Published paper

Fotios, S. and Cheal, C. (2010) *Road lighting for pedestrians in residential areas: choosing the optimum lamp colour characteristics*. Light & Engineering, 18 (1). 91 - 100. ISSN 0236-2945

ROAD LIGHTING FOR PEDESTRIANS IN RESIDENTIAL AREAS: CHOOSING THE OPTIMUM LAMP COLOUR CHARACTERISTICS

Fotios, Steve and Cheal, Chris

University of Sheffield, UK

ABSTRACT

This article examines lamp spectral power distribution and how this can affect lighting for pedestrians at night-time. The results of brightness and obstacle detection tests are presented and compared with predictions made using models of mesopic visual efficiency.

Keywords: residential streets, spectral power distribution, illuminance, mesopic vision

1. INTRODUCTION

In recent years a large amount of work has been devoted to investigating how light source spectral power distribution (SPD) affects vision at mesopic levels to enable better characterisation of night-time lighting. This article considers lighting in residential streets where lighting tends to target primarily the needs of pedestrians. The findings from studies of brightness, obstacle detection and facial recognition, and attempts to predict the relationship between lamp spectrum and illuminance for these tasks are discussed. These findings are discussed within the context of British Standard BS5489-1:2003 which permits the design illuminance to be reduced when using lamps of general colour rendering index $R_a \geq 60$ [BS5489-1:2003].

2. LIGHTING FOR PEDESTRIANS

Lighting is needed to provide a street which is safe for people to use and which is also perceived to be safe.

In residential areas there is a need for areas to appear brightly lit as people link brightness with safety. Empirical data show that lighting makes an important contribution to making a place feel safe [Loewen, Steel & Suedfeld, 1993] and higher illuminance levels increase ratings of perceived safety [Boyce et al, 2000]. Further perceptual factors include visual comfort, which may be defined as a pleasant environment and the absence of glare.

Factors contributing to safe movement are the ability to detect obstacles on the pavement which may otherwise be a trip hazard, visual orientation, and the ability to recognise the faces of other people at a distance sufficient to take avoiding action if necessary.

3. BRIGHTNESS

3.1 Experimental data

There are results from four studies giving evidence that lamp SPD can affect spatial brightness at mesopic levels [Fotios & Cheal, 2007a; Fotios & Cheal in progress; Rea, 1996; Rea, Bullough & Akashi, in press].

Two series of tests used simultaneous evaluation of lamps in side-by-side booths [Fotios & Cheal, 2007a]. These studies used a high pressure sodium lamp (HPS) as the reference, and compared this with a compact fluorescent (CFL) and two types of metal halide lamp (MH1, MH2). In the matching task, one booth was set to one of three reference illuminances (2.0, 7.5 and 15.0 lux) and test participants adjusted the illuminance of the second booth until it appeared as-near-as-possible equally bright. The procedure was designed to counterbalance experimental error due to dimming application, dimming direction and positional bias [Fotios, Houser & Cheal, 2008] and a null condition was included to evaluate the magnitude of any such bias. The results from twenty one observers are shown in Table 1. The illuminance ratios depart significantly from unity, suggesting that lamp SPD has affected the brightness judgement.

Reference illuminance (lux)	**Mean illuminance ratio**		
	CFL/ HPS	**MH1/ HPS**	**MH2/ HPS**
2.0	0.694	0.729	0.679
7.5	0.718	0.733	0.724
15.0	0.732	0.724	0.738

Table 1. Results of brightness matching tests; mean illuminance ratios at equal brightness [Fotios & Cheal, 2007a].

Brightness discrimination was carried out by setting the illuminance of one booth to one of the three reference illuminances (2.0, 7.5 and 15.0 lux) and presenting the second stimulus at a range of illuminances above and below this reference [Fotios & Cheal, 2007a]. The 21 test participants identified which booth appeared brighter. When presented at equal illuminances, the CFL, MH1 and MH2 lamps were significantly brighter than the HPS lamp; when presented at an illuminance reduced by one class of the S-series [BS EN 13201-2:2003] the CFL, MH1 and MH2 lamps were not different in brightness to the HPS lamp at the reference illuminance. Using the four-parameter logistic equation to determine the illuminance ratio giving equal judgements yields the illuminance ratios shown in Table 2. Other than for the CFL/HPS lamp pair at 2.0 lux, these ratios depart slightly further from unity than do the brightness matching results (Table 1).

Reference illuminance (lux)	Illuminance ratio CFL/ HPS	MH1/ HPS	MH2/ HPS
2.0	0.71	0.64	0.67
7.5	0.59	0.68	0.64
15.0	0.65	0.66	0.65

Table 2. Illuminance ratios for equal brightness as determined from brightness discrimination judgements [Fotios & Cheal, 2007a]

We have carried out a further brightness matching trial to investigate how the illuminance ratio is affected by design of the visual field [Fotios & Cheal, article in progress]. This study also used side-by-side booths and similar lamps to the previous brightness matching study; the main differences were that only one reference illuminance was used (7.5 lux), and the MH1 lamp was used as the reference stimulus. The results are shown in Table 3. The mean illuminance ratios at equal brightness are again significantly different to unity.

