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Obstacle detection: A pilot study investigating the effects of lamp type, illuminance and age

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A novel apparatus was used to examine the effect of light source, illuminance and observer's age on the ability to detect obstacles in peripheral vision, simulating a raised paving slab under mesopic visual conditions. The data collected were used to determine the height of obstacles above the paving surface required for 50% detection. From these detection heights it was determined that: (1) obstacle detection was influenced by illuminance, the 50% detection height being lower at 20 lux than at 0.2 lux, (2) the young observers (<45 years old) showed the smaller 50% detection height at 0.2 lux, but at 20 lux there was no difference in obstacle detection height between the younger and older (>60 years old) age groups, and (3) obstacle detection was affected by lamp type at 0.2 lux, with the 50% detection height decreasing as lamp S/P ratio increased, but at 2.0 and 20 lux there was no significant difference between the three test lamps.

1. Introduction

Obstacle detection is a critical visual task for pedestrians.[1] Street lighting must provide for adequate obstacle detection as a countermeasure to trip hazards and collisions.

An obstacle is an approaching object or irregularity that may cause a pedestrian to trip, or is not noticed in time to avoid collision – a potential safety hazard. Potential obstacles include uneven pavements (e.g. a raised paving slab or manhole cover), a hole in the pavement, construction works and construction barriers, bicycle racks, discarded bicycles outside shops, motor vehicles parked on footpaths, street furniture (e.g. tables, chairs and benches) and posts such as bollards, bus stops and lighting columns. These obstacles are of two types. One is a small discontinuity that might not be seen, e.g. a raised paving slab. The other is a large object that is not seen because people are not paying attention and its presence is unexpected. This research examined the former type of obstacle, the raised paving slab or kerb; outside of the home, kerbs are the most frequently reported location of falls.[2] Visual space is mapped using peripheral vision[3] and therefore this research investigated obstacle detection in peripheral vision.

The CIE Standard Photopic Observer V(λ) represents a spectral response dominated by the long-wavelength sensitive and medium-wavelength sensitive cone photoreceptors in the fovea and activity in the achromatic luminance channel. Standard photometry is expected to be a good predictor of achromatic task performance that relies primarily on foveal vision. But as light levels fall in the mesopic region, spectral sensitivity outside the fovea becomes increasingly dominated by the response of the rod photoreceptors for which V(λ) is a poor representation. Therefore photopic illuminance is not expected to be a reliable predictor of off-axis visual performance under light sources of

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different spectral power distribution (SPD) at mesopic light levels.

Street lighting in the UK previously tended to use low-pressure sodium (LPS) and high-pressure sodium (HPS) lamps. However, there is now a move toward using lamps such as metal halide (MH) and fluorescent which have a whiter appearance (higher correlated colour temperature – CCT), a higher colour rendering index (CRI) and a higher Scotopic/Photopic (S/P) ratio than HPS or LPS lamps. The S/P ratio quantifies the relative extent to which a light source stimulates the rod and cone photoreceptors, and thus its relative efficacy under scotopic and photopic conditions. The higher the S/P ratio, the greater the stimulation of the rods relative to the cones. Obstacle detection in mesopic conditions depends on rods in the peripheral regions of the retina in addition to the cones, and so performance is expected to improve under lamps of higher S/P ratio.

Previous studies suggest that light source type and luminance will affect the performance of peripheral visual tasks.[4–6] The detection capability of the eye is mainly determined by contrast sensitivity.[7] Consider threshold luminance contrast under MH and HPS lamps at mesopic levels: if the task extends beyond the fovea then SPD does affect threshold contrast[8] with MH lamps having a significantly lower relative luminance contrast threshold than HPS (and LPS) lamps, but if the task is foveal then there is no difference in threshold contrast between these lamps.[9] There is an increase in the rate of detection of peripheral targets as luminance increases and also as the S/P ratio of the light source increases;[10,11] these were simulated driving tasks where the visual attention of the subject, the apparent movement of the subject, and the location of potential obstacles differs to that for pedestrians. Mulder and Boyce[12] studied pedestrian movement through an obstructed space under emergency lighting conditions and found that both speed of escape and the number of collisions are affected by light source SPD; at similar photopic illuminances, blue lamps ($S/P = 14.0$) permitted faster speed and fewer collisions than did red lamps ($S/P \approx 0.06$).

Vision deteriorates with age due to reductions in both the quality of the retinal image and the image processing capabilities of the retina and visual cortex. The proportion of the illumination at the eye that reaches the retina is reduced for older people. For example, the retinal illumination for a 60-year-old person could be a third of that for a 20-year-old person.[13] Of the light that does reach the retina a greater proportion in the older eye is in the form of scattered light; there is approximately 2.5 times more scattered light in the eye at 75 years than at 25 years. Light scattered within the eye tends to decrease the contrast of the retinal image and thus increase contrast threshold.[14] Another problem that increases with age is lens fluorescence which generates stray light inside the eye. This effect is greater for SPDs with significant emissions below 450 nm.[15] The spectrum of the light reaching the retina is changed in the older eye as the spectral transmission of the cornea and lens decreases more in the blue part of spectrum indicating a yellowing effect.[15,16] Decreasing densities of photoreceptors and ganglion cells in the retina affect the image processing stage of visual function in the older eye.[16] These changes in the normal aging eye will tend to increase thresholds of acuity, contrast sensitivity, colour discrimination and reaction time.

It was thus predicted that lighting of higher S/P ratio would provide better obstacle detection ability than lighting of lower S/P ratio; that obstacle detection ability would decrease at lower luminances; and that younger people would have better obstacle detection ability than older people. The following work was carried out to test these predictions.

2. Method

2.1 Description of the apparatus

Obstacle detection was tested using a single booth, the interior of which was lit from above and was viewed through a small aperture in the front screen (Figures 1 and 2). The floor was of dimensions 1200 mm × 1080 mm and comprised a 10 × 9 array (width × depth) of cylindrical blocks. The upper surfaces of the blocks were normally flush with the surrounding floor but could be individually raised by incremental amounts using stepper motors, thus providing a surface irregularity – a target obstacle.

The test lamps were hidden from direct view, with light transported into the booth using an internally reflective pipe, and the visible chamber of the booth was lit by reflection from the ceiling of the booth. An iris in the pipe enabled the lighting to be dimmed without affecting the spectral power distribution. The ceiling of the booth, which had a matt white finish, approximated a hemisphere to promote an even distribution of luminance across the floor of the booths, and this was further aided by a diffusing filter fitted above the viewing chamber (opal/white cast acrylic with a light transmission factor of 0.70 and a diffusion factor of 0.46). The interior surfaces of the booth visible to observers, including the top and sides of the cylindrical obstacles, were painted with a grey paint (Munsell N5) of diffuse reflectance ($r = 0.20$).

