Published paper

Fotios, S.A. and Cheal, C. (2011) *Predicting lamp spectrum effects at mesopic levels. Part 1: Spatial brightness*. Lighting Research and Technology, 43 (2). 143 - 157. ISSN 1477-1535

http://dx.doi.org/10.1177/1477153510393932

Predicting Lamp Spectrum Effects At Mesopic Levels
Part 1: Spatial Brightness

Steve Fotios, PhD, and Chris Cheal, PhD
University of Sheffield, School of Architecture

Fotios SA & Cheal C, Predicting Lamp Spectrum Effects At Mesopic Levels. Part 1: Spatial Brightness, Lighting Research & Technology, 2011; 43(2); 143-157.

Abstract

This article reports on experimental work carried out to test metrics for predicting spatial brightness at mesopic levels under lamps of different spectral power distribution. The side-by-side matching technique was used following an extensive review of experimental design. Five different types of lamp were presented in all ten possible pairs, these being selected to compare brightness predictions based on established characteristics of lamp spectrum such as CRI, CCT and the S/P ratio. The results were also used to test proposed systems for predicting brightness and visual performance at mesopic levels. Of the lamp characteristics examined the S/P ratio exhibited the highest correlation with the test results. The new CIE recommended system for visual performance based mesopic photometry was found to give an acceptable prediction of the brightness results.

Short title: Predicting spatial brightness at mesopic levels

1. Introduction

This article discusses lamp spectral power distribution (SPD), spatial brightness and lighting for pedestrians in residential streets. In the UK, where lighting in subsidiary streets is designed for the demands of the pedestrian, the design illuminance is specified through two documents. BS EN 13201-2:2003 [BS EN 13201-2:2003] specifies the minimum maintained average horizontal photopic illuminance for six lighting classes, the S-series, ranging from S6 = 2.0 lux to S1 = 15.0 lux. BS5489-1:2003 [BS5489-1:2003] is a code of practice and this suggests a strategy for the selection of a lighting class according to crime rate, environmental zone and traffic flow. Furthermore, it suggests a reduction of one S class (i.e. a reduced illuminance) if lamps of General Colour Rendering Index (CRI) $R_a \geq 60$ are used. CRI may be an unreliable metric upon which to base such a trade-off, giving a limited description of one aspect of a complex spectral power distribution. The limitations of CRI for describing colour rendering are well recognised [Guo & Houser 2004; van Trigt 1999], and CRI alone fails to predict the relationship between lamp type and illuminance for equal satisfaction in visual appearance at photopic levels [Boyce, 1977], so its ability to characterise the range of visual benefits of lighting at mesopic levels is doubtful. Thus CRI is not expected to provide a satisfactory means of discriminating between the brightness of lighting from different lamps (indeed it was never intended to do so) and this is more so as new lighting technologies such as LEDs start to be considered for road lighting for which it is acknowledged that CRI fails to predict even colour rendering properties [Sandor & Schanda, 2006; Szabo et al, 2009]. Thus further experimental work was carried out to identify a better means of specification.

Anecdotal evidence suggests that in residential areas there is a need for areas to appear brightly lit as people link spatial brightness with safety. Lighting makes an important contribution to making a place feel safe [Loewen et al, 1993] and the higher the perception of brightness, the greater the feeling of safety [Boyce et al, 2000]. The results from both controlled studies [Fotios & Cheal, 2007, 2010, in press; Rea et al, 2009; Rea, 1996] and field surveys [Morante 2008; Akashi et al, 2004] suggest that at mesopic light levels lamp SPD affects brightness. Light sources that provide a perception of greater brightness than others at the same photopic luminance are likely to be perceived as producing a safer environment. Alternatively, light sources that maintain the same level of brightness and perceived safety but at a reduced illuminance may lead to reductions in energy consumption.

Fotios & Cheal used three experimental procedures, category rating, side-by-side discrimination and side-by-side matching, and found that lighting from metal halide (MH) and compact fluorescent (CFL) lamps was considered brighter than from high pressure sodium lamps (HPS) of the same illuminance, and that HPS was in turn brighter than low pressure sodium (LPS) lighting [Fotios & Cheal, 2007]. These methods enabled both mixed and complete chromatic adaptation. Fotios & Cheal have subsequently found that results from the side-by-side matching and discrimination tasks hold if this simultaneous evaluation is replaced by rapid sequential evaluation [Fotios & Cheal, 2010] and if the design of the visual field is changed [Fotios & Cheal, in press].

Rea [Rea, 1996] had subjects view a coloured diorama of a landscape and used a moveable mirror to switch quickly between MH and HPS lighting. The photopic luminance of the background of the diorama provided by the MH was set to one of three levels, 0.01, 0.10 and 1.00 cd/m^2. At each luminance, sixteen subjects were asked to adjust the amount of light from the HPS source until the diorama looked equally bright when alternately lit by the two light sources. The mean photopic luminance ratios for equal brightness (MH/HPS) were 0.71, 0.71 and 0.48 at 1.00 cd/m^2, 0.10 cd/m^2, 0.01 cd/m^2, respectively.

Rea et al compared MH and HPS lighting in an outdoor environment using a discrimination task [Rea et al, 2009]. Opposite ends of a road were lit using MH and HPS lamps, and test participants located at the centre reported at which end did the street appear brighter and also at which end would they feel safer walking at night. Interpolation of the results suggested illuminance ratios (MH/HPS) of 0.79 for equal brightness and 0.66 for equal perceived safety.

Morante reports a survey of two streets in the US [Morante, 2008]. In one street, HPS lighting providing an average illuminance of 8.7 lux was replaced by QL induction lighting providing 2.7 lux. In a second street HPS lighting providing an average illuminance of 3.2 lux was replaced by MH lighting providing 3.1 lux. In each street, the two lighting installations were matched for equal mesopic luminance as defined by Unified Luminance, these being 0.17 cd/m^2 in the first street and 0.05 cd/m^2 in the second street. Surveys of residents suggested that they found that the QL and MH lighting created environments that were considered to be safer and brighter than when using HPS lighting. Akashi, Rea & Morante compared HPS street lighting with that from a 6500K fluorescent lamp [Akashi, Rea & Morante, 2004]. Lighting from the two lamps was balanced for equal mesopic luminance (0.22 cd/m^2) as defined by Unified Luminance; these were average photopic illuminances of 3.4 lux for the HPS lamp and 2.8 lux for the fluorescent lamp. Lighting under the fluorescent lamp was considered to be brighter and create an environment that was safer and more comfortable than under HPS lighting.

Boyce and Bruno also compared the brightness of lighting from MH and HPS lamps but did not find a difference [Boyce & Bruno, 1999].This study employed category rating applied to car park lighting, the brightness judgements being recorded towards the end of each 15 minute trial, and they used illuminances in the range 22 lux to 49 lux, with lamps being compared on the basis of wattage rather than illuminance. Lower illuminances were achieved by asking test subjects to wear glasses with neutral lenses of transmittance 0.1 and all observations were from within a car with a windscreen of transmittance 0.72: mean pavement luminances (incorporating the constant effect of the car windscreen and the intermittent effect of the glasses) were in the range 0.07 to 1.49 cd/m^2. Subsequent studies have offered explanations as to why the experimental procedure used in this work meant this study did not reveal a difference in brightness due to SPD [Fotios & Cheal, 2007; Rea et al, 2009].

