Investigating the visual tasks of pedestrians and how one of these tasks, obstacle detection, is influenced by lighting

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by

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ABSTRACT

Current guidelines for pedestrian road lighting are not based on empirical evidence. One approach to providing suitable evidence is to examine the effect of lighting on the visual tasks of pedestrians. This first requires an understanding of what these visual tasks are. An eye-tracking study was carried out in which pedestrians walked a real, outdoor route during the day and after-dark. A novel dual-task method was used to identify the critical visual tasks of the pedestrians. Reaction times to a concurrent audio response task were used to indicate instances when attention may have been diverted towards something significant in the visual environment. Analysis of the eye-tracking videos at these critical times found that the path and other people were the two most significant items looked at.

Observation of the path is important for detection and avoidance of obstacles and trip hazards. Good road lighting should therefore facilitate obstacle detection. An obstacle detection experiment was therefore carried out examining the effect of illuminance and Scotopic/Photopic (S/P) ratio on obstacle detection. The experiment improved the realism and ecological validity of previous research by introducing a dynamic fixation target, realistic apparatus scales and real walking (on a treadmill) whilst carrying out an obstacle detection task. Results showed that obstacle detection only improved with illuminance increases up to 2.0 lux. A higher S/P ratio (2.0) provided better detection performance than a low S/P ratio (1.2), but only at the lowest illuminance used of 0.2 lux.

The data is used to discuss optimal design criteria for pedestrian road lighting based on obstacle detection. However, other purposes of road lighting, such as creating a feeling of reassurance and enabling accurate interpersonal judgements to be carried out, should also be considered when designing pedestrian road lighting.

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JOURNAL PAPERS ARISING FROM WORK REPORTED IN THESIS

Fotios, S., **Uttley, J**., Cheal, C., & Hara, N. (2015). Using eye-tracking to identify pedestrians' critical visual tasks, Part 1. Dual task approach. *Lighting Research and Technology*, *47*(2), 133-148.

Fotios, S., **Uttley, J**., & Yang, B. (2015). Using eye-tracking to identify pedestrians' critical visual tasks. Part 2. Fixation on pedestrians. *Lighting Research and Technology*, *47*(2), 149-160.

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CHAPTER 1. ROAD LIGHTING FOR PEDESTRIANS

1.1 Introduction

Human vision is a complex perceptual system that enables us to successfully interact with and experience the world around us. However, without light the visual system is useless. The photoreceptors in our eyes are only activated when hit by photons of visible light, the part of the electromagnetic spectrum with wavelengths between 390 and 700 nm. This triggers a chain reaction of processes, both biological and perceptual, that give us sight. Light is essential to our day-to-day lives. During daylight hours the sun provides us with light, and this can be supplemented by artificial light. The sun can also provide us with some light during the night too, in the reflected form of moonlight. However, artificial light becomes much more essential when the sun has set, enabling humans to continue with their daily tasks.

The research reported in this thesis relates to artificial light after dark, that period after the sun has set and before it rises the following morning. More specifically, it is about road lighting[1], particularly road lighting that is predominantly designed with pedestrians in mind. Road lighting enables pedestrians to see after dark, allowing them to carry out activities or walk to locations they perhaps would not otherwise have done.

For pedestrian road lighting to adequately achieve its purpose it must provide appropriate lighting. This chapter outlines existing guidelines that specify what lighting is deemed appropriate for the needs of pedestrians, but highlights that these guidelines may not be satisfactory. Further evidence is required to either confirm the existing guidelines are correct or to suggest new, more appropriate guidelines. Different approaches can be taken to providing such evidence and this chapter concludes by suggesting the specification of lighting requirements should be based on the purpose of road lighting for pedestrians and what it is designed to do. Further understanding about what pedestrians need from lighting after dark is required.

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[1] The term ‘road lighting’ refers to outdoor lighting for public areas and roads. Although it includes the word ‘road’, it can also refer to lighting in environments that do not include a road, such as a footpath or pedestrianised area. The term ‘road lighting’ is used throughout this thesis although it may also be known as ‘street lighting’.

1.2 Providing sufficient lighting

Road lighting in the UK is estimated to use around 2.5-2.6 TWh of energy each year (DEFRA, 2008, as cited in Boyce et al, 2009; Parry, 2014). This represents nearly 3% of all electricity used within the service sector, based on statistics from 2013 (DECC, 2014, Table 1.04). This may seem a relatively small proportion but the energy consumed by road lighting is symbolically important as it is funded through taxpayer money and it is visible to the general public (Boyce et al, 2009). The development of Light Emitting Diodes (LEDs) as an affordable lighting option in recent decades appears to offer considerable energy savings (Pimputkar et al, 2009) and many local authorities in the UK have begun replacing existing road lighting lamps with the more efficacious LEDs (Parry, 2014). However, the potential energy savings provided by LEDs are unlikely to be fully realised due to the Rebound Effect (e.g. Sorrell et al, 2009). This term refers to how any savings produced by an increase in energy efficiency are usually offset by an increase in use. In the context of road lighting this could mean more luminaires, increased burn time or increased intensity.

Regardless of the energy implications of providing unnecessary and unwarranted light, there are other environmental factors to consider when evaluating the necessity of road lighting. Light pollution is the “alteration of natural light levels in the night environment produced by introduction of artificial light” (Falchi et al, 2011, p. 2714). According to Cinzano et al (2001) 99% of the population in Europe and the US live under light-polluted skies. Light pollution not only reduces the visibility of the night sky, it can also impact on human health (e.g. Pauley, 2004). Exposure to an illuminance at the eye of just 1.5 lux can influence circadian cycles (Wright et al, 2001), which could have subsequent health effects (e.g. Stevens, 2005; Haus and Smolensky, 2006). Research has shown a correlation between the level of light at night in an area and rates of some forms of cancer (Kloog et al, 2008, 2009). Light at night does not only affect humans; it can and does have wider ecological consequences (Longcore and Rich, 2004). Artificial light can lead to changes in reproductive activities in wildlife, alterations to the interactions between predator and prey, and animals’ ability to orient themselves (Navara and Nelson, 2007). The ‘skyglow’ created above urban areas as a result of light pollution gives a graphic illustration that artificial light at night is not being used as effectively as it could be, as the light is being directed upwards and away from its intended target. It is therefore important to ask the question, is road lighting necessary and if so, how can we ensure it is only used as required and not in excess?

1.3 Pedestrian road lighting guidelines

The lighting provided by road lighting should be appropriate and proportionate to requirements. One method for ensuring this is by having guidelines or recommendations about the lighting provision. In the UK, such guidelines are provided by the British Standards documents BS 5489-1:2013 and BS EN 13201-2:2003 (British Standards Institution, 2012; 2003), with CIE 115-2010 (CIE, 2010) providing an international equivalent. These standards provide general principles for installing and maintaining road lighting for different purposes and environments. BS EN 13201-2:2003 define a number of lighting 'classes', which specify lighting requirements for different types of roads and situations. Six classes are described, and these are summarised in Table 1.1.

Table 1.1. Types of lighting class described in BS EN 13201-2:2003 (British Standards Institution, 2003)

Lighting class	Description of purpose / situation
ME	Intended for drivers of motorised vehicles on traffic routes, allowing medium to high driving speeds
CE	Intended for drivers of motorised vehicles in conflict situations, e.g. shopping streets or complex road junctions / roundabouts. Also have implications for cyclists and pedestrians.
S and A	Intended for pedestrians and cyclists on footpaths and cycleways, other road areas separate from or alongside the main road carriageway, residential and pedestrian streets, schoolyards etc. 'S' class provides guidance in horizontal illuminance, 'A' class provides alternative, near-equivalent values in hemispherical illuminance.
ES	Intended for areas where public lighting is required for identifying people and objects in areas with higher than normal risk of crime
EV	Intended for areas where vertical surfaces need to be seen such as toll stations or interchange areas

The S-class and A-class are of greatest relevance when considering lighting for pedestrians. BS EN 13201-2:2003 provides seven categories within the S-class, S1 – S7, and six categories within the A-class, A1 – A6. For each category recommended illuminance levels are given. These are provided as minimum maintained illuminance and average illuminance for the S-class. The A-class provides alternative values in average hemispherical illuminance and overall uniformity of the hemispherical illuminance as these may be required in some situations. Category A1 equates to S2, A2 to S3 and so on. See table 4 in CEN/TR 13201-1 (CEN, 2004). The recommended illuminance values for each category in the S-class and A-class are given in Table 1.2.

Table 1.2. Recommended illuminances for S-class and A-class roads and areas, taken from BS EN 13201-2:2003. Note: Horizontal illuminances refer to S-class, hemispherical illuminances refer to alternative A-class.

Category	**Horizontal illuminance (for S-class)**		**Hemispherical illuminance (for A-class)**	
	Average (minimum maintained), lux	**Minimum (maintained), lux**	**Average (minimum maintained), lux**	**Overall uniformity (minimum)**
S1	15	5	N/A	N/A
S2 / A1	10	3	5	0.15
S3 / A2	7.5	1.5	3	0.15
S4 / A3	5	1	2	0.15
S5 / A4	3	0.6	1.5	0.15
S6 / A5	2	0.6	1	0.15
S7 / A6 *	N/A	N/A	N/A	N/A

The category of road within each lighting class is selected based on a set of environmental and situational factors set out in CEN/TR 13201-1. The general situation type the lighting is to be used in is defined based on the expected users of the area, such as motorised traffic, pedestrians, cyclists or slow-moving vehicles, and the typical speeds of these users. Specific parameters related to this defined situation are then assessed and a decision made on which class category to use, and hence what recommended illuminance should be used. These parameters are based on a number of environmental and situational considerations. For lighting situations relevant to pedestrians, these include:

- Whether there are geometric measures for traffic calming
- The risk of crime
- Whether facial recognition of other pedestrians is necessary
- The difficulty of the navigational task
- Whether parked vehicles are present
- The complexity of the visual field
- The traffic flow of pedestrians
- The ambient luminance

An example of how these parameters are assessed and applied to define the lighting class to use is shown in Table 1.3 and 1.4. Table 1.3 is used to identify three potential lighting classes for a situation. Table 1.4 is then used to identify which of these three classes should be used. For example, if an area is assessed as having no traffic calming measures, no parked vehicles, higher than normal difficulty of navigational task, and normal traffic flow, the possible classes that could be chosen would be S5, S4 or S3. The decision of which one would be based on the assessment of the complexity of the visual field, the crime risk, whether facial recognition was necessary, and the ambient luminance. An area with normal complexity of visual field, normal risk of crime, unnecessary facial recognition and low ambient luminance would be defined as class S5.

Table 1.3. Example lighting situation tables to define recommended lighting class for a particular area. Table shown is a reproduction of Table A. 15 from CEN/TR 13201-1:2004.

Geometric measures for traffic calming	Parked vehicles	Difficulty of navigational task	Traffic flow pedestrians and cyclists					
			Normal			**High**		
			←	**0**	→	←	**0**	→
No	Not present	Normal	S6	S5	S4	S5	S4	S3
		Higher than normal	S5	S4	S3	S4	S3	S2
	Present	Normal	S5	S4	S3	S4	S3	S2
		Higher than normal	S4	S3	S2	S3	S2	S1
Yes			Choice as above, but select S4 only at area of traffic calming					

Table 1.4. Example table showing how to select from range of lighting classes defined in Table 1.3. Table shown is a reproduction of Table A. 16 from CEN/TR 13201-1:2004.

Complexity of visual field	Crime risk	Facial recognition	Ambient luminance		
			Low	**Medium**	**High**
Normal	Normal	Unnecessary	←	0	0
		Necessary	←	0	→
	Higher than normal		0	→	→
High	Normal	Unnecessary	0	0	0
		Necessary	0	→	→
	Higher than normal		→	→	→

1.4 Evidence for road lighting guidelines

The criteria used to define the lighting class to be used are arbitrary and the decisions about which parameters are met is likely to be subjective. It appears that no empirical evidence exists to justify the criteria used. That is not to say they have no merit. They may be based on best estimates from design experience, and use of these criteria may lead to more appropriate and consistently-applied lighting than had no criteria been applied. However, it is important for guidelines such as these to have some form of evidence base, given the potential energy and environmental implications of getting it wrong.

In addition, there is considerable international variation in road lighting guidelines, even between countries with similarly-developed road and urban networks. For example, the recommended range of horizontal illuminances for local roads in Australia and New

Zealand is 0.5 – 7.0 lux (Standards Australia, 2005), and in Japan it is 3.0 – 5.0 lux (Japanese Standards Association, 1988). These ranges are lower than in the UK (2.0 – 15.0 lux for S-class situations). Whilst cultural and environmental variation between areas may partly account for these differences, a greater level of consensus might be expected if guidelines were based on consistent, universal evidence. This suggests further investigation of the evidence base for such road lighting guidelines may be required (Boyce et al, 2009).

It is likely that the recommended illuminances for the different lighting classes (given in BS EN 13201-2:2003) are not based on sound empirical evidence. Fotios and Goodman (2012) discuss why this may be the case. The illuminance values suggested in BS EN 13201-2:2003 are indirectly derived from a study by Simons et al (1987). In this study participants were asked to rate how satisfied they were with the lighting on 12 streets in the UK. A 9-point rating scale was used, ranging from '1 – very poor', through '3 – poor', '5 – adequate' and '7 – good', to '9 – very good'. The average horizontal illuminances on the streets being assessed ranged from 1 to 12 lux. Higher illuminances led to higher ratings of satisfaction. Horizontal illuminances of 10 lux, 5 lux and 2.5 lux were proposed as three appropriate levels as these corresponded to illuminances receiving average ratings of good, adequate and poor-to-adequate. However, the average ratings found in the Simons et al study are likely to have been affected by range or 'stimulus-equalising' bias (Poulton, 1982). When a respondent is asked to make a series of judgements about something, such as how satisfied they are with the road lighting on a street as was the case in the Simons et al study, their responses tend to use the full range of responses available to them, regardless of the range of stimuli they are being asked to judge. This means that any judgement is only relative to the range of other judgements made, and cannot be taken as absolute. Such range biases have been demonstrated in judgements about brightness (Teller et al, 2003), internal illuminance preferences (Logadottir et al, 2011; Uttley et al, 2013) and other sensory judgements (Harvey and Campbell, 1963; Conner et al, 1987). If a different range of stimuli is offered, for example if the range of horizontal illuminances on the streets used in Simons et al was 10-20 lux, not 1-12 lux, different conclusions may have been drawn about which illuminances correlate with which ratings. A direct example of this is highlighted by Fotios and Cheal (2013). In studies by de Boer (de Boer, 1961; de Boer et al, 1959) participants were asked to rate the lighting on 70 different streets, using a 9-point scale similar to that used by Simons et al. The light levels on these streets ranged from 0.06 to 5.0 cd/m^2. Assuming an average road surface reflectance of approximately 20% and a luminance coefficient of 0.07 (see Fotios et al, 2005 for discussion about road surface reflectances) this equates to an illuminance range of approximately 1 – 71 lux. A rating of 'Good' in the de Boer studies resulted in an average inferred illuminance of 21 lux, compared with only 10 lux for the same rating in Simons et al. This difference is a clear indication of the range bias resulting from the larger range of illuminances participants were being asked to rate in de Boer's studies.

Poulton claims that stimulus range bias in category ratings, the method used by Simons et al, is unavoidable. This suggests we cannot rely on the illuminances suggested by Simons et al's study, based on average ratings of the light levels participants were exposed to. In turn, we therefore cannot rely on the recommended illuminances put forward in existing road lighting guidelines, which are based on the initial values suggested by Simons et al. Further evidence is required about the light levels that should be provided by pedestrian road lighting. This evidence may ultimately provide justification for the existing recommendations, but they may also suggest that alternative recommendations should be made.

1.5 Identifying appropriate evidence

Current lighting guidelines are not based on empirical evidence. This is summarised neatly by Boyce (1996), who suggests the idea that illuminance recommendations for various applications (not just road lighting) are based on visual performance is a 'fairy story', and that guidelines all over the world are instead based on consensus views amongst lighting practitioners and professionals. Consensus does not necessarily equal objectivity however, and it is worth considering alternative ways to define lighting guidelines.

One approach might be to consider the economic costs of providing the lighting. Road lighting is usually provided through public funding and is therefore in competition with other public services for financial support. Decisions about how much light should be provided and where it should be provided could be based on existing financial priorities or limitations. Reductions in local authority budgets in the UK since the 2008 financial crisis and increases in energy prices have contributed to many local authorities dimming or switching road lights off for periods of time, to save money. A review of road lighting initiatives undertaken for the UK Government found that *"Local authorities reported that the most significant driver for exploring new ways of delivering public road lighting services was the increasing running costs*" (DEFRA, 2011, p. 12).

Another approach to justifying road lighting levels would be to consider environmental and energy implications. Anthropogenic climate change is a global issue with huge implications (IPCC, 2013) and public bodies are expected to set an example in taking action to mitigate climate change. One method for doing this is by reducing their energy consumption, or as a minimum ensuring energy is not needlessly wasted. This obligation could provide justification for setting road lighting levels to particular values.

Public and individual perceptions could provide a further approach to justifying road lighting levels. Ultimately road lighting is a public facility and how the lighting is perceived and its effect on perceptions of the lit area are important considerations. This appears to have been the approach taken to justify existing road lighting guidelines for pedestrians in the UK (see BS EN 13201-2:2003). The study by Simons et al (1987) that was used as evidence for the recommended lighting levels asked participants how they perceived different road lighting conditions on different streets. However, as described earlier, this approach is susceptible to influence by inherent human biases and may lead to inappropriate recommendations.

A final approach to defining guidelines for road lighting is to consider the purpose of the lighting. This is perhaps the most fundamental approach that could be taken, as unless the purpose of the lighting is being met other considerations appear to be secondary. For example, it seems pointless reducing the time road lighting is on in order to save expenditure if by doing this the lighting is rendered useless, in terms of what it is meant to do. Similarly, it again seems pointless to save energy consumption by reducing the amount of light provided if this again renders the lighting useless when considering its purpose – it would be better to save even more energy and have no lighting at all. Therefore, an understanding of the purpose of road lighting for pedestrians is required before decisions can be made about how to justify recommendations for lighting levels, and whether compromises need to be taken between competing considerations.

1.6 Purpose of road lighting for pedestrians

Existing guidelines in the UK provide an indication of what road lighting for pedestrians should do. BS 5489-1:2013 states that road lighting should:

> *"…allow pedestrians to see hazards, orientate themselves, recognize other pedestrians and feel more secure. It also has a wider social role, with the potential of helping to reduce crime and the fear of crime, and can contribute to commercial and social use at night of town centres and tourist locations by improving the daytime and night-time appearance"* (British Standards Institution, 2012, p. 5).

This description suggests road lighting should enable pedestrians to perform certain tasks, such as identifying hazards, recognising other pedestrians and making judgements about the safety of the area. This can be distilled into two main purposes:

creating perceptions of safety and allowing safe movement. The guidance goes on to describe what this means:

- Perceptions of safety
- General feeling of safety created by an appropriately-lit street
- Visual comfort – pleasant environment without glare
- Perceived ability to judge intent or identity of other road users

Safe movement:

- Ability to detect obstacles on pavement which could act as trip hazard
- Judge intent or identity of others at a distance that would allow avoiding action to be taken if necessary

One question that arises is whether these requirements are indeed appropriate and reflect what pedestrians actually need from road lighting. It appears they may have been based on work by Caminada and van Bommel (Raynham & Saksvikronning, 2003). Caminada and van Bommel (1984) suggested a number of requirements by pedestrians that should be satisfied by residential lighting. These included enabling the pedestrian to:

- See details of their surroundings for orientation purposes
- See and identify other people on the street, or at least identify the intentions of other people
- Detect obstacles on the footpath and the road surface when crossing the street

Caminada and van Bommel also suggested the light should have a pleasant appearance, which included taking into consideration glare, light colour and rendering, naturalness and light penetration in homes.

However, Caminada and van Bommel do not confirm whether their suggestions about the key requirements for pedestrian road lighting are accurate with empirical evidence. Further data is required to assess Caminada and van Bommel’s suggestions and determine what the key purposes of road lighting for pedestrians should be, including what factors need to be considered in design guidance documents. The Mesopically Enhanced Road Lighting: Improving Night-vision (MERLIN) project was established to address this requirement (EPSRC grant EP/H050817/1). The MERLIN project has four main aspects:

1. Examine pedestrian perceptions of safety on streets and how lighting influences these perceptions

2. Identify what the important visual tasks performed by pedestrians are, which should be facilitated by road lighting
3. Investigate how lighting influences the important visual tasks of pedestrians
4. Determine optimum design criteria for road lighting for pedestrians

This thesis is focused on the second and third aspects described above, but also provides some initial commentary related to the fourth aspect. Determining the critical visual tasks of pedestrians will allow clarification of the key purposes of pedestrian road lighting.

1.7 Research aims

The research reported in this thesis has 3 main aims:

1. Identify what the critical visual tasks are carried out by pedestrians when walking along a street (Chapters 2, 3 and 4). This information will then be used to help address the next research aim:
2. Investigate the effect of lighting on these critical visual tasks (Chapters 5, 6 and 7). This research will focus on one specific visual task, obstacle detection, and examine how changes to lighting intensity and spectrum affect performance of this visual task. This data, alongside other relevant data from the research literature, will be used to address the third research aim:
3. Provide an initial commentary on requirements for appropriate pedestrian road lighting, based on data about the influence of lighting on pedestrian visual tasks, and compare this with existing recommendations for road lighting specifications (Chapter 8)

1.8 Thesis structure

The thesis can be split into four parts. The first part, comprising this current chapter (Chapter 1), provides background about pedestrian road lighting and why new evidence is required to justify existing guidelines or develop new guidelines.

The second part discusses one method for producing this new evidence, based on the visual needs of pedestrians. Chapter 2 reviews eye-tracking literature and what it can tell us about the visual tasks performed by pedestrians, but highlights potential issues and limitations with this previous body of work. Chapter 3 discusses a method for addressing some of these limitations and presents a pilot study testing this method. Chapter 4 reports an eye-tracking experiment that that was carried out in a real-world setting using the method tested in Chapter 3. The results of this experiment show that obstacle detection is a critical visual task for pedestrians and therefore road lighting should facilitate this task.

Part three relates to obstacle detection by pedestrians and particularly how lighting affects this task. Chapter 5 presents a review of previous research about lighting and peripheral detection, highlighting key questions and gaps in knowledge, concluding that there is a need for further data about the role of lighting in obstacle detection for pedestrians. Chapter 6 reports two pilot studies that test a new experiment setup for investigating obstacle detection. This new setup introduces key improvements and developments from previous peripheral detection work. Chapter 7 presents the results of a full experiment using the new apparatus, which measures obstacle detection performance under different lighting conditions.

Part four of the thesis, the final part, summaries the work discussed in the previous three parts and synthesises the results and conclusions presented in relation to implications for pedestrian road lighting guidelines. Limitations with the work presented in the thesis, and potential future areas of research, are also discussed.

The structure of the thesis is summarised in Figure 1.1.