Observation of the interior was controlled using two shutters, a rotating disc and a sliding shutter, fitted in series behind the aperture in the front screen of the booth as shown in Figure 3. Normally, the rotating disc was in constant revolution and the sliding

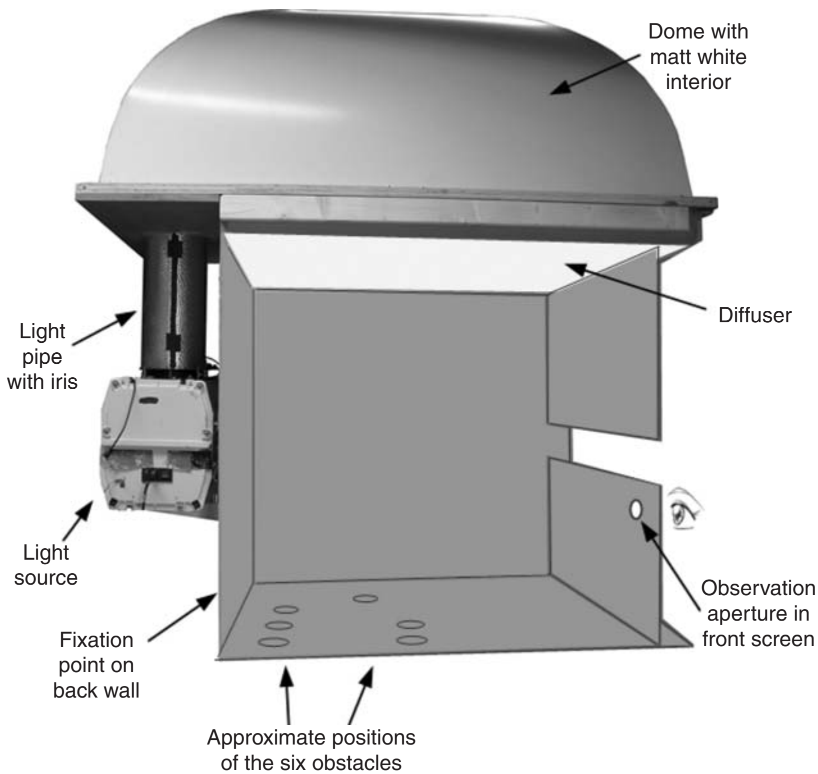

Figure 1 Side elevation of apparatus with left-hand side panel removed

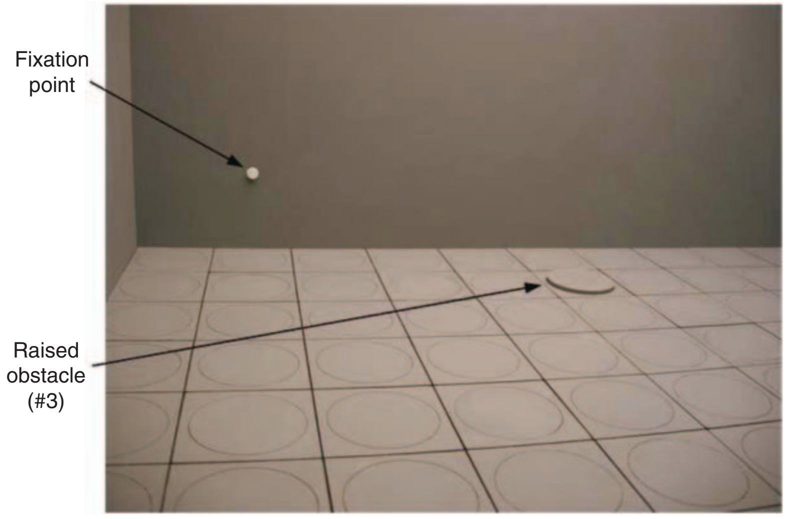

Figure 2 Photograph of interior of the obstacle detection apparatus as seen through the aperture

shutter was in the closed position to shield the aperture. The purpose of the rotating disc was to control the exposure time; the slot in the constantly rotating disc provided an exposure of approximately 300 ms every 1.35 s. The purpose of the sliding shutter was to allow observation of the interior through the rotating disc only when the experimenter was ready to present the next stimulus.

The aperture in the front screen was a kidney shape of height 50 mm and width 90 mm, this being a width of 57° as measured from the centre of the rotating disc. The rotating disc had a slot cut out; when the slot aligned with the aperture in the front screen, and when the sliding shutter was drawn back, this slot permitted the interior to be seen. The sliding shutter was drawn back automatically, in response to the experimenter's cue, before the disc slot aligned with the aperture, and then automatically closed afterwards. The leading- and trailing-edges of the slot in the disc were 80° apart as measured from the centre of rotation, and the disc speed was 0.74 revolutions per second (i.e. 1.35 seconds per revolution). The leading edge of the slot in the rotating disc took 0.21 s to cross the aperture in the front screen. The aperture was fully open for 0.09 s and then the trailing edge of the slot in the rotating disc took a further 0.21 s to cross the aperture, which was hence subsequently covered. Thus, assuming that fixation was maintained throughout the transition, all parts of the visual field were exposed for equal time, 300 ms. This exposure time was chosen because visual information is acquired from the outside world during the inter-saccadic intervals (fixational pauses or glimpses), the duration of which is approximately one third of a second.[3] The sliding shutter had a small hole (5 mm diameter) so that when in the closed position it enabled the fixation point, but not the floor of the booth, to be seen in between trials, for 300 ms every 1.35 s, when the slot in the rotating disc was passing the aperture in the front screen.

The front screen of the apparatus had separate upper and lower sections. A gap between the two permitted the experimenter to observe the interior space during trials to confirm the intended stimulus action took place; during trials this gap was not visible to test participants. The front screen was set 120 mm inwards from ceiling of the apparatus.

