of stimulus conditions consisting of a green and fuchsia condition was displayed sequentially to subjects in a randomized order, with the order of control and test conditions for each pair balanced to account for any potential order bias. Each pair of conditions was shown a total of six times, three times in each sequential order.

Each individual stimulus presentation was timed to last approximately 5 s; stimulus presentations no longer than this duration had been used in previously published brightness studies using a sequential presentation technique (Fotios and Cheal, 2010; Brown et al., 2012). Between each individual stimulus presentation, subjects wore an opaque sleep mask and closed their eyes for a time period between approximately 10 s and 25 s, while an experimenter adjusted the apparatus to present the next stimulus. Subjects were asked, following each pair of sequential stimulus conditions, to report which of the two conditions appeared brighter using a forced-choice response (they could not report that the conditions appeared equally bright). They were also asked to judge, as a percentage, how much brighter the brighter condition was relative to the less bright condition. Each experiment included 30 sequential stimulus presentation pairs and took each between 30 and 40 minutes to complete.

4. RESULTS

Figure 7 contains the results of the low light level range experiment with the green SPD as the control condition. Figure 7a contains the overall brightness judgment results for all subjects, and Figure 7b shows the mean percentages when the subjects were asked to report the relative brightness difference percentage between the conditions. In each case the data are plotted as a function of the (photopic) illuminance from the test condition. The best-fitting sigmoid (Figure 7a; $r^2=0.99$) and linear (Figure 7b; $r^2=0.91$) functions to the data are also shown in Figure 7.