Reference illuminance (lux)	Mean illuminance ratio HPS/ MH1	CFL/ MH1	MH3 /MH1
7.5	1.263	0.904	0.916

Table 3. Mean illuminance ratios at equal brightness determined from *field design* experiment [Fotios & Cheal, article in progress]

Rea used a matching task but with sequential rather than simultaneous presentation of two stimuli, HPS and MH lamps. This was a laboratory trial where subjects adjusted the illuminance on a scale model scene from the HPS source until it matched the brightness of the same scene illuminated by an MH source [Rea, 1996]. The MH lighting was set to three reference luminances, i.e. 0.01, 0.10 and 1.00 cd/m^2. The corresponding mean MH/HPS luminance ratios needed for equal brightness were 0.48, 0.71, and 0.71 (whereupon HPS luminances were 0.02, 0.14 and 1.41 cd/m^2 respectively).

Two further studies have used methods permitting full field stimulation of the retina. Fotios & Cheal [Fotios & Cheal, 2007a] used the same set of lamps (HPS, CFL, MH1, MH2) to illuminate a large room to two illuminances (2.0 and 15.0 lux). The lighting was evaluated separately using the category rating method. To counter potential response contraction bias [Fotios & Houser, 2009] an eight-point response range was used, the stimuli were presented in random order, and visual demonstration was used to anchor the ends of the brightness response range. It was found that the CFL, MH1 and MH2 lamps were rated significantly brighter than the HPS lamp at the same illuminance.

Rea, Bullough & Akashi compared lamps in a real exterior environment using a discrimination task [Rea, Bullough & Akashi, in press]. Opposite ends of a road were lit using MH and HPS lamps at a range of illuminances; test participants located at the centre reported at which end did the street appear brighter and at which end they would 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

These studies have all compared the brightness of spaces lit by HPS and MH lamps. The results from these suggest an MH/HPS illuminance ratio in the range 0.68 to 0.79 (Table 4). That this has been found in tests using different levels of chromatic adaptation (mixed and complete), different procedures (matching and discrimination), different evaluation modes (simultaneous and sequential), in laboratory and outdoor environments and from different research groups, suggests the results are robust. It must be noted that MH lamps are available with a wide range of spectral characteristics and this may explain some of the differences in results.

Study	Method	Adaptation level	MH/HPS illum. ratio
Fotios & Cheal (2007)	matching	7.5 lux	0.73
Fotios & Cheal (2007)	discrimination	7.5 lux	0.68
Fotios & Cheal, (article in progress)	matching	7.5 lux	0.79
Rea (1996)	matching	0.1 and 1.0 cd/m²	0.71
Rea, Bullough & Akashi (in press)	discrimination	5.0 to 30 lux	0.79

Table 4. Comparison of MH/HPS illuminance ratios for equal brightness in different studies.

3.2 Predicting brightness

We are currently investigating means for predicting the effect of lamp SPD on brightness at mesopic levels. In addition to simple tools such as consideration of colour rendering index as used in BS 5489-1:2003 [BS5489-1:2003] the analysis also includes recently proposed models of mesopic photometry.

Two models are Unified Luminance [Rea et al, 2004] and that proposed by the MOVE consortium [Goodman et al, 2007]. These models were developed from visual performance data and therefore application to brightness data might be considered inappropriate, but this is what may happen in practice and thus their accuracy for predicting brightness is of interest. A third model is that reported by Sagawa [Sagawa, 2006] which adds a chromatic contribution to the photopic and scotopic luminances. Analysis of these models is being made using brightness matching data [Fotios & Cheal, 2007a].

Table 5 shows predicted ratios of mesopic luminances at equal brightness. The input data are derived from the photopic luminances of the reference lamp (HPS) and test lamps (CFL, MH1, MH2) at equal brightness, as defined by the mean results from brightness matching trials (Table 1). A successful prediction of equal brightness would be a mesopic luminance ratio of 1.0. To compare predictions the final column of Table 5 shows the root-mean-squared (RMS) error between the predicted ratios and unity. At 0.1 cd/m^2 (2.0 lux) the Sagawa model best fits the data, although the MOVE model is not far off. At 0.38 cd/m^2 (7.5 lux) and 0.76 cd/m^2 (15 lux) the MOVE model gives the best fit to the data.

Table 6 presents ratios of photopic luminance for equal mesopic luminance derived using the three models of mesopic photometry. If equal mesopic luminances predict equal brightness, these ratios will match the photopic illuminance ratios found in the experimental work. A successful prediction is suggested to be one which lies within the 99.9% confidence interval about the mean value.

