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Road lighting for pedestrians: Effects of luminaire position on the detection of raised and lowered trip hazards

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Abstract
Previous work investigating how lighting enhances peripheral detection for pedestrians has tend to consider only raised hazards and lighting from a directly overhead source. An experiment was conducted to determine the extent to which variations in these parameters would influence the recommendations for optimal lighting. The results did not suggest a difference in the detection of raised and lowered trip hazards of the same change in vertical height relative to ground level. The results suggest that variation in light source position relative to the target does have a significant effect: to establish the implication of this requires further work to investigate detection under the least-favourable spatial arrangement.

1 Introduction

Lighting along minor roads is designed for the needs of pedestrians.[1,2] A key visual task of pedestrians is the detection of pavement hazards which might otherwise lead to a tripping accident if not seen in sufficient time to take avoiding action. Evidence for this comes from application experience,[3] the findings of eye tracking carried out in outdoor environments,[4] accident records[5-7] and studies focussing on the elderly.[8-10] In England, from 2007-2009, approximately 26,000 pedestrians were injured in road traffic accidents with vehicles: in comparison, over the same period approximately 76,000 pedestrians were hospitalised from falls on the highway.[11] Research in New Zealand found that around 700 pedestrians were admitted to hospital each year as a result of slips, trips and stumbles in the road environment.[7] It is therefore necessary to study the relationship between road lighting design and the ability of pedestrians to detect pavement obstacles after dark.

Table 1 shows previous studies investigating obstacle detection under variations in the illuminance and spectral power distribution (SPD) of lighting.[12-14] Under road lighting conditions the visual system is expected to be adapted to light levels in the mesopic range, where the effect of changes in SPD on the detection of peripheral targets is characterised by the ratio of scotopic and photopic luminances (S/P ratio).[15] These results suggest that higher illuminances and higher S/P ratios increase the probability of detecting an obstacle. The results also show that this association reaches a ceiling in the region of 2.0 lux beyond which further increases in illuminance bring a negligible increase in detection and variation in S/P ratio leads to negligible change. Furthermore, at illuminances less than approximately 2.0 lux, the difference in detection of peripheral obstacles is significantly lower for older people than for younger people. As shown in Table 1, these results have been established under a range of test conditions.

A review of foot clearance when walking, injury records and trip probability suggested that the critical height of an obstacle is 10 mm; a review of eye tracking records suggested that obstacles tend to be detected a distance ahead of 3.4 m.[16] Interpolation of the results of past studies suggested that an illuminance of 1.0 lux is required to detect a hazard of this size, and that variation in SPD and observer age have a negligible effect.[16]

Two uncertainties of the past studies were that the obstacles were always raised relative to the surrounding pavement and tended to be located directly beneath the source of lighting. In reality, trip hazards also occur in the form of lowered or sunken sections of pavement, such as potholes. Variation in the locations of the obstacle and lighting relative to the observation point change the luminance of the facing side of the obstacle and hence the contrast and shadow pattern, factors which may influence their detection probability. This article describes an experiment carried out to explore whether these uncertainties have significant effect on the recommended illuminance of 1.0 lux.

One reason to suspect that raised and lowered hazards might be detected differently is that we tend to observe them differently. This was investigated by Cheng *et al*[17] who used eye tracking to record the gaze behavior of people walking along a 13 m corridor towards an approaching pavement hazard – a raised or lowered step. Two of the measures recorded were the number and duration of fixations toward the hazard (Table 2). The ratios for raised to lowered steps suggest that raised and lowered hazards are observed differently and also show different trends for the older (65-74 years) and younger (25-34 years) groups of test participants. For the younger group, these ratios are greater than 1.0 in each case, meaning a tendency to devote more and longer fixations towards raised hazards than to lowered hazards. However, for the older group, these ratios tend to be less than 1.0.

Table 1. Past studies investigating the effects of illuminance and SPD on the detection of peripheral obstacles

Study	Experimental design			Participants		Lighting conditions	
	Task	**Observation period**	**Participant's position**	**Younger (<45 y)**	**Older (>50 y)**	**Target illuminances**	**SPD**
Fotios and Cheal, 2009[12]	Forced-choice; which of 6 obstacles was raised.*	300 ms	Seated	11	10	0.2, 2.0, 20.0 lux	Three types of lamp (HPS and two types of MH lamp)
Fotios and Cheal 2013[13]	Forced-choice; which of 4 obstacles was raised.*	300 ms	Seated	4	0	0.20, 0.63, 2.00, 6.32, 20.0 lux	One HPS lamp
Uttley *et al* 2017[14]	Detection rate and detection height of a slowly rising obstacle	Continuous	Walking on a treadmill	15	15	0.2, 0.6, 2.0, 6.3, 20.0 lux	Three S/P ratios (S/P=1.2, 1.6 and 2.0)

*In these tests, the task response was primarily yes/no (is there an obstacle) with location used to indicate a correct response rather than a false positive.

Table 2. Characteristics of gaze behaviour toward an approaching obstacle, for younger and older test participants. These data were estimated from Figures 5 and 6 of Cheng *et al.*[17]

Observer age group	Variation in hazard height (mm)	Number of fixations			Fixation duration (%)		
		Raised step	Lowered step	Ratio	Raised step	Lowered step	Ratio
Younger	30	2.85	2.60	**1.10**	5.15	4.60	**1.12**
	60	3.20	2.35	**1.36**	5.20	3.90	**1.33**
	90	3.25	2.40	**1.35**	5.75	4.05	**1.42**
	125	3.65	2.90	**1.26**	6.30	5.25	**1.20**
Older	30	3.65	3.70	**0.99**	5.90	5.70	**1.04**
	60	3.30	3.65	**0.90**	5.75	5.90	**0.97**
	90	2.80	3.55	**0.79**	4.90	6.00	**0.82**
	125	3.50	4.05	**0.86**	5.70	6.40	**0.89**

Note: (1) Ratio = raised step/lowered step; (2) Fixation duration (%) is the proportion of the overall fixation duration in each trial to the trial time.

2. Method

2.1. Apparatus

The experiment was set up in a single booth (Figure 1) located in a laboratory to which daylight was excluded. A single booth (2090 mm depth × 1200 mm width) was constructed from medium-density fibreboard (MDF). The vertical surfaces and visible rear section of the ceiling were matt black. The surface of the pavement, the tops and sides of the obstacles, and the inner surfaces of the tubular housing of each obstacle (which became visible when an obstacle descended, thus representing the sidewall of a pavement hollow, pothole or depression) were all painted in Munsell N5 matt grey. The front of the booth was open for participants to observe the interior (Figure 1). A rectangular screen displaying a fixation mark was placed at the back of the booth. A chin rest was positioned at the front of the test booth to maintain a constant location relative to the task. The horizontal distance between the centre of the fixation mark on the screen and the participant's eyes (with head positioned on the chin rest) was 2290 mm.