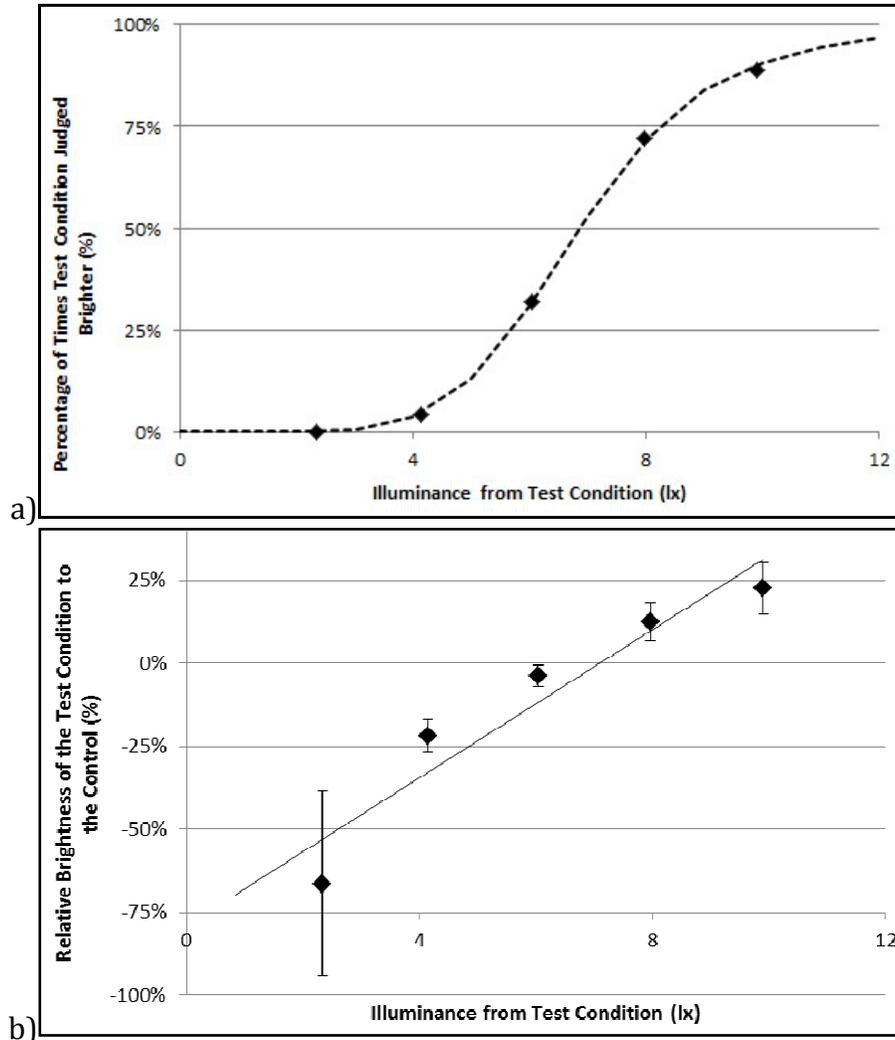


Figure 7. a) Brightness judgment data and best-fitting sigmoid function and b) relative brightness percentages (and standard errors of the mean) and best-fitting line, plotted as a function of the illuminance from the fuchsia SPD test stimulus conditions, for the low light level range (compared to the green reference stimulus at 12 lx).