Mesopic Visual Efficiency Model	**Luminance of HPS, cd/m^2**	**Predicted L_{mes} ratio at equal brightness**			**RMS error from unity**
		CFL/HPS	**MH1/HPS**	**MH2/HPS**	
MOVE	0.10 cd/m^2	1.04	0.98	1.12	0.074
	0.38 cd/m^2	0.91	0.87	0.98	0.092
	0.76 cd/m^2	0.87	0.82	0.93	0.134
Unified Luminance	0.10 cd/m^2	1.40	1.25	1.56	0.423
	0.38 cd/m^2	0.90	0.86	0.96	0.102
	0.76 cd/m^2	0.71	0.69	0.71	0.297
Sagawa	0.10 cd/m^2	0.96	0.93	1.02	0.048
	0.38 cd/m^2	0.79	0.78	0.81	0.207
	0.76 cd/m^2	0.75	0.74	0.76	0.250

Table 5: Predicted ratios of mesopic luminances (L_{mes}) at equal brightness. An accurate prediction would be 1.0.

Reference luminance, cd/m^2	Lamp pair	Experimental results		Predicted ratio of photopic illuminances for equal mesopic illuminances		
		Mean illuminance ratio	99.9% Confidence Interval	Unified Luminance	MOVE	Sagawa
0.10 cd/m^2 *(2.0 lux)*	MH1 / HPS	0.729	0.670-0.788	0.577	**0.745**	**0.785**
	MH2 / HPS	0.679	0.610-0.748	0.411	0.599	**0.665**
	CFL / HPS	0.694	0.639-0.749	0.483	**0.667**	**0.722**
0.38 cd/m^2 *(7.5 lux)*	MH1 / HPS	0.733	0.675-0.791	0.860	0.846	0.939
	MH2 / HPS	0.724	0.664-0.784	**0.758**	**0.737**	0.904
	CFL / HPS	0.718	0.675-0.761	0.807	0.790	0.924
0.76 cd/m^2 *(15.0 lux)*	MH1 / HPS	0.724	0.668-0.780	1.000	0.886	0.987
	MH2 / HPS	0.738	0.669-0.807	1.000	**0.799**	0.978
	CFL / HPS	0.732	0.674-0.790	1.000	0.841	0.986

Table 6. Predicted ratios of photopic illuminance for equal mesopic illuminances using three models of mesopic photometry. The predicted photopic illuminance ratios in **bold** font are those which lie within the 99.9% confidence interval of the experimental mean value

The Sagawa model provides accurate predictions of all three lamp combinations at 0.10 cd/m^2 but at the higher reference luminances it is less accurate, suggesting a lower effect of lamp SPD (illuminance ratios closer to unity) than the test results suggest. Unified Luminance provides only one accurate prediction, that for the MH2/HPS lamp pair at the middle reference luminance. The MOVE model makes accurate predictions for four lamp pairs and these are spread across all three reference luminances.

From Tables 5 and 6 it appears that the MOVE model provides the most consistently accurate predictions of the brightness matching data, more so than does the Sagawa model and Unified Luminance, but even this model gives an accurate prediction for less than half of the test results.

4. THRESHOLD VISUAL PERFORMANCE

Previous studies have examined how luminance and SPD affect threshold performance. For foveal vision, threshold performance has examined acuity and contrast detection using achromatic targets. These studies have tended to find that at mesopic luminances, lamp SPD does not affect acuity or contrast detection thresholds, but that luminance does; as task luminance decreases, threshold acuity and threshold contrast increase (Figure 1). These results imply that if design luminance were to be reduced, there would be a reduction in foveal visual performance, and that this is not offset in any significant way by lamp SPD.

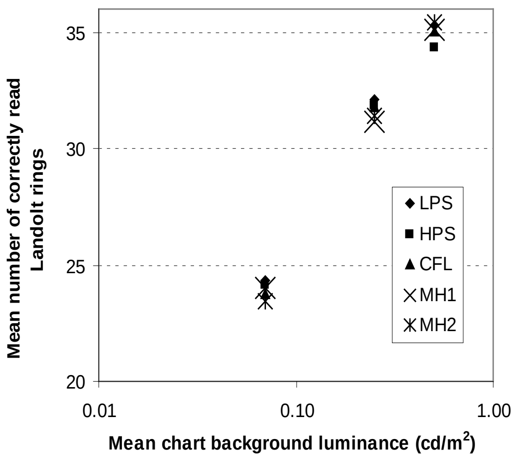

Figure 1. Results of achromatic visual acuity test; mean number of correctly read Landolt rings under each lamp and luminance combination [Fotios & Cheal, 2007b].

The performance of off-axis (peripheral) visual tasks in mesopic conditions has been examined, frequently with application to driving tasks. These studies have investigated contrast detection threshold, the rate of detection of peripheral targets, and reaction time to detection of peripheral targets.