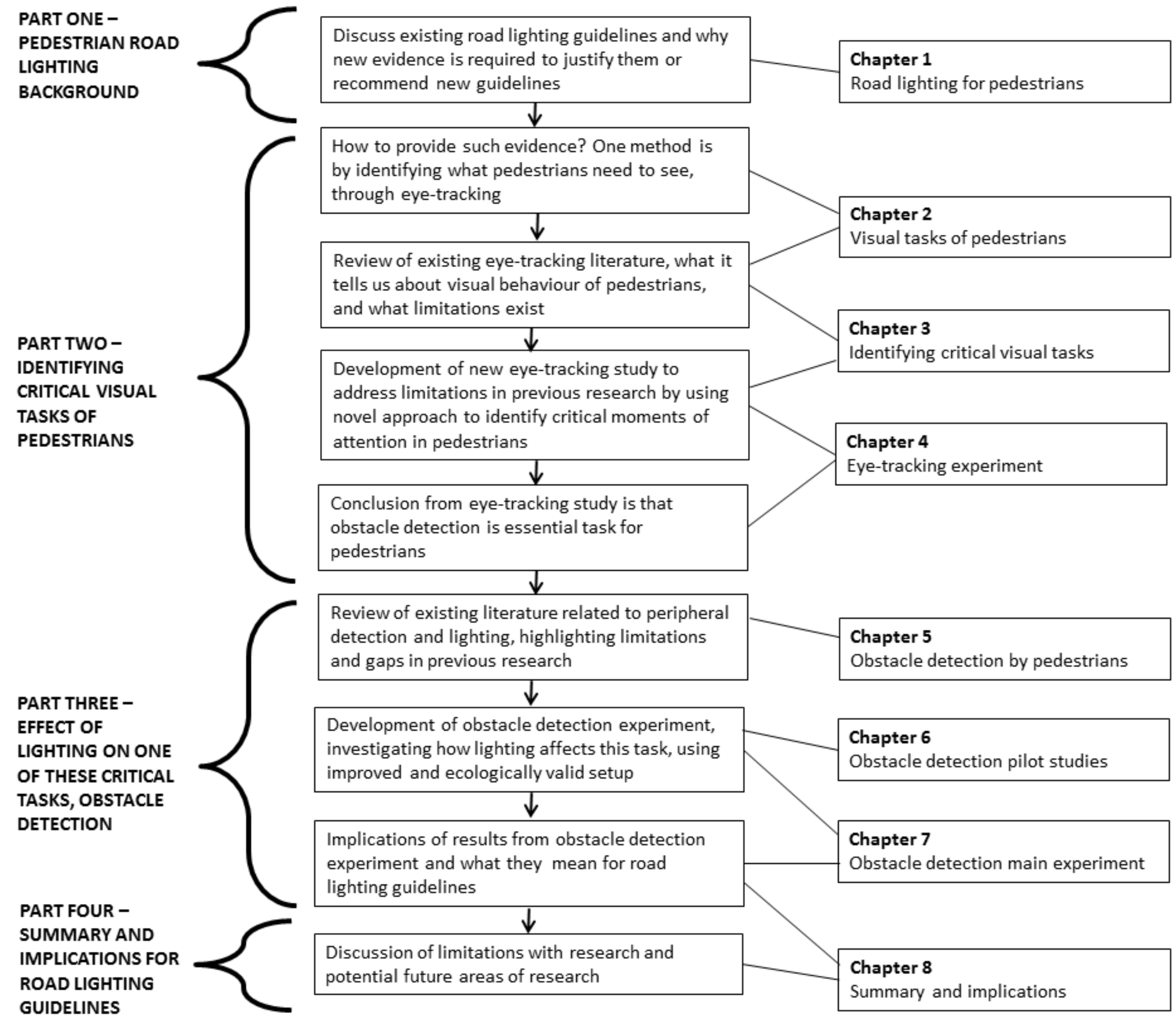


Figure 1.1. Summary of thesis structure and chapters relating to subject areas discussed in thesis.

1.9 Summary

It is important that road lighting for pedestrians is appropriate and proportionate to its purpose, from a number of perspectives including economic, energy conservation and ecological outlooks. In the UK guidelines exist to specify parameters of road lighting, such as the illuminance provided. However it appears that these guidelines are not based on sound evidence, and further evidence is required to either substantiate the current guidelines or contribute to the proposal of new guidelines. This new evidence should be based on the main purposes of road lighting for pedestrians. Previous suggestions about the purpose of road lighting suggest it should provide a feeling of safety and comfort, and enable safe walking to take place. No evidence exists to support these assertions however. One approach to determining the key purposes of road lighting is to identify the important visual tasks pedestrians need to carry out after dark. These tasks should be facilitated by road lighting. The next chapter discusses methods for gathering evidence about the visual tasks of pedestrians and what previous research tells us about this topic.

CHAPTER 2. VISUAL TASKS OF PEDESTRIANS

2.1 Introduction

The previous chapter highlighted that current road lighting guidelines are not based on empirical evidence, and there is a need to provide such evidence. A fundamental approach to providing this evidence is to ask what visual tasks pedestrians have to perform when walking after-dark. Lighting guidelines should then provide for sufficient and appropriate light to accomplish these tasks. One method for identifying pedestrian visual tasks is to record what they look at. This chapter reviews previous eye-tracking research, outlining what it can and cannot tell us about what visual elements of the environment may be important to pedestrians.

2.2 Method of identifying visual tasks

One method of determining the visual tasks of pedestrians is simply to ask them – ‘what do you need to see in order to walk down the street safely?’. This introspective or self-report method is commonly used in many areas of behavioural research, such as personality psychology (Paulhus and Vazire, 2007), health psychology (Eatough and Spector, 2013) and cognitive psychology (Jobe, 2003). One example of the self-report method’s use in an attempt to identify important visual tasks or objects for safe navigation is provided by Fabriek, de Waard and Schepers (2012). They used questionnaires and focus groups with cyclists to try and identify the critical visual elements of the environment that could potentially reduce safe cycling.

This self-report method allows access to subjective experience and incorporates the pedestrians’ own thoughts and experiences into answering the question. It can also provide insights that otherwise would not be possible, and can be used in conjunction with other methods to triangulate on more revealing conclusions (e.g. Jack and Roepstorff, 2002). However, the approach has flaws if it is to be relied upon to provide reliable, objective information. This is because the person providing this introspective report may be unaware of three things (Nisbett and Wilson, 1977):

- The stimulus that caused a particular response from them
- The existence of the response they made
- The fact that the stimulus affected their response

In the context of pedestrians reporting their important visual tasks, this would equate to not knowing what caused a particular action or response when walking down a street, not knowing that they even took a particular action or response, and not knowing that something they observed was causally linked to a particular action or response. For example, a pedestrian could walk down the street and slightly adjust their gait in order to avoid a raised paving slab in the path. They may be unaware that they had noticed this paving slab, unaware that they adjusted their gait in response to it, or unaware that noticing the paving slab caused the adjustment in gait. Awareness of our behavioural and cognitive responses to the world is limited (e.g. Kahneman, 2011), leading neuroscientist David Eagleman to assert: “Most of what we do and think and feel is not under our conscious control” (Eagleman, 2011, p. 4).

Self-reporting of visual behaviour inherently requires an awareness of what is being looked at. However, we are not always capable of reporting where our eyes are directed. Buswell (1935) suggested that “a person is entirely unconscious of the characteristics of these tiny movements of his eyes and it is entirely impossible for him to describe them accurately even when he gives his close attention to them” (p. 9). In addition, there may be social pressures or expectations that influence what is reported. For example, self-reporting suggests use of nutrition labels on food is high, but more objective measures suggested processing of nutrition labels was lower (Cowburn and Stockley, 2005).

An objective method of measuring visual behaviour is to record a person’s eye movements. We move our eyes and head to direct the part of our vision with the highest resolution, the fovea, to a particular location within our visual field. This is done usually because this location is of interest to us, and attention is often directed towards this specific location: “…under most circumstances, the direction of gaze reflects ongoing computations and can be used to infer the moment-to-moment cognitive processing that subjects are engaged in” (Rothkopf et al, 2007, p. 1). This can provide insights into what the observer may have noticed and had interest in, and therefore what aspects of the visual scene may affect their perceptions of the area they are in and any decision-making processes (Duchowski, 2003).

2.3 The human eye

The eye allows humans to receive visual information from the surrounding environment. It is the initial, sensory part of a complex visual system which enables the processing and interpretation of visual stimuli into meaningful information. Our visual field extends up to about 100° laterally and 60-75° vertically (Boyce, 2014). Visual information outside these limits is therefore not available to us. The retina (see Figure 2.1) is the part of the eye that receives the incoming light and converts it to meaningful signals, via photoreceptor cells.

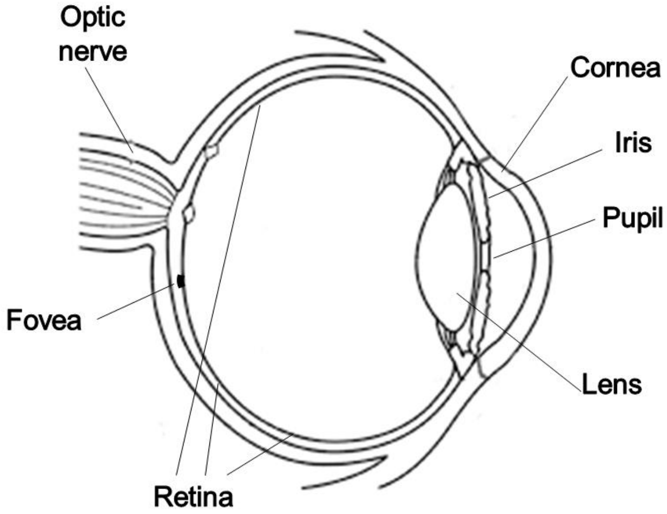


Figure 2.1. Diagram of eye, with main features labelled. Blank eye diagram downloaded from Google Images, labels added.

There are two types of photoreceptor in the eye – rods and cones. There are significantly more rods in the retina than there are cones (around 91 million compared with 4.5 million). Rods are more sensitive to light than cones, and are therefore the main contributor to vision in dark conditions. As illumination increases however rods contribute less and less to our vision, as their response to incoming light saturates and they are no longer responsive to further increases in illumination. In addition, rods cannot discriminate colour as they contain only one type of pigment. In contrast, there are three different types of cone, each containing a different pigment and therefore having different sensitivities for different parts of the spectrum (short-wavelength, medium-wavelength or high-wavelength light). This gives the cones the ability to discriminate colour. Cones do not function at low light levels, but are the only photoreceptor contributing to vision at high light levels. The relative contributions of the rods and cones to our vision under a given illuminance can be classified under three lighting conditions – scotopic, mesopic and photopic. Scotopic vision occurs at very low light levels (luminances < 0.003 cd/m^2), when rods are almost entirely dominant. Photopic vision occurs at higher light levels (luminances > 3 cd/m^2), when the cones are almost entirely dominant. Mesopic vision occurs at light levels in between scotopic and photopic, and both rods and cones contribute towards our vision.

Rods and cones have different spectral sensitivities. Rods are more sensitive to shorter-wavelength light whereas cones are more sensitive to longer-wavelength light. One implication of this is that our spectral sensitivity is more attuned towards shorter-wavelength light at lower light intensities, as the rods will be more dominant than the cones. We therefore have a different spectral sensitivity during scotopic vision compared with photopic vision, see Figure 2.2. This is relevant when considering vision under road lighting conditions, as light in these conditions is generally in the mesopic range. The relative contributions of rods and cones will influence our sensitivity for shorter- or longer-wavelength light.

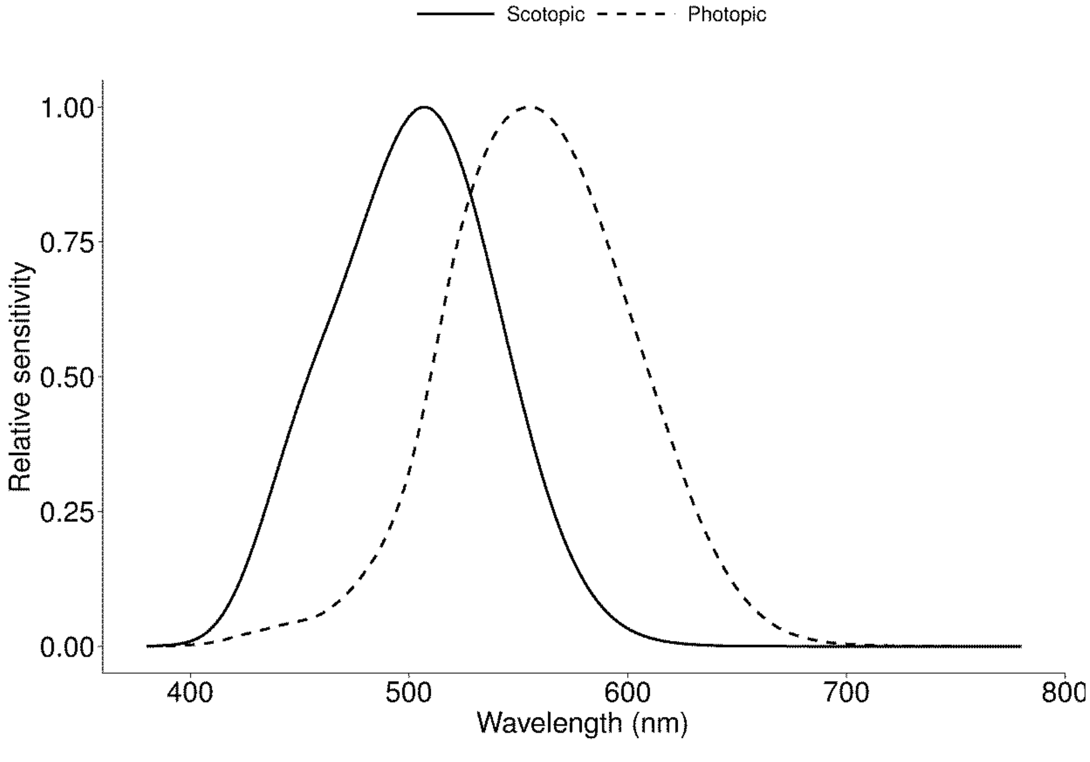


Figure 2.2. Relative spectral sensitivities of human vision under scotopic (< 0.003 cd/m^2) and photopic (> 3 cd/m^2) light conditions

The distribution of rods and cones across the retina is not even (Figure 2.3). Virtually all cones are found in the central part of the retina, the fovea. This provides visual information about an area just 2° visual angle in size. However, the density of cones in the fovea is extremely high, around 150,000 per mm^2 of retina. Combined with other anatomical features of the fovea, this gives it a high degree of spatial resolution allowing detailed visual information to be perceived. Relative to the foveal area, the rest of the visual field has low resolution and provides little detailed information about the visible world around us. Therefore, to extract detailed information about our visual environment we must redirect our eyes, in order for the 'spotlight' of our fovea to be placed on the area of interest.

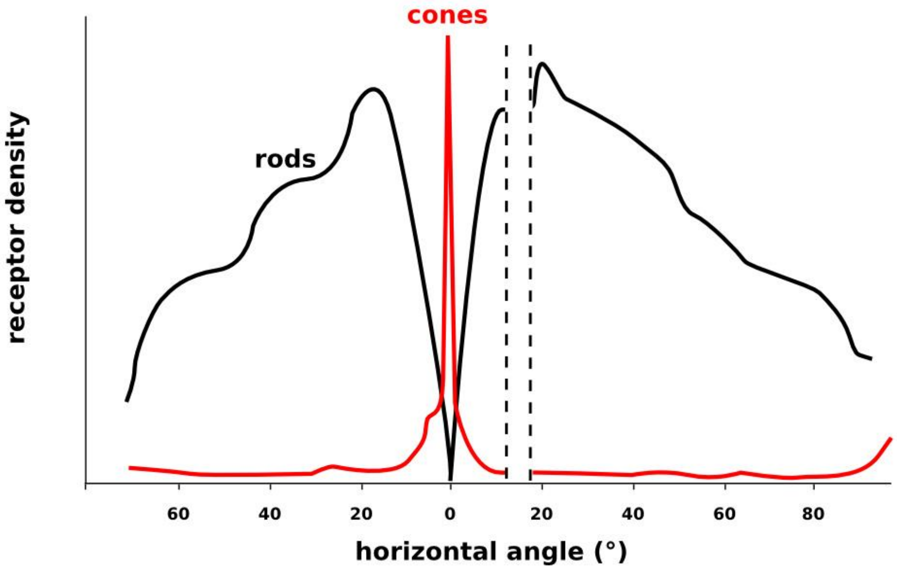


Figure 2.3. Relative densities of rod and cone photoreceptors by horizontal angle across retina (0° represents centre of fovea). Image produced by Jonas Tallus, reproduced under Creative Commons license. Based on data from Osterberg (1935).

2.4 Eye movements

Humans, like most animals, have evolved to move their eyes. Eye movements are controlled through three pairs of antagonistic muscles, providing movement along three axes - horizontal, vertical and torsional. Under the control of these extraocular muscles we produce four types of eye movement - saccades, smooth pursuit, vergence and vestibulo-ocular (Purves et al, 2001). See Table 2.1.

Saccades are potentially the most informative type of eye movement for developing an understanding of how someone visually samples the world around them. Saccades allow the rapid redirection of our gaze so that the fovea points to an area of interest in the environment, thus allowing visual analysis of that area at a detailed level. Visual input during a saccadic movement is suppressed however (Matin,1974). Visual analysis takes place when the eye has come to a stop, and this period when the eye is relatively static is known as a fixation. Fixations are essentially the means through which we gather visual information from the world.

Table 2.1. Types of eye movement.

Eye movement type	**Description**
Saccades	Fast, ballistic movements which can reach speeds of up to 100°/s, used to change the point of fixation
Smooth pursuit	Slow movements for tracking motion, designed to maintain the position of a moving stimulus on the fovea. Generally initiated voluntarily, and require a moving target to be initiated.
Vergence	Due to binocular nature of vision, these movements align the fovea of both eyes with the same target when distance from the target changes. Looking at something at a nearer distance produces convergent movements, looking at something further away produces divergent movements.
Vestibulo-ocular	Provide reflex movements to create stable image of external world, compensating for movements of the head. For example when an object is fixated these movements are initiated when head moved side to side but fixation on object maintained.

2.5 Studying eye movements

Eye movements, and the subsequent fixations that occur in between these movements, can tell us much about the cognitive processes occurring within someone and the behaviour of their visual system. This is due to the assumed relationship between what we look at and what we are thinking about, paying attention to, or cognitively processing in some other way. Eye movements provide a direct and measurable link to underlying processes within the brain and visual attention system (Hoffman and Subramaniam, 1995; Corbetta et al, 1998; Findlay and Gilchrist, 2003). This is why, as the technology for recording eye movements has improved, eye movement research has become a significant area within the psychological sciences. Eye tracking has been around since the 19th century (Huey, 1898) and methods for recording eye movements have developed significantly and become less intrusive over time. Existing methods for measuring eye movements include (from Duchowski, 2003):

- Electro-oculography – electric potential differences of the skin are measured using electrodes placed around the eye
- Scleral contact lens / search coil – a device is attached to a contact lens worn by the observer. Movement of this device is then measured, as the eye moves.
- Photo-oculography / Video-oculography – features of the eye such as shape of the pupil or position of the limbus are measured
- Video-based pupil/corneal reflection – cameras and image processing hardware are used to compute eye movements relative to external world

Unless the head is held completely still, only the last of these methods is able to provide ‘Point of Regard’ (POR) information, i.e. information about where the observer is looking relative to their external environment, as it can differentiate between head movements and eye movements. It is this POR data that is potentially useful in identifying the visual tasks of pedestrians as it indicates what they may look at if walking down a street. These systems work by recording the corneal reflection (also known as the Purkinje image or reflex) and centre of the pupil with an eye camera, using algorithms to calculate the direction of the eye. The corneal reflection is produced by shining an infrared light at the eye, and its location is recorded. Infrared is used to avoid other light reflections interfering with the process.

Video-based measurement of the pupil and corneal reflection is relatively unobtrusive and allows measurement of eye movements relative to the external world. This makes this method ideal for recording eye movements in natural situations, such as a pedestrian walking along a street. Three different types of video-based eye-trackers exist, and further details are given in Table 2.2.

Table 2.2. Types of video-based eye-tracker.

Type of video-based eye-tracker	**Description**
Static eye-tracker	Illumination source and eye camera are placed on table in front of participant. Can either be ‘tower-mounted’, with participant close up to eye-tracking equipment and head movements are restrained, or ‘remote’, with equipment distant from participant and little or nothing attached to head.
Head-mounted eye-tracker	Illumination and eye camera attached to helmet, cap or glasses worn by participant. A forward-facing scene camera is also attached to the equipment, to record the line-of-sight scene in front of the participant.
Head-tracker	Similar to head-mounted eye-tracker but also capable of calculating the position of the head in space using magnets. This can provide absolute measurements of head and eye movements within an environment, compared with only relative movements of the eye in reference to head position, as done by head-mounted eye-trackers.

2.6 Previous eye-tracking research

This section discusses previous eye-tracking research and what it tells us about what a pedestrian may look at or what may be visually important to a pedestrian. The research can be split into two types of study – laboratory-based studies and naturalistic, outdoor studies. Relevant literature was identified using searches in academic databases including Google Scholar and Web of Science, using keywords that included ‘Eye-tracking’, ‘Visual behaviour’, ‘Eye movements’, ‘Gaze’, in addition to keywords that included ‘Real world’, ‘Natural’, ‘Outdoor’, ‘Scene’, ‘Pedestrian’, ‘Walking’. Reference lists from identified research papers were also used to identify further potential research papers for inclusion in the review.

2.6.1 Eye-tracking research in laboratory settings

Much eye-tracking research takes place in laboratory or artificial settings. This is partly due to the greater control offered by this approach over the variables of interest, and partly due to limitations with the eye-tracking equipment and method. For example, some types of eye-trackers have to be fixed in place which limits the types of situations that can be investigated. Although eye-trackers have developed considerably since they began to be used, they can still be sensitive in their operation and liable to fail if conditions are not controlled and favourable for recording eye movements, with data loss sometimes being considerable Holmqvist et al (2011). This can be due to participant-related factors, such as having particular eye-types that do not work well with the method of eye-tracking used, or to environmental factors, such as using the eye-tracker outdoors or near sunlight. These factors can be better controlled and mitigated in laboratory conditions.

One approach to using eye-tracking in the laboratory is to record gaze behaviour when images or videos of real scenes are viewed. Results from this type of research show that gaze is not directed evenly across the whole scene, it is clustered around certain areas. A major goal of this research is to explain why people look at these ‘interesting and informative’ areas (Henderson, 2003). One explanation, the ‘bottom-up’ approach, suggests the properties of the stimulus (the image or scene being presented) determine where people look. For example, density of edges and areas of high contrast (Mannan et al, 1996; Tatler, Baddeley and Gilchrist, 2005), changes in colour (Turatto and Galfano, 2001) and motion (Mital et al, 2011) can all predict where fixations occur when viewing a scene. A number of computational models have been developed using these ‘salient’ features to successfully predict the location of fixations when viewing natural scenes (e.g. Itti and Koch, 2000; Parkhurst, Law and Nieber, 2002; Nuthmann and Einhauser, 2015).