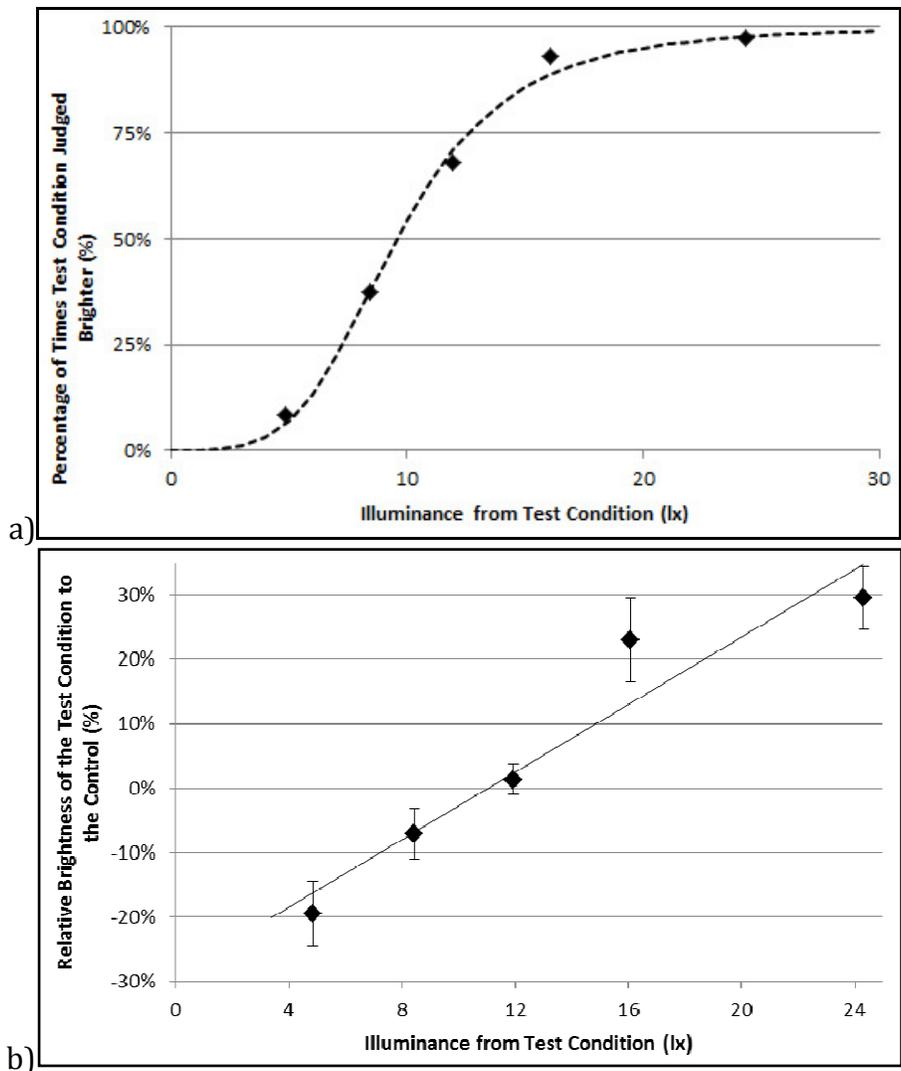


Figure 8. a) Brightness judgment data and best-fitting sigmoid function and b) relative brightness percentages (and standard errors of the mean) and best-fitting line, plotted as a function of the illuminance from the green SPD test stimulus conditions, for the low light level range (compared to the fuchsia reference stimulus at 6 lx).