For on-axis targets that are large and extend beyond the fovea, lamp SPD does affect threshold contrast, with MH lamps allowing a significantly lower relative luminance contrast threshold than HPS lamps [Lewis, 1999]. This result suggests that off-axis detection would be better under MH lighting than under HPS, and this is confirmed by two studies which found that the rate of detection of peripheral targets increased as the Scotopic/Photopic (S/P) ratio of the light source increased and also as luminance increased [Lingard & Rea, 2002; Bullough & Rea, 2000].

Reaction time to the detection of a peripheral target is also affected by lamp SPD and luminance, with MH lighting offering a significantly shorter reaction time than HPS lighting, and higher luminances yielding shorter reaction times than lower luminances [He et al, 1997]. At 0.10 cd/m^2 the reaction time under HPS is matched by the MH lamp at a photopic luminance of 0.052 cd/m^2 i.e., a MH/HPS luminance ratio of 0.52.

Thus for off-axis tasks, a reduction in visual performance associated with a reduction in luminance can be offset by lamp SPD, with lamps of higher S/P ratio improving visual performance.

Further investigations have examined tasks considered to be representative of those for pedestrians, facial recognition and obstacle detection.

5. OBSTACLE DETECTION

5.1 Test Apparatus

An important visual task for pedestrians is the detection of objects and irregularities on the pavement surface. Street lighting is expected to increase the detection probability for these types of obstacle and thus reduce the number of tripping accidents.

A test was carried out to examine how lamp type, illuminance and observer age affected the detection of an obstacle (simulating a raised paving slab) in peripheral vision [Fotios & Cheal, in press]. Visual space is mapped using peripheral vision [Inditsky et al, 1982] and therefore this research investigated obstacle detection in peripheral vision.

Obstacles varying in height and position relative to the line of sight were presented using the apparatus shown in Figure 2. This is an enclosed booth, lit from above by reflection from the underside of the domed roof. Light is conveyed into the booth through an internally reflective pipe and a mechanical iris in this pipe permits dimming without affecting the SPD. The floor, simulating a paved surface, is formed by a grid of blocks painted the same matt grey (Munsell N5) as the rest of the enclosure to give a diffuse reflectance (r=0.20).

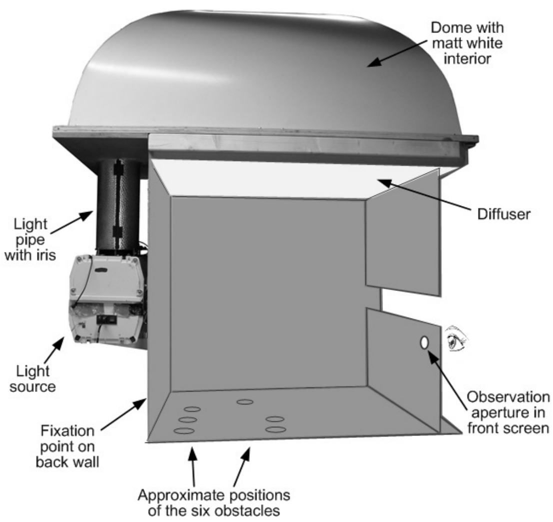

Figure 2. Side elevation of obstacle detection apparatus (with left-hand side of booth removed).

An obstacle in the form of a surface irregularity is introduced to the otherwise flat pavement by raising the cylindrical segment of one of the blocks, numbered 1 to 6 in Figure 3. A PC-controlled stepper motor and lead screw within each block allowed precise control of the obstacle height.

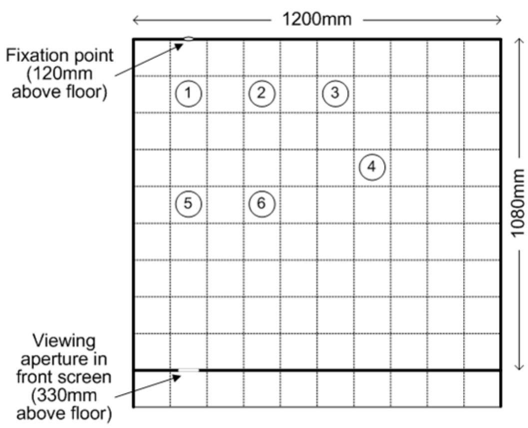

Figure 3. Plan of obstacle field showing relative locations of viewing aperture, fixation point and obstacles 1-6

Figure 4 shows the observer's view of the obstacle detection field as seen through the small aperture in the front screen of the enclosure. This was opened for 300ms per trial.

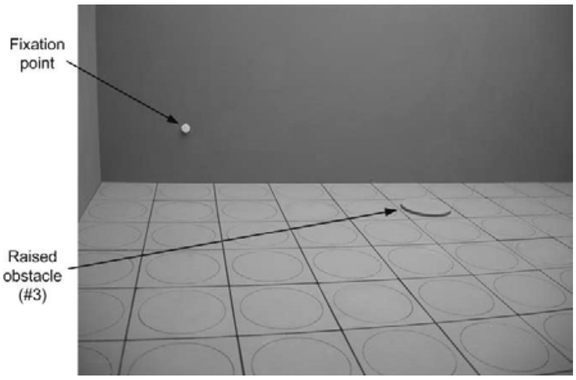

Figure 4. Observer's view of fixation point & obstacle field.