An alternative explanation for the allocation of visual attention to this bottom-up, saliency approach is a ‘top-down’, voluntarily-directed approach. An early example of how top-down processes influence where we look is shown in Yarbus’ work (Yarbus, 1967). Participants were asked to view a picture whilst their eye movements were recorded. They were given different instructions on how to examine this picture, for example “estimate the material circumstances of the family shown in the picture”, or “give the ages of the people shown in the picture”. The scanpaths (the path the eye moves through as it observes something) created under these different instruction conditions were very different, even within the same participant, see Figure 2.4. This demonstrated how eye movements can vary depending on task, context and instructions. Yarbus’ results have been replicated more recently, e.g. Tatler et al (2010), and task requirements and context have repeatedly been shown to influence our gaze behaviour and the objects of our visual attention (e.g. Castelhano, Mack and Henderson, 2009; Ballard, Hayhoe and Pelz, 1995; Jovancevic, Sullivan and Hayhoe, 2006). There is some debate over the relative influences of the bottom-up saliency explanation of where we look and the top-down contextual explanation. Although there is evidence of the link between visual saliency and where we fixate (Foulsham and Underwood, 2008; Itti, 2006; Parkhurst, Law and Nieber, 2002) much of this evidence is based on correlation and cannot imply causality. For example, salient features in an environment may often have an association with being important based on the observers prior knowledge, and it may be this prior knowledge that is driving the fixation rather than the saliency of the feature itself. In addition, some studies have failed to find a link between saliency and fixations (Henderson et al, 2007), or have suggested saliency cannot explain patterns of fixation found during natural tasks (Turano, Geruschat and Baker, 2003).

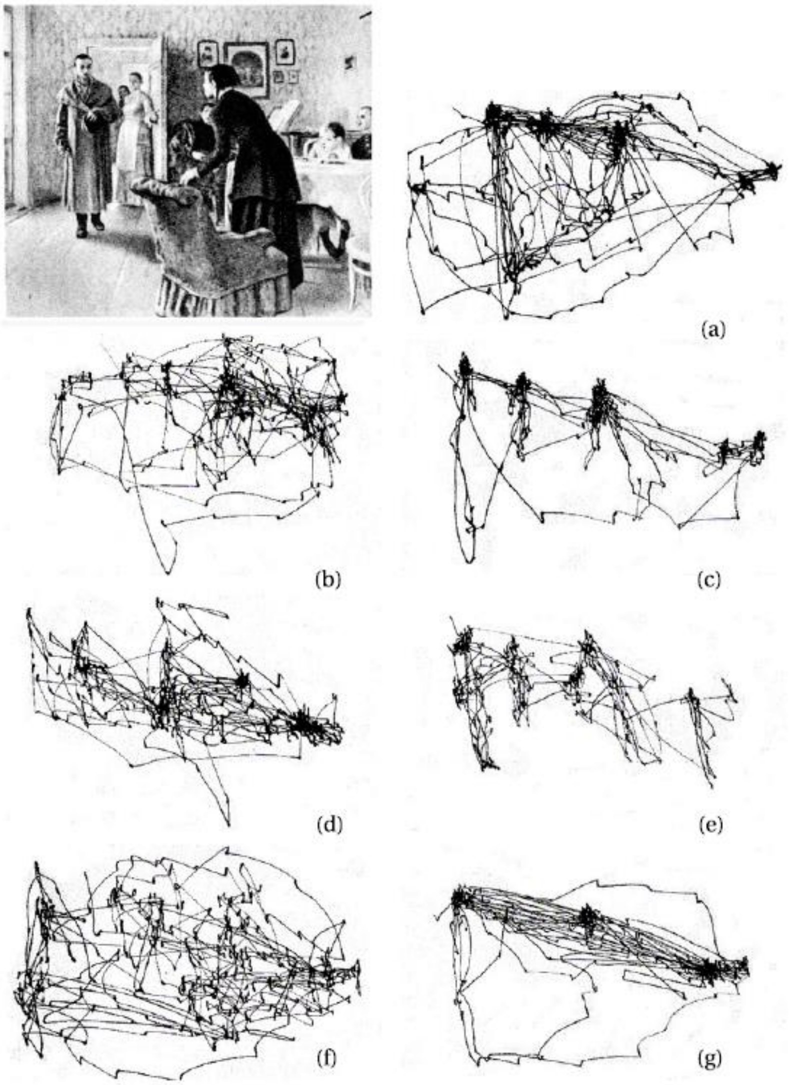


Figure 2.4. Effect of instructions on eye movements, from Yarbus (1967). Scanpaths from one participant examining a picture (“The Unexpected Visitor”, top left), under different instructions: a) Free viewing; b) Estimate material circumstances of the family in the picture; c) Give the ages of the people; d) Surmise what the family had been doing before the arrival of the visitor; e) Remember the clothes worn by the people; f) Remember the position of the people and objects in the room; g) Estimate how long the visitor had been away from the family. Illustration adapted from fig. 109 in Yarbus, 1967, for Land and Tatler, 2009)

The goal in briefly reviewing this debate over the relative influences of bottom-up and top-down approaches is to determine what factors are likely to influence what a pedestrian looks at when walking down a street. One study by Cristino and Baddeley (2009) examined the role of these two explanations in a pedestrian setting. They used point-of-view video clips of someone walking down a street to investigate whether eye movements are driven by low-level image features of the scene, such as edges, high contrast areas and motion, or by “world salience” - the meaning and rewards associated with these features, which can also be interpreted as a top-down, contextual explanation. They found that world salience was a greater predictor of fixation patterns than image salience. For example, fixations to kerbs, which have low image salience but high world salience due to being a potential trip hazard, were very frequent. They also found that participants fixated the feet of other pedestrians in the video clips more than their faces, which appeared curious given that another person’s face is usually the most informative part of their body. However, this was explained as being a compromise between avoiding collisions and making direct eye-contact with other pedestrians, which can have a social cost attached to it. Thus, fixating feet appears to provide greater long-term reward than fixating faces.

Dorr et al (2010) also carried out a study in which participants viewed natural images in a laboratory setting. The eye movements of observers were recorded whilst they watched four different types of stimuli: natural movies showing outdoor environments; trailers from Hollywood movies; stop motion videos taken from the natural outdoor movies; and static images taken from the natural movies shown in a non-sequential, randomised order. Results showed considerable variability in eye movements between the stimuli conditions. For example, initial fixations during the static images were drawn towards the centre of the image when initially displayed, before becoming unnatural and idiosyncratic, suggesting eye movement patterns using this stimulus were unrealistic. Fixation patterns during the movie trailers were more coherent and similar across participants than in other conditions, suggesting eye movement variability can be artificially reduced if using stimuli that deliberately attempt to capture the observer's visual attention. These results led Dorr et al to conclude: "…the stimuli types often used in laboratory experiments, static images and professionally-cut material, are not very representative of natural viewing behaviour" (Dorr et al, 2010, p. 1).

Similar results to those found by Dorr et al have been found by 't Hart et al (2009). Clips of eye movements in a number of natural indoor and outdoor settings were recorded and played back to observers in a laboratory (without the gaze location displayed), either as a continuous motion video or as a sequence of still frames taken from the video and displayed in a random order. Results suggested there was a 'centring' bias in the static video frames, in which gaze returns to the centre of the display at the onset of each new frame. This centring bias has been shown in numerous other lab-based, scene-viewing studies (e.g. Tatler, 2007; Tseng et al, 2009; Foulsham et al, 2011). Some support was found for Itti and Koch's (2000) saliency model of visual attention but 't Hart et al suggested this was due in large part to the experimental setup and conditions used, and the stimuli presented to observers which can cause spatial biases such as the centring bias for video-displayed scenes. The gaze patterns recorded by observers of the videos in the lab were found to have some predictive power for the eye movements recorded in the real-world setting. However, gaze in the real world had a bias towards looking at the path to be walked on which was not present in the lab-based conditions. This path bias was interpreted as a mechanism for providing prior information that will be useful in the future, e.g. motor planning and navigation, tasks that were not required in the lab-based viewing conditions. The authors suggested that eye movements during stereotypic motor tasks such as driving or playing sports cannot be replicated using a visual display.

This raises a question about how well a visual display can recreate the eye movements of a real pedestrian, as walking down a street can also be seen as a routine motor task. Eye movements recorded whilst viewing natural scenes on a screen can provide some insights into what a pedestrian may look at on a street. For example, visually salient features, such as a moving vehicle or a bright window, may attract their visual attention. Some of the studies reported above also infer looking at areas that may prompt some action or motor planning, such as the path or trip hazards in the path, could have importance. However, a number of limitations exist with this method of investigating eye movements that limit what it can tell us about where pedestrians look and what is visually important to them. Firstly, the stimuli can create spatial biases such as fixating the centre of the scene. Secondly, fixation patterns are highly task-dependent and it may be difficult for experiments involving the static viewing of scenes and videos to recreate the type of tasks a pedestrian is likely to perform in reality. Finally, viewing images on a screen may not provide the same context as a pedestrian would find in a real environment (e.g. Foulsham et al, 2011), and limit what the observer can see to what is displayed on the screen.

One step towards addressing these limitations with static viewing is to use virtual reality (VR) to create circumstances and a surrounding environment more similar to those a real pedestrian might face. Jovancevic, Sullivan and Hayhoe (2006) used VR to examine gaze behaviour whilst walking in the presence of other ‘pedestrians’ (single colour avatars in the VR world). Only 30% of fixations were on other pedestrians and the majority of these occurred shortly after they appeared within the participant’s visual field, suggesting a general strategy to look at other pedestrians at a distance, potentially to predict their path. Pedestrians that began to take a collision course with participants were more likely to be fixated than non-colliding pedestrians. However, this difference was not apparent when participants were undertaking an additional visual task, tracking a ‘lead’ pedestrian walking continuously in front of them. This suggested that the increased perceptual load created by following the lead pedestrian reduced detection of the colliding pedestrians.

Rothkopf et al (2007) used a VR environment to examine how task and context influence eye movements and fixations. Participants walked in a VR cityscape and were given instructions to either avoid obstacle blocks or pick up litter blocks in the environment. The task had a significant effect on where they looked, with participants looking more at the items that were relevant to their task. They also looked more at the path when avoiding obstacle blocks compared with picking up litter blocks. In addition, the more frequently the task-relevant blocks appeared, the greater the probability that they were fixated.

In another VR study, Karacan and Hayhoe (2008) asked participants to walk a rectangular path in a VR environment. Other pedestrians were also walking the path, and a number of objects were placed along the outer edge of the path. During the experiment some of these objects changed. One group of participants, the *experienced* group, were allowed to walk the path a number of times before the objects changed. The other, *inexperienced* group only walked the path once before changes were made to the objects. Around 54% of fixations were towards the path for both conditions. However, the experienced group looked significantly less at the surrounding environment (11%) compared with the inexperienced group (30%), but more at the other pedestrians (19% vs 7%, approximated from Figure 4 in Karacan and Hayhoe, 2008). In addition, the experienced group spent significantly longer looking at objects that had changed compared with the inexperienced group. These results suggested experience of an environment influences how we visually sample it. We learn the structure of an environment over time meaning we do not need to look at certain aspects of it as often but may be more sensitive to changes that occur to it, compared with if the environment is new to us.

VR studies like those of Jovancevic, Sullivan and Hayhoe (2006), Rothkopf et al (2007) and Karacan and Hayhoe (2008) provide a step closer to a more realistic paradigm for studying eye movements in natural situations, compared with viewing images or videos on a screen. However, they may lack the authenticity of interacting with a physical environment (e.g. Aghajan et al, 2015; Taube, Valerio and Yoder, 2013). A number of studies have however examined the eye movements of people completing natural tasks, and these can tell us more about the potential fixation behaviour of pedestrians.

In a study by Patla and Vickers (2003), the eye movements of participants walking a 10 m path in a laboratory space were recorded. The path had footprints placed at regular or irregular intervals and participants were instructed to place their feet on the footprints. Around 60% of fixations could be defined as ‘travel gaze’, where gaze was held stable on the path in front of the participant and moved forward at the speed of locomotion. In addition, around 15% of fixations were ‘landing target fixations’, located on the footprints ahead of the participant. Participants on average looked at footprints when they were two steps ahead of them.

A similar study was undertaken by Marigold and Patla (2007). Participants walked a short pathway which contained a series of uneven or irregular surfaces in the middle section. In contrast to Patla and Vickers (2003), only a very small proportion of fixations (0.27%) were found to be travel gaze fixations. However they did find a high proportion (91%) were ‘task-relevant’, directed towards areas to be stepped on. Fixations to the multi-surface terrain (91% of all fixations) were also significantly higher than fixations to the equivalent area during control walking trials (56% of all fixations), in which no multi-surface terrain was present.

Hollands, Patla and Vickers (2002) asked participants to walk a 9 m path in a laboratory space, at the mid-point of which they had to change direction. Participants spent the majority of the time looking at features in their ‘plane of progression’, i.e. in the direction they were heading. If they were not looking at such features, they tended to be looking at features related to future routes. This data indicates a significant proportion of a person’s looking behaviour is dictated by the direction they are currently walking or the direction they may walk in the future.

The work undertaken by Patla, Vickers and colleagues, using variations on a walking task, suggests that people predominantly look to areas that provide information for planning their future motor actions, such as locations they intend to step onto or that are relevant to their future path. However, Franchak and Adolph (2010) found evidence suggesting areas of the environment involved in motor planning may not need to be fixated. They investigated gaze behaviour in children and adults during a spontaneous visual search task, in which participants freely explored a large room containing various obstacles, objects and barriers, searching for particular items. Obstacles were fixated in the preceding 5 s period for 59% of the time in children, and only 32% of the time in adults. If an obstacle was fixated, this was generally done about 3 steps before it was reached. Franchak and Adolph contrast their findings with those of other lab-based studies which found higher rates of obstacle fixation. They suggest previous studies may overestimate obstacle fixations as participants had no reason to look at anything other than the obstacle. Eye movements are predominantly directed towards task-relevant locations. In previous studies the task was to negotiate the obstacles participants faced, whereas in this study obstacle negotiation was secondary to the visual search task.

Marigold et al (2007) also found that fixations to an obstacle were not required for successful avoidance. Participants walked on a treadmill and had to avoid an obstacle dropped onto the treadmill at unexpected intervals. Viewing the obstacle in central or peripheral vision did not affect avoidance, participants were able to successfully avoid it under both viewing conditions. Very few downward saccades towards the obstacle were made, and those that were tended to be towards the foot landing area beyond the obstacle, not the obstacle itself. These results suggested foveal vision of a suddenly-appearing obstacle in the travel path is not required for successful avoidance.

Much of the previous laboratory eye-tracking research has examined how eye movements relate to motor planning and the physical environment, such as negotiating obstacles or planning when to turn. There are other features of the environment that may require the planning of future action however, and one important feature for pedestrians may be the presence of other pedestrians. In a development of their previous research using a VR environment (Jovancevic, Sullivan and Hayhoe, 2006), Jovancevic-Misic and Hayhoe (2009) examined fixations on ‘real’ pedestrians. Participants walked around an oval path within a large room. Five other people also walked along the path, two in the direction the participant was walking and three in the opposite direction. The three walking in the opposite direction were each given instructions on how to interact with the participant upon approaching them. The *Rogue* walker would begin a collision path with the participant, starting from about 4 m away but without ever colliding, every time they approached them. The *Risky* walker would begin a collision path with the participant on half the occasions they approached them. The *Safe* walker would never approach the participant on a collision path. Results showed that the *Rogue* walkers had the highest probability of being fixated (approximately a 90% chance of being fixated), the *Safe* walkers having the least probability (approximately a 60% change of being fixated). Results also showed that the time participants fixated the different types of walkers changed as the experimental session progressed. Initially, each type of walker was fixated for around 500 ms. By the end of the session (12 laps of the oval path), fixation duration on *Rogue* walkers had increased to around 900 ms but had decreased to around 200 ms for *Safe* walkers, see Figure 2.5. The delay until fixation occurred also changed over the course of the session, with fixation latency increasing for *Safe* walkers and decreasing for *Rogue* walkers. These results were interpreted as demonstrating how gaze patterns and decisions about where we look are determined by the probabilistic nature of the world around us. Gaze is allocated to items in our environment based on what we know or have learned about them, and how important it is for them to be fixated.

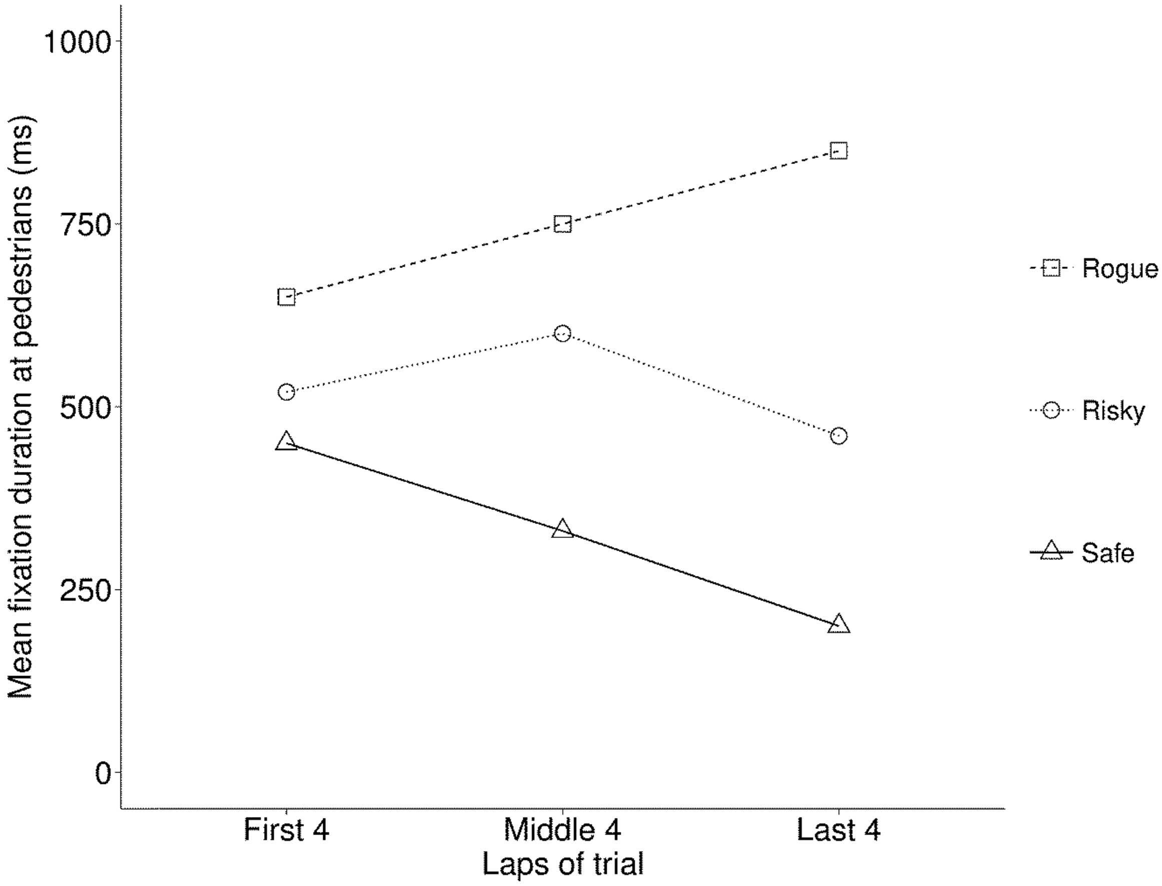


Figure 2.5. Mean fixation durations on other pedestrians by colliding condition, for first middle and last 4 laps of the 12-lap trial, from Jovancevic et al (2009). Adapted from figure 4a in Jovancevic et al (2009).

In another study investigating eye movements in the presence of other people Kitazawa and Fujiyama (2010) examined the fixation behaviour of pedestrians walking along a platform in a large laboratory space, with other real pedestrians and static mannequins. Kitazawa and Fujiyama only provide graphical data, with no summary statistics, but it appears items with the highest proportions of fixations were the platform surface, the end of the platform facing the participant, and the static mannequins. Fixations at the other pedestrians walking along the platform were infrequent. When they did occur, the majority took place when the other pedestrian was less than 3 m away. In contrast, fixations at the static mannequins, acting as obstacles, took place across a greater range of distances with a median value between 3 and 4 m.

The research reviewed so far has involved the eye movements of ‘pedestrians’, people walking. However, one eye-tracking study using cyclists can also provide some insights into how gaze behaviour may be influenced by the environment. Participants in Vansteenkiste et al’s (2013) study cycled at varying speeds through lanes of varying widths in a large sports hall. The results suggested task-irrelevant fixations reduce as task demands increase. For example, when the lane was narrower participants fixated more at relevant areas such as the path than irrelevant areas such as the surrounding environment. Increased fixations at the path when the lane was narrow also indicated a greater need for direct control of locomotion. This can be demonstrated in pedestrian studies also, for example when walking over difficult or uneven terrain. In such circumstances more control may be required over foot placement and limb movements, resulting in increased fixations towards the near path. Evidence for this is provided by Pelz and Rothkopf (2007), who reported pedestrians looked more at an uneven dirt path in a wooded area than a paved walkway in a man-made environment. Further evidence comes from Marigold and Patla (2007), who showed that people look predominantly at the near path when the surface is rough, with occasional looks towards distant areas. The rough surface meant that direct control was required, and therefore gaze at the near area was increased.

A summary of the laboratory-based eye-tracking studies reviewed above is given in Table 2.3.