Figure 8 shows the same data (Figure 8a: $r^2=0.99$; Figure 8b: $r^2=0.92$) for the low light level range experiment with the fuchsia control SPD condition. In both Figures 7 and 8, the results were consistent between the two types of questions asked of subjects. From the best fitting equations in Figures 7 and 8, the illuminances at which the sigmoid curves had a value of 50% and at which the linear functions had a value of 0% were determined. These values, taken as the illuminances from the test conditions that produced equivalent brightness to the reference condition in each experiment, were:

- For the green SPD control condition (12 lx): 6.9 lx (judgment choice data), 7.0 lx (relative percentage data) from the fuchsia SPD test condition

- For the fuchsia SPD control condition (6 lx): 9.6 lx (judgment choice data), 11 lx (relative percentage data) from the green SPD test condition

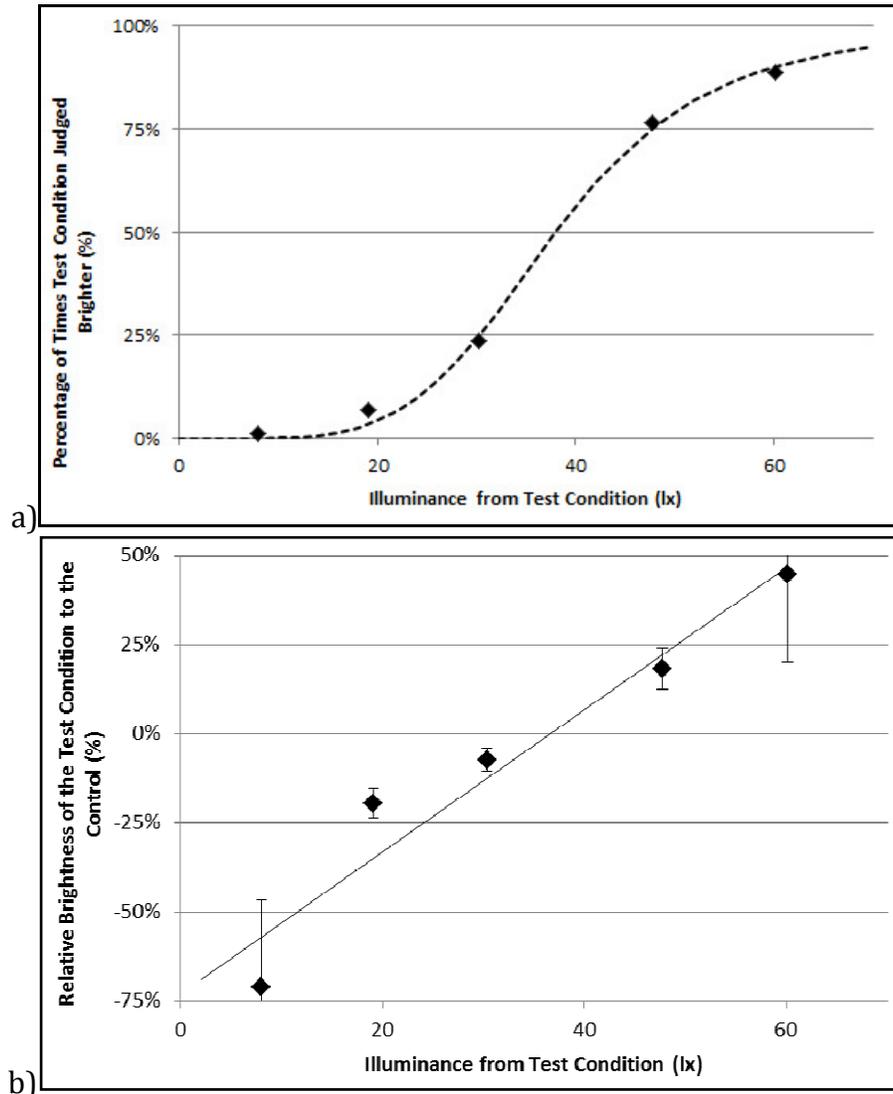


Figure 9. a) Brightness judgment data and best-fitting sigmoid function and b) relative brightness percentages (and standard errors of the mean) and best-fitting line, plotted as a function of the illuminance from the fuchsia SPD test stimulus conditions, for the high light level range (compared to the green reference stimulus at 67 lx).

Figure 9 and Figure 10 show the results of the high light level range experiments, with the green (Figure 9) and fuchsia (Figure 10) SPDs as the control conditions, presented in the same manner as in Figures 7 and 8.