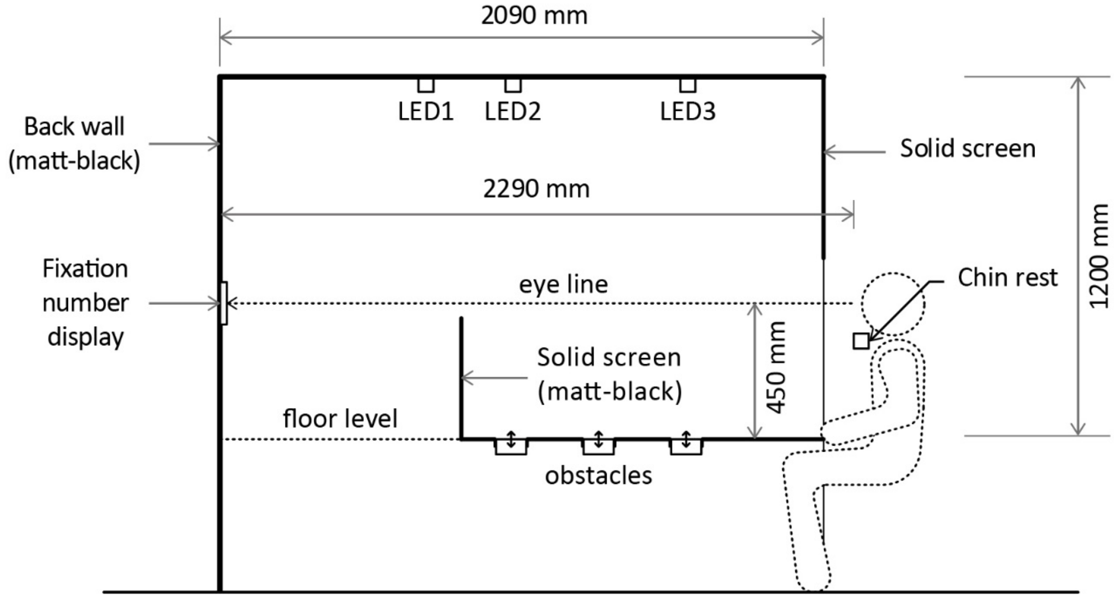

Figure 1. Side elevation of apparatus.

The test booth was lit from above by three identical LED luminaires, each containing an array (Osram Ostar Stage) comprising four chromatically different LEDs, thus allowing the luminance and spectral power distribution (SPD) of each LED luminaire to be tuned. A 45mm-diameter lens and diffuser (3mm thick opal Perspex) in front of each array promoted colour-mixing, and a small tubular baffle (40 mm diameter, 35 mm long) constrained the light distribution. The three LED sources were installed along the same central line as the participant, at three different distances relative to the obstacles (Figure 2). A vertical black screen above the participant blocked a direct view of the overhead luminaires.

The effect of changes in S/P ratio has been investigated in previous work,[12,14] these suggesting changes in SPD have a significant effect only at illuminances less than 0.2 lux. For the current work SPD was held constant, with an S/P ratio of 1.6 chosen as it was the middle of the three S/P ratios used in previous work.[14]

The participant wore a pair of PLATO visual occlusion spectacles that accurately controlled presentation time (Figure 3).[18] In the open state, participants were able to look through the spectacles as with normal clear lenses. In the closed state, the lenses totally diffuse the image so that the participant was not able to resolve visual details of the scene. Whilst closed, however, the lenses still transmit light, helping to maintain visual adaptation in the intervals between trials. With open shutters, the spectacles allowed

90% light transmission compared to 62% with closed shutters (measured using the test light source). The spectacles had a small effect on the light spectrum: S/P ratio decreased from 1.60 (spectacles not present) to 1.57 with open shutters and to 1.56 with closed shutters. Transitions between the fully-open and fully-closed states of the liquid crystal shutters take approximately 4 ms according to the manufacturer.

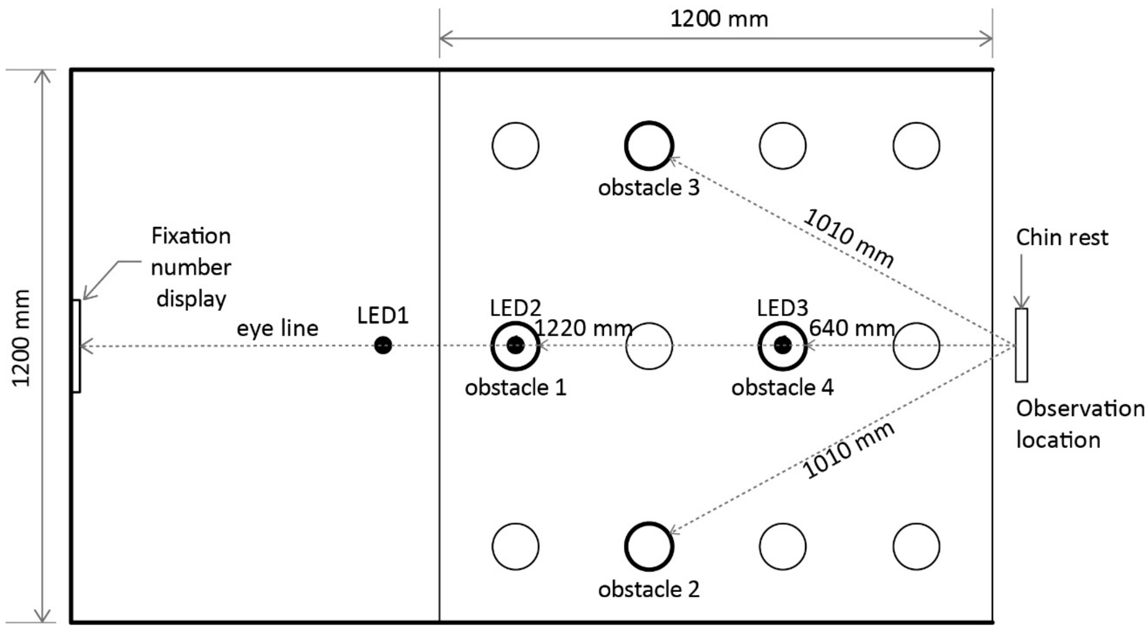

Figure 2. Top view of apparatus.