Table 2.3. Summary of laboratory-based eye-tracking studies

Study	Participants	Method	Key findings	Implications
Cristino & Baddeley (2009)	40 participants (37 female)	Viewing point-of-view video clips of walking down street	World salience greater predictor of fixations than image salience, e.g. high frequency of fixations to kerbs	Top-down processes may be more significant than bottom-up processes. Kerbs likely to be important feature to look at.
Dorr et al (2010)	54 participants (46 female), aged 18-34	Viewed 4 types of video: natural movies, Hollwood trailers, stop motion videos and static images	Considerable variability in eye movements, but this is reduced with stimuli that deliberately attempts to capture visual attention	Stimuli often used in lab experiments are not representative of natural viewing behaviour.
‘t Hart et al (2009)	4 participants in each condition, aged 21-27	Viewing point-of-view videos as either continuous motion video or sequence of still frames in random order	Centring bias in viewing videos. Gaze behaviour when viewing videos did not predict bias towards looking at path in the real world walkers.	Video-displayed stimuli creates spatial biases and do not replicate real motor tasks. In real life we may look at areas involved in planning future actions, such as the path we intend walking.
Jovancevic, Sullivan & Hayhoe (2006)	16 participants (age not reported)	Walking in a VR environment, with other pedestrians walking in same or opposite direction	30% of fixations were on other pedestrians, usually on first appearance. Colliding pedestrians more likely to be fixated, although not when additional perceptual load was added.	Pedestrians more likely to be fixated if they are unpredictable or may require some action in response
Rothkopf et al (2007)	19 participants (age not reported)	Walking in VR environment containing different-coloured blocks, given instructions to either avoid or pic up certain blocks	Task-relevant blocks were looked at more often, and probability of fixation increased with frequency of these task-relevant blocks	Task and context are important in determining where someone looks
Karacan & Hayhoe (2008)	38 participants (age not reported)	Walked VR route with other pedestrians and objects. One group of participants had prior experience of the environment, the other did not. Objects were changed during the experiment.	Over half of fixations were to the path. Experience of the environment reduced looking towards the surrounding environment, but increased looking at objects that changed.	We learn structural nature of environments over time, which influences how we visually sample them
Patla & Vickers (2003)	7 participants (age not reported)	Walking a 10 m path, asked to place feet on regularly- or irregularly-spaced footprints	60% of fixations ‘travel gaze’, 15% of fixations on locations where feet will land. Participants looked on average 2 steps ahead when placing feet on footprints	Look near to us (2 steps) to plan future steps
Marigold & Patla (2007)	7 participants (3 female), aged 18-30	Walked 8.5 m pathway with irregular surfaces on middle section	Low proportion of travel gaze (0.27%). High proportion of task-relevant fixations to areas that would be stepped on.	High number of fixations towards task-relevant areas, e.g. locations we are likely to step on. Irregular surface more

			Irregular surface produced greater number of fixations than regular surface.	likely to attract our gaze than regular surface.
Hollands, Patla & Vickers (2002)	7 participants (4 female), mean age = 25	Walked 9 m pathway, at midpoint had to change direction.	Majority of time spent looking in 'plane of progression', or at features related to potential future route	People frequently look in direction they're travelling, which includes looking at areas relevant for potential future direction
Fracnchak & Adolph (2010)	6 children (4-8 years) and 8 adults (20-22 years)	Carried out visual search task in 6 x 9 m room containing various obstacles and barriers	Obstacles only fixated 32% of time in adults before they are negotiated. If they are fixated this tends to occur about 3 steps before the obstacle is reached.	Fixation of obstacle not necessary for it to be negotiated. Other lab studies may overemphasise importance of fixating obstacles, as this was the only task involved. Fixations tend to be task-appropriate.
Marigold et al (2007)	8 participants (mean age = 25 years)	Walking on treadmill, obstacle dropped unexpectedly on to treadmill. Obstacle viewed either with central or peripheral vision.	Contact made with obstacle in only 14% of trials on both viewing conditions. Downward saccades towards obstacle occurred in only 18% of trials, and these usually to foot landing area obstacle.	Fixation of obstacle is not necessary to successfully avoid it.
Jovancevic-Misic & Hayhoe (2009)	30 participants (age not reported)	Walking around oval path in laboratory space, with other pedestrians walking in opposite direction. Collision behaviour of other pedestrians varied.	'Rogue' walkers, who would always begin collision path with participant, most likely to be fixated, fixated for longer, and fixated more quickly, than 'safe', non-colliding walkers	Gaze behaviour is determined by probabilistic nature of the environment – we learn what is important to look at.
Kitazawa & Fujiyama (2010)	3 participants (age not reported)	Walked 15.6 m pathway with other real pedestrians and static mannequins that acted as obstacles	Fixations predominantly towards floor, end of pathway and static mannequins. Relatively few fixations towards the real pedestrians.	Fixations at other people relatively low which contrasts with other research, suggesting probability of fixating other people is high (e.g. Jovancevic-Misic & Hayhoe, 2009)
Vansteenkiste et al (2013)	12 paticipants, aged 21-28	Cyclists rode down 3 lanes of varying width, at 3 different speeds, in a large sports hall	Wider lane produced more 'task irrelevant' fixations, e.g. fixations to surrounding environment. Narrower lane produced more fixations to path.	More difficult task reduces number of task-irrelevant fixations. If increased control over locomotion is required, may be more fixations towards the nearby path.

2.6.2 Problems with laboratory studies

The eye-tracking research outlined above has been undertaken indoors, within laboratory settings and often with very specific tasks. It provides useful data about the visual behaviour of people, but it has limitations based on its ecological validity that restrict how applicable the results are to the key visual tasks of pedestrians in real street situations.

Firstly, results from lab studies can be inconsistent, often due to the very specific parameters and experimental setups used. For example, one study reported that around 60% of gaze behaviour was travel fixations (Patla and Vickers, 2003), whilst another study reported travel fixations as only accounting for 0.27% of gaze behaviour (Marigold and Patla, 2007). This discrepancy may be due to differences in the presence of visual features in the environment, with travel gaze occurring less frequently when there are more things of interest to look at (Marigold and Patla, 2007).

A further example of this is the interaction between sound and visual behaviour, and the general lack of auditory stimuli in laboratory studies. A common example of the link between auditory and visual stimuli is the ventriloquist effect, where the perceived location of an auditory stimulus, for example the words uttered by the ventriloquist, is influenced by temporally synchronous visual information, the movement of the mouth of the ventriloquist's dummy (e.g. Slutsky and Recanzone, 2001). The ventriloquist effect demonstrates the inherent cross-modality processing that takes place in humans, and how one modality influences the other. It is therefore unsurprising that sounds are likely to influence eye-movements. For example it has been shown that an auditory stimuli presented at the same time as a visual target can reduce the time taken for the eyes to be moved towards that visual target (Frens, Opstal and van der Willigen, 1995). Similarly, a visual target can be identified more quickly when it is accompanied by an unrelated auditory signal (Doyle and Snowden, 2001). Our eye-movements are also more likely to be biased towards the location of sounds in natural scenes (Quigley et al, 2008). In real-world situations there are a huge range of auditory stimuli present, such as passing traffic, talking or shouting, birdsong, construction work and so on. Such auditory stimuli are not present in laboratory settings, and the eye movements produced may therefore be artificial and unrepresentative.

Secondly, visual behaviour is highly task-dependent (Land and Lee, 1994; Land, Mennie and Rusted, 1999; Hayhoe and Ballard, 2005; Ballard and Hayhoe, 2009) and it is therefore important to recreate the tasks and goals a pedestrian is likely to encounter. This is difficult to do realistically in a laboratory setting, meaning the eye movement data recorded will relate to the task being completed in the laboratory but not necessarily to the tasks performed by a pedestrian in a real outdoor setting. It is likely that the laboratory-based data contains artefacts related to the experimental setting. For example, Marigold and Patla found that their participants looked predominantly at the rough terrain surface they were using. However, this may have been because it was an unusual surface and there was little else of interest in the environment for participants to look at. This study and many of the other laboratory-based studies reported above lack the distracting features that would be found in a real pedestrian environment, such as other pedestrians, buildings, vehicles and signage. Such features are likely to influence visual behaviour, but are difficult to recreate convincingly in laboratory settings.

Finally, laboratory experiments tend to involve repeated exposure to the same environment, as a number of trials are completed within the same experiment. Such repeated exposure is likely to change how participants sample their environment, as experience of your surroundings can reduce the time spent looking at certain features (Karacan and Hayhoe, 2008). Evidence of this effect comes from Jovancevic-Misic and Hayhoe (2009). Participants learned the statistical properties of the environment they were in, so that ‘safe’ pedestrians encountered were fixated for less time as the experiment progressed. Such repeated exposure to an environment and task does not reflect the dynamic, changing nature of a real world environment.

Therefore, naturalistic field studies investigating eye movements in an outdoor environment are useful to provide realistic data that can address the question of what a pedestrian’s visual tasks may be when walking down a street. Eye tracking has rarely been used in outdoor settings however. Four studies which have done this are described in the following section.

2.6.3 Eye-tracking in natural outdoor settings

Droll and Eckstein (2009) carried out a study in which participants walked outside around a building. Eight laps of the building were completed. Seven different objects (e.g. broom, backpack, traffic cone) were placed around the route. After participants had completed four laps, these objects were changed, being replaced with different items but within the same category. These changes occurred without the participants’ knowledge. Prior to starting the experiment participants were told to walk at a comfortable pace, as they would normally. A subset of the participants were additionally told that they would be asked about what they saw at the end of the experiment. This created two conditions, a walking only condition and a walking and memory condition. At the end of the experiment, all participants were questioned about what they saw, and whether they noticed the changes that had been made to the objects placed around the route. Results showed that participants in the walking and memory group were more likely to detect the changes to the objects than those just told to walk normally. However, detection of changes, at 32%, was still relatively low even in the walking and memory condition. Objects whose change was detected tended to be fixated for longer before they were changed, compared with objects whose change was not detected. This demonstrates how task and instructions can influence gaze behaviour, and also suggests that longer fixations may be linked to increased processing of environmental attributes.

When examining the data recorded from the eye-tracker, the authors focused on fixations of the objects that were placed around the route and did not categorise all fixations. However, they did state that:

“In other walking tasks, such as being required to step on specific locations, observers’ fixations are directed on the path approximately two steps ahead (Patla and Vickers, 2002 [sic]). However, in the present experiment, and as has been shown in other tasks that encourage participants to walk normally (Pelz and Rothkopf, 2007), our observers typically fixated at much greater distances, including many of the surrounding objects and buildings.” (p. 1171).

This suggests some discrepancy between fixation patterns reported in the laboratory and fixation patterns in a real-world, outdoor setting.

In another real-world study completed outdoors, Davoudian and Raynham (2012) monitored the eye movements of pedestrians during the daytime and after dark. Participants walked three routes along residential streets, measuring between 125 and 290 m in length. The routes were informally categorised as having a *low*, *moderate* or *high* level of obstacles based on the presence of trees, uneven surfaces and pavement width. On the *low* obstacle route the participant was accompanied by an experimenter but on the other two routes the participant would walk on their own. After completing the three routes each participant was interviewed about their gaze behaviour. Five participants completed the study during daylight hours, fifteen different participants completed it during hours of darkness. The categories of ***pavement***, other ***people***, ***signs***, ***transient objects***, or ***other*** objects were used to group what participants looked at during their walk.

The participants spent 51% of their time looking at the pavement during the day and 41% after dark (see Figure 2.6), although this difference was not statistically significant. Only 3-4% of time was spent looking at other people during the day and after dark trials. However, in the interviews that followed the experiment, participants placed a

"…high level of importance on recognising people…" (p. 446). One explanation for this discrepancy is the low number of other pedestrians that were encountered during the experiment, with a mean of 8.4 other pedestrians encountered during the day, and 4.5 after dark.

The amount of time spent looking at the pavement differed between all three routes, with the lowest proportion on the *moderate* route and the highest proportion on the *low* route. This pattern of results does not fit with findings from other research which has suggested more difficult terrain results in increased looking at the ground (Pelz and Rothkopf, 2007; Marigold and Patla, 2007). The authors explain this by suggesting the time spent looking at the pavement *"…is as much a function of time left over after scanning the environment for potential threats as it is of the complexity of the visual task on the pavement"* (p.446). Whilst walking the *low* route participants were accompanied by the experimenter. This may have made them feel more secure and therefore be less vigilant for threats in the environment around them, resulting in more time spent looking downwards at the pavement. This hypothesis is supported by comparisons of the day and after dark sessions. On one of the routes (*moderate*) participants spent significantly less time looking at the pavement after dark compared with during the day. Participants also reported feeling less safe on this route during the after dark trials. This may have resulted in more scanning of the environment for threats and to provide reassurance, and less looking at the pavement.

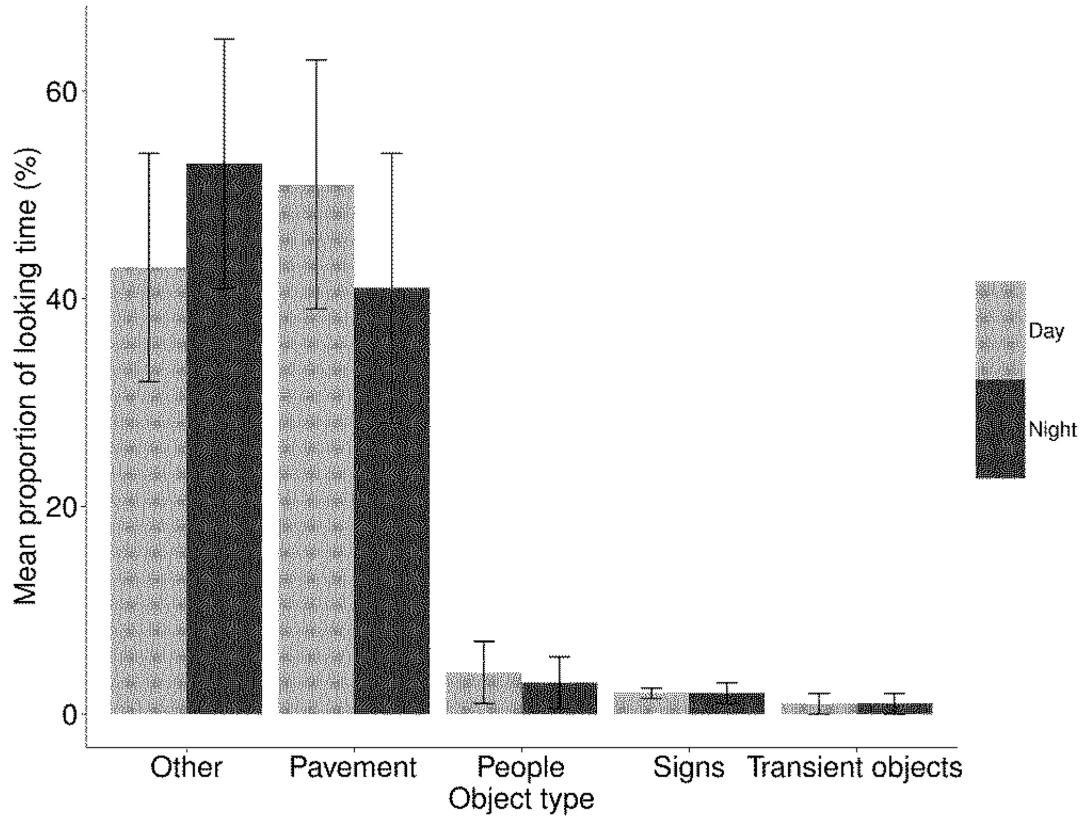


Figure 2.6. Mean proportion of looking time at different categories of object, day and night conditions, from Davoudian and Raynham (2012).

Foulsham et al (2011) also examined gaze behaviour in people during a natural task of walking outside. Participants walked a short route outdoors to buy a coffee or snack from a nearby shop. Minimal instructions were given to make the task as unconstrained and natural as possible. The walk took between 5 and 10 minutes to complete. Examination of the gaze locations during this walk showed that on average participants looked slightly below the horizon, suggesting a possible preference for looking downwards. Gaze location was also categorised based on what was being looked at. *People*, the *Path* and *Objects* were used as categories, and these were further subdivided into *Near* and *Far*, based on distance they were fixated. Results from this categorisation are shown in Figure 2.7. It shows that 37% of participants' gaze was directed at the path, and that this was usually towards the near path. This aligns with other findings that show the path is commonly fixated by people when walking (e.g. Karacan and Hayhoe, 2008; Marigold and Patla, 2007), and that it is more likely to be fixated nearby than further away (Patla and Vickers, 2003, found that people on average looked at the path two steps in front of them). Participants looked at other people for 21% of the time, and fixation of other people was more likely to occur at a distance than nearby.

Foulsham et al compared the looking behaviour of the participants whilst actively walking in the ‘real world’ with that of participants sat in a laboratory viewing the same video scenes captured by the eye-tracker during these real-world walks. A number of differences were found between the real-life ‘walkers’ and the video ‘watchers’. Two of the key differences were firstly that the walkers spent significantly more time looking at the path compared with the watchers. This difference was attributed to the fact that the walkers were engaged in an active walking task, which demanded greater attention to be paid to the path, and give further evidence that looking behaviour is heavily influenced by the task being undertaken. The second major difference was that whilst walkers were rarely likely to look at another pedestrian when they were close by, this was not the case for watchers, who spent significantly longer looking at the close pedestrians compared with the active walkers. One possible explanation for this is that although early fixation of other pedestrians is necessary in order to plan the direction being walked to avoid collisions, or to assess any possible threat, by the time the other pedestrian comes close to the observer and begins passing them, their gaze has already moved on to other, more distant features of the environment in order to adequately plan for them. Those watching the video did not need to plan future actions, they were in essence passive observers. An alternative explanation suggested by Foulsham et al is that the approaching pedestrian provides a social context for the walker which may reduce the likelihood of their gaze being directed towards that other person, who could potentially look back at them. Such an authentic social context is not present when viewing a video of the approaching pedestrian, hence why the watchers may have been less socially constrained and more likely to look at the other pedestrian when close up.

One potential problem with carrying out field eye-tracking studies in natural conditions is the difficulty in controlling the environmental conditions so that specific variables can be isolated for investigation. ‘t Hart and Einhauser (2012) attempted to address this by asking participants to walk a street section with two different surfaces running side-by-side, to investigate the effect these different terrains had on gaze. One side of the street had a stepped path, whilst the other side had a more regular cobbled surface. The stepped path was defined as being more irregular than the cobbled path, creating two different walking surfaces but in a virtually identical environmental setting. Participants walked along both types of path whilst their eye movements were recorded. Gaze whilst walking the more irregular, stepped path was on average directed lower down than when walking the cobbled path. In addition, slower eye movements tended to go downwards more often, and faster eye movements tended to go upwards more often. This pattern suggested to the authors that the slower eye movements are used to track details along the path, whilst this is compensated by faster upwards eye movements that make exploratory gaze scanning in the upper visual field, possibly planning future path direction or searching for important environmental features. Results also showed that gaze on the more irregular path remained in the lower visual field for longer. This may have been because a longer time was required to plan for the next footfall, due to the irregular nature of the terrain.

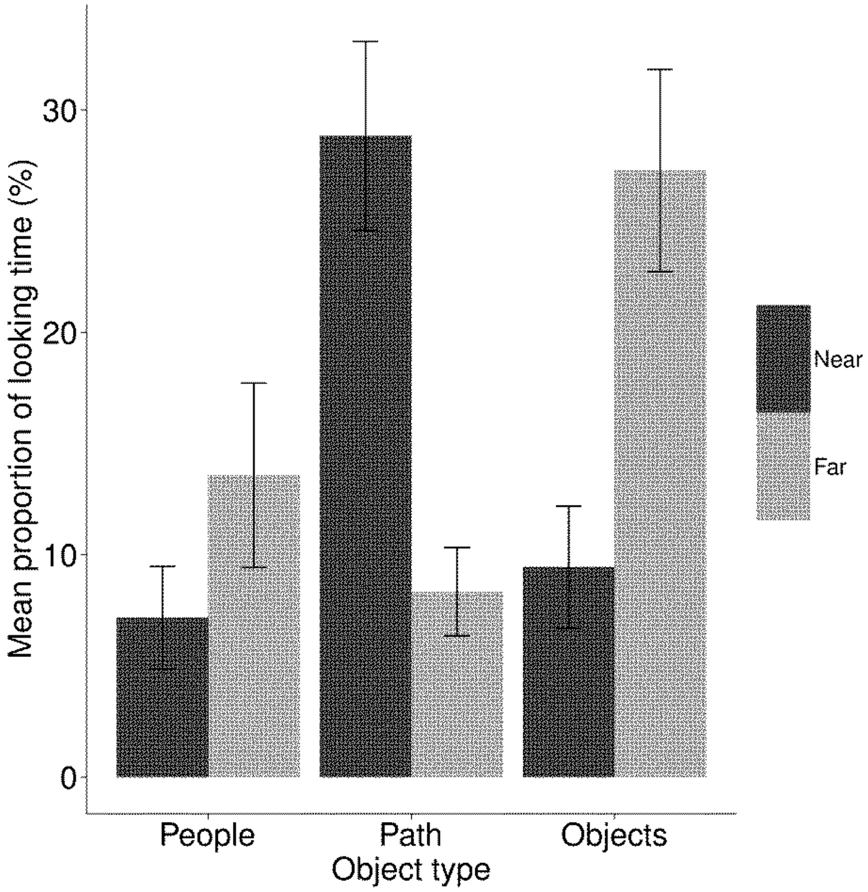


Figure 2.7. Proportion of looking time at different categories of item from Foulsham et al (2011), walking condition. Error bars show Standard Error of the Mean. Note: gaze falling outside the People, Path and Objects categories is not shown, and included other areas such as the sky, or when eye tracking was lost, as reported in the original data from Foulsham et al.

A summary of the natural, outdoor eye-tracking studies reviewed above is given in Table 2.4.

Table 2.4. Summary of eye-tracking studies in natural outdoor settings

Study	Participants	Method	Key findings	Implications
Droll & Eckstein (2009)	24 participants (age not reported)	Walk around building outside. Objects placed around route, and these were changed for similar items halfway through trial. Some of participants told they would be asked about what they saw.	Detection of changes was higher in memory group, but detection of changes, at 32%, was still relatively low. Participants typically fixated at greater distances than some lab-based studies.	Discrepancy in how far ahead pedestrians tend to look, based on these results and those from lab studies (Patla and colleagues)
Davoudian & Raynham (2012)	5 participants during day condition, 15 after-dark	Walked three routes along residential roads during day and after-dark	Around half of time spent looking at pavement. Only 3-4% of fixations were towards other pedestrians.	Authors suggest amount of time spent looking at pavement is function of whether there is a need to look elsewhere. No direct evidence for this though. Difficult in knowing whether a fixation is truly important or significant to a pedestrian.
Foulsham et al (2011)	14 participants (age not reported)	Walked short route (5-10 minutes) outdoors	37% of gaze directed towards path, and this predominantly towards near path. 21% of gaze directed towards other pedestrians, and this predominantly in distance. Significant differences found between gaze behaviour of real walkers and additional participants viewing the point-of-view videos captured.	Pedestrians appear to look towards the near path, or towards other people in the distance. Data gathered from observations of video footage show key differences to data gathered in real outdoor situation.
‘t Hart & Einhauser (2012)	8 participants (mean age = 30 years)	Walked a street section that had two distinct surfaces – regular cobbled surface and a stepped path	Gaze directed downwards more when walking along the more difficult, stepped path, and gaze remained in lower visual field for longer	Difficulty of terrain influences how often we look downwards towards the path, and for how long.

2.7 Conclusions from previous eye-tracking research

The previous section reviewed a selection of eye-tracking research that may be able to provide insights into how a pedestrian may view his/her environment and what visual tasks may be important. It is clear that very few studies have been carried out with the specific goal of investigating pedestrians' eye movements. The goal of much of the research reviewed was to investigate more fundamental aspects of gaze behaviour, and how it is influenced under different task conditions and settings, such as obstacle avoidance tasks, visual search tasks and memory tasks. Despite this it is possible to draw certain conclusions from this previous research that is of relevance to the research question of what a pedestrian's important visual tasks are.