Table 1 shows the results of trials using HPS and MH lamps in these different studies. It can be seen that illuminance ratios for equal brightness are similar across differences in evaluation mode, response task, visual field and research group. These previous data provide a comparison of the brightness of lighting from a limited range of lamps, primarily MH and HPS lamps. What is needed is a method of generalisation so that the relative brightness of lighting from other types of lamp can be predicted. This article reports further experimental work carried out to provide data with which to screen a range of potential metrics for spatial brightness at mesopic levels.

Extensive evaluation of methods for evaluating spatial brightness was carried out before the current study commenced [Fotios, Houser & Cheal, 2008; Fotios & Houser, 2009]. There are three fundamental methods for comparing different stimuli; category rating, matching and discrimination [Poulton, 1989]. Category rating tends to employ separate evaluations of stimuli while matching and discrimination are joint evaluations. Whilst joint and separate evaluations lead to different levels of chromatic adaptation, previous work suggests all three methods point towards the same judgements of relative brightness [Fotios & Cheal, 2007]. The matching and discrimination tasks can use simultaneous (side-by-side) or sequential presentation of two stimuli but this does not appear to significantly affect the outcome [Fotios & Cheal, 2010]. There is some evidence that the results of laboratory studies hold for real situations. Firstly, the results of Rea et al [Rea et al, 2009] determined from trials carried out in streets suggest a similar MH/HPS illuminance ratio for equal brightness as did tests carried out using side-by-side booths [Fotios & Cheal, 2007]. In a later study, the matching task was carried out using four different visual fields, including a flat, uniform surface and an interior space containing coloured surfaces, and the results of brightness matching using four lamp pairs did not suggest a difference between the visual fields [Fotios & Cheal, in press]. It is good practice that experimental variables are counterbalanced and that null condition trials are included to quantify the magnitude of any bias.

It is also recommended that more than one type of experimental task is used [Bartleson and Breneman, 1973] and it is not uncommon for studies of visual perception to do so, including judgements of brightness [Akashi & Boyce, 2006; Boyce, 1977; Hu et al, 2006; Vrabel et al, 1998] and glare [Osterhaus and Bailey, 1992; Pawlak and Roll, 1990; Ramasoot, 2010]. All subjective evaluations can be misleading [Poulton article; Fotios, Houser & Cheal, 2008; Fotios & Houser 2009, Fotios & Cheal, 2010]; what is important is to acknowledge the limitations of a method, the expected direction of bias, and to interpret the results with due consideration. The use of two different methods to test the same set of stimuli leads to either more confidence that the results are robust (if findings from the two methods converge) or to interesting questions of experimental design if they do not converge

2. Method

Brightness matching was carried out using the side-by-side booths shown in Figure 1. For concurrent validation of the results a brightness discrimination task was included within the procedure. Preference judgements (of skin appearance, a colour array, and the whole lit environment) were recorded to give a measure of acceptability and on-axis visual acuity was measured using low contrast Landolt rings. Results from the preference and acuity trials are reported in a separate article [Fotios & Cheal, in progress].

Five different lamps were used in these trials, as identified in Table 2 and Figure 2. These were two types of metal halide lamp (MH2, CPO), a compact fluorescent (CFL2), a standard high pressure sodium (HPS) lamp and a solid state device (LED). This LED source was not the usual white LED consisting of a blue LED with a phosphor but rather a two colour LED. The lamps were observed in all ten possible paired comparisons. Following the approach used in a previous study [Boyce, 1977] these particular lamps were chosen to enable brightness predictions from a range of lamp characteristics to be tested. A sixth type of lamp (CFL: 3729K, R_a 79) was used for null condition trials, forming an eleventh lamp pair.

Table 2 displays the values of a range of metrics that use a single index to describe the characteristics of a spectral power distribution. The values in Table 2 were derived from spectral power distributions measured from the observers view point, and are thus the lamp SPDs as modified by the test apparatus. While none of these metrics were originally intended to model brightness they have subsequently been used in such context, and if a reliable prediction were given for the effect of lamp SPD on brightness then this is of interest.

Correlated Colour Temperature (CCT) and Colour Rendering Index (CRI) are well known descriptors of the colour appearance of illumination and illuminated surfaces. Higher CCTs have more power at the short wavelength end of the spectrum and hence provide more stimulation to the rod photoreceptors; Vienot et al have proposed a model of brightness for photopic levels that uses lamp CCT to quantify the effect of lamp SPD [Vienot et al, 2009]. CRI was included in this analysis because it is the metric currently used in BS5489-1:2003 [BS5489-1:2003] to permit an illuminance reduction and so it is of interest to know how well it relates to brightness.

Gamut area was suggested in a previous study to correlate well with judgements of visual appearance of a lit scene using a matching task [Boyce, 1977] and visual appearance may be considered a proxy for brightness judgements [Fotios & Gado, 2005]. Gamut area is a measure of the colour differences between a range of coloured surfaces, with a larger gamut area implying greater saturation of surface colours, and thus that the lighting is brighter [Boyce, 1977]. Gamut area was derived from the u',v' chromaticity coordinates of the eight colour samples used in the CIE General Colour Rendering Index: Gamut Area Index (GAI) is gamut area scaled so that GAI = 100 for the equal energy spectrum [Rea and Freyssinier-Nova, 2008].

The S/P ratio is the ratio of the photopic (P) and scotopic (S) luminances of a source; it correlates with the performance of some visual tasks at mesopic levels and is the basis of the new CIE system of mesopic photometry [CIE 2010]. If the CIE system is adopted as the basis for characterising road lighting at night time then its ability to predict brightness is of interest. The S/P ratio has previously been proposed as a metric for brightness at photopic levels [Berman et al, 1990].

The short wavelength sensitive cones (SWS) were suggested in an earlier study to predict brightness at photopic levels [Fotios & Levermore, 1998], using the SWS/P ratio as an alternative to the S/P ratio, and in a recent study it was suggested that mesopic brightness can be modelled by the sum of V(λ) and the SWS cone response [Rea, Radetsky & Bullough, in press]. For a given illuminance, higher values of SWS/P ratio would therefore suggest brighter lighting. The SWS cone response was determined according to the Smith & Pokorny cone fundamentals [Smith & Pokorny, 1975]. Values were taken from the database hosted by the Colour & Vision Research laboratory which is based at the Institute of Ophthalmology, part of University College London [UCL]. For confirmation, these values were checked against those reported by others [Kaiser & Boynton, 1996].