Figure 3. Side-by-side photos of occlusion spectacles with shutters closed (left) totally diffusing the scene, and open (right) allowing an unobscured view.

In order to place the obstacle detection task in the peripheral visual field a concurrent fixation task (number recognition) was displayed on a small LCD screen mounted in the centre of the back wall of the booth at the same height as the participant's eye. The fixation task presented sequentially two random single digit numbers (1-9) within the 500 ms duration of each trial. These were in a regular Arial font, 100 mm high and white (luminance 0.25 cd/m^2) on a black background. At the viewing distance of 2,290 mm the numbers subtended an angle of 2.57 degrees at the participant's eye.

The floor of the booth represented a level pavement including 12 circular (100 mm diameter) insets in a regular pattern (Figure 2). Four of the circles were the tops of cylindrical obstacles normally level with the surrounding pavement but which were able to move up or down by as much as 25mm on servo-driven linear slides.

Of the four active obstacles (Figure 2), obstacles 1 and 4 were located on the centre line of the chamber, directly ahead of the observer if walking towards the fixation screen, with obstacle 1 towards the rear and obstacle 4 towards the front of the booth. These had horizontal distances of 1,220 mm and 640 mm from the observation position. Obstacles 2 and 3 were symmetrically located to the left and right of the centre line, at a horizontal distance of 1,010 mm from the observer's eyes. Visual angles to each obstacle, assuming the participant was looking directly ahead at the fixation target, are given in Table 3.

Table 3. Obstacle locations relative to fixation point.

Target	Angular deviation of obstacle from fixation point (degrees)		
	Down	Left/Right	Central angle
Obstacle 1	19.7	0	19.7
Obstacle 2	23.0	24.3	33.0
Obstacle 3	23.0	24.3	33.0
Obstacle 4	33.7	0	33.7

Surrounding each obstacle was a gap of 3-4 mm, a tolerance to allow free vertical movement. When flush with the floor, this gap created a shadow (Figure 4) and so the eight inactive obstacles were constructed to have the same gap appearance and the resulting visual noise was consistent across the obstacle field.

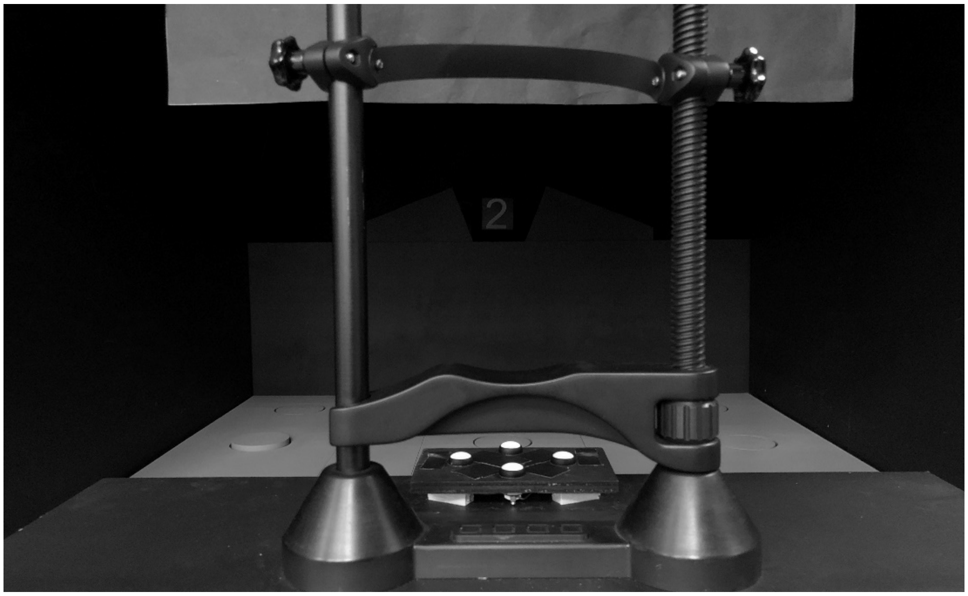

Figure 4. The scene from just behind the observer's position, photographed under daylight from the laboratory windows. Immediately in front of the chin rest is a button box, which was used by test participants to indicate a detected obstacle. In this photograph, Obstacle 2 is raised.

Although moving obstacles made little sound, a masking noise was added to rule out audible cues that otherwise may have helped participants identify the occurrence and/or location of a target obstacle. This masking noise was generated by an electric motor hidden beneath the obstacle field that switched on for two seconds coinciding with the resetting of the obstacle conditions (whether or not this actually involved a moving obstacle). The masking noise was controlled by the same Python program as for the obstacles, light sources, occlusion spectacles, fixation task and response button logging.

2.2. Test variables

Four independent variables were used in this experiment: The location of the light source; location of target obstacle; obstacle configuration (above / below surrounding surface); and size (raised height or lowered depth) of an obstacle.

Four detection targets were used, and each was presented at 10 different sizes, five raised above and five lowered below the pavement surface. Of primary interest was the detection of obstacle 1 (Figure 2) when it simulated an obstacle raised 10 mm above the ground (suggested in previous work[16] to be a critical obstacle height for pedestrians). Two heights greater and lesser than 10 mm were included in trials to enable better characterisation of detection performance, these chosen to give a geometric progression ratio of 1.58 (0.2 log unit steps) based on the Bailey–Lovie acuity chart and were expected to bracket detection rates from near zero (unable to detect) to 100% (easily detectable).[19] The five simulated sizes (heights and depths) examined were thus 4.0, 6.3, 10.0, 15.9 and 25.1 mm.

Previous research suggests a tendency to detect obstacles at an average distance ahead of 3.4 m.[16] The obstacle heights and depths used in trials were scaled so that, for the different obstacle locations, they subtended the same visual angle as if observed 3.4 m ahead, with an eye height of 1.5 m above ground, as shown in Table 4.

Table 4. Size (height and depth) of the obstacles used in the experiment.