Three types of lamp were used, a standard high pressure sodium lamp (HPS), and two types of metal halide lamp (CDM and CPO). The lamps are defined in Table 7.

Lamp type	CCT (K)	CRI	S/P
HPS	2000	25	0.57
CPO	2730	66	1.22
CDM	4200	92	1.77

Table 7. Lamps used in the obstacle detection tests. CCT and CRI as stated in manufacturers literature; S/P ratios were determined from SPD measured inside the test booth.

The experimenter set the interior light level to one of three illuminances, 0.2, 2.0 and 20.0 lux, as measured in the centre of the floor. This range was chosen to cover those illuminances expected from lighting designed to meet the S-series of lighting classes for subsidiary streets [BS EN 13201-1:2003] and with a range of 2 log units was expected to be sufficient to yield a difference in obstacle detection if a real effect exists.

Twenty-one colour-normal test participants were used. To examine the expected change in visual performance with age, two groups of test participants were used, the Young group being less than 45 years old (n=11) and the Old group being more than 60 years old (n=10). Each participant saw all test lamps and illuminances.

Data obtained using four obstacles (#1 to #4 in Figure 3) are examined, as these were approximately equidistant from the observation aperture, and hence presented targets of similar shape and size. Two further obstacles (#5 and #6) were used in the trials to reduce the probability of making a correct response by chance. Each obstacle was presented at eight different raised heights within the range 0.40mm to 7.94mm. The range of obstacle heights followed the same progression as used for increasing gap sizes on the Bailey-Lovie acuity chart [Bailey & Lovie, 1976].

5.2 Procedure

Each test session commenced with twenty minutes dark adaptation. The test participant looked through the aperture with their right eye and was instructed to maintain their attention upon the fixation point located opposite the aperture on the rear wall. Practice trials were carried out before the main test; the first six trials presented the six obstacles to illustrate their location and this was followed by random presentations to confirm that the obstacle identification numbers were known by the participant. A null condition was also presented to demonstrate that the response of 'no obstacle seen' was possible and appropriate.

With the aperture closed, a single obstacle was raised. The choice of obstacle, the amount by which it was raised, and the illuminance were randomly assigned. The aperture was opened for 300ms, and the observer instructed to report if a raised block was present by stating its identification number (1 to 6), or to state 'none' if no raised obstacles were noticed. There were 144 presentations (3 illuminances x 6 obstacles x 8 obstacle heights) and 18 null conditions (six per illuminance). Null presentations (no obstacles lifted) were included to identify the degree of false-positive reporting (false-alarm). Participants attended three separate two-hour sessions to carry out the tests using the three different lamps, the order in which the lamps were used being balanced between subjects. In each test session only one lamp was used.

5.3 Results

An example of the test results is shown in Figure 5, this being for obstacle #2 at 0.2 lux for the older and younger age groups combined, and it shows the probability of correctly detecting an obstacle when raised from the surface by a given height. The data points in Figure 5 are the experimental results, the frequency with which an obstacle of a given height was detected. The best-fit curves in Figure 5 were drawn using the Four Parameter Logistic Equation.

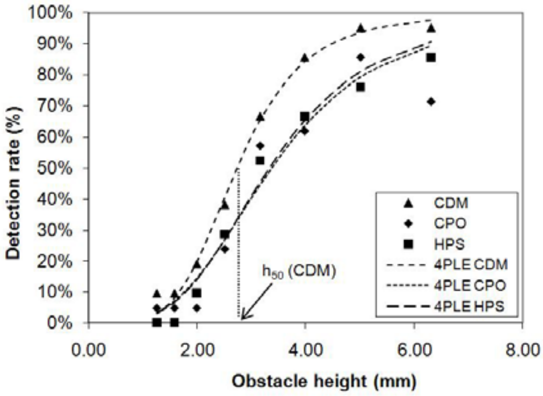

Figure 5. Sample test result: detection rate (%) for obstacle #2 at 0.2 lux for the older and younger age groups combined.

Figure 6 shows the overall effect of lamp type, illuminance and age on obstacle detection. The data points are the mean heights for 50% detection rate (h_{50}) for each lamp x illuminance x age combination averaged across the four obstacle locations.