A common theme running through much of the eye-tracking research is that people tend to look at areas that provide useful information, perhaps even to areas that maximise the amount of information they can glean from the visual environment. For example, Marigold and Patla found that fixations were frequently directed to the transitions between the different surfaces they used on the path confronting participants. They suggested this was to obtain information about two surfaces rather than just one, thus maximising the rewards gained from a single fixation. Cristino and Baddeley (2009) also produced data that suggested people look at things that give them significant rewards in terms what they can tell them about the world. It is possible to direct our gaze at things we know will provide rewarding information because we have built an understanding of the world around us and important aspects of the environment that require our attention. For example, people are more likely to look, or look longer, at things they know may require action (Jovancevic-Misic and Hayhoe, 2009). We learn the statistical properties of our environment from experience (Karacan and Hayhoe, 2008). Given that street environments have a degree of homogeneity, and most pedestrians are experienced walkers, we can infer that they have learned what may be the important visual elements that should be looked at and attended to. It is this information that is sought, for informing road lighting practice.

A range of research has shown the intrinsic link between eye movements and the task being undertaken. The gathering of visual information often occurs at important or time-dependent occasions. For example, when carrying out simple everyday tasks such as making a cup of tea or a sandwich we usually fixate objects or areas that are necessary for completing these tasks, and these fixations occur just before the particular action takes place (Land and Hayhoe, 2001; Land, Mennie and Rusted, 1999). These 'just-in-time' fixations demonstrate we often obtain information about our environment as it is required, in order to carry out actions upon that environment. During specific actions, these fixations occur in a structured and seamless sequence, suggesting we learn where to look and this becomes part of a schema for regular actions or behaviours (Land, 2009; Hayhoe and Ballard, 2014). This can be seen during the process of walking, as well as other everyday actions. Walking involves the coordination of movements and the negotiation of variable terrain and an environment containing a variety of different-sized objects and features, and observation of the path is required to navigate successfully. Research that has recorded gaze during walking has shown that our fixations also frequently follow a 'just-in-time' method, with the pedestrian generally looking only two steps ahead, at an area that will be traversed only one second later (Patla and Vickers, 2003). Foulsham, Walker and Kingstone (2011) also found that pedestrians were more likely to look at the near path than the far path, presumably because they were looking at the area that they were about to immediately encounter.

This research showing the 'just-in-time' nature of gaze behaviour during the completion of everyday tasks highlights the need to study eye movements in the context and environment that is of interest, and during completion of realistic tasks, as *"learned eye movement routines are inseparable from the everyday tasks that make up natural human behaviour"* (Foulsham, 2014, p.4). The research also suggests certain features of the visual environment are likely to be sought at by a walking pedestrian, such as areas that inform motor planning, for example where the feet are placed when walking (e.g. Patla and Vickers, 2003; Marigold and Patla, 2007). A pedestrian walking down a street may need to see areas of the environment to help plan his/her steps and foot placement. This implies looking at the path in front may be important, and fixations to the path or ground ahead of the participant have been shown to occur frequently (e.g. Marigold and Patla, 2007; Karacan and Hayhoe, 2008; Davoudian and Raynham, 2012). Looking at the path may be more likely to occur nearby than at a distance (Patla and Vickers, 2003; Foulsham et al, 2011), perhaps because only at a short distance can enough detail be made out to be useful in planning accurate foot placements, and also because information about the path may only be required when close, requiring immediate action. Research also suggests that pedestrians may look longer at the path if the terrain is difficult (Marigold and Patla, 2007; Pelz and Rothkopf, 2007; Vansteenkiste et al, 2013), as planning foot placement is likely to be a more difficult task requiring more detailed visual information or longer processing of that visual information. However, it should also be noted that other research has produced results that question the relatively high frequencies with which the nearby path is fixated. For example, Droll and Eckstein (2009) found that fixations generally occurred at greater distances, often at items other than the path such as surrounding objects and buildings. Pelz and Rothkopf (2007) also found that the amount of time gaze was directed to the immediate path was low, a result similar to that produced in Turano et al (2001).

Furthermore, it may not even be necessary for obstacles in the path to be fixated for them to be successfully avoided (Franchak and Adolph, 2010; Marigold et al, 2007).There is also some inconsistency in previous research about whether more difficult terrain does actually lead to increased fixation. Davoudian and Raynham (2012) found that fixations to the path was highest for the route defined as having lowest difficulty in terms of obstacles and terrain, the opposite to what might be expected given results from other research.

Therefore, whilst it appears looking at the near path may be important for pedestrians, and the difficulty of negotiating the path may mediate the amount of time spent fixating it, this is not a unanimous finding.

Another feature of the street environment that pedestrians may have learned is important is other pedestrians. These are usually moving, potentially unpredictable agents in the world that may require a response from the pedestrian. It may also be necessary to make some judgement about the potential threat or risk the other pedestrians pose. However, previous eye-tracking research on this topic has found mixed results about the propensity to look at other pedestrians. Jovancevic-Misic and Hayhoe (2009) found relatively high probabilities that other pedestrians were fixated, although it could be argued that there was little else in the environment used by Jovancevic –Misic and Hayhoe to attract the participants' gaze away from the other pedestrians. However, in a real world, outdoor study that did provide other distractions for participants, Foulsham et al (2011) also found fixating other pedestrians had a high probability. In the same study though, overall time spent looking at other pedestrians was lower than other environmental categories such as the path. Other research has also suggested time spent looking at other pedestrians is low (e.g. Davoudian and Raynham, 2012; Kitazawa and Fujiyama, 2010), and if they are fixated it is more likely to be their feet than their faces (Cristino and Baddeley, 2009). In summary, the importance and nature of looking at other people by pedestrians is uncertain.

There is some debate over the relative influences of top-down and bottom-up processes in determining where someone looks. Whilst salient features of the visual environment are likely to attract someone's attention, this mechanism can be overridden by the task being undertaken (Ballard and Hayhoe, 2009). Task is a significant determinant of where someone looks whilst they are walking (Rothkopf et al, 2007; Droll and Eckstein, 2009), it is therefore important to replicate or at least attempt to simulate the tasks a pedestrian has whilst walking down a street. This is difficult to achieve in lab conditions ('t Hart et al, 2006; Dorr et al, 2010), hence why natural field studies are essential for studying the visual behaviour of pedestrians. In addition lab studies often only require a single task to be completed, such as stepping on footprints

(Patla and Vickers, 2003) or avoiding an obstacle (Marigold et al, 2007) yet in reality, pedestrians are involved in a number of tasks simultaneously, such as planning their footsteps, wayfinding and scanning their environment. Involvement in secondary tasks can influence where we look (Jovancevic et al, 2006), which means single-task laboratory studies may not be reliable predictors of where a real pedestrian looks.

2.8 Limitations with previous eye-tracking research

A major premise of eye-tracking research is that eye movements and fixations are linked to the observer's cognitive processes and distribution of attention. This is a reasonable assumption. For example, when carrying out an everyday task the vast majority of our fixations are related to the completion of that task, suggesting our visual behaviour is strongly linked to our actions and decision making (Land et al, 1999). Eye movements play an important determining role in how we perceive the world (Findlay and Gilchrist, 2003), and attention can be directed towards an area in our visual field immediately before a saccade and fixation is made to that location (Hoffman and Subramaniam, 1995). However, this link between where we look, where our attention is directed to and what we are actively processing is not ever-present. For example, it is possible to fixate something without it being cognitively processed or entering working memory. Triesch et al (2003) used an object sorting task in a VR environment to study attention and task demands on detection of changes to the environment. They found that a significant proportion of the changes made to the objects went unnoticed by participants even when the object was directly fixated. This inattentional blindness to features in our visual field has been demonstrated in a range of other contexts (Simons and Chabris, 1999; Memmert, 2006; Kovisto, Hyona and Revonsuo, 2004). It has even been demonstrated in expert observers working in their domain of expertise. Drew, Vo and Wolfe (2013) asked 24 radiologists to carry out a lung nodule detection task similar to what they may have to do in their day-to-day work. The shape of a gorilla, 48-times larger than the average nodule, was placed in some of the scans being assessed by the radiologists. This conspicuous gorilla went unnoticed by 83% of the radiologists, even though the majority of them fixated it, with an average fixation time of 547 ms.

This research on inattentional blindness shows that looking at something is not always sufficient for processing or attending to it. To compliment this, research has also shown that we can actively attend to an area in our visual field without fixating it (e.g. Posner, 1980). Such covert attention provides another mechanism by which we can extract information from parts of our environment without necessarily having to direct our gaze towards them. For example, in an eye-tracking study involving observation of driving videos (Underwood et al, 2003) participants were able to recall 20% of objects that were not fixated. In addition, only 50% of objects that were fixated were recalled. Another example of the use of covert attention, this time during a physical task, is provided by Franchak and Adolph (2010), who showed fixation of objects and obstacles was not required in order for successful negotiation of those items.

The focus of our attention does not always have to be directed outwards, towards our physical environment. We frequently direct our attention inwards, for example when we are caught up in our own thoughts or when our mind wanders. When this happens, our fixations are not linked to where our attention is focused, and we cannot assume awareness of what is being looked at. This disconnection between fixations and attention during mind-wandering has particularly been demonstrated in eye-tracking studies involving reading, where comprehension of the text being read reduces during episodes of mind-wandering despite words continuing to be fixated (Foulsham, Farley and Kingstone, 2013).

A final reason we cannot have complete confidence in the premise that where we look indicates what is visually important to us is that gaze may not always be related to the primary task being undertaken, particularly if that task is relatively simple or routine. Walking down a street is a relatively automated cognitive task, and may not require constant input from our visual system. Therefore, it is unlikely that everything a pedestrian may look at is of importance to the actual task of walking safely – task-irrelevant fixations are highly likely. It is only when a task becomes more difficult that task-irrelevant fixations are likely to reduce (Vansteenkiste et al, 2013; Pelz and Rothkopf, 2007). For example, Davoudian and Raynham found that around half of all fixations were directed towards the path, but suggested that for some of the time spent doing this the pedestrians *“were not performing visual tasks that were important to them walking along the road”* (p. 446). A further problem with interpreting the amount of time or frequency of looking at different items as correlated with that item’s importance to the observer is it may be dependent on how much exposure that item has had to the observer. An item that is in the observer’s visual field for a longer time has greater opportunity to be looked at more frequently and for longer. Evidence of this is suggested by Droll and Eckstein (2009). Differences were found in the amount of time spent fixating each of the different objects placed around the path that participants walked, but the authors suggest this may have been due to the amount of time each object was exposed to the participant. For example, an object that appeared shortly after participants turned the corner of the building would have been in their field of view for less time before they passed it compared with an object placed towards the end of the path, just before a turn.

The goal of using eye-tracking with pedestrians is to identify the important visual tasks they perform when walking down a street. Given that fixations do always indicate where attention is directed, or whether it is directed towards something that may be relevant to the task of safe walking, a method is required to highlight gaze behaviour that is of relevance to the goal of identifying a pedestrian’s critical visual tasks.

2.9 Summary

Eye-tracking is a potentially useful and objective method for measuring what aspects of the visual environment may be important to a pedestrian. The physiology of our eye and visual system means we move our eyes to point the fovea, the area of the retina that provides fine spatial detail, to areas of interest in our environment. Previous laboratory-based eye-tracking studies reveal varous facets of our gaze behaviour, and can hint at what pedestrians may find important or tend to look when walking. However, they do not provide the context or represent the tasks involved when a pedestrian walks along a street, and they may be prone to spatial biases. There are relatively few eye-tracking studies in natural outdoor environments, and the results from these are somewhat discrepant. They also have a number of limitations in relation to what they tell us about pedestrian visual tasks, primarily because there is no guarantee that what is being looked is actually being paid attention to, or is important to the task of safe walking. The following chapter discusses a method for addressing this limitation, use of a secondary task alongside walking with an eye-tracker.

CHAPTER 3. IDENTIFYING CRITICAL VISUAL TASKS

3.1 Introduction

The previous chapter highlighted that a major limitation of previous eye-tracking research is it is unable to confirm whether attention is being directed towards what is being looked at, or whether what is being looked at is of significance or relevance to the pedestrian task of walking along a street. This limitation makes it difficult to interpret results from previous research on gaze behaviour in terms of what are the critical visual tasks of pedestrians. This chapter introduces a method for potentially identifying these critical visual tasks by highlighting instances when attention may be directed towards something significant in the visual environment – the dual task method. A secondary cognitive task is used as a measure of attention, and reductions in performance on this secondary task suggest a diversion of attention away from the task potentially towards a visual stimuli. A pilot study was carried out to test this concept. This showed that visual distractions do indeed cause a decrement in performance on the secondary cognitive task.

3.2 Identifying critical visual tasks – dual-task approach

Attention was described by William James as *"… the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought."* (James, 1890). The world provides vast amounts of information and it is impossible for our mental processing faculties to absorb and use all this information. Attention is our mechanism for selecting aspects of the world to focus on and process in some manner, in preference to other aspects of the world. However, our attentional resources have limited capacity (Kahneman, 1973) – we cannot allocate our attention to every stimulus we encounter. Evidence of this comes from research on divided attention and the completion of multiple tasks. If a single task is being carried out, all our attention can be focused on it. If however we are carrying out more than one task, our attentional resources have to be divided between the tasks, due to the limited 'pool' of attention available to us. This implies that performance on these multiple tasks may be reduced compared with performance on the single task, as less of our cognitive processing capacity is being applied (Pashler and Johnston, 1989). This description may be a slight simplification of the role of attention in single and multiple task completion but it is sufficient for the purpose of this section. Numerous studies demonstrate this reduction in multiple-task performance, in a range of contexts.

Research on the subject of attentional capture has shown that a visual working memory task influences visual attention, with singleton distractors having a greater detrimental effect on a visual search task when accompanied by an additional memory task (Olivers, Meijer and Theeuwes, 2006). The work of Theeuwes and colleagues (e.g. Theeuwes, 1994; Theeuwes, Kramer and Kingstone, 2004) suggested that visual attention was captured by visual distractors before it could be redirected towards a target that was task-relevant. Other research has demonstrated similar findings about the role of task-irrelevant stimuli on the performance of a particular task. For example, carrying out a visual search task whilst also trying to remember the spatial locations of two dots on a screen impairs performance on both these tasks, compared with if they were carried out separately (Woodman and Luck, 2004). Carrying out a concurrent cognitive task (talking on a mobile phone) whilst driving reduces driving performance, leading to increased failure to detect traffic signals and slower reactions to the signals when they are detected (Strayer and Johnston, 2001). Completing a secondary task whilst walking has been shown to adversely affect gait and walking, particularly in the elderly or in clinical populations, for example inducing slower walking or stopping walking altogether (Gulich and Zeitler, 2000; Lundin-Olsson, Nyberg and Gustafson, 1997).

One potential consequence of our limited attention capacity and the effects of carrying out more than one task requiring our attention is that in such dual task situations, performance on the two tasks may be related. In dual-task situations our attention can be voluntarily allocated preferentially to one of the tasks, and this will reduce performance on the other task. For example, in a dual-task experiment involving completion of a cognitive task whilst walking, Kelly, Janke and Shumway-Cook (2010) showed that task instructions to focus either on the cognitive task or walking changed performance on these tasks. Instructions to focus on the cognitive task led to faster performance of that task, whilst instructions to focus on walking led to increased walking speed and more accurate walking. This suggests participants were able to selectively allocate their attention preferentially to one of the two tasks being undertaken, creating differences in performance. It is therefore possible that in a dual-task situation, a relative reduction in performance on one of the tasks may indicate an increase in the attentional resources allocated to the other task, resulting in improved performance on that task. This selective allocation of attention between two tasks may occur because of instructions given by the experimenter, as described by Kelly, Janke and Shumway-Cook (2010), but it will also likely occur in natural conditions when we may have to prioritise one task above another in order to minimise danger and maximise pleasure (Williams, 2006). An example of this is in dual-task experiments involving walking and a secondary cognitive task. Participants generally prioritise walking and maintaining gait and posture over performance in the cognitive task (e.g. Schrodt et al, 2004), probably because failure in walking and gait stability would have more drastic consequences (such as tripping or falling over) than failure in the cognitive task.

Therefore, people may differentially allocate their attention to multiple tasks based on how important those tasks are at that point in time, and this will be reflected in performance on those tasks. This prioritisation of attention is likely to happen in a top-down, actively controlled manner, responding to immediate circumstances (e.g. Meyer and Kieras, 1997). As a result, in dual-task circumstances ongoing performance on one task can provide a continuous indication of the attention allocated to the other task.

This concept was used in the research reported in this thesis, and a dual-task method was developed to identify instances when the attention of a pedestrian was potentially directed towards something important in their visual environment. The two tasks involved would be some secondary cognitive task, alongside the primary task of observing and walking in the physical environment. It was hypothesised that performance on a continuous auditory task would fluctuate depending on how much focused attention pedestrians applied to what they were looking at. Previous work around visual distractions have also used a visual main task, i.e. the same modality (see the work of Theeuwes and others, referenced above). However, there is reason to believe performance on concurrent auditory and visual tasks can be linked, despite being different modalities. For example, Boot, Brockmole and Simons (2005) found that carrying out an auditory task (counting sequential repetitions in an auditory string of digits) affected the allocation of cognitive resources to a visual search task. Therefore, performance on the auditory task was expected to reduce at times when the participant was attending to a significant visual stimulus, or something visually distracting. This theory was tested in a proof-of-concept pilot study, described in the next section.

3.3 Visual distractions pilot study

A pilot study was designed to test whether visual distractions increased reaction times to an auditory stimulus. The pilot study was also designed to assess the effect visual distractions alongside a motor skills task had on reaction times to an auditory stimulus. The study involved two screen-based tasks completed by participants in a laboratory setting.

Nine naive participants took part in the pilot study. All participants were postgraduate students at the University of Sheffield, aged under-35. The relatively small sample size of the pilot study means it is difficult to test resulting data for normality of distribution. It also means assumptions about sample sizes for certain parametric statistical tests may be violated. Therefore only non-parametric statistical tests are used to compare data (Siegel and Castellan, 1988).

Presentation of visual stimuli on the screen, auditory stimuli and recording of reaction times were all controlled by DirectRT, version 2004, developed by Empirisoft (Jarvis, 2004).

3.3.1 Task one

For the first task participants were asked to respond as quickly as possible to auditory beeps whilst observing a computer screen. They were asked to use their writing hand when holding the mouse and pressing the mouse button. They were also instructed to watch the screen, as they would be asked questions about what appeared when the experiment was over. This was not true, but they were told this as a way of ensuring they kept watching the screen whilst carrying out the reaction time task.

For the first stage of the task the screen remained blank. There were 10 beep stimuli for participants to respond to during this stage. During the second stage, which continued without interruption from the first stage, a series of 20 distracting images appeared on the screen, whilst the beep stimuli continued. There were 20 auditory stimuli during this stage. For the final stage of the task, the screen became blank again and there were 10 further auditory stimuli for the participants to respond to. The blank-screen stages were separated before and after the distracting images stage so that reaction times could be assessed for practice effects. If a practice effect was present then an improvement in reaction times during the second blank-screen stage would be anticipated, compared with the first blank-screen stage. Reaction times to each auditory stimuli were recorded through the DirectRT software.

The presentation of each auditory stimulus was pseudo-randomised, with the interval between each beep being either 1.0, 1.5, 2.0, 2.5 or 3.0 seconds. The distracting images varied between strange photos or pictures, pictures of famous people, and distracting text. Some examples are shown in Figure 3.1.

The distribution of reaction times for the different stages of the task are shown in Figure 3.2. Reaction times were approximately twice as long in the distraction stage compared with the two blank-screen stages. A Friedman's ANOVA suggested there were significant differences between the reaction times on the different stages of the task, and follow-up Wilcoxon signed rank tests confirmed that the visual distraction reaction times were significantly longer than reaction times in both blank-screen stages (Z = -2.66, p = 0.004 for both comparisons). In addition, the reaction time in the second blank-screen stage was suggested to be significantly longer than in the first blank-screen stage (Z = -2.55, p = 0.008). This is a reversal of any expectation of practice effects. One possible reason for this is that following the distraction stage of the task participants may have anticipated further distractions producing slight delays in their reaction times during the second blank-screen stage.

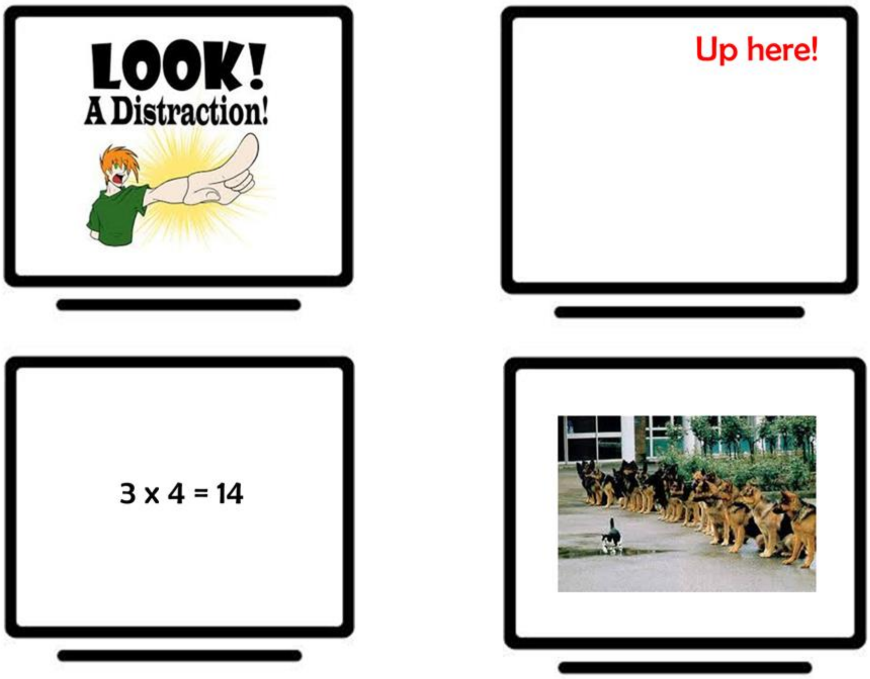


Figure 3.1. Examples of distracting images used during task one of pilot study

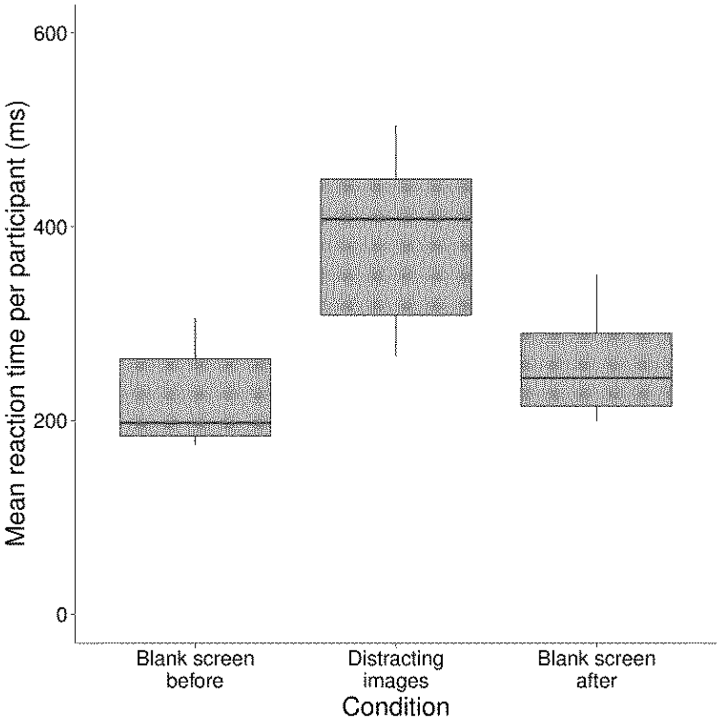


Figure 3.2. Boxplot of reaction times during blank screen stages and distracting images stage of pilot test task one. Darker horizontal bar shows median reaction time.