Simulated obstacle size (mm)	Obstacle number	Obstacle size (min. arc)	Horizontal distance from eye to front edge of obstacle (mm)	Test obstacle size (mm)
4.0	4	3.37	640	0.9
	2 & 3		1010	1.2
	1		1220	1.3
6.3	4	5.34	640	1.4
	2 & 3		1010	1.9
	1		1220	2.1
10.0	4	8.47	640	2.3
	2 & 3		1010	2.9
	1		1220	3.4
15.9	4	13.44	640	3.6
	2 & 3		1010	4.7
	1		1220	5.4
25.1	4	21.32	640	5.7
	2 & 3		1010	7.4
	1		1220	8.5

Note: 'Size' refers to both height above ground level and depth below ground level.

In each trial, the test booth was lit from above by one of the three LED luminaires as shown in Table 5. LED2 was located directly above obstacle 1, thus repeating the spatial arrangement of previous work,[14] and was set to provide a pavement illuminance of 1.0 lux on the top surface of obstacle 1 when flush with the ground level. The other two luminaires were used to explore the influence of spatial distribution of light. From the observer's position, LED1 was located behind obstacle 1 and LED3 was located in front of obstacle 1. The three LEDs were set to provide the same illuminance (1.0 lux on obstacle 1); the variation in position therefore meant that the luminance of the front face of obstacle 1 varied (Table 5). For each lighting condition, Table 6 shows the horizontal illuminances on the top surface of each obstacle when level with the surround, and the contrast between the luminance of the target (revealed vertical section of object) and its background (adjacent horizontal surface). Since detection is associated with target contrast against its background, these variations in luminance could affect detection performance. Specifically, the low contrast of obstacle 1 under LED3 predicts a low detection rate in this condition. Alternative approaches to exploring spatial distribution include setting each luminaire to the same luminous intensity or setting the luminaires to provide the same target luminance.

The illuminance of 1.0 lux was chosen from the studies from Boyce[20] and Fotios and Uttley[16] which suggest that 1 lux is sufficient for pedestrians of all ages to avoid trip hazards under any type of lamp. The LEDs were set to provide an S/P ratio of 1.6 (correlated colour temperature approximately 2600 K).

Table 5. Summary of lighting metrics.

Test light condition	**Illuminance (lux) ***	**Chromaticity (x, y)**	**S/P ratio**	**Luminance (cd/m^2) ****
LED 1	1.0	0.47, 0.41	1.6	0.007
LED 2	1.0	0.47, 0.41	1.6	0.01
LED 3	1.0	0.47, 0.41	1.6	0.07

Note:
*Horizontal illuminance at the centre of obstacle 1 when flush with ground level.
** Luminance of front face of raised obstacle 1.

Table 6. Illuminances on the top surface of each obstacle, when level with the surround, under each lighting condition.

Target	**Horizontal illuminance (lux) on top surface of obstacle**			**Contrast $\|(L_T-L_B)/L_B\|$**		
	LED1	**LED2**	**LED3**	**LED1**	**LED2**	**LED3**
Obstacle 1	1.0	1.0	1.0	0.91	0.86	0.31
Obstacle 2 & 3	0.14	0.24	1.38	0.91	0.88	0.64
Obstacle 4	0.06	0.18	5.88	0.91	0.94	0.86

2.3. Test procedure

Twenty participants were recruited from the students in the School of Architecture of the University of Sheffield. All test participants were young, aged 19 to 35 years, and included 10 males and 10 females. While past work (Table 2) suggests a difference between older and younger observers, for this first experiment only a younger sample was included. They received a small payment for taking part in this experiment.

Before each test, participants gave informed, written consent agreeing to continue the experiment. Under a simulated daylight source (Verivide D65), they completed a Landolt-ring acuity test and Ishihara colour test to confirm normal or corrected-to-normal visual acuity and normal colour vision. Lighting was then switched over to the test apparatus to begin adaptation of the participant's visual system to the mesopic conditions of the experiment. Over the next 20 minutes the experimenter discussed the test procedure, demonstrated the locations of the four target obstacles and corresponding response buttons, and the appearance of the fixation task. The participant completed a practice run of 10 trials to gain familiarity with the procedure.

Each trial began with the occlusion spectacle shutters closed, during which time the obstacle conditions and the first fixation number were set. Following an electronic bleep to alert the participant and a random delay of 1 to 2 seconds the spectacle shutters opened for 500 ms. The first fixation number persisted for approximately half the shutter opening time before being replaced by the second number. The spectacle shutters then closed for 4 seconds while the participant said aloud the numbers they had seen (which the experimenter recorded), the active obstacle returned to ground level and the fixation number changed to a cross. The shutters then reopened for 4 seconds allowing the participant to locate and press the response button corresponding to the obstacle they had detected (if any), and to relocate the fixation point currently displaying a cross. The shutters then closed again to initiate the start of the next trial.

Each test participant viewed all 120 combinations of the 4 obstacle locations, 10 obstacle sizes (5 higher and 5 lower than the surrounding pavement) and 3 luminaire positions. Additionally, 16 null conditions with no obstacle raised or lowered were presented for each of the three luminaire positions. The sequential order of these 168 trials was randomised for each participant.

To reduce participant fatigue, a five-minute break was offered after every block of 42 trials (which took approximately 15 minutes to complete). Overall, the experiment took approximately two hours to complete for each participant, including introductions, adaptation, practice, testing and debriefing.

3. Results

This experiment has four within-subjects factors – obstacle location, obstacle size (height or depth), luminaire position and obstacle configuration (raised or lowered relative to the surrounding surface). The one dependent variable is the obstacle detection rate. All test data were checked for normality before the main analysis by visually inspecting distribution plots of the data, checking skewness and kurtosis, and applying the Shapiro-Wilk test of normality. All data in this experiment were suggested to be drawn from normally distributed populations, and therefore, parametric tests have been used throughout. A standard significance level of 0.05 was chosen for all statistical tests.

3.1. Fixation target identification

The fixation target presented two random single-digit numbers sequentially within the observation duration (500 ms) of each trial. Overall, the mean correct identification rate for the numbers was 97% (SD = 2%), and it was thus assumed that the fixation task was sufficiently successful in holding the participant's gaze.

3.2. Null condition

Null trials were those where no obstacle was raised or lowered when the occlusion spectacles opened. Of the 960 null condition trials across all participants (each participant viewed 16 null conditions under each lighting condition) there were 238 (24.8%) false alarms where the participant incorrectly pressed a response button. This is similar to the percentage of false alarms (21.2%) found in previous work.[13]

Null condition trials enable the assessment of response bias, the tendency to say yes or no when unsure about stimulus detection, or random responding. This might be an error in favour of reporting detection in a null condition trial (a false alarm) or not reporting detection in a test trial (a miss). This is investigated using the sensitivity index, d', where a higher value of d' indicates that the target was more readily detected while a near zero value indicates an inability to distinguish the stimulus from noise, and it might suggest the design of the experiment was not appropriate or the participants were not concentrating fully on the task. This bias might affect the apparent threshold of detection.[21] The d' scores for individual test participants ranged from 0.75 to 14.43 (mean = 3.28), which is slightly better than that found in previous work (0.50 – 1.67, mean = 1.06).[13] A d' above zero suggests better than chance performance: participants tended to report detection only when an obstacle was present and not respond when obstacles were absent.