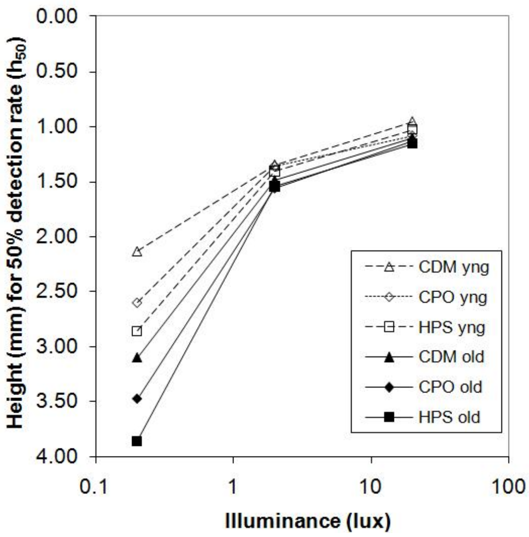

Figure 6. Mean detection height for 50% detection probability of obstacles 1 to 4 plotted against illuminance for the three test lamps and the two age groups.

Figure 6 suggests that at 0.2 lux obstacle detection appears to be better under the CDM lamp and poorest under the HPS lamps; at 2.0 lux and 20 lux there appears to be no difference in obstacle detection between the lamps. The Friedman test suggests that lamp type has significant effect on obstacle detection ($p<0.01$). When data at the three illuminances are considered separately differences between the lamps are significant at 0.2 lux ($p<0.01$), but not at 2.0 lux or 20 lux. Using the Wilcoxon test with the 0.2 lux data reveals a significant difference between the three possible lamp pairs ($p<0.05$). At 2.0 and 20 lux there are no significant differences in h_{50} between lamp pairs.

Figure 6 suggests that obstacle detection ability increases with higher illuminance for all lamp types and obstacle locations, and that the difference in obstacle detection between 0.2 lux and 2.0 lux is greater than that between 2.0 lux and 20 lux. The Friedman test shows that illuminance has a significant effect ($p<0.01$) on obstacle detection and when the three lamps types are analysed individually ($p<0.01$). A matched pairs comparison using the Wilcoxon test confirms that differences between illuminance levels under the same lamp type are significant ($p<0.05$) in all cases.

At the lower illuminance Figure 6 suggests that younger observers were able to detect obstacles of lower height than were older observers, but this difference between age groups is less marked at the higher illuminances. Application of the Mann-Whitney test (age groups are independent samples) suggests that the difference between older and younger test participants is significant at 0.2 lux ($p<0.01$), is near significant at 2.0 lux ($p=0.08$) but is not significant at 20 lux ($p=0.34$).

Analysis of the null condition data and application of Signal Detection Theory suggest that test participants had a strong tendency to report detection of an obstacle when there was an obstacle present and to report no detection when obstacles were absent [Fotios & Cheal, in press].

5.4 Predicting Obstacle Detection

Table 8 compares predictions made using the MOVE model [Goodman et al, 2007] and Unified Luminance [Rea et al, 2004] with the test results. For a photopic luminance of 0.01 cd/m^2 under the HPS lamp, the mesopic visual efficiency systems yield mesopic luminances of 0.0034 (MOVE) and 0.0059 (Unified Luminance); equal values of mesopic lumens are intended to indicate equal visual performance, hence similar values of h_{50}. The photopic luminances giving these mesopic luminances under the CPO and CDM lamps were then calculated using the same mesopic visual efficiency system. From these photopic luminances, obstacle detection (h_{50}) was determined using the equations of the best fit lines drawn to fit Figure 6; (see Fotios & Cheal, in press, for these curves).

HPS luminance (cd/m^2)	0.01			0.1			1.0		
Lamp	HPS	CPO	CDM	HPS	CPO	CDM	HPS	CPO	CDM
MOVE									
Mesopic luminance	0.0034	0.0034	0.0034	0.081	0.081	0.081	0.930	0.930	0.930
Photopic luminance (cd/m^2)	0.0100	0.0025	0.0015	0.100	0.074	0.061	1.000	0.898	0.826
Predicted obstacle detection, h_{50} (mm)	2.94	3.78	3.52	1.75	1.83	1.71	1.04	1.07	1.03
Unified Luminance									
Mesopic luminance	0.0059	0.0059	0.0059	0.068	0.068	0.068	1.000	1.000	1.000
Photopic luminance (cd/m^2)	0.0100	0.0048	0.0033	0.100	0.058	0.043	1.000	1.000	1.000
Predicted obstacle detection, h_{50} (mm)	2.94	3.29	3.02	1.75	1.93	1.83	1.04	1.05	0.99

Table 8. Mean height for 50% obstacle detection (h_{50}) predicted for the HPS, CDM and CPO lamps at photopic luminances defined by equal mesopic luminances.

At the HPS photopic luminances of 0.1 and 1.0 cd/m^2 the values of h_{50} predicted by MOVE in Table 8 are similar, differences between lamp pairs at the same mesopic luminance being less than 0.21mm[†], but at 0.01 cd/m^2 the predicted values of h_{50} are different by more than 0.21mm. Next, consider predictions made using Unified Luminance. At the HPS photopic luminances of 0.1 and 1.0 cd/m^2 the predicted values of h_{50} in Table 8 are similar, differences between lamp pairs at the same mesopic luminance being less than 0.21mm; at 0.01 cd/m^2 the predicted values of h_{50} are different by more than 0.21mm between the CPO and CDM lamps and between the CPO and HPS lamps but not between the CDM and HPS lamps.