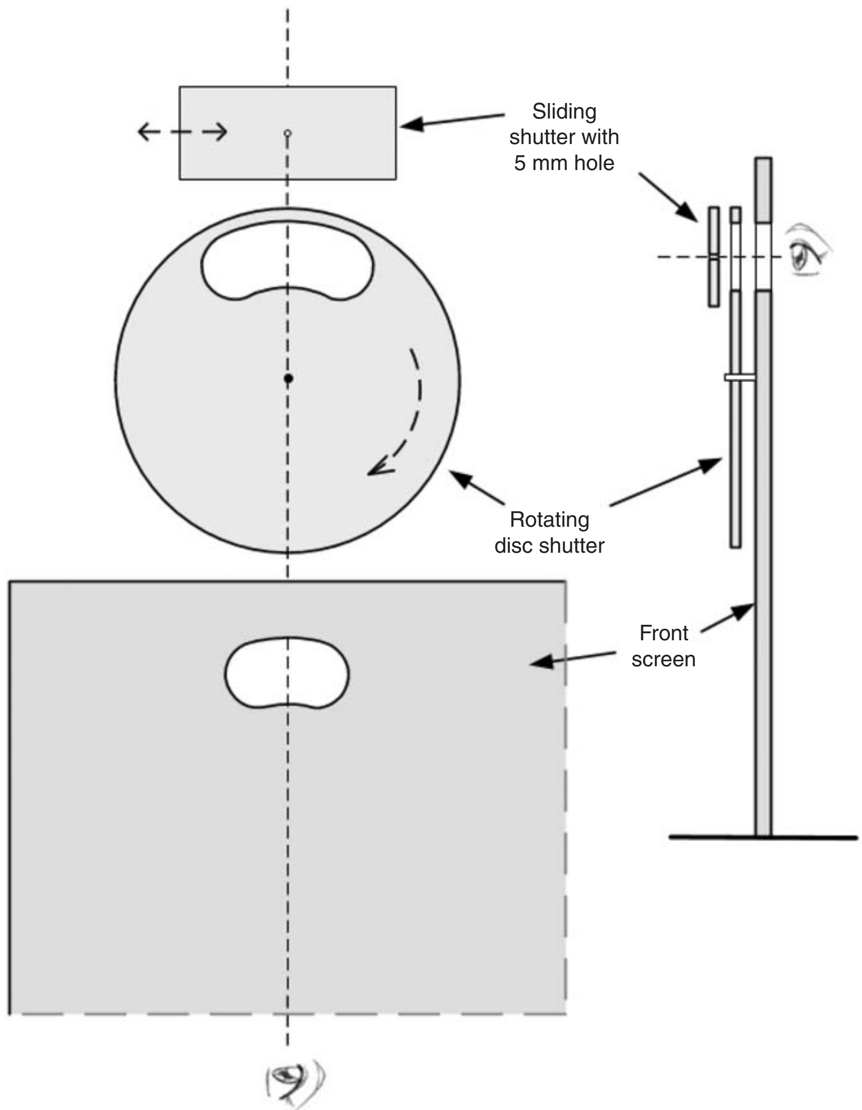

Figure 3 Diagram of the aperture and shutter mechanisms: exploded view and cross section

This offset allowed some interior light to leak through the gap, matching the brightness of the exterior wall to the interior wall allowing observers to maintain their adaptation levels before and after opening the observation aperture.

The aperture was placed on the left-hand side of the front screen and all obstacles were thus straight ahead or to the right-hand side. The fixation point was a white paper disc fixed to the rear wall of the booth, back-illuminated by fibre-optic cable connected to the light box and hence having the same SPD as the test light source. The fixation disc was of diameter 18 mm, presenting a visual size of approximately 57 minutes arc at the eye of the test participant.

This apparatus was designed to simulate the task of detecting an obstacle in peripheral vision during a brief observation and provide quantitative data for analysis. The location of the obstacles, being projections raised from the floor of the booth, were intended to represent an irregular pavement surface, e.g. a raised paving slab. The obstacles were presented in six different locations, countering a possible tendency to fixate on the target area where only one peripheral target location is used; the apparatus enables up to 90 obstacle locations and this will be explored in further work.

A cue to detection of the obstacles in this apparatus is the contrast between the luminance of the sides of a raised obstacle and that of the top surface and the surrounding floor surface. Light reaching the sides of an obstacle is that reflected from the vertical surroundings, and is thus affected by the location and reflection characteristics of the surrounding surfaces. It is intended to explore these effects in further work.

The mapping of visual space is a continuous process, perhaps considered as a stream of 300 ms observations rather than the single 300 ms exposure used in the current work. If continuous exposure had been employed, the movement when raising an obstacle would have provided detection cues, and this is a different task to that of detecting static objects such as the raised paving slab.

Vision was restricted to one eye to simplify design and construction of the aperture and shutter mechanisms, and with the assumption that visual detection is symmetrical about the central axis. Whilst monocular vision may provide a different estimate of detection capability to that of binocular vision this should not affect comparison of detection performance under different types of lamp.

2.2 Test variables

Three types of lamp were used, a standard HPS lamp, and two types of metal halide lamp (hereafter denoted CDM and CPO). These lamps are defined in Table 1 and Figure 4.

Table 1 Summary of lamps used in the obstacle detection tests. S/P ratios were determined from SPD measured inside the test booth

Lamp type		CCT (K)	CRI	S/P
HPS	SON-T Pro 150W	2000	25	0.57
CPO	Master CosmoWhite CPO-T 140W/728	2730	66	1.22
CDM	Master Colour City CDO-TT 150W/942	4200	92	1.77

The CCT and CRI of these lamps are noted to describe the quality of light and to show that they meet the criteria for an illuminance reduction when used to light subsidiary streets in the UK[17] and these data are as reported by the lamp manufacturer. The S/P ratio is suggested below to correlate with obstacle detection ability and the values in Table 1 are hence determined from SPD measured inside the test apparatus (using a Konica-Minolta CS1000a spectroradiometer) for a more accurate representation of the visual stimulus.

The experimenter set the interior light level to one of three illuminances, 0.2 lux, 2.0 lux and 20.0 lux, and these were 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[18] 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.

Table 2 shows the range of illuminances and luminances experienced. The illuminance was set for every trial by the experimenter who adjusted the position of the iris in the light pipe with feedback from a Minolta T-10M illuminance meter.

Twenty-one 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 ($n=11$, estimated mean age 32 years) and the *Old* group being more than 60 years old ($n=10$, estimated

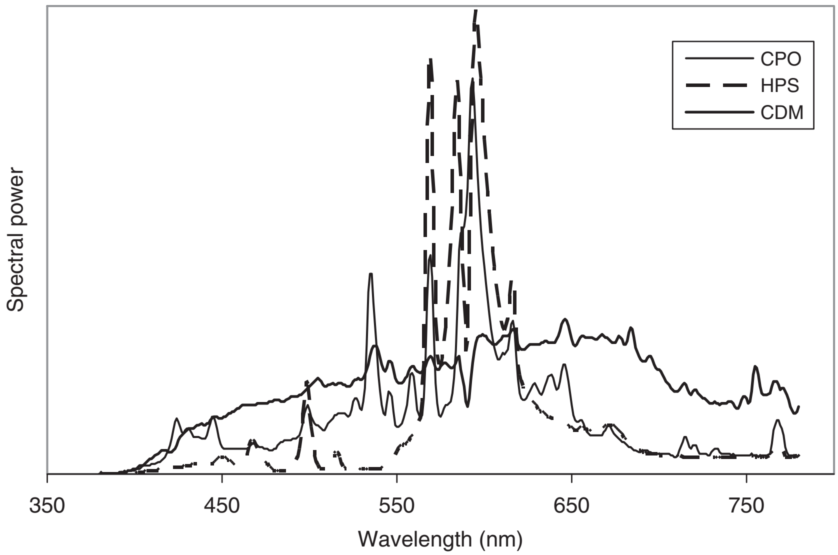

Figure 4 Lamp spectral power distributions as measured inside the test enclosure using a Minolta CS1000a spectroradiometer. Spectral power normalised for equal luminance

Table 2 Luminance distribution inside the booth. These were measured through the viewing aperture using a Minolta LS-100 luminance meter. Vertical illuminance measured using a Minolta T-10M illuminance meter