3.3. Left vs right obstacle location

Obstacles 2 and 3 were located at the same peripheral angle from the participant's line of sight on the left and right side respectively. As shown in Figure 5, no systematic variation in responses to these two obstacles was anticipated due to their symmetrical locations but to confirm this a 4-way ANOVA was carried out that only included responses to obstacles 2 and 3, with light source position, obstacle location (left/right), configuration and size (height/depth) as variables. The purpose of this initial ANOVA was to confirm whether there was a main effect of obstacle location (left vs right) or any interactions among the four variables. Therefore, main effects of light source position, obstacle configuration and size were ignored, with these factors only included in the ANOVA to examine their interaction with obstacle location.

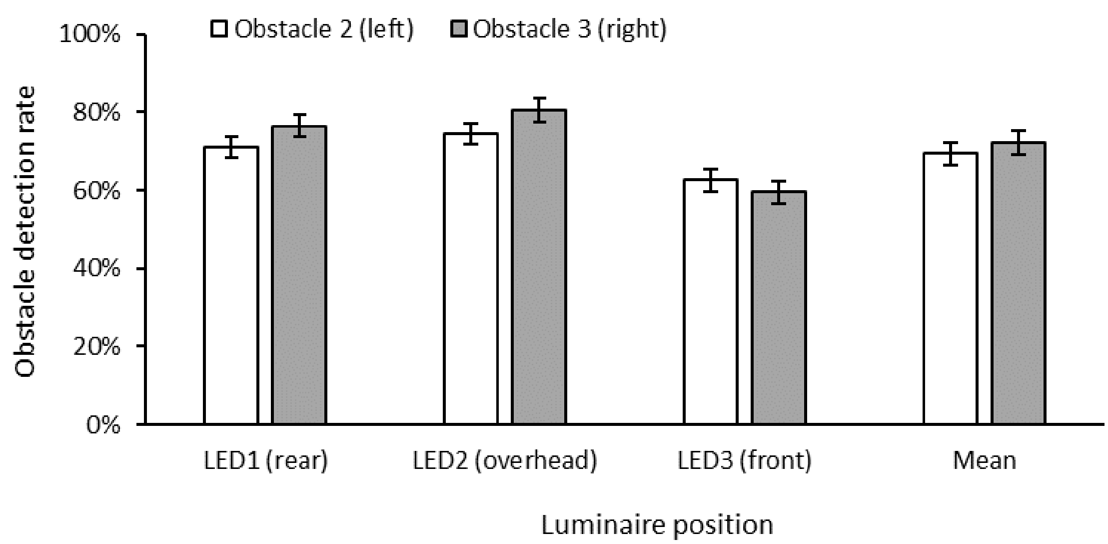

Figure 5. The detection rate of obstacle 2 and 3 under three luminaire positions, and the mean detection rate. Error bars show standard error of the mean.

The results of an initial ANOVA test are shown in Table 7, the threshold *p*-value was corrected using the Holm-Bonferroni method, to account for the multiple tests of main effect and interactions. It confirms no main effect of obstacle location when only obstacle 2 and 3 were included (p = 0.283). The interactions between obstacle location and other factors (luminaire position, obstacle configuration and size) were also not suggested to be significant.

As the ANOVA confirmed there was no systematic variation in responses to obstacles 2 and 3, response data for these two obstacles were therefore combined as a middle-distance obstacle (obstacle mid.), with the mean detection rate across both obstacles used in subsequent analyses.

Table 7. Results of initial ANOVA test for obstacle 2 and 3 (with obstacle location, and interaction with other factors).

Variable/s	F-statistic (df)	*P*-value	Corrected *p*-value threshold†
Obstacle location	1.223 (1, 19)	0.283	n/a
Obstacle location * Luminaire position	1.750 (2, 38)	0.187	n/a
Obstacle location * Size	3.306 (4, 76)	0.015	0.006
Obstacle location * Configuration	3.576 (1, 19)	0.074	n/a
Obstacle location * Luminaire position * Size	1.039 (8, 152)	0.409	n/a
Obstacle location * Luminaire position * Configuration	0.371 (2, 38)	0.693	n/a
Obstacle location * Size * Configuration	0.934 (4, 76)	0.449	n/a
Obstacle location * Luminaire position * Size * Configuration	0.399 (8, 152)	0.920	n/a

Note:

† Holm-Bonferroni (H-B) adjustment was used to test the data and their associated *p*-value at an alpha level of 0.05. The original *p*-values were ordered from smallest to greatest and then corrected *p*-value thresholds calculated using H-B alpha = Target α / (n – rank + 1). The actual p-value is compared with the H-B alpha, if the *p*-value is smaller, reject the null hypothesis for this individual test. The testing stops when the first non-rejected hypothesis is reached. All subsequent hypotheses are non-significant (labelled 'n/a').[22]

3.4. Main effects

A 4-way repeated measures ANOVA was carried out with the four independent variables being obstacle location (3 levels: back, mid and front), luminaire position (3 levels: rear, overhead and front), obstacle size (5 levels: simulating 4.0, 6.3, 10.0, 15.9 and 25.1 mm) and configuration (2 levels: raised and lowered). Obstacle detection rate was the dependent variable. Holm-Bonferroni correction was applied to account for the multiple p-values produced by the ANOVA. *Post-hoc* paired-comparisons using t-tests with Holm-Bonferroni correction were used to assess differences between levels on each variable if a main effect or interaction was significant. The overall results of this ANOVA are shown in Table 8.

As shown in Figures 6 to 9, luminaire position, obstacle location and obstacle size all revealed a significant difference while obstacle configuration did not. When lit by LED3, detection of the obstacles (mean = 52%, SD = 11%) was significantly worse than when lit by LED1 or LED2 (means = 66% and 68%, SD = 10% and 10% respectively, $p < 0.001$ in both cases). Detection rates for LED1 and LED2 showed no difference (Figure 6) ($p = 0.188$).