This analysis suggests some disparity between the test data and the visual efficiency models at the lower luminance (0.01 cd/m^2) but little difference in accuracy of predictions made by the MOVE and Unified Luminance systems of mesopic visual efficiency.

[†] According to the experimental results, a difference in h_{50} of 0.21mm or more represents a significant difference in obstacle detection [Fotios & Cheal, in press].

5. FACIAL RECOGNITION

SPD effects on facial recognition have been explored in four studies. In two of these [Raynham & Saksvikrønning, 2003; Knight & van Kemenade, 2006] it was reported that lamp SPD affected facial recognition whilst the other two studies [Boyce & Rea, 1990; Rea, Bullough & Akashi, in press] reported no significant effect.

Thus for facial recognition there is no clear indication of how this might be affected by lamp SPD and the outcome of reducing illuminance levels. If guidance in BS5489-1:2003 is followed and illuminance is reduced when using MH lamps, then whilst some data suggests facial recognition would also be reduced [Rea, Bullough & Akashi, in press] other studies suggest the better colour rendering quality of the MH lamp would aid it to maintain the same facial recognition performance as HPS lighting at the standard illuminance.

Issues demanding further investigation are specification of what constitutes facial recognition, and at what distance this needs to be achieved.

6. SPECIFYING LAMP SPECTRUM CHARACTERISTICS

The preceding discussion demonstrates that lamp SPD can be expected to affect the safe movement and perceived safety of pedestrians at night-time. What is needed is a means of predicting these effects, in particular the relationship between lamp SPD and illuminance to achieve a given effect.

In Europe, BS EN 13201-2:2003 specifies an average pavement illuminance in six classes (the S-series), ranging from 2.0 to 15.0 lux [BS EN 13201-2:2003]. These average illuminances are higher than those for similar roads in Australia and New Zealand (0.5 to 7.0 lux) and Japan (3.0 to 5.0 lux) [Boyce, Fotios & Richards, in press] which suggests that European streets are lit to an excessive level and that there may be scope for illuminance reductions.

In the UK, BS5489-1:2003 seeks to account for approximate effects of lamp SPD by permitting a reduction in average illuminance (from the established class of the S-series) when using lamps of high general colour rendering index (Ra≥60) [BS5489-1:2003]. To some extent, this reduction offsets the apparent overlighting (relative to Australia, New Zealand and Japan) but it is not expected to provide a reliable specification of all lamp spectrum effects.

For impressions of brightness, experimental data [Fotios & Cheal, 2007a] suggest that R_a provides a simple and convenient metric for discriminating between standard HPS lamps and lamps such as CFL and MH which can appear brighter at the same illuminance, but this is not expected to be a reliable indicator in all cases. The MOVE model of mesopic visual efficiency gave a better explanation of these experimental results than did Unified Luminance and Sagawa's model, but even this was not able to predict the results in all combinations of lamp pair and illuminance.

For the detection of peripheral obstacles, the MOVE model and Unified Luminance both gave good predictions of obstacle detection ability at the two higher luminances of those used in tests, 0.1 and 1.0 cd/m^2, but lost this accuracy at the lower luminance, 0.01 cd/m^2. These models are founded on the ratio of the scotopic to photopic luminances, the S/P ratio.

The BS5489-1:2003 specification of lamp SPD effects, i.e. R_a≥60, does not give a good explanation of the performance of the obstacle detection task. Both of the high colour rendering lamps (CDM & CPO) used by Fotios and Cheal [Fotios & Cheal, in press] provided significantly better performance than the HPS lamp at the 0.2 lux level. But, after an illuminance reduction by one class of the S-series, only the CDM provided an obstacle detection performance level equal to or better than HPS. Although obstacle detection under the CPO lamp at 0.2 lux was significantly better than that under HPS at the same illuminance, the gain was not sufficient to offset the effect of the CPO illuminance reduction (by one step in the S-series). This finding suggests that the lamp spectrum criterion in BS5489-1:2003 (i.e. Ra≥60) required for the illuminance trade-off may actually entail a deterioration in visual performance.

As for facial recognition, it is not possible to suggest a means for predicting the effect of differences in lamp SPD because experimental data from different studies are in dispute as to whether there is an effect.

REFERENCES

BAILEY, IL., LOVIE, JE. New design principles for visual acuity letter charts. *Am. J. Optom. Phys. Optics*, **53**(11), 740-745, 1976

BS 5489-1:2003 *Code of practice for the design of road lighting – Part 1: Lighting of roads and public amenity areas*. London: British Standards Institution, 2003.

BS EN 13201-2:2003 *Road lighting – Part 2: Performance requirements*. London: British Standards Institution, 2003.