A reference illuminance of 5.0 lux was used for these trials, measured at the centre of the floor of each booth. In previous work [Fotios & Cheal, 2007, 2010; in press] a reference of illuminance of 7.5 lux was used, this being in the middle of the range of S-series of lighting classes for subsidiary streets [BS5489-1:2003]. There is however a proposal in the UK to guide against using the highest class, 15 lux, reducing the range to 2.0 to 10.0 lux, and the 5.0 reference illuminance is thus the middle of this range. Results from previous work did not suggest any difference between illuminance ratios for equal brightness evaluated at 2.0, 7.5 and 15.0 lux [Fotios & Cheal, 2007], nor between luminances of 0.1 and 1.0 cd/m^2 [Rea, 1996], so the change from 7.5 lux to 5.0 lux is not expected to have a significant effect on the test results.

The viewing chamber of each booth was of approximate dimensions 575mm deep x 680mm wide x 660mm high, hence each booth presents a visual field of 38° wide by 37° high from the seated viewing distance of one metre in front of the central partition. This size is close to the horizontal band of 40° suggested to be the primary field of view [Loe et al, 1994]. The interior surfaces were painted matt grey (Munsell N5) and contained coloured objects, these being four pyramids 60mm high, one each made from red, green, yellow and blue card. These abstract objects were included to retain consistency with previous a brightness matching study [Fotios & Cheal, 2007 brightness] and it has been found that the mean illuminance ratio at equal brightness is not significantly affected if the objects are removed or replaced with coloured surfaces [Fotios & Cheal, in press 2010].

The test lamps were fitted behind the booths. Light was conveyed into the top of the booth through an internally reflective pipe of diameter 190mm. The illuminance in a booth was adjusted by a rotary control connected to an iris in the pipe, enabling the illuminance to be varied without affecting the spectral power distribution or spatial distribution of light. The rotary controller had three 360-degree turns from minimum to maximum to reduce the chance of a positional cue. A translucent diffuser was placed above the visible chamber of the booths to further reduce differences in spatial distribution of light between stimuli. Surface luminances were measured at 14 points in each booth to assess the stability of the relative luminance distribution between different combinations lamp and illuminance setting and between the two booths. The mean ratio of luminances at the 14 corresponding points in the two booths (left/right) when lit using the same lamp is 0.997 (SD=0.016), with a maximum departure from unity of 0.03, which suggests that differences between the left- and right-hand cabinets are not significant in the determination of luminance distribution. No significant differences in luminance distribution were found between changes in light source and position of the iris. The mean luminance of the stimulus at 5.0 lux was 0.25 cd/m^2.

For brightness matching, one booth was presented at the reference illuminance and the illuminance of the second booth was adjusted by the participant until the two appeared, as near as possible, equally bright. Spatial brightness was described simply as the amount of light in the whole scene which could be judged independently from any other visual differences such as colour. Each test participant provided four brightness matches for each lamp pair, counterbalancing both the initial illuminance of the variable stimulus (set by the experimenter to an illuminance clearly higher or lower than the reference) and application of dimming to both sources, and these four trials were attempted in a random order. The left-right location of stimuli was counterbalanced between subjects.

Brightness discrimination was carried out with both booths set to the reference illuminance, 5.0 lux. The test participant was asked to state which booth was brighter, a forced-choice procedure with the equally bright response option not permitted. The left-right location of stimuli was counterbalanced between subjects.

Preference was judged by appraisal of three items: preferred skin appearance, whilst the test participant had one hand placed into each booth; preferred appearance of colours on the Macbeth Colour Checker Chart; and preferred appearance of the booths in the context of night-time lighting of outdoor spaces (observed without the presence of hands or the colour chart). These preference judgements were recorded on two occasions, firstly at equal illuminance, with both booths set to the reference illuminance (5.0 lux) and secondly at equal brightness, this being the final one of the four brightness matches set by the test participant. The preference judgements were forced choice and the left-right location of stimuli was counterbalanced between subjects. On-axis visual performance was examined using low and high contrast Landolt-ring acuity charts. The methods and results of the preference and acuity trials are reported in a separate article [Fotios & Cheal, in progress].

Tests with each participant were completed in three two-hour sessions. The room lighting for the initial ten minutes of a test session was from a fluorescent (warm white) table lamp which indirectly lit the room and from the first lamp pair in the side-by-side booths; all surfaces visible to the test participant had luminances below 3 cd/m^2. In this time the participant was given instructions for the test procedure. The table lamp was then switched off for a further ten minutes of adaptation. For a given lamp pair the test procedure was:

(1) Preference judgements and brightness discrimination at equal illuminances (5.0 lux);
(2) Brightness matching, with the four procedural variations carried out in a random order;
(3) With the illuminance setting of the test participant's final match, the three preference judgements were then repeated at equal brightness, and;
(4) Visual acuity was examined using the low-contrast and high-contrast charts presented in one booth with an illuminance of 5.0 lux, the other booth being fully dimmed.

The same procedure was used for all ten lamp pairs and the null condition pair (except that the acuity test was not carried out with the null condition), and these lamp pairs were presented in an order that was balanced between participants.

Thirty eight test participants were used, this number chosen to meet the demands of the variance stable rank sums method for analysing data from the discrimination and preference judgements [Dunn-Rankin et al, 2004]. All subjects were confirmed as having colour-normal vision using the Ishihara test. Fourteen test participants were male and 24 were female; 21 were young (aged 18-34), 14 were in the 35-54 age group, and three were older than 55 years.

3. Results

3.1 Null condition results

The brightness matching task was carried out with the same type of lamp (CFL) in both booths. Table 3 shows the results, formatted to analyse for experimental bias: in the absence of experimental bias the mean illuminance ratios would be unity, and departure from unity was tested using the *t*-test. The ratio of the illuminances of the left-hand and right-hand booths at equal brightness is close to unity; the t-test does not suggest a departure from unity and thus negligible bias between the left-hand and right-hand booths. The ratio of the illuminances of the variable and fixed stimuli at equal brightness is also unity, which indicates negligible conservative adjustment bias. The two lamps used in null condition trials were nominally labelled CFL_A and CFL_B. The mean illuminance ratio of these at equal brightness does not depart from unity.

The brightness discrimination judgements were carried out with the same type of lamp (CFL) and illuminance (5.0 lux) in both booths. Of the 38 test participants, 15 identified CFL_A to be brighter and 23 identified CFL_B: the binomial test does not suggest differences between the lamps are significant. The left-hand booth was reported to be brighter by 22 test participants and 16 the right hand booth: the binomial test does not suggest differences between the booths are significant.

Null condition data from the matching and discrimination tests suggest that any differences between the booths other than lamp type were negligible. In any case, the experimental design took the precaution of counterbalancing stimulus location, dimming application and dimming direction.

3.2 Results: brightness matching

The brightness matching results are shown in Table 4. Each test participant carried out four matching trials per lamp pair to counterbalance the application of dimming and the initial setting (high/low) of the variable stimulus. The mean of these four trials was used to provide the best estimate of illuminance ratio per subject. The data in Table 5 are the mean illuminance ratios at equal brightness across the 38 subjects.