Nominal illuminance (lux)	Lamp	Luminance (cd/m^2) of						Vertical illuminance at eye with shutter open (lux)
		Top surface of obstacle #				Fixation point	Fixation point background	
		1	2	3	4			
0.2	HPS	0.009	0.010	0.010	0.010	0.05	0.01	0.02
	CDM	0.010	0.011	0.011	0.011	0.08	0.01	0.03
	CPO	0.010	0.011	0.011	0.011	0.06	0.01	0.02
2.0	HPS	0.108	0.119	0.120	0.121	0.18	0.06	0.30
	CDM	0.109	0.117	0.120	0.124	0.19	0.06	0.31
	CPO	0.110	0.121	0.121	0.126	0.18	0.06	0.29
20	HPS	1.074	1.178	1.162	1.243	1.33	0.53	3.39
	CDM	1.102	1.214	1.206	1.276	1.37	0.54	3.45
	CPO	1.095	1.206	1.204	1.261	1.35	0.53	3.33

mean age 68 years). Each participant saw all conditions (test lamps and illuminances) requiring attendance at three 2-hours test sessions and were paid to participate.

This article examines data obtained using four obstacles (#1 to #4 in Table 3 and Figure 5). These were approximately equidistant from the observation aperture, and hence presented targets of similar shape and size. Two further obstacles were used in trials (#5 and #6). These additional obstacles extended the field in which a target could be expected to appear, and, by increasing the total number of obstacles, reduced the probability of correct response by chance.

Each obstacle was presented at eight different raised heights within the range 0.40–7.94 mm. The range of obstacle heights followed a geometric progression of ratio 1.26 (0.1 log unit steps), which is the same progression as used for increasing gap sizes on the Bailey-Lovie acuity chart.[19] This progression defined a range of obstacle heights: 0.40, 0.50, 0.63, 0.79, 1.00, 1.26, 1.58, 2.00, 2.51, 3.16, 3.98, 5.01, 6.31 and 7.94 mm.

At threshold levels, noise due to background stimuli and random activity of the nervous system adds a degree of subjectivity to the task of obstacle detection. In subjective assessments the stimulus range can have a significant effect on subjects' decisions: identical stimuli have been considered to be both brighter (in 100% of judgements) and dimmer (in 100% of judgements) than a constant surround and this was caused by placing the stimuli at either the upper or lower end of a range of stimuli.[20] To counteract potential stimulus range bias the obstacle height at which 50% detection is reached should be approximately in the middle of the stimulus range, with detection rates approaching 0 and 100% at each end of the range. The range for each block × lamp × illuminance × age were hence explored in two series of pilot studies.[21] Table 4 shows the ranges used.

Table 3 Obstacle positions from observation aperture relative to fixation point

Obstacle	Degrees right of fixation point	Degrees below altitude of fixation point
1	0	10.5
2	14.8	9.8
3	27.9	8.0
4	42.0	10.7
5	0	23.3
6	23.6	20.7

Table 4 Range of obstacle heights for obstacles 1–6 for each combination of illuminance and age group

Illuminance (lux)	Range of obstacle heights (mm)			
	Older participants		Younger participants	
	Lower	Upper	Lower	Upper
0.2	0.794	7.943	0.794	6.310
2.0	0.501	5.012	0.501	3.981
20	0.398	5.012	0.398	3.981

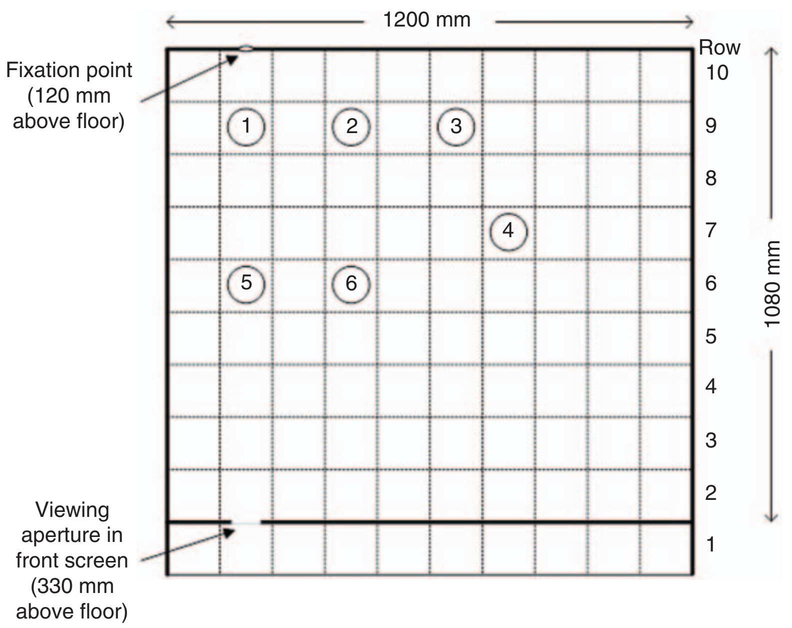

Figure 5 Plan of obstacle detection test booth to show the location of the obstacles

2.3 Procedure

Each test session commenced with 20 minutes dark adaptation during which time the test procedure was explained and colour vision was tested using the Ishihara test charts – all test participants were colour normal.

The test participant looked through the aperture with their right eye (the left was covered with an eye patch or by their hand, according to the participant's preference) and 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 in individual exposures to illustrate their location. 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 300 ms, and the observer instructed to report if a raised block was present by stating its identification number (1–6), or to state 'none' if no raised obstacles were noticed. There were 144 presentations (3 illuminances × 6 obstacles × 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). Breaks of approximately 2 minutes were included on completion of the first, second and third quarters of the stimuli sequence to allow test participants to relax their eyes. Participants attended three separate 2-hours 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.

3. Results and analysis

3.1 Test results

An example of the test results is shown in Figure 6, 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 6 are the experimental results, the frequency with which an obstacle of a given height was detected. The intention of these tests is to compare under different lighting conditions the threshold size at which an obstacle will be detected. A threshold is not an absolutely fixed value and by convention the threshold is the point at which subjects detect the stimulus 50% of the time.

The curves in Figure 6 are the best-fit curves for each lamp type as fitted using the four parameter logistic equation (4PLE). Examples of application of this equation to visual detection data can be seen in Harris[22] and to other visual responses.[23–25] For the current analysis the 4PLE can be expressed as:

$$y = 100 - \frac{100}{1 + (h/h_{50})^s}$$

where y is the detection rate (%), h is the height of obstacle, h_{50} is the height of obstacle at which $y = 50\%$ and s is the slope of curve when $h = h_{50}$.

Best-fit lines were established by varying h_{50} and s to minimise the root-mean-squared error between the detection rates found by experiment and the values predicted by the equation. For each obstacle × lamp × illuminance this included the complete range of detection heights, these ranging from near zero to near 100% detection. As expected, the curves are S-shaped, with changes in obstacle height causing a rapid change in detection rate in the middle of the range, but becoming flatter near the ends of the range of heights where detection approaches 0% or 100%.