BOYCE, PR., EKLUND, NH., HAMILTON, BJ., BRUNO, LD. Perceptions of safety at night in different lighting conditions. *Light. Res. Tech.*, **32**, 79-91, 2000

BOYCE, PR., FOTIOS, S., RICHARDS, M. Road lighting and energy saving. *Light. Res. Tech.*, in press

BOYCE, PR., REA, MS. Security lighting: effects of illuminance and light source on the capabilities of guards and intruders. *Light. Res. Tech.*, **22**, 57–79, 1990

BULLOUGH, JD., REA, MS. Simulated driving performance and peripheral detection at mesopic and low photopic light levels. *Light. Res. Tech.*, **32**(4), 194-198, 2000

FOTIOS, SA., CHEAL, C. Lighting for subsidiary streets: investigation of lamps of different SPD. Part 2 – Brightness. *Light. Res. Tech.*, **39**(3), 233-252, 2007a

FOTIOS, SA., CHEAL, C. Lighting for subsidiary streets: investigation of lamps of different SPD. Part 1 – Visual Performance. *Light. Res. Tech.*, **39**(3), 215-232, 2007b

FOTIOS, SA., CHEAL, C. Obstacle detection: A pilot study investigating the effects of lamp type, illuminance and age. *Light. Res. Tech.* in press.

FOTIOS, SA., CHEAL, C. A Pilot Study Investigating How the Design of the Illuminated Field Affects Brightness Matching. Article in progress

FOTIOS, SA., HOUSER, KW. Research Methods to Avoid Bias in Categorical Ratings of Brightness. *Leukos*, **5**(3), 167-181, 2009

FOTIOS. SA,, HOUSER. KW,, CHEAL, C. Counterbalancing needed to avoid bias in side-by-side brightness matching tasks. *Leukos*, **4**(4), 207-223, 2008

GOODMAN, T., FORBES, A., WALKEY, H., ELOHOLMA, M., HALONEN, L., ALFERDINCK, J., FREIDING, A., BODROGI, P., VARADY, G., SZALMAS, A. Mesopic visual efficiency IV: a model with relevance to nighttime driving and other applications. *Light. Res. Tech.*, **39**(4); 365-388, 2007

HE, Y., REA, MS., BIERMAN, A., BULLOUGH, J. Evaluating light source efficacy under mesopic conditions using reaction times. *J. Illum. Eng. Soc.*, **26**, 125-138, 1997

INDITSKY, B., BODMANN, HW., FLECK, HJ. Elements of visual performance. *Light. Res. Tech.*, **14**(4); 218-231, 1982

KNIGHT, C., VAN KEMENADE, J. Wahrnehmung und Wertschätzung der Endkunden in Bezug auf die öffentliche Beleuchtung (Effect of outdoor lighting on perception and appreciation of end-users). Licht 2006, Berne, 10-13 September 2006

LEWIS, AL. Visual performance as a function of spectral power distribution of light sources at luminances used for general outdoor lighting. *J. Illum. Eng. Soc.*, **28**, 37-42, 1999

LINGARD, R., REA, MS. Off-axis detection at mesopic light levels in a driving context. *J. Illum. Eng. Soc*., 33-39, Winter 2002

LOEWEN, LJ., STEEL, GD., SUEDFELD, P. Perceived safety from crime in the urban environment. *Light. Res. Tech.*, **13**, 323-331, 1993

RAYNHAM, P., SAKSVIKRØNNING, T. White Light and Facial Recognition. *Lighting Journal*, **68**, 29-33, 2003

REA, MS. Essay by invitation. *Light. Des. Appl.*, 15-16, October 1996

REA, MS., BULLOUGH, JD., AKASHI, Y. Several views of metal halide and high pressure sodium lighting for outdoor applications. *Light. Res. Tech.*, in press

REA, MS., BULLOUGH, JD., FREYSSINNIER-NOVA, JP., BIERMAN, A. A proposed unified system of photometry, *Light. Res. Tech*., **36**(2), 85-111, 2004

SAGAWA, K. Toward a CIE supplementary system of photometry: brightness at any level including mesopic vision. *Ophth. Phys. Optics*, **26**, 240-245, 2006

ACKNOWLEDGEMENTS

This work was supported by funding from EPSRC (grant number EP/F035624/1) and Philips Lighting.

First presented as:
Fotios S & Cheal C. Road lighting for pedestrians in residential areas: Choosing the optimum lamp colour characteristics. CIE Light & Lighting conference, Budapest, 27-29 May 2009.

Subsequently selected for conference proceedings:
Fotios S & Cheal C, Road lighting for pedestrians in residential areas: Choosing the optimum lamp colour characteristics. SELECTED PAPERS of the CIE Light and Lighting Conference with Special Emphasis on LEDs and Solid State Lighting. 27-29 May 2009, Budapest, Hungary, CIE x034:2010. pp 29-38.

This version re-published with permission as:
Fotios S & Cheal C, Road lighting for pedestrians in residential areas: Choosing the optimum lamp colour characteristics, Light & Engineering, 2010; 18(1); 91-100.