The t-test was used to determine whether these ratios were a significant departure from unity. HPS lighting needed a significantly higher illuminance than the other four test lamps for equal brightness ($p<0.01$); the CPO lamp required significantly higher illuminance than the LED, MH2 and CFL lamps for equal brightness ($p<0.01$). These results suggest that the MH2, CFL and LED lamps are equally bright; that these three lamps are brighter than the CPO lamp and that this in turn is brighter than the HPS lamp.

A previous brightness matching test also used the MH2/HPS lamp combination and this reported a mean illuminance ratio of 0.724 (sd.=0.186, n=21, 7.5 lux reference) at equal brightness [Fotios & Cheal, 2007]. Although this is a greater departure from unity than found in the current study (0.78) the *t*-test does not suggest the difference to be statistically significant.

3.3 Results: brightness discrimination

The brightness discrimination results are shown in Table 5. These data are the percentage of judgements for each of a pair of stimuli when presented at equal illuminance. Differences between the lamps were analysed using variance stable rank sums [Dunn-Rankin et al, 2004]. This analysis does not suggest any difference in brightness between the CFL2, MH2 and LED lamps but that these are significantly brighter than the CPO lamp ($p<0.05$) and that all four are brighter than the HPS ($p<0.05$). Conclusions as to the difference in brightness between lamps in the discrimination test match those gained for differences in illuminance at equal brightness in the matching test, other than for the CFL2/LED lamp pair. Thus the results of the discrimination test provide validation of the data gained using the matching test.

The brightness discrimination trial was designed with the intent of analysing the results using Variance Stable Rank Sums (VSRS) [Dunn-Rankin et al, 2004]. We chose this statistical test because it was previously applied to discrimination data in the Quellman and Boyce study of preferred skin appearance [Quellman and Boyce, 2002] and because the type of data matches that described for use with VSRS [Dunn-Rankin et al, 2004]. The conclusions drawn from analysis using VSRS were subsequently confirmed using multiple applications of the binomial test.

The results of the brightness tests show that some lamps were considered to be brighter than HPS, and this suggests the illuminance of street lighting using these sources could be reduced whilst maintaining the same level of brightness. However, results of the preference judgements suggest caution [Fotios & Cheal, in progress]. When used at a reduced illuminance such that it was equally bright as the HPS, the appearance of hands and colours under the LED lamp were considered poorer than under the HPS, whereas the MH2 lamp would still offer better skin and colour appearance than under the HPS lamp.

4. Predicting Brightness

Table 6 compares the rank order of brightness with the rank order of lamps according to their characteristics. The brightness order is as estimated from the results of the brightness matching tests. It is clear that the HPS lamp was the least bright, the CPO lamp was the next least bright, and that there is little difference between the LED, CFL2 and MH2 lamps. An estimate of rank order of brightness was determined by comparing the mean illuminance ratios at equal brightness for each lamp in comparison with the four other lamps, as shown in Table 7. This is according to mean of the 152 (4 lamp pairs x 38 subjects) illuminance ratios for each lamp, where each of the 152 ratios is the mean of one person's four matches for a particular lamp pair.

All five characteristics of lamp spectrum (CCT, CRI, GAI, S/P, and SWS/P) correctly predicted that the HPS lamp would be the least bright. The LED lamp was found in tests to be the brightest but only the S/P ratio correctly predicts this, while CRI, gamut area and SWS/P all predicted it to be less bright than the MH2, CFL2 and CPO lamps. CCT predicts the CFL2 lamp to be brighter than the LED but the test results suggest the LED to be brighter than CFL2 ($p<0.05$). CRI, the criterion used to indicate an illuminance reduction in BS5489-1:2003, suggests an incorrect order of lamp brightness other than for the HPS being the dimmest source. Only the S/P ratio correctly predicts the rank order of brightness.

Figure 3 shows linear regression between the test results (illuminance ratios at equal brightness) and ratios of lamp characteristics. The S/P ratio provides the highest correlation (r^2= 0.83); the SWS/P ratio and gamut area index provide the lowest correlation.

This analysis suggests the S/P ratio gives a prediction of spatial brightness at mesopic levels under lighting of different SPD that is more precise than does CCT, CRI, gamut area and the SWS/P ratio.

5. Brightness Models

Three studies have previously reported models developed to fit data from brightness matching studies [Palmer, 1968; Kokoschka & Bodmann, 1975; Sagawa, 2006]. These used on-axis fields of size 3° to 64°, at mesopic luminances, and matched monochromatic lights from across the range of the visible spectrum to a single reference source. The input data for Palmer's model are 10° photopic luminance, $V_{10}(\lambda)$, and scotopic luminance, $V'(\lambda)$. The input values for Kokoschka & Bodmann's model are $V_{10}(\lambda)$, $V'(\lambda)$ and the 10° tristimulus values (X_{10}, Y_{10}, Z_{10}). The input data for Sagawa's model are 2° photopic luminance, $V(\lambda)$, $V'(\lambda)$, and a colour correction defined using the 10° tristimulus values [Fotios & Cheal, 2009 correction].

Rea, Radetsky and Bullough recently proposed a new brightness function, *B(λ)*, a summation of the photopic and SWS cone responses (equation 1) [Rea, Radetsky and Bullough, in press]. In Equation 1, *g* is a constant and is suggested to have a value of around 1.5 at a photopic illuminance of 2 lux, which is close to the reference illuminance (5.0 lux) of the current study.

$$B(\lambda) = V(\lambda) + g.SWS(\lambda) \qquad \text{(Equation 1)}$$

The CIE have published a new visual efficiency function for mesopic vision [CIE 2010] which is a function of the adaptation luminance and the S/P ratio of the light source. Whilst this function was developed from visual performance data (e.g. reaction time to peripheral targets) and is thus strictly only applicable to such situations, once it is approved it will likely be used to characterise vision in all situations. It is therefore of interest to see how well it predicts brightness.

Figure 4 shows linear regression between the test results (mean illuminance ratios at equal brightness) and ratios of brightness values of the lamps as predicted by the five models, these values being determined for an adaptation luminance of 0.25 cd/m^2. The models of Palmer, Kokoschka and Bodmann, and Sagawa exhibit the highest correlation with the test data, having R^2 values of 0.88, 0.92 and 0.89 respectively. The CIE mesopic system makes predictions that correlate only slightly less with the test results than do these (R^2 = 0.86). The model defined by Equation 1 and using the SWS cone response has a relatively poor correlation with the test results (R^2 = 0.05). Bearing in mind the likely international adoption of the CIE system of mesopic photometry, and that it provides correlation with brightness results only slightly below that found using brightness models, it is practical to promote this as a means of predicting brightness under lighting of different SPD at mesopic levels.

6. Conclusion

These results demonstrate that lamp SPD does affect spatial brightness at mesopic levels. When observed at equal brightnesses, lighting from lamps of different SPD may appear significantly different in brightness, or alternatively may require significantly different illuminances for equal brightness. The S/P ratio provides a reasonably precise prediction of relative brightness under lighting of different SPD (R^2 = 0.83). Mesopic luminances predicted by the CIE recommended system of mesopic photometry also correlate well with the test results, exhibiting a correlation only slightly less than that of three proposed brightness models. Given that the CIE system is likely to be internationally adopted this is recommended as a suitable tool for predicting mesopic brightness.