Table 5 shows the obstacle height at which 50% detection is predicted by the 4PLE for each obstacle location × lamp × illuminance combination, for the older and younger subjects separately and combined.

Figure 7 shows the overall effect of lamp type, illuminance and age on obstacle detection. The data points are the mean detection heights (h_{50}) for each lamp × illuminance × age combination averaged across the four

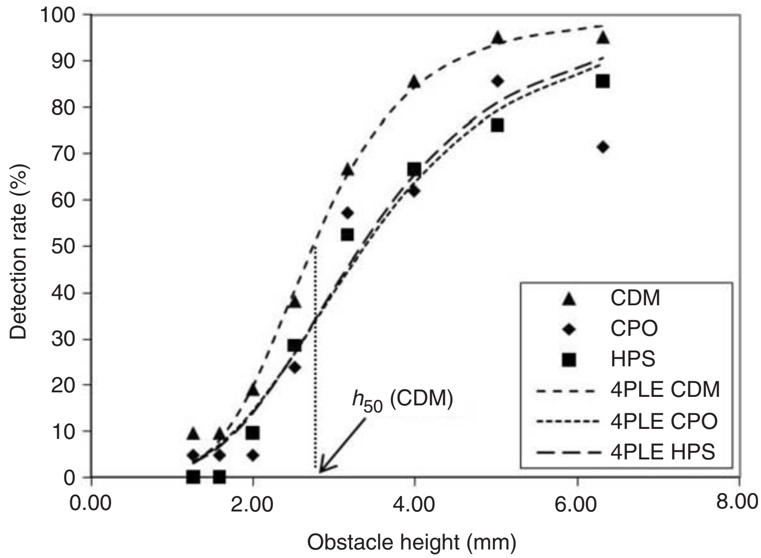

Figure 6 Sample test result: detection rate (%) for obstacle #2 at 0.2 lux for the older and younger age groups combined

Table 5 Obstacle height for 50% detection (h_{50}) as determined using Four Parameter Logistic Equation fitted to the test results. Yng. = young age group; Old = old age group; Comb. = young and old age groups combined

	Obstacle height (mm) for 50% detection (h_{50})								
Lamp	CPO			HPS			CDM		
Age group	Yng.	Old	Comb.	Yng.	Old	Comb.	Yng.	Old	Comb.
Obstacle #	Illuminance = 0.2 lux								
1	2.41	2.68	2.55	2.67	3.19	2.91	2.17	2.61	2.36
2	3.17	3.56	3.37	3.07	3.63	3.32	2.33	3.16	2.73
3	2.35	4.11	3.07	2.87	4.45	3.34	2.29	3.27	2.59
4	2.48	3.56	2.97	2.83	4.15	3.24	1.74	3.37	2.40
	Illuminance = 2.0 lux								
1	1.30	1.22	1.25	1.29	1.32	1.31	1.24	1.23	1.23
2	1.84	1.78	1.81	1.77	1.58	1.68	1.64	1.51	1.58
3	1.16	1.49	1.31	1.20	1.63	1.38	1.30	1.50	1.37
4	1.16	1.76	1.41	1.37	1.65	1.49	1.21	1.73	1.41
	Illuminance = 20 lux								
1	1.06	1.00	1.03	1.18	1.02	1.12	1.02	0.91	0.97
2	1.43	1.33	1.38	1.30	1.21	1.25	1.34	1.21	1.26
3	0.73	1.11	0.88	0.82	1.10	0.93	0.76	1.05	0.89
4	1.12	1.08	1.10	0.82	1.29	1.05	0.71	1.25	0.91

obstacle locations. It can be seen that illuminance and age affect obstacle detection, with younger participants being able to detect smaller targets than older participants, and height needed for 50% detection increasing as illuminance decreases. Lamp type appears to affect obstacle detection, although only at the lower illuminance, with the CDM lamp providing the best obstacle detection ability and the HPS lamp providing the poorest obstacle detection ability.

3.2 Analysis of results

Three variables are examined – lamp type, illuminance and age. The data were examined statistically by comparison of obstacle heights yielding 50% detection (h_{50}) under different lamps and illuminances, and this was done by considering each *obstacle* × *age* to be an individual case. A lower h_{50} indicates better obstacle detection performance.

The current data were not found to be drawn from a normally distributed population and hence non-parametric statistical tests were used. While parametric tests may be misleading because of non-normal distribution, they have greater power for detecting differences associated with a variable than do non-parametric tests.[26] Hence, the statistical analyses were subsequently checked using parametric tests and conclusions were drawn by interpretation of both analyses. With repeated application of a statistical test there is an increased risk of making a type I error – erroneous rejection of the null hypothesis. This risk was addressed by considering the overall pattern of results in addition to individual cases.

Figure 7 suggests that at 0.2 lux obstacle detection under the CDM lamp appears to be

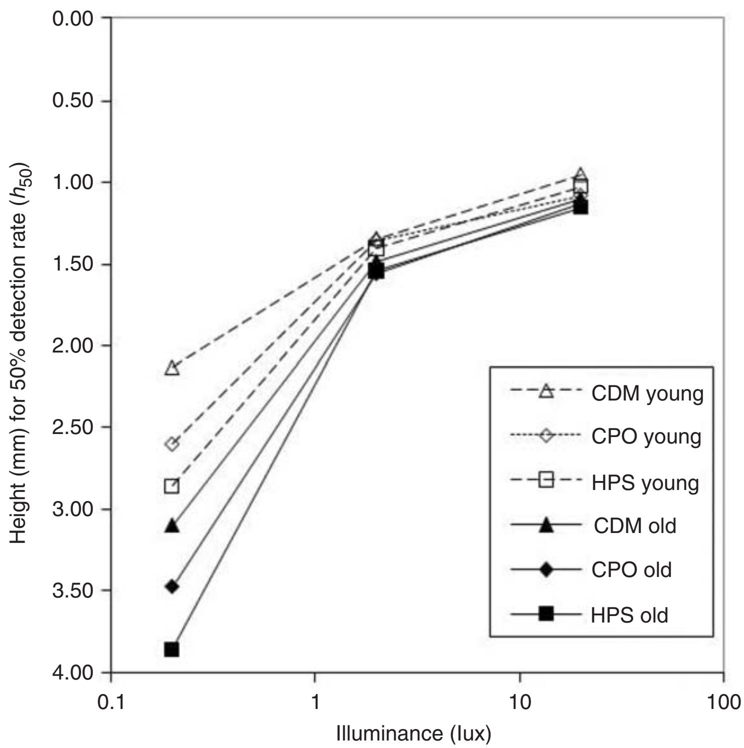

Figure 7 Mean detection height for 50% detection probability of obstacles 1–4 plotted against illuminance for the three test lamps and the two age groups. Note: smaller values of h_{50} imply better obstacle detection ability

better than the other lamps while the HPS lamps appears to give the worse obstacle detection performance; 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 other than between the CDM and HPS at 20 lux ($p < 0.05$): this one significant result does not follow the trend set by the other analyses and is not apparent in Figure 7, and is hence considered to be a type I error. These findings were confirmed using ANOVA and matched pairs *t*-tests.