Table 8. Results of 4-way repeated-measures ANOVA, with obstacle location, luminaire position, obstacle size and configuration as independent variables and detection rate as the dependent variable.

Variable(s)	F-statistic (df)	*P*-value	Holm-Bonferroni corrected *p*-value threshold	Significant difference
Luminaire position	26.422 (2, 38)	<0.001	0.005	Yes
Obstacle location	11.694 (2, 38)	<0.001	0.006	Yes
Configuration	0.710 (1, 19)	0.410	n/a	No
Size	154.807 (4, 76)	<0.001	0.006	Yes
Obstacle location * Luminaire position	8.540 (4, 76)	<0.001	0.00625	Yes
Luminaire position * Configuration	3.347 (2, 38)	0.046	0.017	No
Obstacle location * Configuration	3.707 (2, 38)	0.034	0.0125	No
Obstacle location * Size	2.753 (8, 152)	0.007	0.007	Yes
Luminaire position * Size	1.167 (8, 152)	0.323	n/a	No
Configuration * Size	1.547 (4, 76)	0.197	n/a	No
Obstacle location * Luminaire position * Configuration	0.461 (4, 76)	0.764	n/a	No
Obstacle location * Luminaire position * Size	1.827 (16, 304)	0.027	n/a	No
Luminaire position * Configuration * Size	0.620 (8, 152)	0.760	n/a	No
Obstacle location * Configuration * Size	1.052 (8, 152)	0.400	n/a	No
Obstacle location * Luminaire position * Configuration * Size	1.835 (16, 304)	0.026	n/a	No

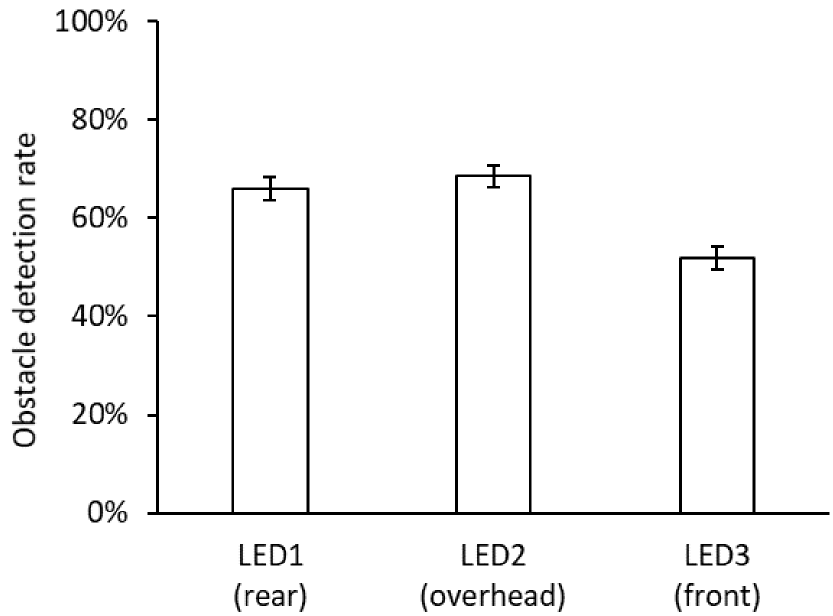

Figure 6. Mean obstacle detection rate under three luminaire positions. Error bars show standard error of the mean.

Detection performance for the mid. obstacles (mean = 53%, SD = 8%, after results for obstacles 2 and 3 were combined) was significantly better than for obstacles 1 and 4 (means = 37% and 43%, SD = 11% and 12% respectively, $p < 0\ .005$ in both cases) (Figure 7). Detection for obstacles 1 and 4 were not suggested to be different (p = 0.159).

Five obstacle sizes were used in the experiment. The obstacle detection rate increased for larger sizes (heights and depths) as can be seen in Figure 8. At the smallest simulated size of 4.0 mm the detection rate was 25% (SD = 15%), compared with a detection rate of 92% (SD = 6%) at 25 mm. A series of paired t-tests with Holm-Bonferroni correction suggested detection rates for each obstacle size were significantly different to detection rates on the other obstacle sizes ($p < 0.001$ for all comparisons), suggesting each level of obstacle size produced a different degree of performance from the participants.

Detection rates for raised and lowered obstacles were very similar (means = 47% and 47%, SD = 8% and 6% respectively) (Figure 9). The ANOVA did not suggest a significant difference between the two obstacle configurations (p = 0.410).

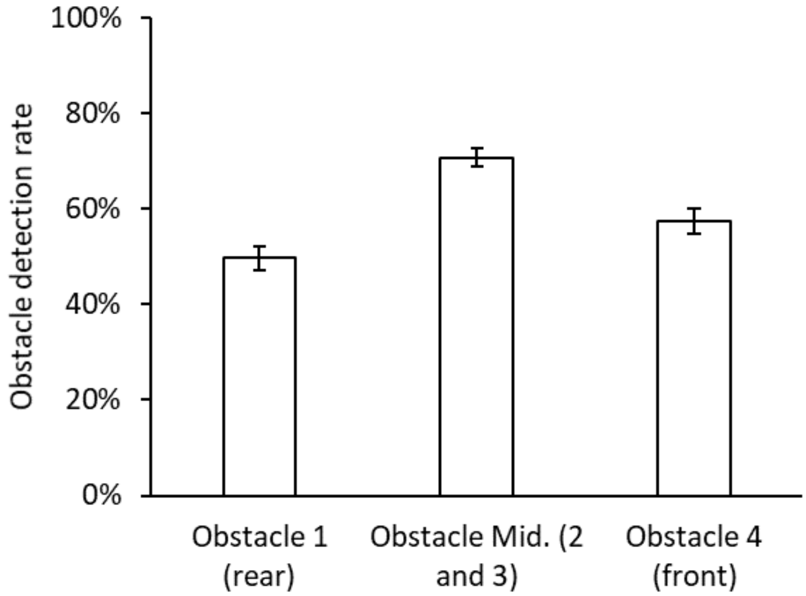

Figure 7. Mean obstacle detection rate for three different obstacle locations. Error bars show standard error of the mean.