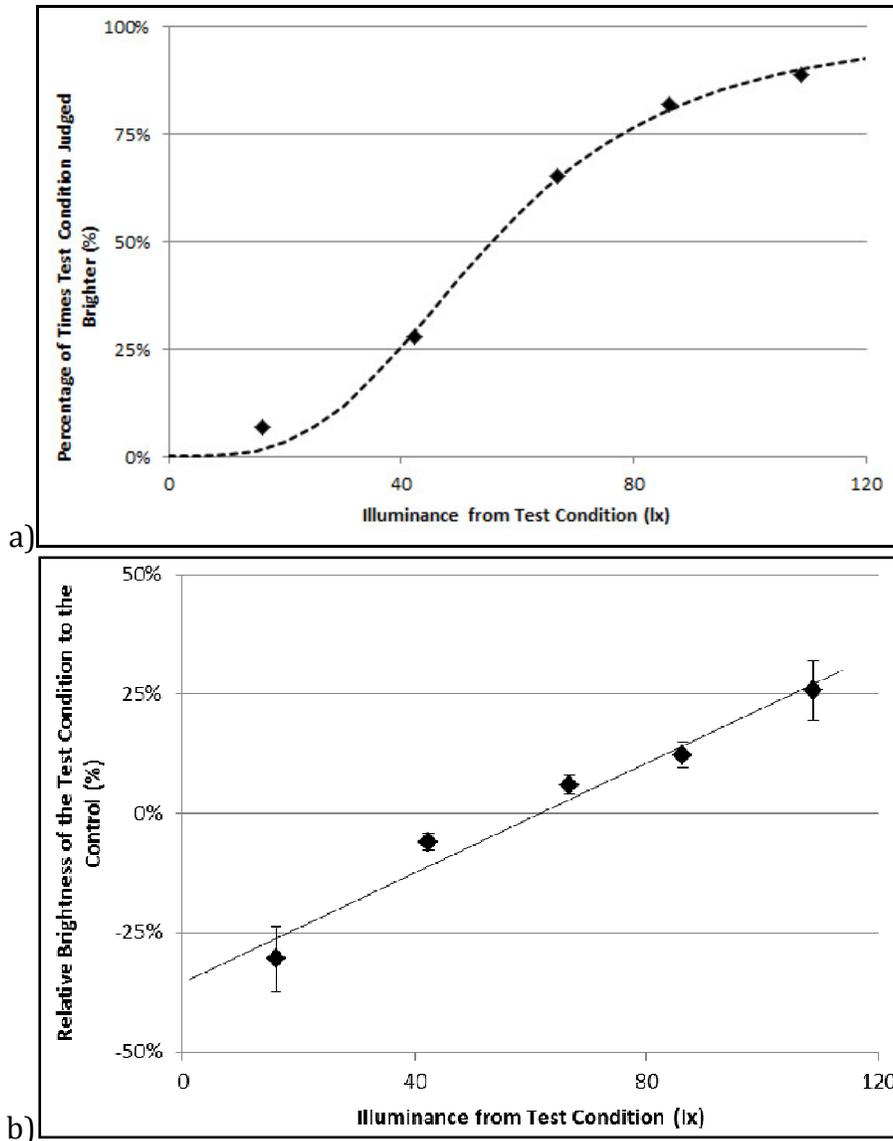


Figure 10. a) Brightness judgment data and best-fitting sigmoid function and b) relative brightness percentages (and standard errors of the mean) and best-fitting line, plotted as a function of the illuminance from the green SPD test stimulus conditions, for the high light level range (compared to the fuchsia reference stimulus at 30 lx).

Based on the best-fitting equations in Figure 9 (Figure 9a: $r^2=0.99$; Figure 9b: $r^2=0.94$) and in Figure 10 (Figure 10a: $r^2=0.99$; Figure 10b: $r^2=0.97$), the test condition illuminances determined from the best fitting equations to be equivalent to the reference condition (with ordinate values of 50% for Figures 9a and 10a, and ordinate values of 0% for Figures 9b and 10b) are as follows:

- For the green SPD control condition (67 lx): 38 lx (judgment choice data), 37 lx (relative percentage data) from the fuchsia test condition
- For the fuchsia SPD control condition (30 lx): 56 lx (judgment choice data), 61 lx (relative percentage data) from the green test condition

5. DISCUSSION AND CONCLUSIONS

5.1. Model Comparisons

The data in Figures through 10 show that scene brightness perception at the two light level ranges employed in the experiment (~ 10 lx for the low light level range and ~ 50 lx for the high light level range) was not predicted by the photopic illuminance produced by the conditions. For the low light level range, the green and fuchsia SPDs were judged equally bright when the ratio between the illuminances from them was about 1.7 (e.g., 12 lx / 7.0 lx ≈ 1.7). For the high light level range, the green and fuchsia SPDs were judged equally bright when the ratio between their illuminances was about 1.9 (e.g., 56 lx / 30 lx ≈ 1.9). Using spectral sensitivity functions having the form of Equation (1) for the green and fuchsia SPDs when they were judged equally bright, the following values of g were determined from the experimental results:

- Green SPD: $g=1.2$ at 12 lx; $g=3.0$ at 67 lx
- Fuchsia SPD: $g=1.1$ at 6.9 lx; $g=1.3$ at 38 lx

For both SPDs, the values of g increase at the higher light level, a finding which is consistent with the published spectral sensitivity data from Weale (1953), Wooten et al. (1975), and Rea et al. (2011, 2013). The values are somewhat lower than the predicted values (for green, $g=2.3$ at 12 lx and $g=3.0$ at 67 lx; for fuchsia, $g=2.0$ at 6.9 lx and $g=2.8$ at 38 lx). This is a consequence of using photopic illuminance in the provisional model by Rea et al. (2011) to specify the magnitude of the gain in short-wavelength spectral sensitivity.

Using spectral sensitivity functions having the form of Equation (2) for the green and fuchsia SPDs when they were judged equally bright, the following values of g_2 were determined from the experimental results:

- Green SPD: $g_2=0.9$ at 12 lx; $g_2=1.8$ at 67 lx
- Fuchsia SPD: $g_2=0.8$ at 6.9 lx; $g_2=1.0$ at 38 lx

For both SPDs, the values of g_2 also increase at the higher light level, but the differences from the predicted values are somewhat smaller (for green, $g_2=1.4$ at 12 lx and $g_2=1.8$ at 67 lx; for fuchsia, $g_2=1.2$ at 6.9 lx and $g_2=1.7$ at 38 lx), suggesting that the model incorporating input from ipRGCs is an improvement over the cone-only model provisionally suggested by Rea et al. (2011).