References

Akashi Y & Boyce PR, A field study of illuminance reduction, Energy & Buildings, 2006; 38(6); 588-599

Akashi Y, Rea M & Morante P. Progress Report: Improving acceptance and use of energy-efficient lighting. Unified photometry: An energy-efficient street lighting demonstration in Easthampton, Massachusetts. Lighting Research Center, 2004

Bartleson CJ, Breneman EJ, Differences among responses of observers in scaling brightness, Die Farbe, 1973; 22; 200-212

Berman SM, Jewett DL, Fein G, Saika G & Ashford F, Photopic luminance does not always predict perceived room brightness, Lighting Research & Technology 1990; 22(1); 37-41

British Standards Institution (BSI) BS EN 13201-2:2003, Road lighting - Part 2: Performance requirements, London: BSI, 2003

British Standards Institution (BSI) BS5489-1:2003, Code of practice for the design of road lighting —Part 1: Lighting of roads and public amenity areas, London: BSI, 2003

Boyce PR, Eklund NH, Hamilton BJ & Bruno LD, Perceptions of safety at night in different lighting conditions, Lighting Research & Technology, 2000; 32; 79-91

Boyce PR & Bruno LD, An evaluation of high pressure sodium and metal halide light sources for parking lot lighting, Journal of the Illuminating Engineering Society, 1999; 28; 16-32.

Boyce PR, Investigations of the subjective balance between illuminance and lamp colour properties, Lighting Research and Technology, 1977; 9; 11-24

Commission Internationale de l'Éclairage, *Recommended system for visual performance based mesopic photometry*, CIE publication 191, Vienna: CIE, 2010

Dunn-Rankin P, Knezek GA, Wallace S & Zhang S, Scaling methods. 2nd Edition, 2004; Lawrence Erlbaum Associates, Mahwah, New Jersey.

Fotios SA & Cheal C, Lighting for subsidiary streets: investigation of lamps of different SPD. Part 2 – Brightness, Lighting Research & Technology, 2007; 39(3); 233-252

Fotios S & Cheal C, Correspondence. Correction: Lighting for subsidiary streets: Investigation of lamps of different SPD. Part 2 – Brightness, Lighting Research & Technology, 2009; 41(4); 381-383

Fotios SA & Cheal C, A Comparison of Simultaneous and Sequential Brightness Judgements. Lighting Research & Technology, 2010; 42(2); 183-197

Fotios SA & Cheal C, Brightness Matching With Visual Fields Of Different Types, Lighting Research & Technology, in press doi:10.1177/1477153510369478

Fotios S and Cheal C, Predicting Lamp Spectrum Effects At Mesopic Levels, Part 2: Preferred Appearance and Visual Acuity. Lighting Research & Technology, 2011; 43(2); 159-172.

Fotios S & Gado T, A comparison of visual objectives used in side-by-side matching tests, Lighting Research & Technology, 2005; 37(2); 117-131

Fotios SA & Houser KW, Research Methods to Avoid Bias in Categorical Ratings of Brightness, Leukos, 2009; 5(3); 167-181

Fotios SA, Houser KW, & Cheal C, Counterbalancing needed to avoid bias in side-by-side brightness matching tasks, Leukos, 2008; 4(4); 207-223

Guo X and Houser KW, A review of colour rendering indices and their application to commercial light sources, Lighting Research & Technology, 2004; 36(3); 183-199

Fotios SA & Levermore GJ, Chromatic effect on apparent brightness in interior spaces, II: SWS lumens model, Lighting Research & Technology, 1998; 30(3); 103-106

Hu X, Houser KW & Tiller DK, Higher colour temperature lamps may not appear brighter, Leukos, 2006; 3(1) 69-81

Kaiser PK, Boynton RM. Human Color Vision. 2nd ed. Washington DC: Optical Society of America; 1996. p 558.

Kokoschka S, Bodmann HW, A consistent system for the photometric evaluation of radiation over the whole range of adaptation. Proceedings: 18th session, London. CIE publication #36, 1975, 217-25.

Loe DL, Mansfield KP & Rowlands E, Appearance of lit environment and its relevance in lighting design: Experimental study, Lighting Research & Technology, 1994; 26(3); 119-133

Loewen LJ Steel GD & Suedfeld P. Perceived safety from crime in the urban environment, Journal of Environmental Psychology, 1993; 13; 323-33

Morante P. mesopic street lighting demonstration and evaluation. Final Report for Groton Utilities, Groton, Connecticut. Lighting Research Center. 2008.

Osterhaus WKE and Bailey IL, Large area glare sources and their effect on discomfort and visual performance at computer workstations, IEEE Industry Applications Society Annual Meeting, 1992, October 4-9, Houston, Texas.

Palmer DA, Standard observer for large-field photometry at any level. Journal of the Optical Society of America, 1968; 58; 1296-1299

Pawlak, U. and K.-F. Roll (1990). VDTs: Setting Levels for Reflected Luminance. Siemens Review, (4): p.27-29.

Poulton EC. 1989. Bias in quantifying judgements. London: Lawrence Erlbaum Associates Ltd.

Poulton EC, Quantitative subjective assessments are almost always biased, sometimes completely misleading, British Journal of Psychology, 68, 409-425 (1977)

Quellman EM, Boyce PB, The light source color preferences of people of different skin tones. Journal of the Illuminating Engineering Society, Winter 2002; 31(1); 109-118.

Ramasoot T, Investigation of Lighting and Disturbing Reflections on Display Screens: A New Model for Judging Acceptability, PhD thesis, University of Sheffield, UK, 2010

Rea MS, Essay by invitation, Lighting Design and Application; October, 1996, pp. 15-16.

Rea MS, Bullough JD & Akashi Y, Several views of metal halide and high pressure sodium lighting for outdoor applications, Lighting Research & Technology, 2009; 41(4); 297-320

Rea M S and Freyssinier-Nova J P. Color rendering: A tale of two metrics. Color Research and Application 2008; 33(3); 192-202

Rea MS, Radetsky LC & Bullough JD. Toward a Model of Outdoor Lighting Scene Brightness. Lighting Research & Technology, in press, doi:10.1177/1477153510370821

Sandor N and Schanda J, Visual colour rendering based on colour difference evaluations, Lighting Research & Technology 2006; 38(3); 225-236

Sagawa K, Toward a CIE supplementary system of photometry: brightness at any level including mesopic vision, Ophthalmic and Physiological Optics, 2006; 26; 240-245.

Smith V, Pokorny J. Spectral sensitivity of the foveal cone photopigments between 400 and 500 nm. Vision Research 1975; 15: 161-171.