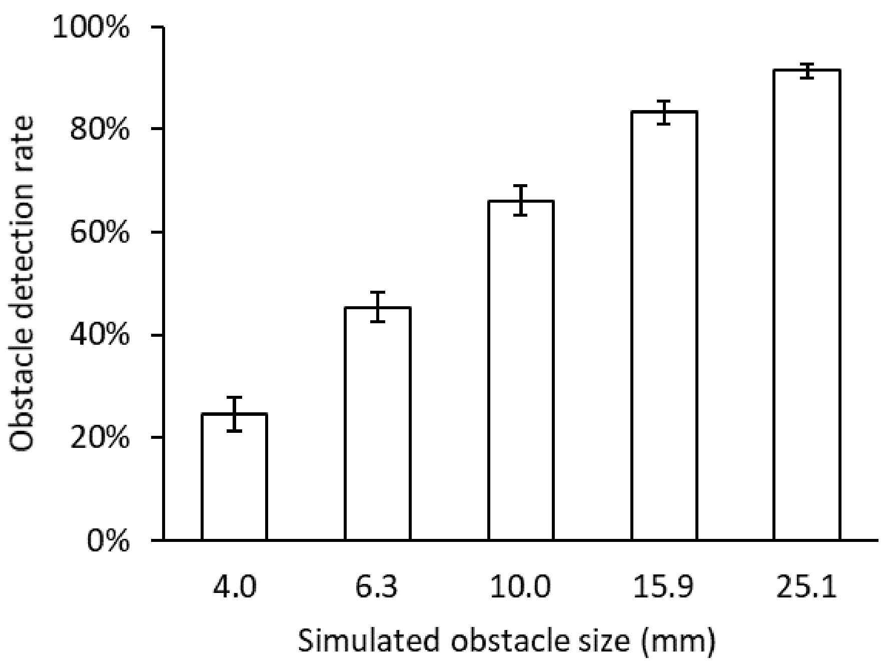

Figure 8. The mean detection rate for five different obstacle heights. Error bars show standard error of the mean.

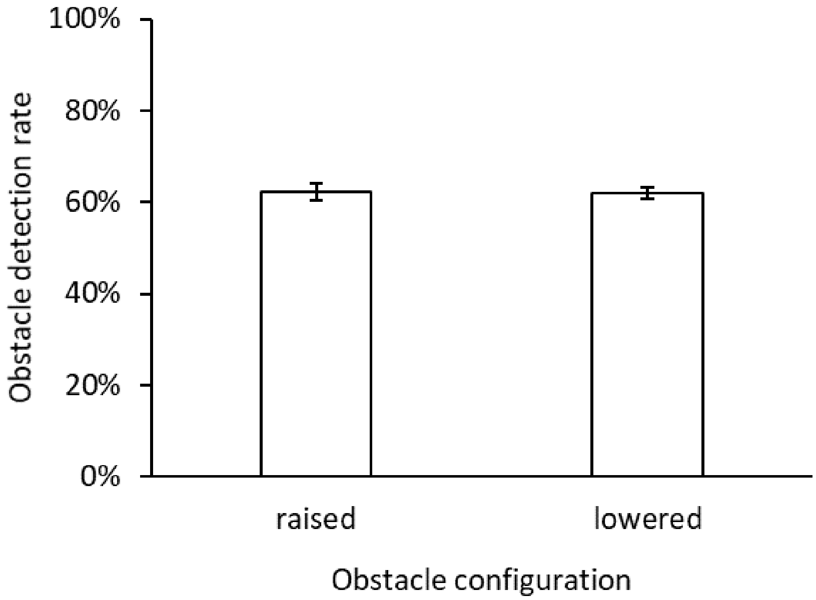

Figure 9. The mean detection rate for raised and lowered obstacles. Error bars show standard error of the mean.

3.5. Interactions between factors

One significant interaction was between obstacle location and size ($p = 0.007$) (Table 5). Figure 10 suggests that the detection rate was less sensitive to obstacle location for the smallest and largest obstacle sizes than for the intermediate sizes. One-way ANOVA was carried out at each obstacle size, comparing the three obstacle locations, using a Holm-Bonferroni corrected *p*-value threshold to account for the multiple tests. These indicate that the differences in detection rates between obstacle locations were not significant for the smallest size ($p = 0.079$), but were significant for the larger four obstacle sizes ($p = 0.001$, $= 0.001$, < 0.001 and $= 0.015$ respectively). In other words, detection for the smallest obstacle size is at approximately chance level but increases to above chance for the larger obstacle sizes.

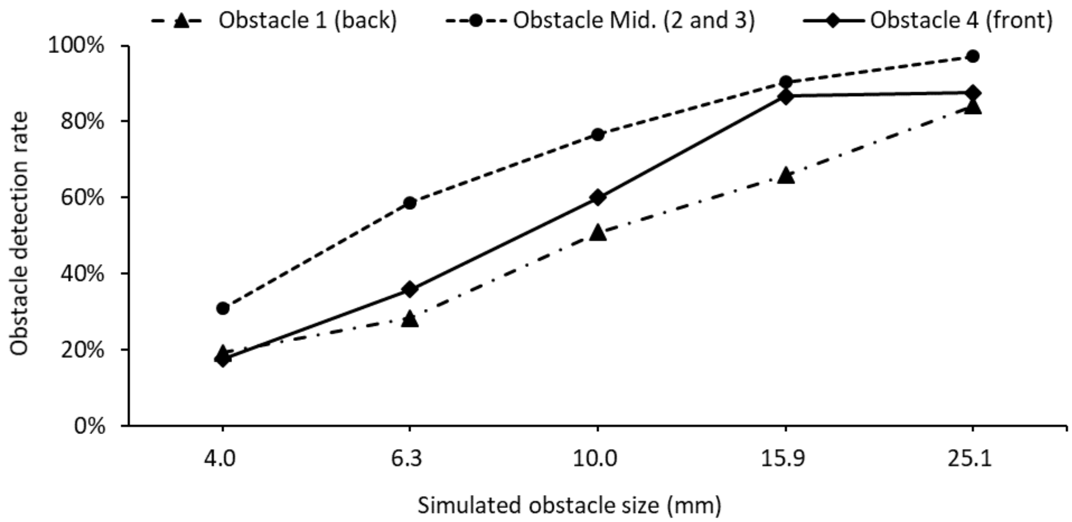

Figure 10. Mean obstacle detection rates plotted against obstacle size for the three obstacle locations.

Table 7 also suggests that the interaction between obstacle location and luminaire position is significant (p<0.001). Figure 11 shows the detection of obstacle 4 to be relatively unaffected by the luminaire position, behind or above the obstacle relative to the observation location (Figure 2). Detection of the other obstacles fell as the luminaire position moved from behind or above (LED1, LED2) to in front of (LED3) the obstacle.