5.2. Conclusions and Implications for Lighting Practice

In North America, most recommendations for lighting along streets and roadways (IES, 2000) and in other outdoor locations (IES, 1999) are based on photopic illuminance or luminance. Recent guidance from the United Kingdom (Fotios, 2013) suggests that light levels for residential streets can sometimes be adjusted to maintain brightness perception in the mesopic range. The method described by Fotios (2013) uses the unified system of mesopic photometry recommended by the CIE (2010) to adjust the photopic illuminance.

However, it is clear that photopic illuminance is a poor specification of the stimulus for scene brightness at either of the two light level ranges investigated, and further that using the CIE (2010) system of unified photometry is also inappropriate, because it incorporates a shift in spectral sensitivity that is opposite in direction to the spectral sensitivity shift that scene brightness exhibits. Moreover, a contribution of melanopsin-containing ipRGCs to scene brightness is consistent with both the analyses described in the Background and with the present data from the experiments described in the present report. These data suggest that lamp spectra can be evaluated with respect to impressions of brightness, which in turn are probably related to impressions of safety and security (Rea et al., 2009).

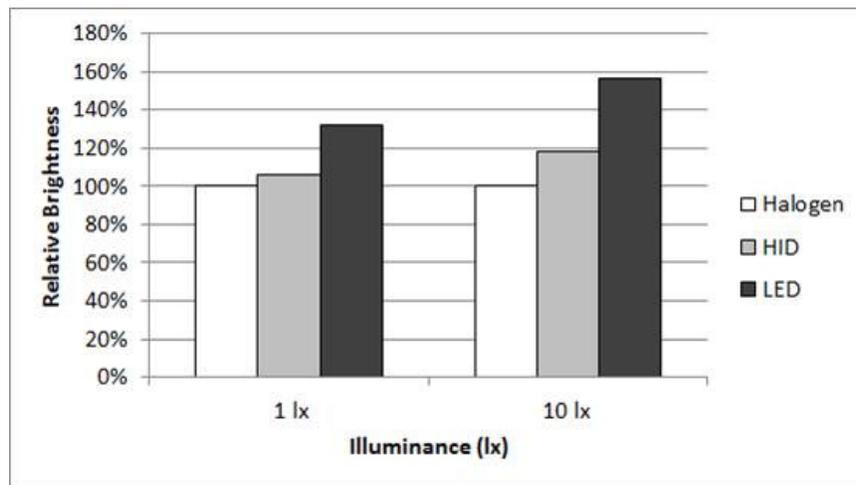


Figure 6. Predicted brightness (relative to halogen) of HID and LED sources at two illuminances, based on Equation (2).

As an initial comparison, the provisional model in Equation 2 was used to compare halogen, high-intensity discharge (HID) and LED (with a correlated color temperature [CCT] of 6500 K) sources used for vehicle headlamps in terms of their relative brightness for illuminated roadway scenes at horizontal illuminances of 1 lx and 10 lx, as illustrated in Figure 11.

For roadway and area lighting, as an example, a 6500 K LED could be compared to an HPS lamp at a light level of 20 lx. Using the model in Equation 2, 20 lux from an HPS lighting system would be judged as 55% lower in brightness than 20 lux from the 6500 K LED. Approximately 9 lux from the LED would provide the same brightness as 20 lux from the LED. Using luminous efficacies for these sources of 96 lumens/watt for HPS and 80 lumens/watt for LED (Rea, 2013), it would be possible to achieve the same level of perceived brightness (and by extension, the same level of perceived pedestrian safety and security) with a 45% reduction in lighting energy use with the LED source compared to the HPS.

Of course, there are a number of other factors related to the use of roadway lighting, but such comparisons lend themselves readily to empirical validation and could be useful in further refining the revised provisional model described above.