Szabo F, Bodrogi P and Schanda J, A colour harmony rendering index based on predictions of colour harmony impression, Lighting Research & Technology 2009; 41(2); 165-179

van Trigt C, Color rendering, a reassessment, Color Research & Application, 1999; 24(3) 197-206

Vienot F, Durand M-L and Mahler E, Kruithof 's rule revisited using LED illumination, Journal of Modern Optics 2009; 56(13); 1433-1446

Vrabel PL, Bernecker CA & Mistrick RG, Visual performance & visual clarity under electric light sources: Part II - Visual Clarity, Journal of the Illuminating Engineering Society 27(1) 29-41 (1998)

Cone fundamental database hosted by the Colour & Vision Research laboratory, Institute of Ophthalmology, University College London. http://www-cvrl.ucsd.edu/cones.htm. Retrieved 07/07/2010.

Acknowledgement
This work was carried out with support from EPSRC, grant reference EP/F035624/1. Lamps and luminaires were supplied by Philips Lighting, Lemnis Lighting and Urbis Lighting; the side-by-side booths were procured through a CIE-UK grant.

Study	Evaluation mode and response task	Field	Reference level	MH/HPS illuminance ratio for equal brightness
Fotios & Cheal (2007)	Simultaneous matching	Side-by-side 40° booths; achromatic surfaces + coloured objects	7.5 lux	0.73
Fotios & Cheal (2007)	Simultaneous discrimination	Side-by-side 40° booths; achromatic surfaces + coloured objects	7.5 lux	0.68
Fotios & Cheal (2010)	Sequential matching	Single 40° booth; achromatic surfaces + coloured objects	7.5 lux	0.74
Fotios & Cheal (2010)	Sequential discrimination	Single 40° booth; achromatic surfaces + coloured objects	7.5 lux	0.69
Fotios & Cheal, (in press)	Simultaneous matching	Side-by-side 40° booths; range of field designs;	7.5 lux	0.79
Rea (1996)	Sequential matching	Single booth;	0.1 and 1.0 cd/m^2	0.71
Rea, Bullough & Akashi (2009)	Sequential discrimination	Full field – real street;	5.0 to 30 lux	0.79 (0.66 for equal perceived safety)

Table 1. Results of brightness judgements at mesopic levels comparing MH and HPS lamps. Note that the MH lamps used in different studies may have different SPD.

Lamp	CCT (K)	CRI (R_a)	Gamut Area Index	SWS/P	S/P
HPS	1855	4.6	6.7	0.048	0.48
MH2	3581	94.6	70.7	0.315	1.66
CFL2	5550	71.7	81.4	0.472	1.86
CPO	2953	70.8	44.2	0.204	1.25
LED	5022	30.2	20.1	0.144	2.80

Table 2. Description of the lamps used in brightness assessments. All properties derived from SPD measured from observer's view of test apparatus.

Illuminance ratio	Left/Right	Variable/Fixed	CFL_B/CFL_A
Mean	0.997	0.990	1.01
Std dev	0.066	0.047	0.064
n	38	38	38
Departure from unity (*t*-test)	n.s.	n.s.	n.s.

Table 3. Results of brightness matching null-condition tests. (n.s. = not significant, p>0.05).

Lamp pair	**CPO/ HPS**	**MH2/ HPS**	**LED/ HPS**	**CFL2 /HPS**	**MH2/ CPO**	**LED/ CPO**	**CFL2 /CPO**	**LED/ MH2**	**CFL2 /MH2**	**CFL2 /LED**
Mean illuminance ratio	0.84	0.78	0.75	0.78	0.94	0.86	0.91	0.97	0.99	1.06
Std. Dev.	0.15	0.15	0.15	0.15	0.10	0.14	0.09	0.18	0.10	0.14
n	38	38	38	38	38	38	38	38	38	38
Departure from unity (*t*-test)	p<0.01	p<0.01	p<0.01	p<0.01	p<0.01	p<0.01	p<0.01	n.s	n.s.	p<0.05

Table 4. Results of the brightness matching tests: mean illuminance ratios at equal brightness.

Lamp pair (A/B)	CPO/ HPS	MH2/ HPS	LED/ HPS	CFL2 /HPS	MH2/ CPO	LED/ CPO	CFL2 /CPO	LED/ MH2	CFL2 /MH2	CFL2 /LED
Lamp A is brighter (%)	95	97	100	95	84	84	84	68	61	58
Lamp B is brighter (%)	5	3	0	5	16	16	16	32	39	42
n	38	38	38	38	38	38	38	38	38	38
difference in brightness	p<0.05	p<0.05	p<0.05	p<0.05	p<0.05	p<0.05	p<0.05	n.s	n.s	n.s

Table 5. Results of brightness discrimination tests: percentage of judgements for each of a pair of stimuli when presented at equal illuminance (n=38 for all lamp pairs)

Brightness (test results)	CCT (K)	CRI (R_a)	Gamut Area Index	SWS/P	S/P
LED	CFL2	MH2	CFL2	CFL2	LED
CFL2	LED	CFL2	MH2	MH2	CFL2
MH2	MH2	CPO	CPO	CPO	MH2
CPO	CPO	LED	LED	LED	CPO
HPS	HPS	HPS	HPS	HPS	HPS

Table 6. Rank order of the five test lamps according to the brightness results and according to characteristic derived from their SPD.

	Illuminance ratio at equal brightness (lamp/all 4 other lamps)				
	HPS	**CPO**	**MH2**	**CFL2**	**LED**
mean	1.37	1.08	0.96	0.94	0.89
std. dev.	0.26	0.21	0.19	0.16	0.18
n	152	152	152	152	152

Table 7. Mean illuminance ratios at equal brightness (lamp/all four other lamps).