3.3.2 Task two

The first task in the pilot study was designed to test whether visual distractions cause delayed reaction times to an auditory stimulus. The second task in the pilot study introduced an additional motor skills element to the reaction time task, to represent the motor task involved in locomotion when a pedestrian walks along a street. Participants were again required to respond as quickly as possible to a frequent but irregular beep, the same stimuli as used in Task One, by pressing a mouse button. The computer screen in front of the participants began as a blank screen but at irregular intervals a name would briefly appear for between 1 and 3 s on the screen. Participants were instructed to immediately write down the name that appeared on a sheet of paper with their writing hand whilst continuing to respond to any beeps they heard by pressing the mouse button with their other hand. There were 96 beeps in total during the task, and a total of ten different names appeared. The names were all of well-known people such as celebrities, politicians or characters from films. The interval between each name appearing was pseudo-randomised and ranged between 8.0 and 30.1 seconds, with a mean interval of 20.1 seconds. It was predicted that reaction times to the two auditory stimuli that immediately followed the appearance of a name would be significantly slower than reaction times during other parts of the task, due to the combination of the visual distraction provided by the appearance of the name and the manual motor skills task of writing the name down. Reaction times to the two auditory stimuli immediately following the appearance of a name are shown in Figure 3.3, alongside reaction times to other auditory stimuli during the task.

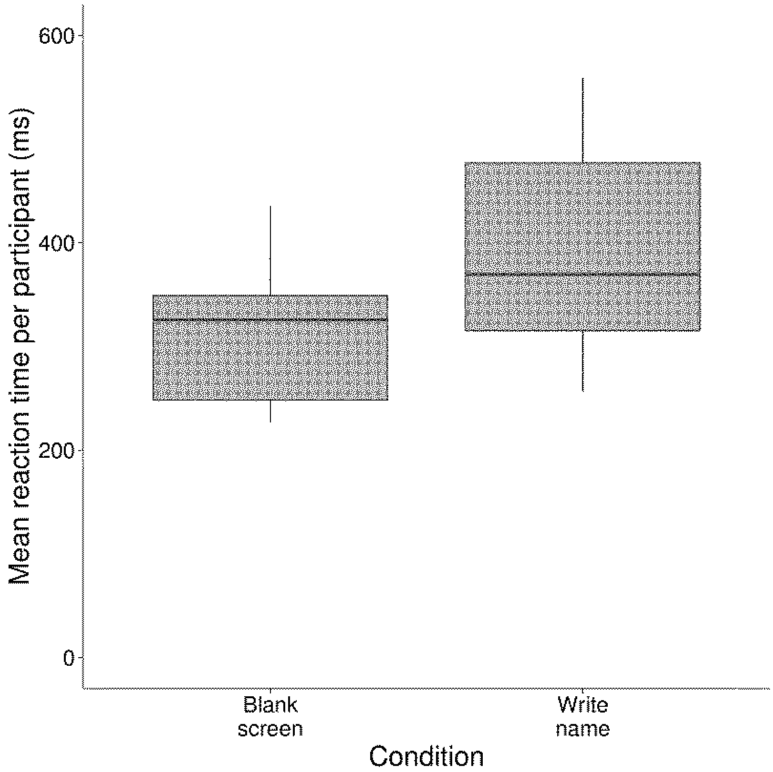


Figure 3.3. Boxplot of reaction times during blank screen stage and writing name stage of pilot test task two. Darker horizontal bar shows median reaction time.

Median reaction time immediately following presentation of a name appeared longer than reaction times during the rest of the task. This difference was suggested to be significant by a Wilcoxon signed-rank test (Z = -2.67, p = 0.004).

3.3.3 Conclusions from pilot study

Results from this pilot study suggest that an auditory reaction time test, using irregular, pseudo-randomised time intervals between auditory stimuli, can be used to demonstrate when someone is ‘distracted’, or their attention is diverted somewhere else. The first task demonstrated that visual distractions lead to a drop in performance on the auditory response time task, resulting in significantly slower reaction times. This is interpreted as being caused by a shifting of attention away from the response task to stimuli in the visual environment. The second task also demonstrated that visual distractions (in the form of intermittent names appearing on the screen) combined with a motor skills task (writing a name down) also leads to a drop in performance on the auditory response time task and slower reaction times. This second task could be taken as a proxy for someone being distracted by something in their visual environment (visual distraction) whilst they are walking (motor skills task). In both tasks, it is possible that the distracting images proved to be distracting because they were seen as task-relevant by the participants, as they were told prior to starting they would be asked about what they saw on the screen. This does not undermine the implications of the results however, as regardless of whether the visual distractors were seen as task-relevant or task-irrelevant, the point is that a visually salient feature prompted a reduction in performance on the auditory response task. Indeed, in some ways if the distracting images were seen as task-relevant it may make these results more applicable to real-world use of the dual task. The overall intention was to use a dual-task approach in the main experiment to identify visual features that were significant to the pedestrian. Such visual features can be seen as being ‘task-relevant’, i.e. necessary to see for the task of walking safely. Therefore if indeed the distracting images in the pilot test were deemed to be task-relevant by participants then the results are more supportive of the overall aim of using this type of auditory reaction time task in a dual-task paradigm.

Therefore, the conclusion from these pilot test results is that the reaction to auditory stimuli task could be used successfully to identify when pedestrians have focused their attention on something in the visual environment.

3.4 Defining critical visual tasks – limitations

In the context of pedestrians walking after-dark, a critical visual task can be defined as observing something that is significant and vital that enables the pedestrian to walk safely. An inability to carry out this ‘critical’ visual task, or complete it adequately, would have a negative effect on the pedestrian walking safely. This effect could be a number of things, such as making the pedestrian more likely to trip, stumble or slip, more likely to be fearful or create anxiety in the pedestrian, or more likely to result in appropriate decisions about the journey the pedestrian is making, e.g. when to cross a road or who to approach on the street. This chapter suggests using a concurrent auditory task alongside eye-tracking can identify these critical visual tasks by indicating when attention may be diverted away from this concurrent task and potentially towards something significant in the visual environment. However, it is worth pointing out that the direction of attention towards a visual feature does not necessarily mean it is significant for safe walking; it may have attracted the pedestrian’s attention for another reason, such as it being of personal interest, or it being conspicuous or unusual. This presents a limitation in the dual-task approach. That being said, the identification of instances when attention may be diverted towards the visual environment, for whatever reason, is more likely to include moments when the pedestrian is performing a visual task critical for safe-walking than if such attention-diverting moments were not identified and all fixations, regardless of where attention was directed, were used to define what was important for pedestrians to see. For this reason, the dual-task approach to identifying critical visual tasks offers an improvement on previous eye-tracking methods for identifying these critical visual tasks.

Furthermore, it may be possible to confirm the accuracy of the identification of ‘critical’ visual tasks through the dual-task approach by cross-referencing its findings with data from laboratory-based studies that manipulate what can be seen to identify the effect on safe walking or perceptions of the environment. One example of this is research that occludes different parts of the visual field to determine effects on walking or descending a step (e.g. Marigold and Patla, 2008; Timmis, Bennett and Buckley, 2009).

3.5 Summary

It was hypothesised that a dual-task method could highlight significant moments when pedestrians are paying close attention to what they are looking at. Instances of reduced performance on a cognitive task may suggest attention has been diverted away from that task, potentially towards something significant in the visual environment. This concept was tested in a pilot study, in which participants had to respond to an auditory stimulus by pressing a mouse button whilst viewing a computer screen. The pilot study showed that performance on the auditory response task was reduced when visually distracting images were viewed, suggesting attention was diverted away from this task as a result of viewing something distracting. The following chapter describes an eye-tracking study that uses this dual-task method to highlight significant viewing behaviour of pedestrians, in an attempt to identify their critical visual tasks.

CHAPTER 4. EYE-TRACKING EXPERIMENT

4.1 Introduction

Previous chapters have shown that research on the gaze behaviour of pedestrians is limited, and few studies have been carried out in real-life, outdoor settings. Of the few field studies that have been completed, none are able to distinguish important gaze behaviour, when a pedestrian may be looking at something important for safe walking, from other gaze behaviour. A dual-task method, using reductions in performance on a secondary cognitive task to indicate possible occasions attention is focused on something visual, was suggested to be a useful way of better identifying the important fixations of pedestrians.

This chapter describes an eye-tracking experiment carried out in a real outdoor environment. A dual-task method was used with participants carrying out an auditory reaction task was whilst wearing the eye-tracker. Critical times were identified using this concurrent task. Examination of the eye-tracking videos showed that the most frequent features viewed at these critical times were the path and other pedestrians.

Results from the dual-task method were compared with data in which all fixations are counted rather than just those at critical times. This comparison suggested the dual-task method offered benefit over the all-fixations method, as it was robust against any limitations caused by the frequency with which environmental features were encountered. Analysis of the probability with which other people are fixated corroborated the finding from the dual-task approach that observing other people is an important visual task for pedestrians.

4.2 Eye-tracking experiment

An experiment was developed in which a concurrent auditory reaction time task alongside eye-tracking aimed to identify important aspects of the visual environment that pedestrians attend to. Participants walked a short outdoor route during the day and after-dark, whilst wearing an eye-tracker and responding to auditory beeps by pressing a response button. Instances when attention may have been diverted away from this response task and potentially towards something important in the visual environment were identified and defined as *Critical Times*. The eye-tracking video at these *Critical Times* was examined and a judgement made about what the significant object or feature was that the participant was looking at during that time. This was placed into one of eight gaze location categories, and defined as a *Critical Observation*. Data about the proportion of *Critical Observations* in each category were analysed to determine the most significant types of environmental feature looked at by pedestrians.

4.3 Method

4.3.1 Equipment

The eye-tracking system used in this experiment was the iView X HED by SensoMotoric Instruments (see Figure 4.1). This system is a head-mounted eye-tracker (see Table 2.2) and allows the wearer to walk around his/her environment freely. It attaches to a laptop via a USB cable, which is carried by the participant in a rucksack. Two cameras are mounted to the helmet worn by the participant. One records the outwards image, capturing the 'point-of-view' scene facing the participant. This uses a wide-angle, 3.6 mm lens, with a visual angle of 56° vertically and 74° horizontally. The other camera captures an image of one of the participant's eyes (always the right eye during this experiment), via an angled mirror. An infrared light source is also attached to the helmet. This is reflected onto the eye via the mirror, creating high contrast between the pupil and surrounding area. The centre of the pupil is determined, and from this the direction of gaze is calculated following a calibration procedure. The infrared light also creates a corneal reflection, which is used to compensate for changes to the camera's position relative to the head, for example due to slippage.

Figure 4.1. SMI iView X HED mobile eye-tracker. Cameras attached to helmet are connected via cables to laptop, carried in rucksack.

A five-point calibration was used to create a reliable track of the participant's gaze position. Participants were asked to fixate 5 separate points on a wall, with each gaze location recorded on the eye-tracker video image. Calibration took place outside at a distance of 2 m, following manufacturer guidance.

The eye-tracking system provides a video output that shows where the participant is looking as a cursor, overlaid on the image captured by the outward-facing scene camera. In addition a data file is created with details of the eye-tracking samples recorded by the system, including Cartesian coordinates of the gaze position, relative to the scene video. The accuracy of this gaze position is reported by the manufacturer to be typically between 0.5° and 1.0° in visual angle. This samples data can be used to detect fixations, saccades and blinks using software provided with the system. The samples are captured at a rate of 50 Hz. The frame rate of the video captured by the scene camera is 25 Hz.

An Arduino microcontroller with connected mini-speaker and response button was used to provide the concurrent auditory task. The speaker was attached to the underside of the eye-tracking helmet, close to the left ear. The speaker emits an audible beep when power is supplied through connection to the eye-tracking laptop. The beeps occurred at random intervals between 1 and 3 seconds. The timing of each beep and each press on the response button was recorded on an SD card within the microcontroller.

The eye-tracker output and data recorded from the concurrent task were synchronised using the video recording from the eye-tracker. At the beginning of each trial participants were asked to hold the response button in front of their face, visible to the outward-facing eye-tracker camera, and press the button five times in quick succession. This produced a distinctive timestamp within the dual task data, and the timing of the first button press could be synchronised with the frame number in the eye-tracking video in which the button was first depressed.

4.3.2 Procedure

Participants walked a short route near to the University campus whilst wearing the eye-tracker and carrying out the concurrent task by pressing the response button every time they heard a beep. The route was approximately 900 m in length and took approximately 10-15 minutes to complete, depending on the participant's walking speed. The route was split into four sections, labelled A, B C and D, and is shown in Figure 4.2. Each section was chosen to provide different characteristics, such as road crossings or uneven terrain. A description of each section is given in Table 4.1, and example images showing each section are given in Figure 4.2. This route was chosen for a number of reasons. First, it provided a convenient location, starting and finishing near to the lighting laboratory where the experimenter was based. This was important as participants had to attend the laboratory at the beginning of each session, to be given instructions and to be equipped with the eye-tracker and other apparatus. It would therefore not have been practical to have travelled a large distance from the laboratory to the start of the route. Second, the route provided a good mix of environment characteristics, and these could be broadly characterised through the four different sections the route was partitioned into (see Table 4.1). The route did not therefore present a limited environment through which participants walked, instead providing a situation representative of different environments that pedestrians may encounter in day-to-day life. Third, the route was an appropriate length, being long enough to provide significant amounts of eye-tracking data, but not too long that the data quantity would be overwhelming or that the participants would become fatigued.

Figure 4.2. Route walked by participants. Route shown is clockwise direction; anti-clockwise direction is simply in reverse. The four sections of the route are shown; these sections are labelled A, B C and D regardless of route direction.

Figure 4.3. Photographs of four route sections. Clockwise from top left: Section A, B, C and D

Each participant carried out the walk on two separate days – once during daylight hours (08:00 – 16:00) and once after-dark (17:00 – 20:00). The mean time taken to complete the daylight trial was 12 minutes 38 seconds, compared with 13 minutes and 18 seconds for the after-dark trial. A paired-samples t-test showed that this difference was statistically significant ($t(37) = -2.858$, $p = 0.007$), possibly suggesting people walk more slowly when it is dark compared with during the daytime.

The route was walked in either a clockwise or anti-clockwise direction, with the starting location for the clockwise direction being the finishing location for the anticlockwise direction and vice versa. Each participant walked both route directions, one on their first trial and one on their second trial. The order in which daylight and after-dark trials and route directions took place was counterbalanced between participants.

Table 4.1. Descriptions of four route sections.

Section	**Length**	**Description**	**Relative volume of other pedestrians**
A	210 m	Pedestrianised area on University campus. Generally busy with a high number of people. Flat, uniform pathway surface, few obstacles and bright road lighting.	High
B	270 m	Mainly side streets close to University hub, mixed levels of traffic volumes. Irregular pathway surface, high number of obstacles. Includes steps and a road crossing. Generally high number of people, road lighting of medium brightness.	High
C	100 m	Short section with uniform pathway surface. Adjacent to busy road. Generally some other people present but not high volumes. Bright road lighting.	Moderate
D	320 m	Residential estate that participants were generally unfamiliar with (as confirmed in debrief interviews). Residential roads with low traffic volumes. Pathway surface generally good but included changing gradients. Low numbers of other people. Some areas without road lighting, other areas with dim road lighting.	Low

Participants attended the lighting laboratory at the University of Sheffield at the beginning of each trial. If it was the participant's first trial, they completed the Landolt ring acuity test and Ishihara colour vision test. These were carried out under standard office lighting conditions. It was not necessary to repeat these tests on the second trial. Participants were then set up with the eye-tracking and response task equipment, and given an opportunity to practice responding to the auditory beep by pressing the response button. Participants were then taken outside to complete the eye-tracking calibration procedure. Following successful calibration they were taken to the beginning of the route for that trial and shown a schematic map of the section of the route they were about to walk, and given a verbal description of where to go. Instructions were given to walk at a normal and comfortable pace, and press the response button as quickly as possible whenever they heard a beep. Task instructions have been shown to focus attention allocation in a dual-task setting (Kelly, Janke and Shumway-Cook, 2010), and so the instruction to respond to the beep as quickly as possible was intended to reduce instances of mind-wandering. Once the participant had begun walking, the experimenter followed a short distance behind, approximately 5 m, and out of the sight of the participant. The experimenter alerted the participant when they had reached the end of the section, and preparations were made to walk the next section of the route, which included showing a schematic map of the section and giving a verbal description of where to go. This procedure was repeated for all four sections of the route.

When the participant reached the end of the final section they were taken back to the lighting laboratory to have the equipment removed. If the participant had completed the second trial, they were also debriefed about the study and given an explanation of the purpose of the research. This was not made explicit before the participant took part to avoid any influence this may have had on their eye movements and behaviour. Participants were also asked to rate out of 5 their overall familiarity with the route as a whole, and their familiarity with section D, with 1 being very unfamiliar and 5 being very familiar. It was believed that section D would be less familiar to participants than the rest of the route, as it was not on the University campus and was a quiet, residential area. Familiarity with an area may influence where and what pedestrians look at, as we sample the visual environment partly based on what we already know about it (e.g. Jovancevic-Misic and Hayhoe, 2009). This needed accounting for when analysing the gaze data of the participants.

4.3.3 Participants

As this study was exploratory in nature with little previous comparable data available, sample size power calculations were not carried out (Jones, Carley and Harrison, 2003). However, one limitation of previous eye-tracking research is the tendency to recruit relatively small samples. In the previous eye-tracking studies reviewed in Chapter 2, few used more than 20 participants, with many using less than 10. However, eye movements can vary significantly between different people, even with the same visual stimulus (Dorr et al, 2010), and variation is more likely in natural real-world settings than in laboratory settings which induce spatial biases (‘t Hart et al, 2009). Such variation may limit the conclusions that can be drawn from a small sample. An additional consideration in determining sample size was to use a sample large enough that could withstand potential loss of eye-tracking data, particularly because the experiment would take place outdoors in conditions that could not be easily controlled (Holmqvist et al, 2011). An appropriate sample size was considered to be 40 participants, this being larger than most other eye-tracking research but within the logistical constraints for this project.

These 40 participants were recruited from staff and students at the University of Sheffield, and through personal contacts of the author. A snowballing recruitment technique was also used, with participants recommending other people to take part that they knew. Participants were paid £20 upon completing the experiment. Twenty one of the participants were male, and 29 were aged under-35. They were predominantly of white European ethnic background. The sample was to some extent a convenience sample but the sample demographics were not so skewed to make the findings from this experiment so exclusive to be uninformative. As the experiment was exploratory in nature and no specific hypotheses were being tested, there was no need to tailor the sample in order to compare between specific groups.

Participants were screened for their vision using a Landolt ring acuity test at 3 m, with all participants showing normal or corrected-to-normal vision, and the Ishihara colour perception test, with all participants found to be colour normal. All participants reported having normal or good hearing, a requirement given that the experiment involved an auditory task. Adequate hearing was confirmed in all participants by checking they could hear the noise produced by the auditory task whilst outdoors.

4.4 Results

4.4.1 Approach to analysis

Two sets of data were collected from the experiment. The eye-tracker recorded information about the participant's eye movements. This included a point-of-view video image from the scene camera with the participant's gaze position displayed as a cursor on this video. It also included the raw samples data based on the gaze direction of the eyes and other eye data such as pupil size. In addition to the eye-tracking data, data from the secondary auditory task was also collected. This produced a series of reaction time data for each participant, with the delay between when a beep was made and when the participant pressed the response button being calculated. These reaction time data were used to identify *Critical Times*, instances when the participant may have diverted attention away from the auditory task, potentially towards something important in the visual environment. These critical times would be indicated by a slower-than-average reaction time. The eye-tracking video with overlaid gaze position was examined at these critical times, following synchronisation of the reaction time data and the eye-tracking output. Whatever type of object or area was being observed at this critical time was recorded, and defined as a *Critical Observation*.

4.4.2 Reaction times

Reaction time data was not available for the after-dark trial of one participant, and for the daytime trial of another participant, due to a failure of the auditory task equipment during these trials. The sample size of reaction time data for each trial was therefore 39.

The auditory task produced a beep a mean of 274 times during each trial (standard deviation ± 33), excluding times between sections. The overall mean reaction time

(MRT) to the beeps across both trials was 345 ms (SD ± 83 ms). Paired-samples t-tests confirmed MRTs did not significantly differ between the day and after-dark trials (p = 0.988) or between the clockwise and anticlockwise routes (p = 0.901).

The MRT on each section of the route was compared. As there were no differences between the day and after-dark trials, and the clockwise and anticlockwise directions, the MRTs on each section were averaged across both trials, to give an overall MRT for each section. These overall MRTs are shown in Figure 4.4, and were compared using a one-way repeated-measures ANOVA. This suggested there were significant differences between MRTs on the four sections (F(3,117) = 6.742, p < 0.001). Post-hoc comparisons using the Tukey HSD test suggested that section C produced significantly lower MRTs than section A (p < 0.001) and section D (p <0.001). The difference between section C and section B was also approaching significance (p = 0.0595). No other significant differences were found between sections.

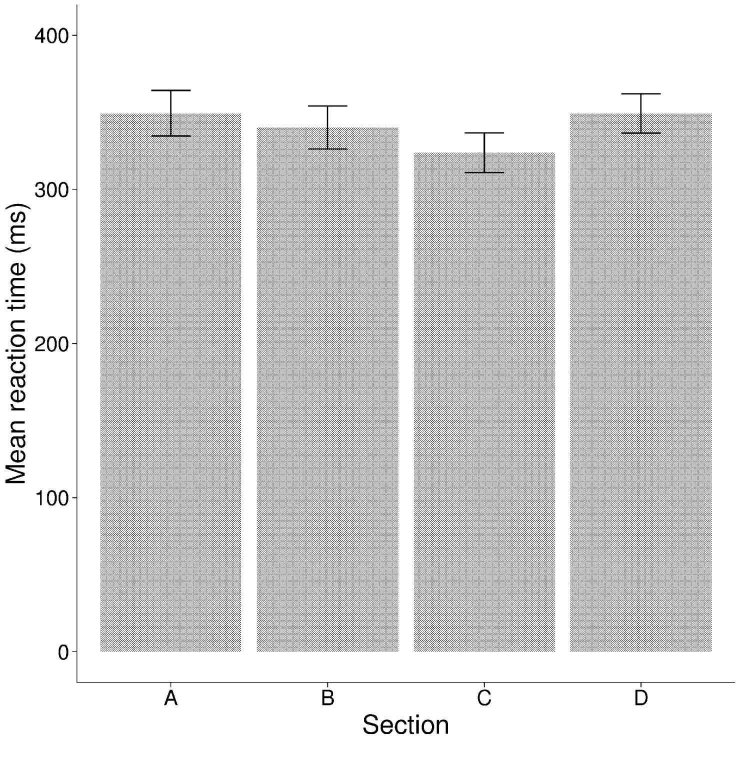


Figure 4.4. Overall mean reaction times by route section. Error bars show one standard error of the mean.