6. ACKNOWLEDGMENTS

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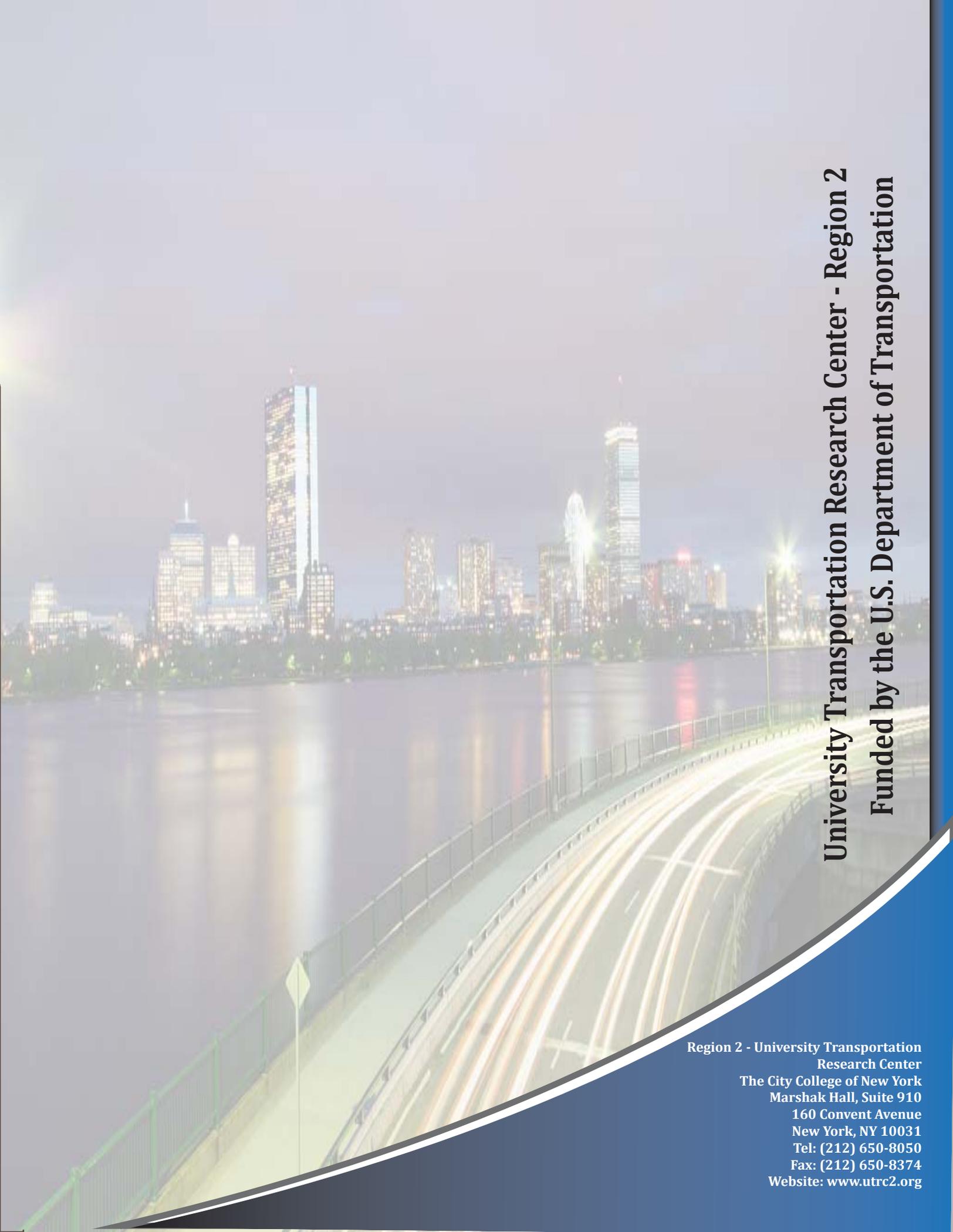
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A long-exposure photograph of a city skyline at night, reflected in a body of water. In the foreground, a bridge or highway is visible with light trails from moving vehicles. The sky is dark, and the city lights are bright and colorful.

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