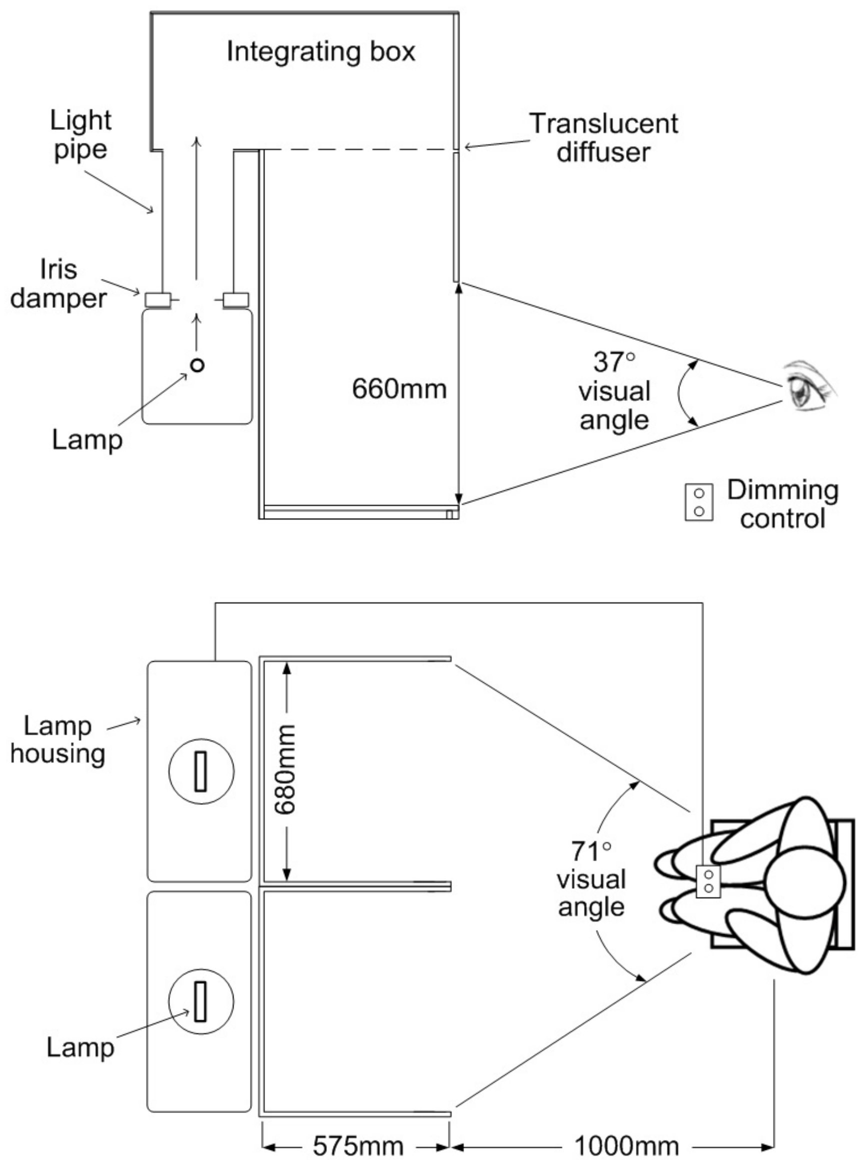

Figure 1

Vertical and horizontal sections through the side-by-side booths used in brightness ranking and brightness matching tests.

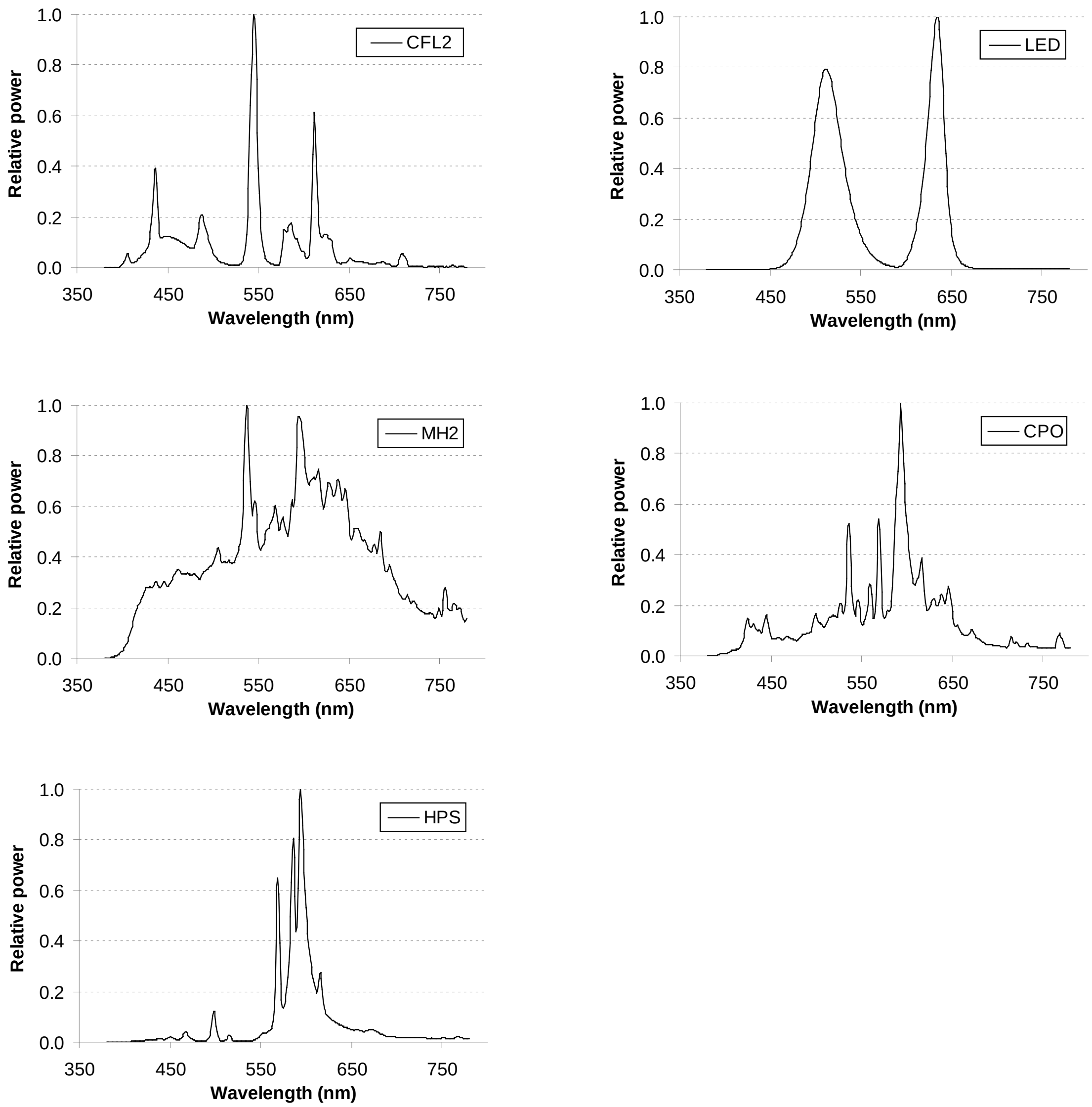

Figure 2

Spectral power distributions of the test lamps. These are as measured from the observers view point and hence include modification by the test apparatus, and are normalised for a peak response of 1.0.