Figure 7 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. These findings were confirmed using ANOVA and matched pairs *t*-tests.

At the lower illuminance Figure 7 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 ($p = 0.34$).

3.3 Null condition results

The quality of the decisions made in this experiment can be evaluated through analysis of null condition data and by applying signal detection theory. Here, decision quality means how well test participants avoided making incorrect responses. Correct responses are hits, saying yes when the stimulus is present, and correct rejections, saying no when the stimulus is not presented; incorrect responses are false alarms, reporting the presence of an obstacle when none are raised, and misses, saying no when the stimulus is presented.

Together with the 144 raised obstacles presented in a single test session the participant also saw 18 null conditions (six per illuminance) where no obstacles were raised. Table 6 shows that on some occasions participants reported seeing a raised block even though none were presented.

There were 1134 null presentations in total. The 155 false alarms identified in Table 6 represent a probability of 0.137. Figure 8 shows the pattern of false alarm probability according to the lamp type, illuminance and observer age. There is a tendency for the probability of false alarms to increase with illuminance. This may be because at higher illuminance, and hence higher brightness, there is a higher expectation of being able to detect an obstacle and test participants were thus biased to making a false alarm. There is a tendency for lamps of higher S/P ratio to appear brighter, and for the lamps used in the current work this would suggest the CDM lamp as brightest and the HPS lamp as least bright: Figure 8 shows the CDM lamp has the highest probability of a false alarm and the HPS lamp has the least probability of a false alarm, and this again suggests the tendency

Table 6 Number of false alarms found during the trials. These are the number of occasions when test participants reported seeing a raised obstacle when none had been raised. The total number of null conditions per illuminance x lamp combination is 66 for the younger age group ($n=11$) and 60 for the older age group ($n=10$)

	Number of false alarms								
	0.2 lux			2.0 lux			20.0 lux		
Observer age group	HPS	CPO	CDM	HPS	CPO	CDM	HPS	CPO	CDM
Young	2	2	8	5	6	8	10	7	9
Old	7	9	9	8	12	12	10	15	16

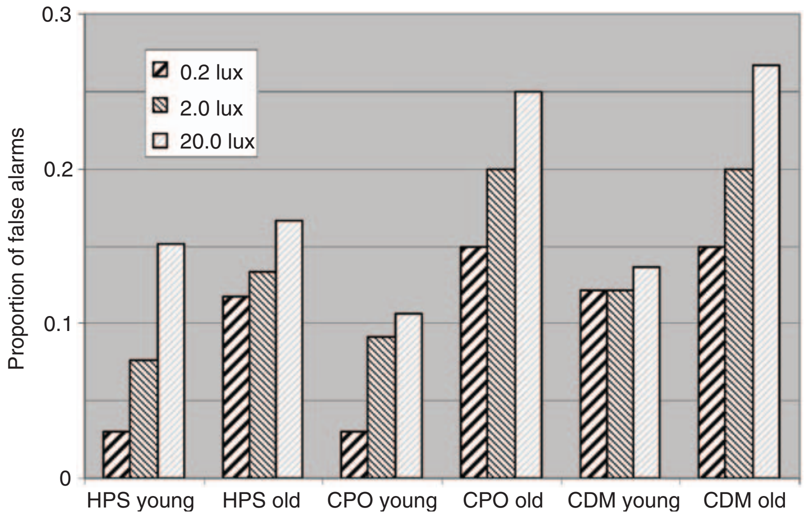

Figure 8 Probability of false alarms. These are the proportion of the null presentations on which the participants reported seeing a raised obstacle

for test participants to expect to be better able to detect obstacles at higher brightness. For each lamp × illuminance the probability of false alarms is higher for the older age group than for the younger age group.

Signal detection theory (SDT) is a system for analysing how well subjects are able to discriminate between a signal (stimulus) and noise (background stimuli and random activity of the nervous system) – in this case, to discriminate whether or not a raised obstacle was present.[27] Response bias is the tendency to say yes or no when unsure of detecting a stimulus. This might be an error in favour of detecting all stimuli at the risk of making false alarms, or alternatively a cautious approach at the risk of making misses. Such bias affects estimates of the threshold of detection. The sensitivity index (d') is a measure for analysing response bias. d' describes the detectability of a signal – how well the presence or absence of the signal (in this work a raised obstacle) can be distinguished. Values of d' near zero indicate chance performance (no discrimination) and a higher d' indicates that the signal can be more readily detected. If performance was no better than chance it would suggest that either the experimental design did not provide an appropriate visual task or that the sample of test participants were not motivated to perform the task properly. For the current results the sensitivity index (d') is above zero in all cases, which suggests better than chance performance (the full analysis is reported elsewhere[21]).

The null condition data and SDT both suggest that the current data are of good quality; test participants tended to report detection of an obstacle only when there was an actual obstacle present and to report no detection when obstacles were absent.

4 Mesopic visual efficiency

Systems of mesopic visual efficiency based on visual performance were recently proposed, the MOVE model[28] and Unified Luminance,[29] and Table 7 compares predictions made using these systems 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 luminance 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 in Figure 9.

Figure 9 is drawn from the same data as Figure 7 and shows the obstacle height for 50% detection (h_{50}) for obstacles 1 to 4 at luminances corresponding to the three test illuminances and for the three test lamps. Best-fit lines are drawn for each of the three test lamps and these are used to interpolate obstacle detection ability (h_{50}) under other luminances. Linear best-fit lines provide a good fit to the data ($r^2 > 0.8$) but conceal the different rates of change of h_{50} with illuminance – the larger rate of change in h_{50} between the 0.2 and 2.0 lux and the smaller rate of change in h_{50} between 2.0 and 20 lux. Connecting the mean h_{50} data points reveals this (Figure 7) but would confound comparison of interpolated values just above and just below the point of inflection, a particular problem because the location (luminance) of this inflection is not known. The best-fit lines are hence drawn using the equation $h_{50} = aL^b$ which achieves a correlation coefficient of $r^2 > 0.85$ for all three lamps, and does exhibit a slight change of effect with luminance. This provides a compromise between the linear fit and simply connecting the mean values.

The data in Table 5 are used as a guide as to what is a meaningful difference in h_{50} values. At 0.2 lux the mean difference in the height of obstacles 1 to 4, for the combined age groups under the HPS lamp and the CDM lamp, is 0.21 mm, while at 2.0 and 20 lux the mean differences are 0.02 mm and 0.01 mm, respectively. This suggests a difference of 0.21mm or more represents a significant difference in obstacle detection.