4.4.3 Critical times

Performance on the auditory task was used to identify critical times. This was done by finding responses that were significantly slower than average. The MRT for each participant was calculated for each trial, and responses that were 2 standard deviations greater than the participant's trial MRT were defined as being a critical time. This threshold was derived from methods for identifying outliers or abnormalities in data (e.g. Field, 2013). In a normal distribution, 2.5% of values would be expected to be ≥ 2 standard deviations above the mean. Using this threshold provides a simple yet effective way of highlighting relatively poor performance in the auditory reaction time task.

Previous analysis has discussed outliers in reaction time data, and concluded that “Outliers are response times generated by processes that are not the ones being studied” (Ratcliff, 1993, p.510). In the context of this experiment, the process being ‘studied’ through the dual task is attention directed towards the auditory stimulus and producing a button-press in response. Outlying values can be seen as instances when something interferes with this process, such as the diversion of attention away from the reaction time task (Ratcliff, 1993). It is precisely these outlying values that are of interest in this paradigm, as they may indicate when attention is diverted to something visually significant. A standard approach to identifying outlying slow values in reaction time data is to use a cutoff threshold of some combination of the mean and standard deviation, the threshold frequently used being the mean plus 2 standard deviations, as is the approach here (Whelan, 2008).

A histogram of all reaction times recorded during the experiment is given in Figure 4.5, and reaction time data for one individual participant is shown in Figure 4.6. These clearly show the unimodal, ex-Gaussian distribution that is common to reaction-time data (Luce, 1986). The long tail of this distribution highlights that there are particularly slow responses which are not representative of a normal response to the auditory stimulus. It is these responses that should be highlighted, and using the mean plus 2 standard deviations is a convenient, reliable method for doing this that has precedence in other reaction time analyses (see Ratcliff, 1993; Whelan, 2008). However, it is also worth noting that other methods for identifying significant critical times exist, such as identifying the *n* percentage of slowest reaction times, or using a threshold such as mean + 2SD in each section of the route, rather than across the route as a whole.

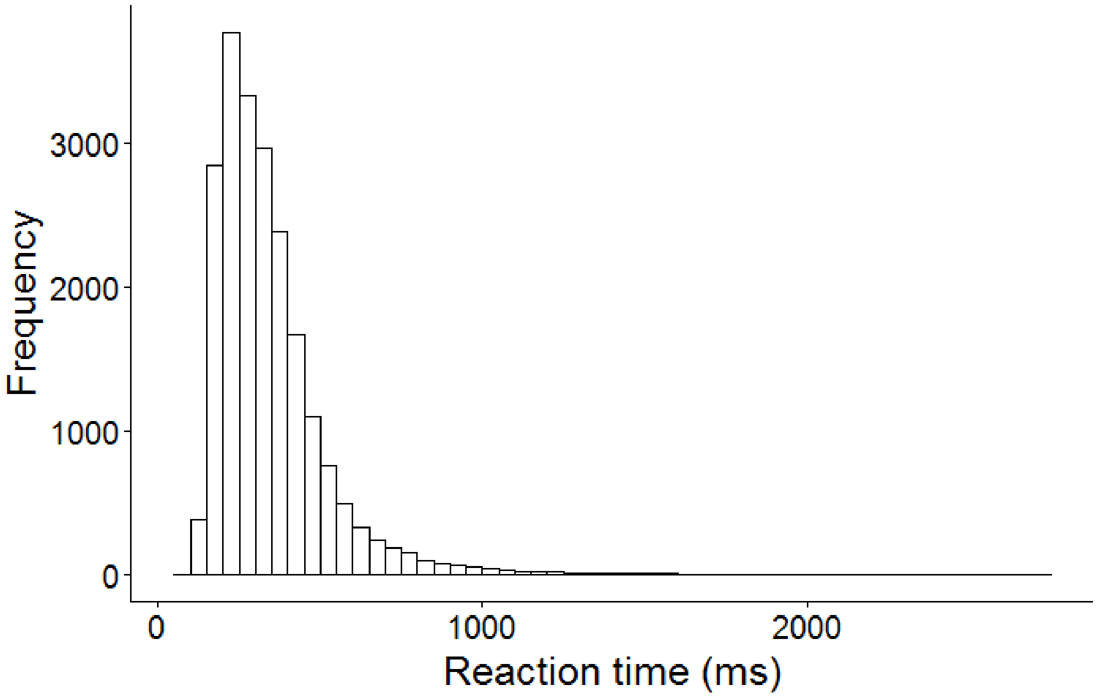


Figure 4.5. Histogram of all reaction times in response to concurrent task, across all participants and day / after-dark sessions.

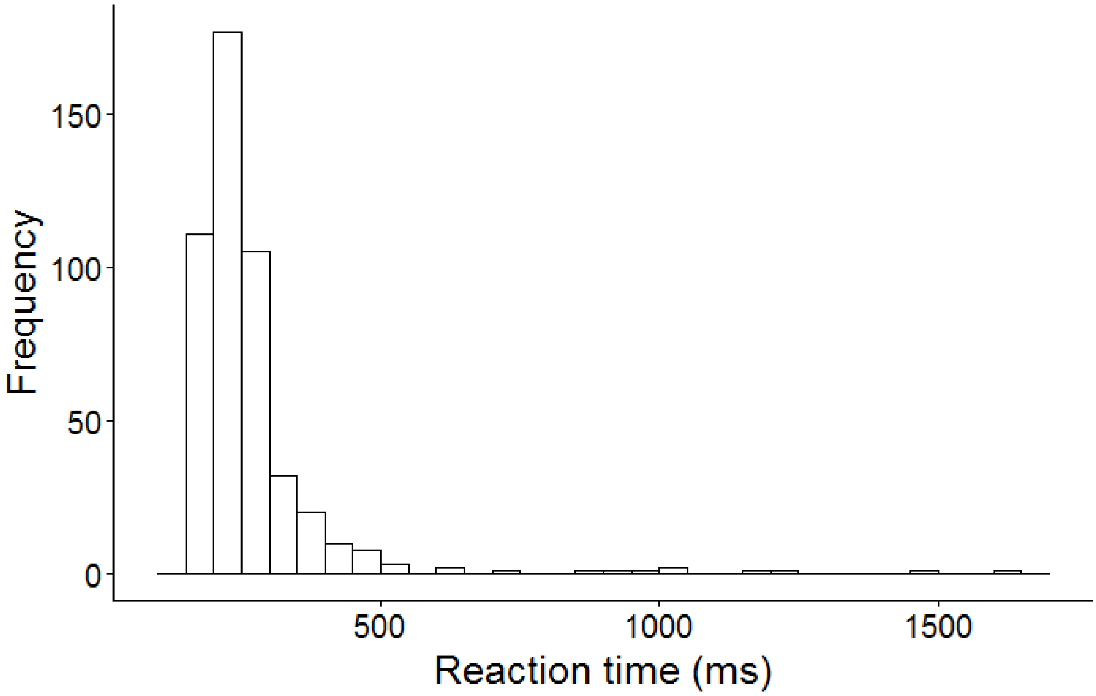


Figure 4.6. Histogram of reaction times for one participant, across both day and after-dark sessions.

An indication of poor performance is also given when the participant does not even react to the beep. Such a missed response suggests attention may have been diverted away from the task, towards something else. It was unlikely that participants missed a response due to being unable to hear the beep as all participants reported having normal hearing, and prior to starting each trial it was confirmed they could hear the beep whilst outside with general outdoor noise in the environment. A missed response was defined as any occasion when a beep was produced but the response button was not pressed before the next beep occurred.

An example of the reaction time data from the trial of one participant is shown in Figure 4.5. The reaction time for every response during the trial is shown, with MRT and MRT + 2 standard deviations also plotted. Responses with reaction times above the +2 standard deviations threshold were defined as critical times for this participant, as were missed responses. Missed responses are indicated on the plot by responses at the maximum value on the y axis, 1600 ms. In reality a missed response would not show on the plot as no response was provided, but this would not be visible.

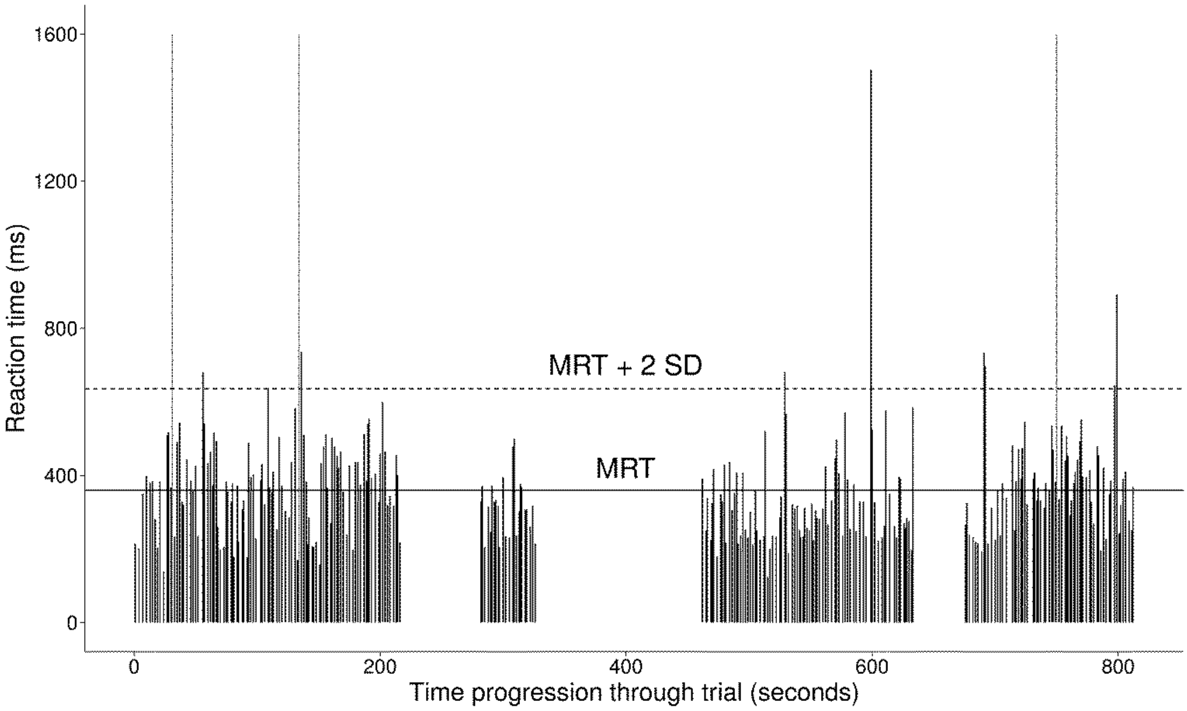


Figure 4.7. Example set of reaction time data from one participant on one trial. The x-axis shows time as the trial progressed, the y-axis shows reaction time for each response. This data comes from an after-dark, clockwise direction trial. A total of 280 responses were provided during the trial, with 3 missed responses. To make them visible, missed responses are indicated by lines reaching the maximum value on the y-axis, 1600 ms, but in reality there would be no line for a missed response. The solid horizontal line indicates the MRT for this trial, and the dashed horizontal line indicates the MRT + 2 standard deviations. Responses that were above this threshold would be defined as critical times. The gaps in the data, at 216-282 s, 326-462 s

and 633-676 s, are the intervals between sections on the route, where no response data was collected.

The number of critical times on each trial varied between participants (range = 6 to 42). This variation was significant as indicated by large kurtosis values for both day and after-dark trials (kurtosis values = 2.24 and 4.50 respectively). When converted to z-scores both these values were above 2.58, the criterion recommended by Field for indicating significant kurtosis in small samples (Field, 2013). However, the number of critical times for each participant appeared consistent between trials. Data were not normally distributed so the Spearman's rank correlation test was used to confirm this consistency ($r_s = 0.55$, $p <0.001$). There were a median of 14.0 critical times during both daytime and after-dark trials. However, the number of critical times did vary by route direction (clockwise median = 16.5, anticlockwise median = 12.0). A Wilcoxon signed-rank test confirmed this difference was significant ($V = 136.5$, $p = 0.006$).

The mean number of critical times on each section of the route was also compared. The sections differed in length which influenced the number of beeps produced and responses provided. Frequency of critical times was therefore standardised by calculating the critical response rate – the number of critical responses as a proportion of the total number of responses and missed responses. For example, if a participant provided 100 responses on one of the route sections, and 10 of these were defined as critical times, the critical response proportion for that section would be 10%. Figure 4.6 shows the critical response proportions for each section, with both trials being combined and the mean value used. Differences between the sections are apparent, and a Friedman's ANOVA was used to confirm these as the data was not normally distributed ($\chi^2 = 34.95$, $p < 0.001$). Post-hoc pairwise comparisons using the Nemenyi test (Demsar, 2006) suggested that section C had a significantly lower proportion of critical times than the other three sections (p-values all < 0.001); there were no other significant differences between the other sections.

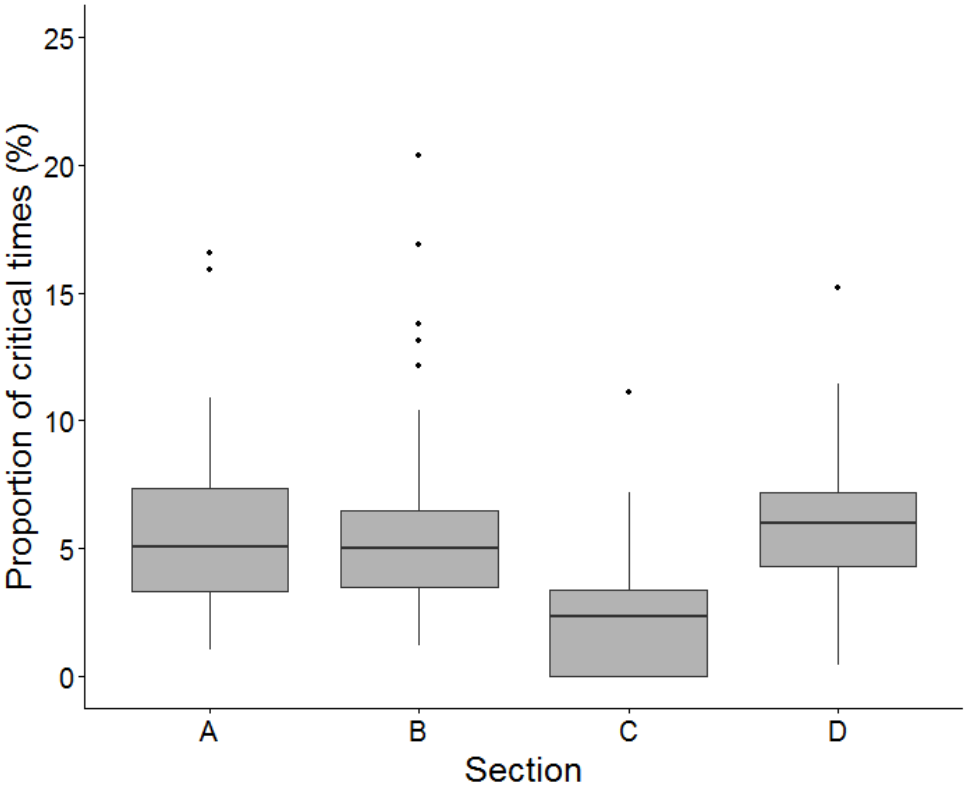


Figure 4.8. Boxplot showing proportion of auditory task responses that were defined as critical times by route section, both trials combined. Darker horizontal bars show median value; datapoints indicate values that are 1.5 x Interquartile Range above the 3rd quartile.

4.4.4 Gaze location categories

A number of categories of object, area or gaze behaviour were defined, to collate the gaze location of participants at the critical times. These categories were chosen partly based on previous work about what people look at (see Chapter 2), and partly based on preliminary viewing of a small sample of the eye-tracking videos. Such post-hoc definition of gaze categories is not ideal and can potentially introduce a degree of subjectivity which could influence the end results (Holmqvist et al, 2011). Given the dynamic, unpredictable nature of the environment the participants were walking through however, this post-hoc definition was felt necessary to determine useful and meaningful gaze categories.

A total of eight gaze location categories were defined. These are described in Table 4.2. A ninth, ‘Unknown’ category was also used to categorise occasions when it was not possible to determine what was being looked at because the gaze cursor was not present on the scene video, either due to a loss of the eye-tracking signal or because the gaze location was off-screen.

Table 4.2. Description of gaze location categories, used to classify where someone was looking at critical times.

Object category	**Description**	**Justification**
Person	Other pedestrians	People hypothesised to be important to look at whilst walking (e.g. Emery, 2000; Kingstone, 2009)
Path	Pathway in direction of travel	Previous research has shown pedestrians look a lot at the path, and this is assumed to be important in order to look for trip hazards
Latent threat	Potential hazard not visible yet, anticipated location of a potential threat	Previous research (Taylor et al, 2013) has identified latent threats as important category for classifying anticipatory gaze behaviour. Preliminary examination of videos also suggested this would be a useful category.
Goal	Target destination or waypoint towards destination	People expected to make fixations related to wayfinding/navigation – given instructions on route and target destination. This category used in other research too (e.g. Vansteenkie et al, 2013; Turano et al, 2001).
Vehicle	Stationary or moving vehicle, or moving bicycle.	Pedestrians likely to want to know about current and anticipated positions of vehicles, as this may influence the pedestrian's decision-making about travel path etc., and thus influence gaze behaviour.
Trip hazard	Small object or pathway irregularity that could cause pedestrian to trip	Trip hazards currently hypothesised to be important object pedestrians look at in order to avoid them
Large objects	Larger object in pathway that pedestrian has to navigate around, e.g. street furniture or lamp post	Pedestrians likely to need to see these in order to navigate around them on way to destination
General environment	Areas of environment not fitting into other categories	Capture other fixations that aren't thought to be critical to safer walking in direction of travel

4.4.5 Critical observations

The eye-tracking video was examined at the same time point as each critical time within a trial. The precise timing of the critical time was defined as when the beep occurred that resulted in the slow or missed response. Whatever the observer was looking at, at this critical time, was classified into one of the eight gaze location categories. However, the auditory task was not able to provide a very precise timing for when attention may have been diverted away. For example, the environmental feature that diverted attention may have been seen just before a beep occurred, or it may have occurred after the beep occurred but before the participant had pressed the response button. Both these circumstances are likely to produce a delayed reaction. There is therefore a ‘window’ around the critical time, at some point during which attention was diverted away from the auditory task. A 2-second window was chosen for analysing the gaze location around critical times in this experiment, 1 second either side of the critical time. This was chosen as any larger and the window could potentially overlap with contiguous beeps, as the minimum interval between beeps was 1 second. This could result in the duplication of data or conflicting specification of critical and non-critical times.

All fixations that occurred within the 2-second window around the critical time were identified. Fixations were defined using a dispersion-based algorithm supplied with the eye-tracking software. This algorithm was applied to the gaze coordinates in the raw eye-tracking samples data. One sample, which included the gaze coordinates of the eye in video pixels, was captured by the eye-tracker every 20 ms. Consecutive samples were grouped together as a fixation if they lay within 15 pixels of each other, and extended for at least 100 ms. These parameters were selected based on recommendations in eye-tracking literature (e.g. Salvucci and Goldberg, 2000; Blignaut, 2009). The video frames relating to each fixation were grouped together and could be played successively using bespoke software written in Visual C++ by Dr. Naoya Hara (Kansai University, Japan), to gain an understanding of what the fixation was directed at. A judgement was made about the most significant thing being looked at during the 2-second window. This was made by watching the 2-second period through in normal speed, and also watching a period of the video immediately prior to this period, to gain some context of what the participant had been looking at and a sense of their pattern of eye-movements, their immediate situation, and any possible distracting features or incidents that could have resulted in the critical time. This judgement was used to categorise each critical time into one of the eight gaze location categories. These will be referred to as *critical observations*. If no judgement could be made about what was the most significant item being observed, for example if the eye-tracking signal was lost or no fixations were apparent during the 2-second window, the critical time was categorised as ‘Unknown’. For a small number of critical times more than one category of item could potentially have been labelled as the most significant thing being looked at. In these cases the vote for which category should be used was divided equally between the possible items. For example, if the participant looked at both another person and a trip hazard during the 2-second window, and both items were judged to be potentially significant, a frequency of 0.5 was recorded for each.

Using the 2-second window and making a judgement about what was the significant item being looked at during that time may introduce a degree of subjectivity into the coding of the critical observations. Some eye-tracking studies do not report methods to check coding reliability (e.g. Davoudian and Raynham, 2012), or do not report data about inter-coder reliability (Marigold and Patla, 2007). Other studies report agreement measures of 85% and above (Vansteenkiste et al, 2013; Foulsham, Walker and Kingstone, 2013). Holmqvist et al (2011) report that “Inter-coder reliability is virtually never reported, probably because the frame-by-frame coding method is considered very precise” (p. 227). However, this may not apply to eye-tracking studies undertaken in dynamic and unpredictable environments, as is the case with this experiment. Given the potential for subjectivity in the coding of the critical observations, the reliability and consistency of this coding was checked. A sample of trials from 10 participants (all daytime trials) were selected for categorisation by a second coder, who was blind to the original coding of those trials and had no involvement in the experiment. Categorisations between the first and second coder agreed for 63% of critical observations. This measure of inter-coder reliability appears relatively low, compared with other studies that have reported a similar measure. However, this may be due to differences in the number of coding categories used. For example, Foulsham et al (2013) only used the three categories of Person, Path and Other. If critical observations were placed into only these three categories then coding agreement between coder one and coder two is > 90%. This suggests it was mostly the categories included in ‘Other’ that the coders disagreed on; agreement on whether the critical observation was to the Path or Person was high.

4.4.6 Where did people look?

The critical observations data were not normally distributed, so median values are reported and nonparametric tests have been used to examine differences in the data. The number of critical observations varied between participants (range = 6 – 42 across both trials). To create a standardised measure the frequency of critical observations in each of the gaze location categories was calculated as a proportion of all critical observations made during that trial. Observations placed in the *Unknown* category (median = 3 per trial) were excluded from the total number of critical observations used to calculate these proportions. For example, if a participant made a total of 10 critical observations during one trial, excluding those in the *Unknown* category, and 3 of these observations were to the *Path*, the *Path* category accounted for 30% of critical observations. However, some participants had relatively high numbers of critical observations in the *Unknown* category on one or both of their trials, due to loss of eye-tracking signal or the gaze location occurring off-screen. This resulted in potentially inflated proportions in the other categories due to low frequencies in those categories. Therefore participants were excluded from further analysis if they had less than 5 critical observations in categories other than *Unknown* in either of their trials. This criterion resulted in 12 participants being excluded, with 28 remaining for the final analysis.

Figure 4.7 shows the proportion of critical observations in each category for the day and after-dark trials. Differences are suggested between the categories, for example the *Person* and *Path* categories appear to have relatively high median proportions whereas other categories such as *Object* have much lower median proportions. Differences are also suggested between the day and after-dark trials, for example the median proportion for the *Person* category is lower after-dark than during the day, but this pattern is reversed for the *Path* category. To assess whether the suggested differences between categories was significant a Friedman's ANOVA was applied to both trials. The test for daytime trials was significant (χ^2 = 47.44, p < 0.001), as was the test for after-dark trials (χ^2 = 51.08, p < 0.001).