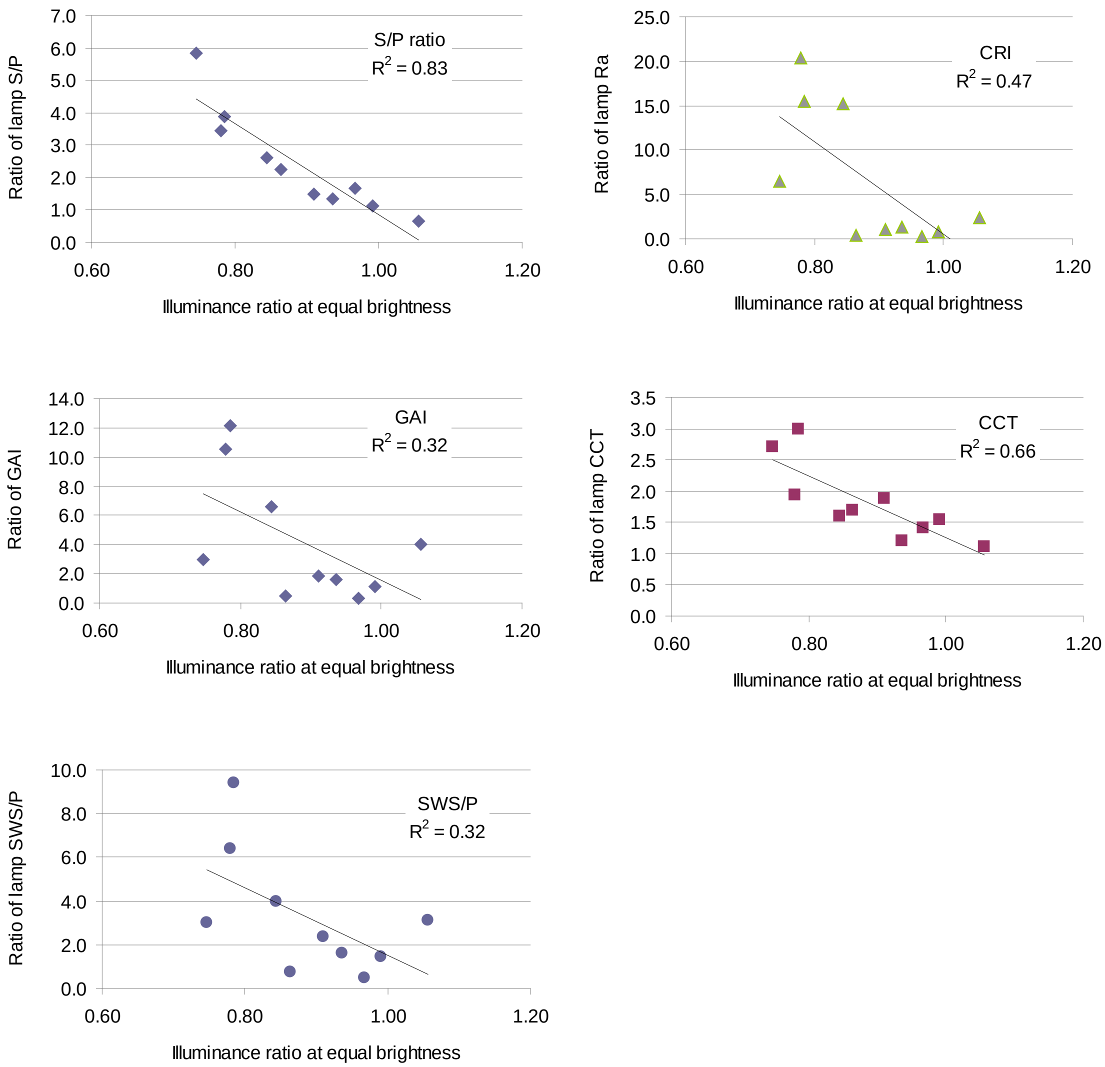

Figure 3.

Test results (mean illuminance ratios at equal brightness) plotted against brightness predictions (ratios of lamp characteristics).

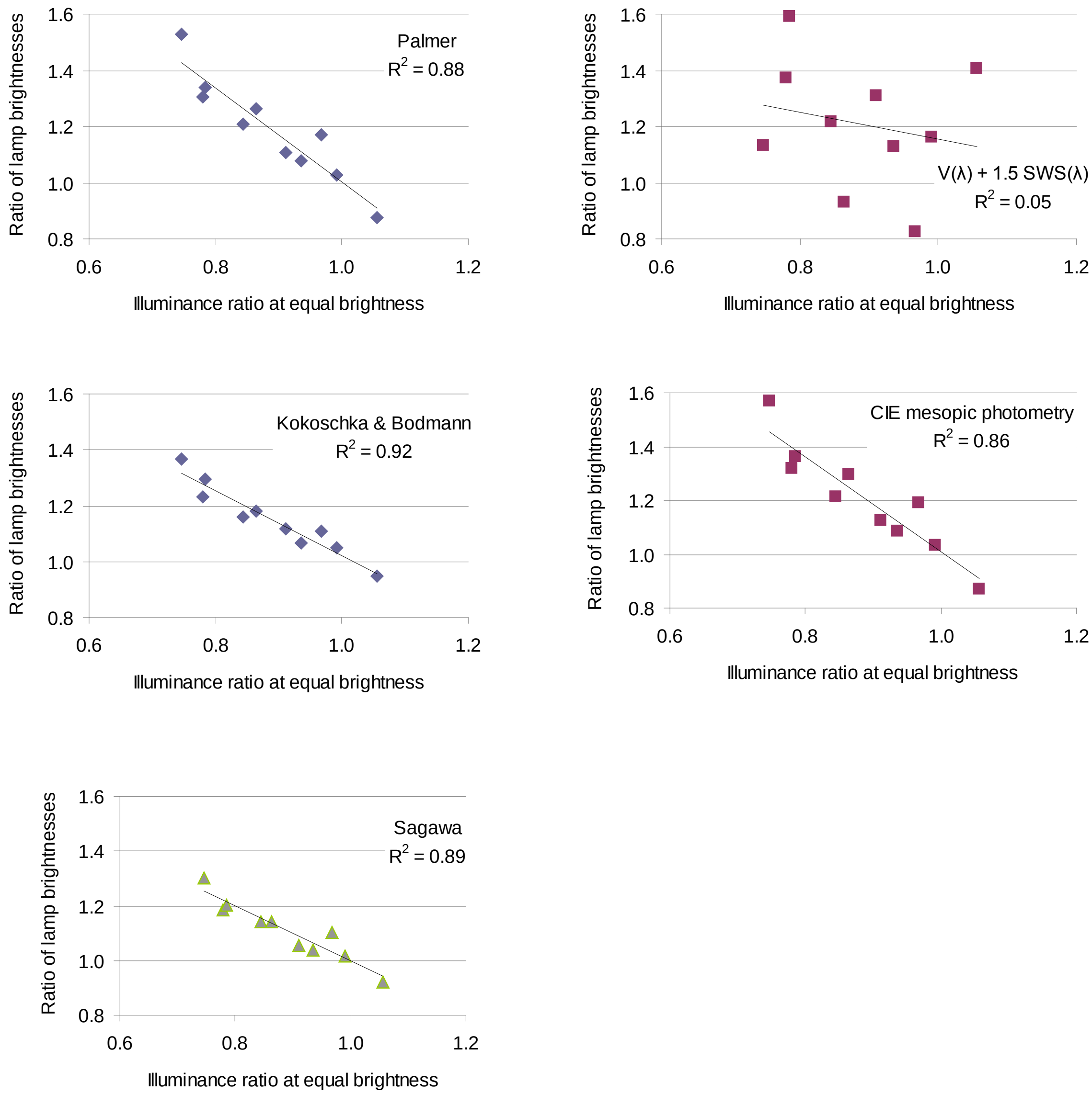

Figure 4. Test results (mean illuminance ratios at equal brightness) plotted against brightness predictions (ratios of brightness model outputs).