Firstly consider the MOVE model. At the HPS photopic luminances of 0.1 and 1.0 cd/m^2

Table 7 Obstacle detection (h_{50}) predicted for the HPS, CDM and CPO lamps at photopic luminances defined by equal mesopic luminances

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

the predicted values of h_{50} in Table 7 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 7 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.

Table 7 could be interpreted as suggesting that HPS lighting enables smaller obstacles to be seen than under CDM or CPO lighting, but this is erroneous. It is not that the HPS is better, but rather that the CPO and CDM do not provide as good obstacle detection as the models predict.

5. Conclusion

This work examined the effect of light source, illuminance and observer's age on the ability to detect an obstacle simulating a raised paving slab, presented for 300 ms in four different positions relative to the line of fixation. The light sources used were a HPS, a metal halide lamp of CCT 4200K (CDM) and a metal halide lamp of CCT 2700K (CPO). The illuminances used were 0.2 lux, 2.0 lux and 20 lux, measured on the paving surface. These illuminances cover the range of those recommended for subsidiary streets and ensure the human visual system is operating in the mesopic state. Two age groups were used as observers, one group being less than 45 years of age and the other being more than 60 years of age. The positions of the obstacle varied from 0° to 42° to the right of fixation and were from 8° to 10 degrees below fixation.

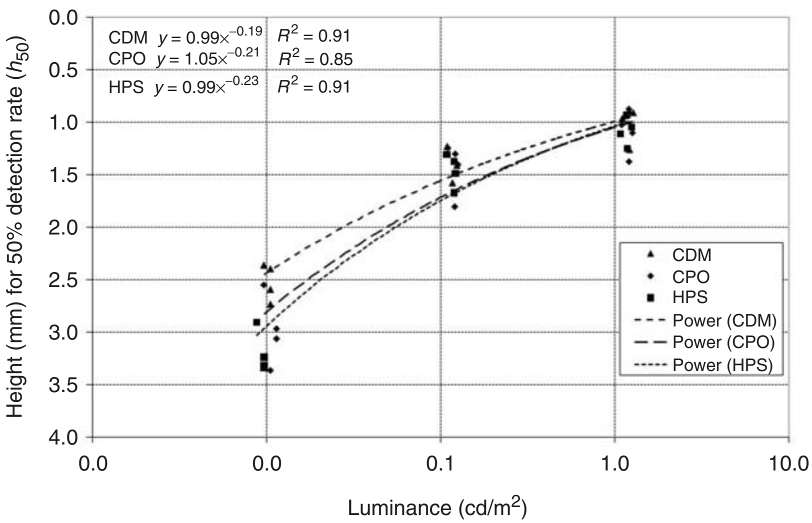

Figure 9 Height at which 50% obstacle detection is found plotted against luminance (obstacles 1–4). The three luminances correspond to the three test illuminances, 0.2 lux, 2.0 lux and 20 lux. These are the data also presented in Figure 7

The data collected were used to determine the height of the obstacle above the paving surface required for 50% detection at each position, for all combinations of light source, illuminance and age. A lower height for 50% detection suggests better obstacle detection ability. From these detection heights it was determined that:

- Obstacle detection was influenced by the illuminance, the 50% detection height being less at 20 lux than at 0.2 lux.
- At 0.2 lux, the CDM lamp gave the smallest 50% detection height while the HPS light source gave the largest. The 50% detection height for the CPO was in between these – larger than the CDM but smaller than the HPS. There were no statistically significant differences between the 50% detection heights for the three light sources at 2.0 and 20 lux.
- The young observers showed the smaller 50% detection height at 0.2 lux but at 20 lux there was no difference in 50% detection height for the two age groups.

It is concluded that lamp type can affect obstacle detection, and that the effect is weak when approaching the photopic state and increases as the (photopic) luminance decreases through the mesopic range toward the scotopic. This change in effect with illuminance is as seen in other peripheral visual performance tasks.[8,30]

At 0.2 lux, the effect of lamp type on obstacle detection follows the S/P ratio of the lamps: the CDM lamp has the highest S/P ratio of the lamps used in these tests and, where lamp type affected obstacle detection, the CDM lamp had the better obstacle detection ability. Similarly the HPS lamp had the lowest S/P ratio and tended to provide the poorest obstacle detection ability. At higher illuminances, there is no apparent relationship between obstacle detection and lamp S/P ratio. The MOVE and Unified Luminance systems of mesopic visual efficiency were applied to make predictions of obstacle detection: the analysis suggests some disparity between the test data and the visual efficiency models at the lower illuminance (0.2 lux) but little difference in accuracy of predictions between the two models.

The difference between the older and younger subjects was that at 0.2 lux the older subjects tended to require obstacles to be raised to a higher level for 50% detection than did younger subjects. This suggests a decrease in the rod response, which may be due to the lens yellowing with age and decreasing transmittance in the short-wavelength region.

Acknowledgements

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Disscussion

Comment 1:

P Raynham (The Bartlett School of Graduate Studies, University College, London, UK)

The study by Fotios and Cheal is very useful as it presents another piece of evidence that we need to consider the way we light our streets at night. Whist one can argue that the task used in the study does not truly represent what pedestrians do when walking on the streets at night it does give some indication of the likely change in performance with age, illuminance and source spectrum. The findings with regard to age and illuminance are fairly intuitive but even so it is nice to see confirmation. The interesting result from my point of view is the results with regard to source spectrum. The trend towards improved performance when using sources with higher scotopic to photopic ratio is what one would expect. However, the fact that these findings do not fit easily into one of the existing models of mesopic vision leads one to think that the processes involved with the task of obstacle detection are complex and do not easily fit into a simple model of mesopic photometry. One interesting point to note is that age was a more important factor in obstacle detection than source spectrum.

I have previously worked on another pedestrian task, that of facial recognition. In this area too there are plenty of findings that the spectrum of the light source is important but it is still not clear if the effect is due to colour rendering or scotopic to photopic ratio. Again it seems to be that this is a topic that does not fit nicely into a model of mesopic photometry. This leads me to suggest that time has now come where we need to conduct a thorough investigation into the lighting required for pedestrians. Such a review is very much overdue as no holistic study of the subject has been carried out for the best part of 30 years and previous studies paid minimal attention to source spectrum. Given the need to reduce the energy used for lighting the streets and the aging population such a study is needed to work out the optimum way to light residential roads and give the details of any trade off in lighting level against benefits of street lighting.

Comment 2:

MS Rea and JD Bullough (Lighting Research Center, Rensselaer Polytechnic Institute Troy, NY 12180 USA)

Fotios and Cheal provide new data on visual performance at mesopic light levels using an interesting visual stimulus. A variety of studies have now appeared in the literature demonstrating that the relative contribution of rods and cones to visual performance changes systematically with light level.[1–10] An *a posteriori* assessment of their data can be performed to compare the precision of specifying the visual stimulus using a photopic luminous efficiency function [$V(\lambda)$] with that using a more complicated set of mesopic functions that combine $V(\lambda)$ and the scotopic luminous efficiency function [$V'(\lambda)$] in different proportions, depending upon light level. Figure 1 compares the functional relationship between the 50% constant criterion response in the present experiment and luminance, as characterised by $V(\lambda)$ and by mesopic functions from the Unified System of Photometry.[11] Of interest, the MOVE formulation[12] provides identical results as to the best fitting equations and the goodness-of-fit (r^2) values.