Figure 11 shows mean obstacle detection rates plotted against luminaire position for the three obstacle locations. In six cases the detection rate is approximately 60%. The detection rates for the middle position obstacles (numbers 2 and 3) when lit by LED1 or LED2 are slightly higher, approximately 75%, and for obstacle 1 the detection rate is reduced to 29% under LED3. Testing the significance of luminaire position with a one-way ANOVA applied to each obstacle location (Holm-Bonferroni correction applied) shows no differences in detection (p=0.781) for obstacle 4 but significant differences in detection (p<0.001) for the other obstacles. Figure 12 shows obstacle detection rate plotted against target contrast for the nine combinations of obstacle location and light source location. This shows that luminance contrast does explain some of the variance in detection rates but also that there is some noise in these data.

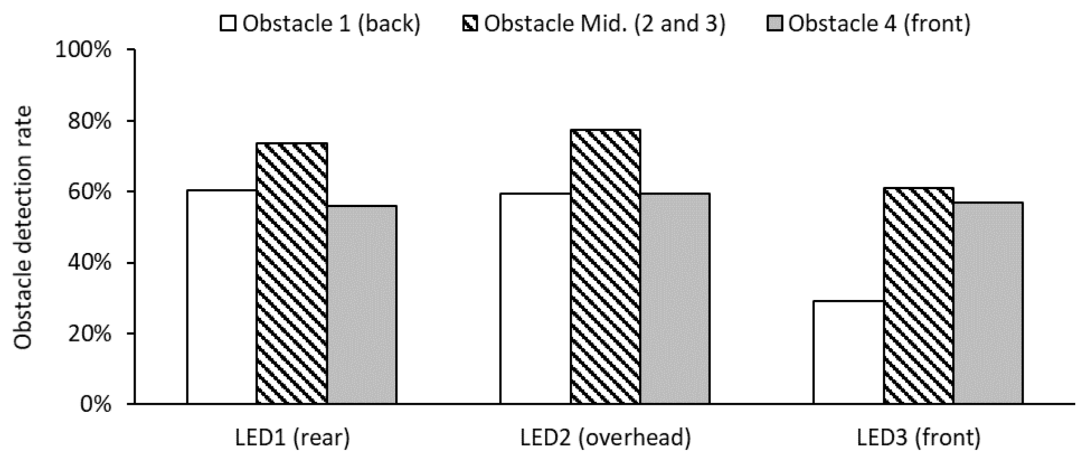

Figure 11. Mean obstacle detection rates plotted against luminaire position for the three obstacle locations.

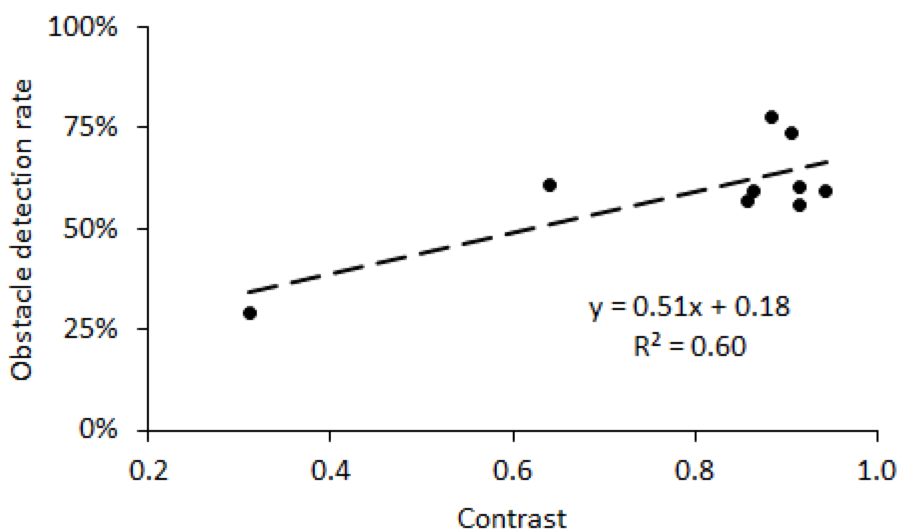

Figure 12. Obstacle detection rate plotted against target contrast for the nine combinations of obstacle location and light source location. Note that in these data the two middle obstacles are combined as one item.

4. Conclusion

This paper describes an experiment carried out primarily to explore two aspects of experimental design in an obstacle detection task, whether the obstacle is raised or lowered relative to the ground level, and the position of the light source relative to the obstacle and observer.

The results did not suggest a difference in detection performance between raised and lowered obstacles for a given change in vertical size (height or depth): this suggests that the results of past studies[12-14] using only raised obstacles are valid also for lowered obstacles. However, those previous studies used only a single luminaire position. The current experiment used three luminaire positions and this was suggested to significantly affect detection probability, with a higher detection rate provided when the luminaire was overhead or behind the obstacle than when the luminaire was in front of the obstacle. In natural settings, the spatial relationship between observer, dominant sources of light and obstacle location, is variable and it would be impractical to conduct trials for all possible geometries. If the current finding is confirmed, this would suggest that further work to identify appropriate lighting for hazard detection should consider the least favorable spatial geometries.

The obstacle used in the current experiment is highly simplified and may not resemble all trip hazards and pot holes encountered in natural settings. The top surface of the hazard remained flat. For lowered hazards, the apparatus resembled a pedestrian's view of a pothole with the whole surface or the trailing edge being lower than ground level but did not present a pothole with only the leading edge being lowered – a change of walking direction means both scenarios are likely. The task conducted in this experiment may therefore be more precisely defined as detection of a trip hazard by its leading edge and detection of a pothole by its trailing edge.

While the results did not suggest a significant difference in the detection of raised and lowered surfaces of a given height, there may be differences in the consequences of non-detection. An unexpected trip hazard means that foot swing is interrupted: the foot is delayed in its travel and may not even make contact with the ground. An unexpected pothole means the leading foot makes contact with the ground at a slightly later and lower than expected moment but still reaches the ground to absorb transfer of the pedestrian's mass. An unexpected pothole may also lead to a twisted ankle if the foot lands on the edge of the pothole. There are many scenarios. Data were not identified to substantiate possible differences in consequences of accidents involving trip hazards and potholes.

One limitation of the current study and other studies[12-14] is that no glare source was added in the experiment: it would be useful to investigate how obstacle detection is affected by glare. Furthermore, given that older people may observe raised and lowered steps differently to younger people (Table 2) further experiments should recruit participants from an older age group.

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