As can be seen from Figure 1, mesopic characterisations of the stimuli explain more variance in the data, but only marginally more than a photopic characterisation of the stimuli. Mulder and Boyce[6] similarly found only marginal differences between a mesopic and a scotopic characterisation of their stimuli for an emergency lighting application.

Nevertheless, and without any question, a comprehensive system of photometry, spanning $V(\lambda)$ and $V'(\lambda)$ through the mesopic region is better for characterising visual stimuli than the limited system we use today based solely on $V(\lambda)$; both theory and empirical data

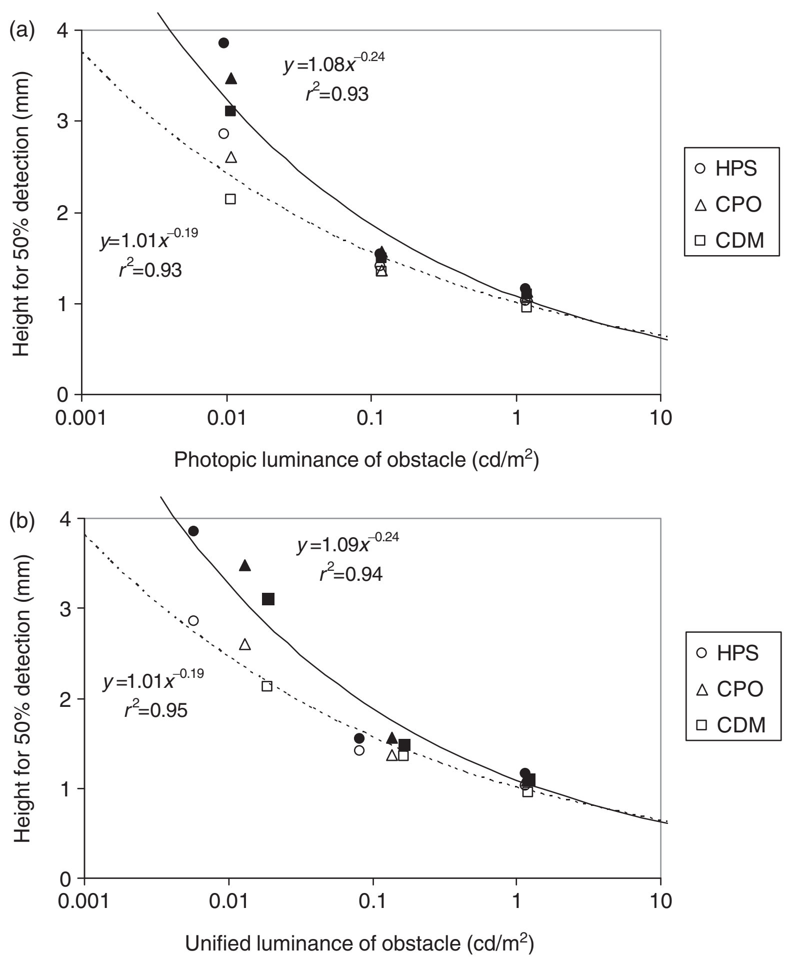

Figure 1 Mean object heights for 50% detection (collapsed across all four objects) as a function of (a) photopic luminance, and (b) unified luminance for each light source used by Fotios and Cheal. Filled symbols: older group; open symbols, younger group

support the development of such a comprehensive system. Yet, it must be recognised that the improvements in describing the stimuli for visual performance experiments are rather modest when one considers the full range of light levels provided by electric lighting (e.g. two orders of magnitude in the present study, and more than four in Mulder's and Boyce's study[6]). Uncertainty in the equations relating visual stimuli to visual performance over a wide range of light levels is not, however, the best criterion to consider when deciding whether a comprehensive system of photometry should be embraced by the lighting industry. Notwithstanding the essential orthodox tenets underlying photometry,[11,13] vision changes in (approximately) logarithmic steps with light level, but energy and cost change in arithmetic steps with light level. In other words, small changes in light level make almost no difference to the visual system, as seen in Figure 1, whereas small changes in light level can make measurable and important changes in energy use and cost of operation. These energy and cost changes will matter a great deal to those who have to pay for those differences.

Therefore, it becomes important to shift gears in our collective lighting research agenda toward one more focused on *a priori* hypothesis testing of specific, more precise experimental questions about mesopic vision as they might impact a comprehensive system of photometry. Two broadly consistent comprehensive systems of photometry have now been published, the Unified System of Photometry from our centre[11] and another from the MOVE consortium.[12] These two systems weight $V(\lambda)$ and $V'(\lambda)$ slightly differently with changes in light level.[13] Since small differences can make a large difference in energy use and cost, a more focused and precise set of visual performance data could inform the development of a more refined and comprehensive system of photometry than the two currently under consideration. We strongly encourage the authors of the present paper to continue their work with this important objective in mind.

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Reply to comment:

S Fotios and C Cheal

We are pleased that work with this novel apparatus seems to have been well received. Rather than being a true representation of the task of a person walking along a street, the apparatus presents an abstract task which attempts to isolate the visual component of obstacle detection, hence to determine how lighting affects the visual component. There was also the advantage of being able to collect a large amount of data within a reasonable timeframe.

We disagree that the effect of age was intuitive, in particular the interaction between age and illuminance. With regard to expected effects of age on visual performance[1] we were surprised that the difference between the younger and older age groups was not significant at 20.0 lux, as it was at 0.2 lux.

Raynham suggests that the effect of age appears to be a more important factor in obstacle detection than light source spectrum; any such effect may be due to the choice of levels within the independent variables. We intentionally chose to leave a large interval between the two age groups to reveal any effect of age, the young group being less than 45 years old and the old group being more than 60 years old. Similarly, a luminance range of two log units was chosen to ensure an effect on obstacle detection would be revealed if there was one, thus to provide some validation of the apparatus. Lamps were chosen to suit practical issues rather than to test directly mesopic visual efficiency, and this means the lamp spectrum effect reported may not be as strong as it could be. We are intending to carry out further work with this apparatus and this will include consideration of lamp spectrum characteristics as suggested by Rea and Bullough.

Obstacle detection and facial recognition are often suggested to be two critical tasks for pedestrians at night-time. The current work is the first direct examination of obstacle detection; further validation is needed. Of four studies which have examined lamp spectrum and facial recognition, two report a significant effect of light source spectrum[2,3] and two suggest a negligible effect.[4,5] Further consideration is needed to resolve this conflict. We agree with Raynham that an investigation of the fundamental requirements of lighting for pedestrians is long overdue; improvements in understanding of mesopic vision and in the technology of lamps and luminaires suggest there is much scope for improvements in street lighting.

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