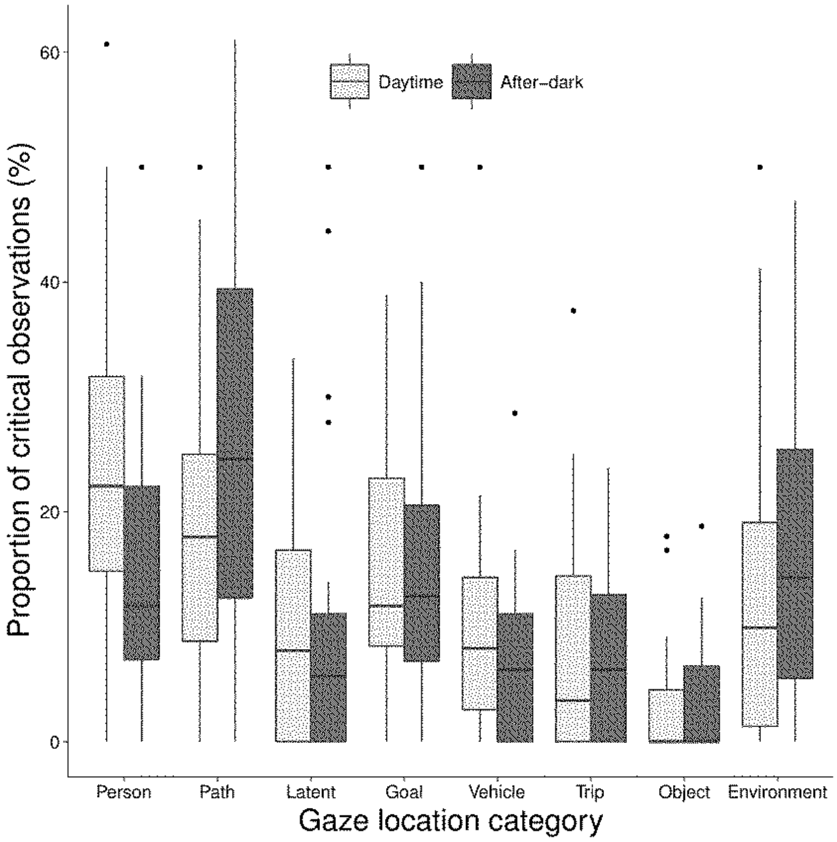


Figure 4.9. Boxplots showing proportions of critical observations in each gaze location category, by day and after-dark trials

Post-hoc pairwise comparisons between categories on the day and after-dark trials were carried out using the Nemenyi test. The resulting p-values for these comparisons are shown in Table 4.3. A number of categories were suggested to differ significantly. The two categories that showed the greatest differences with other categories were *Person* and *Path*. During the daytime trial there were significantly more critical observations in the *Person* category (median = 22.2%, IQR = 16.9%) compared with the *Latent Threat* (median = 7.9%, IQR = 16.6%), *Vehicle* (median = 8.1%, IQR = 11.5%), *Trip Hazard* (median = 3.6%, IQR = 14.4%) and *Large Object* (median = 0.0%, IQR = 4.5%) categories. During the after-dark trial there were significantly more critical observations in the *Path* category (median = 24.6%, IQR = 26.9%) compared with the *Latent Threat* (median = 5.7%, IQR = 11.1%), *Vehicle* (median = 6.3%, IQR = 11.1%), *Trip Hazard* (median = 6.3%, IQR = 12.8%) and *Large Object* (median = 0.0%, IQR = 6.6%) categories.

Table 4.3. Calculated p-values from pairwise comparisons of proportions of critical observations in each gaze location category for daytime and after-dark trials, using Nemenyi post-hoc test. * Significant at p < 0.05. ** Significant at p < 0.01.

DAY TRIAL							
	Person	***Path***	***Latent Threat***	***Goal***	***Vehicle***	***Trip Hazard***	***Large Object***
Path	0.836	-	-	-	-	-	-
Latent Threat	0.006**	0.346	-	-	-	-	-
Goal	0.761	1.000	0.433	-	-	-	-
Vehicle	0.015*	0.507	1.000	0.601	-	-	-
Trip Hazard	0.001**	0.131	1.000	0.180	0.997	-	-
Large Object	<0.001**	0.001**	0.488	0.001**	0.330	0.793	-
General Environment	0.241	0.980	0.915	0.992	0.973	0.675	0.026*
AFTER-DARK TRIAL							
	Person	***Path***	***Latent Threat***	***Goal***	***Vehicle***	***Trip Hazard***	***Large Object***
Path	0.761	-	-	-	-	-	-
Latent Threat	0.314	0.003**	-	-	-	-	-
Goal	1.000	0.849	0.228	-	-	-	-
Vehicle	0.346	0.004**	1.000	0.255	-	-	-
Trip Hazard	0.563	0.012*	1.000	0.451	1.000	-	-
Large Object	0.002**	<0.001**	0.728	0.001**	0.693	0.469	-
General Environment	0.998	0.983	0.069	1.000	0.080	0.180	<0.001**

The day and after-dark trials were compared for each category using Wilcoxon signed-rank tests. These suggested a difference between the trials for the *Person* category, with a greater proportion of critical observations in the daytime trial (median = 22.2%, IQR = 16.9%) compared with the after-dark trial (median = 11.8%, IQR = 15.1%, V = 296, p = 0.034). The difference between trials for the *Path* category was also tending towards significance, with the after-dark trial suggested to have a higher proportion of critical observations (median = 24.6%, IQR = 26.9%) than the daytime trial (median =

17.8%, IQR = 16.3%, V = 122.5, p = 0.068). No other category comparisons approached significance, with p-values ranging from 0.141 to 0.849.

Multiple paired comparisons bring an increased risk of making a Type I error. Therefore, p-values were adjusted using the False Discovery Rate (FDR) method (Benjamini and Hochberg, 1995). This adjustment resulted in no p-values below the 0.05 significance level. P-values for the *Person* and *Path* categories were 0.269 and 0.274 respectively. As FDR adjustment suggested there may not be significant differences between day and after-dark trials on any of the categories, the mean proportion of critical observations across both trials was calculated for each participant. These combined proportions are shown in Figure 4.8. This illustrates that the *Person* and *Path* categories have the highest proportions of critical observations.

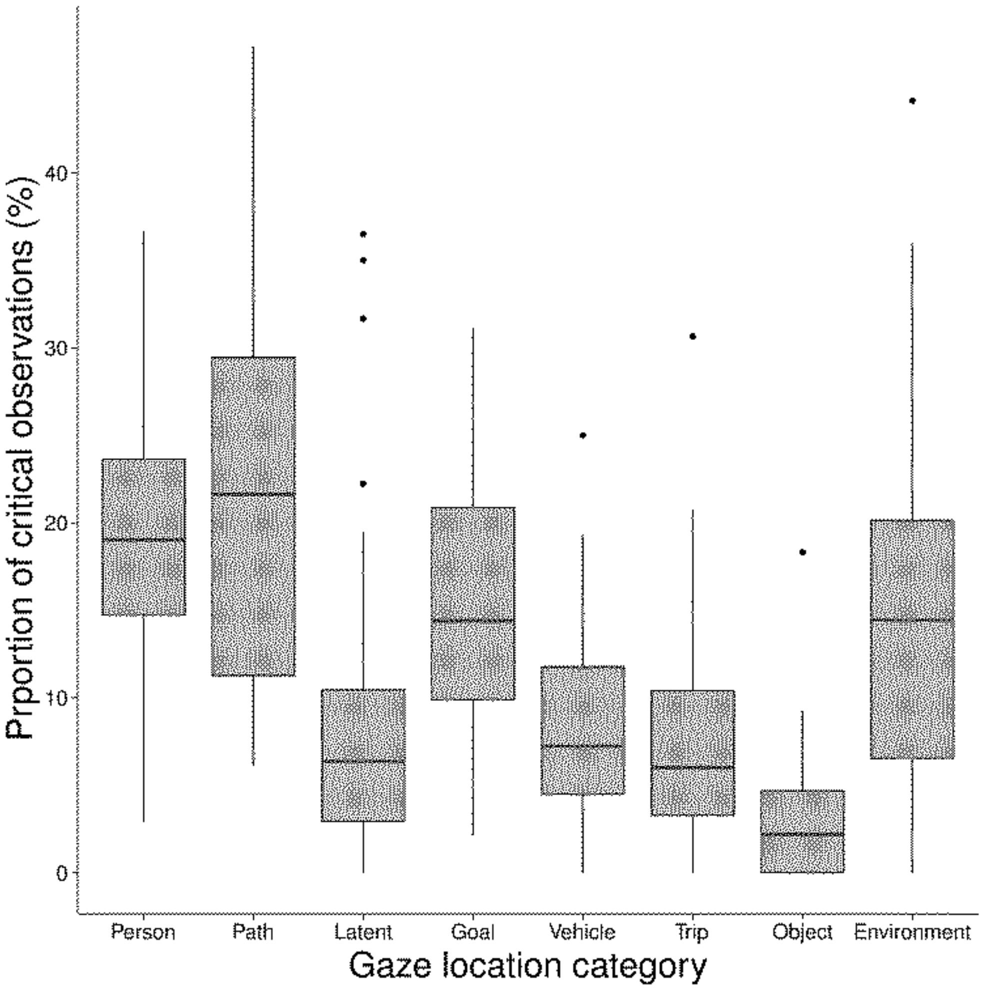


Figure 4.10. Boxplots showing proportions of critical observations in each gaze location category, combined across day and after-dark trials.

A Friedman's ANOVA suggested there were significant differences between gaze location categories ($\chi^2 = 80.09$, $p < 0.001$). Post hoc analysis using the Nemenyi test compared each pair of categories. These comparisons confirmed that the proportion of critical observations in the *Person* and *Path* categories (medians = 19.0% and 21.6%, IQRs = 8.9% and 18.1% respectively) was significantly higher than most of the other categories, including the *Latent Threat* (median = 6.4%, IQR = 7.5%), *Vehicle* (median = 7.2%, IQR = 7.3%)*, Trip Hazard* (Median = 6.0%, IQR = 7.1%) and *Object* (median = 2.2%, IQR = 4.7%) categories. P-values for each paired comparison are shown in Table 4.4.

Table 4.4. Calculated p-values from pairwise comparisons of proportions of combined day and after-dark critical observations in each gaze location category, using Nemenyi post-hoc test. * Significant at p < 0.05. ** Significant at p < 0.01.

COMBINED DAY AND AFTER-DARK TRIALS							
	Person	***Path***	***Latent Threat***	***Goal***	***Vehicle***	***Trip Hazard***	***Large Object***
Path	0.999	-	-	-	-	-	-
Latent Threat	0.004**	<0.001**	-	-	-	-	-
Goal	0.997	0.915	0.047*	-	-	-	-
Vehicle	0.014*	<0.001**	1.000	0.114	-	-	-
Trip Hazard	0.001**	<0.001**	1.000	0.012*	0.996	-	-
Large Object	<0.001**	<0.001**	0.191	<0.001**	0.086	0.415	-
General Environment	0.862	0.525	0.255	0.997	0.451	0.099	<0.001**

The next stage of analysis was to compare the sections of the route to determine if they differed in the proportions of critical observations in each category. The combined proportion of critical observations across both day and after-dark trials was used, as differences between the two trials were limited. In addition, Section C was excluded from this part of the analysis as it produced a very low number of critical observations (section C median = 1, section A, B and D medians = 7, 8 and 12 respectively). Figure 4.9 suggests there were differences between route sections in terms of what was looked at during critical observations, as was anticipated due to the variations in characteristics between the sections (see Table 4.1).

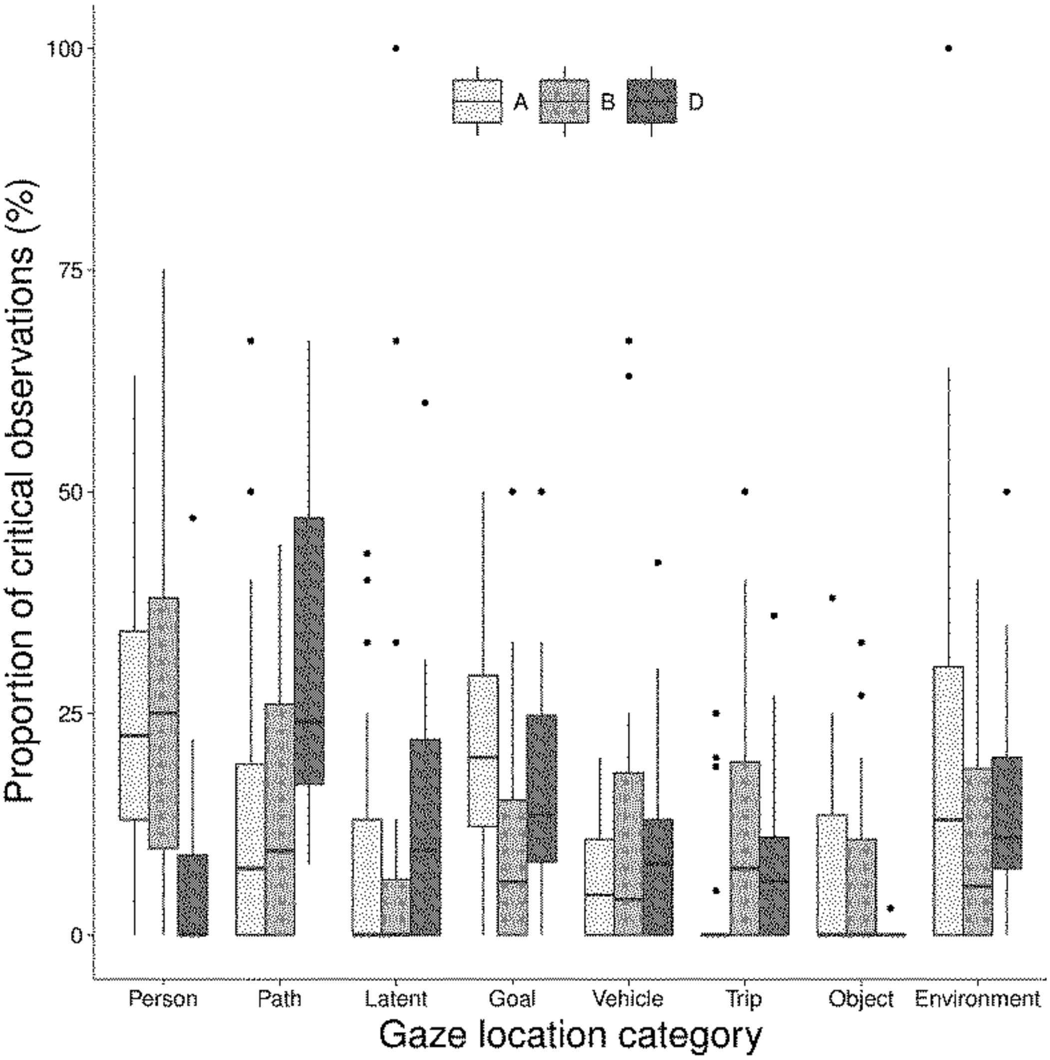


Figure 4.11. Boxplots showing proportion of critical observations in each gaze location category by route section. Note: Section C was excluded due to low numbers of critical observations.

A series of Friedman's ANOVAs with FDR adjustment of p-values confirmed that significant differences existed between sections on some of the gaze location categories. Those categories that showed a significant difference between sections were *Person* (χ^2 = 19.87, adjusted p-value < 0.001), *Path* (χ^2 = 15.50, adjusted p-value = 0.002), *Goal* (χ^2 = 9.74, adjusted p-value = 0.012), *Trip Hazard* ((χ^2 = 13.47, adjusted p-value = 0.003) and *Large Object* ((χ^2 = 10.58, adjusted p-value = 0.010). Post-hoc testing using the Nemenyi test suggested that section D produced fewer critical observations in the *Person* category compared with the other sections and fewer critical observations in the *Large Object* category compared with section B. However, section D produced more observations in the *Path* category compared with the other sections. Section B produced a lower proportion in the *Goal* category compared with the other two categories, and section A produced a lower proportion in the *Trip Hazard* category compared with the other two categories.

Figure 4.10 shows the proportion of critical observations in each gaze location category by the direction participants walked the route, clockwise or anticlockwise. Some possible differences exist between route directions. To test these suggested differences a Wilcoxon signed-rank test was carried out for each gaze location category, comparing the two different route directions. The results suggested that the proportion of critical observations within the *Goal* and *Large Object* categories significantly differed depending on the direction of the route (p-values of 0.016 and 0.033 respectively), with a greater proportion of critical observations in these categories during the clockwise route (medians = 17.5% and 0.9%, IQRs = 16.9% and 7.7% respectively) compared with during the anticlockwise route (medians = 9.7% and 0.0%, IQRs = 8.0% and 2.8% respectively). However, when p-values were adjusted using the FDR method, to account for the multiple pairwise comparisons, no differences between directions were suggested to be significant, for any of the categories (adjusted p-values ranged between 0.125 and 0.853).

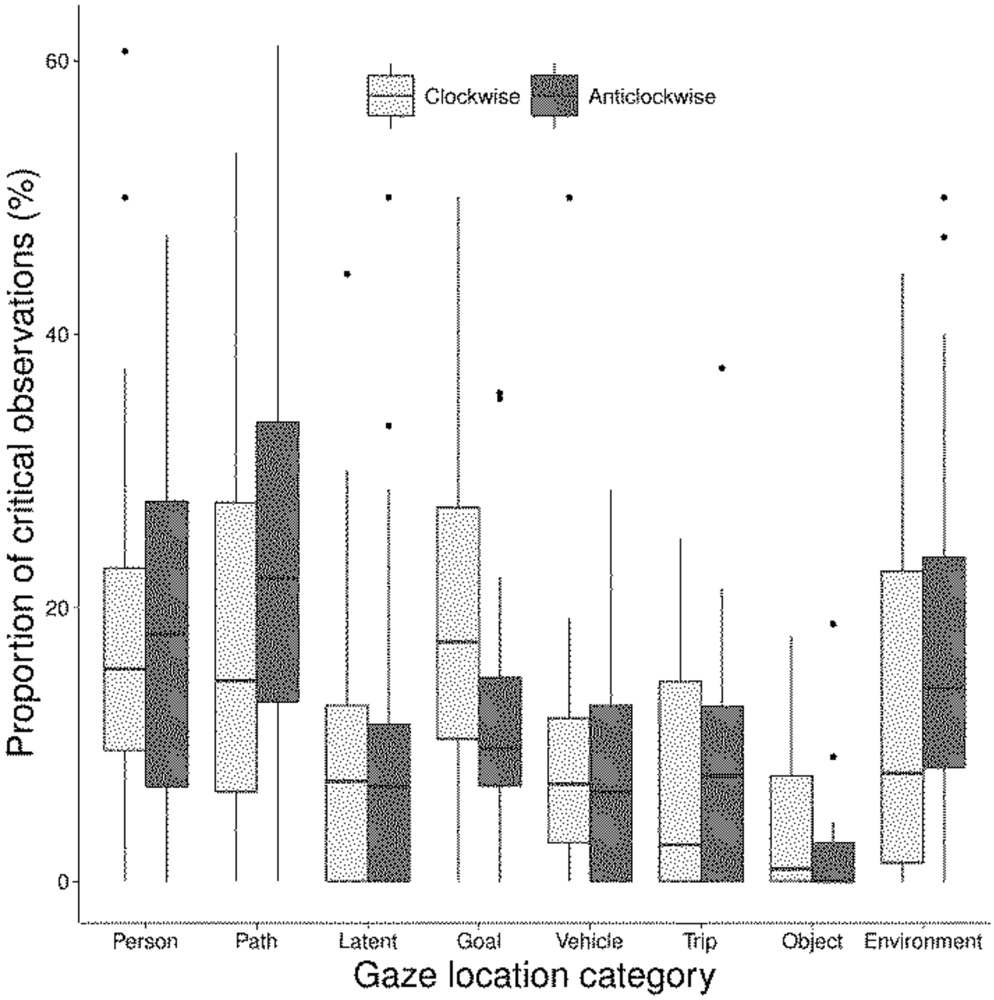


Figure 4.12. Boxplots showing proportions of critical observations in each gaze location category, by clockwise and anticlockwise route directions.

Differences between male and female participants in terms of their critical observations were examined, using Wilcoxon rank-sum tests to compare between the genders on each gaze location category, using the combined proportions across both trials. These tests found no significant differences between the genders on any of the categories, with p-values ranging between 0.114 and 1.00.

4.4.7 How far ahead do people look at critical things?

The *Path* and *Person* categories had the highest overall proportions of critical observations (see Figure 4.8). The proportion of critical observations in these two categories is also significantly higher than many of the other categories, and they were the only two categories that had any suggestion of a difference between the day and after-dark trials. For these reasons, the path and other people are likely to be important things for pedestrians to look at. To create a better understanding of how and potentially why pedestrians look at the path and other people further analysis was carried out on the critical observations in these two categories, examining whether the observations took place at a near or far distance. This information is useful as it may help us understand the purpose of looking at the path and other people and what information pedestrians are trying to obtain from their visual environment. This in turn could be useful in determining how road lighting can facilitate the visual tasks of pedestrians, and can provide useful data in designing future laboratory experiments to realistically assess visual tasks under different lighting conditions.

Critical observations in the *Path* or *Person* categories were selected for further analysis. Critical observations in the *Trip Hazard* category were also included for further analysis and combined with those in the *Path* category, as trip hazards were always located on the path. All instances of *Path* (including *Trip Hazard*) and *Person* critical observations were categorised as taking place at a near or far distance from the participant, as has been done in previous work (Foulsham et al, 2011). Near items were judged to be within 4 m of the participant when the critical observation took place; far items were judged to be 4 m or greater away from the participant. This distance was used as a threshold for near and far as previous work by Hall (1969) suggests this is an important interpersonal distance, at which pedestrians are still able to take action in response to what they see. Accurate physical measurement of this distance based on the eye-tracking video was not possible however and a judgement was made about whether the critical observation took place within or outside the 4 m distance. Generally, distance could be inferred from the size of other known objects in the scene and the position of the gaze cursor, with a near item usually located in the lower half of the screen. This approach of using coder judgements about distance has been used in previous work (e.g. Foulsham et al, 2011).

As with the earlier analysis of critical observation proportions, the 12 participants who had less than 5 observations in categories other than *Unknown* on either trial were excluded, leaving a sample of 28 participants. Data from this sample was not normally distributed, so boxplots have been used to show the proportions of critical observations at a near or far distance for the *Path* (including *Trip Hazard*) and *Person* categories – see Figure 4.11. From this figure it appears the only difference between day and after-dark trials was when viewing other people at a far distance. Participants also appear more likely to view the path at a near rather than far distance. To test these differences a series of Wilcoxon signed-rank tests were carried out. Initially, day and after-dark trials were compared on each subcategory (i.e. Person (Near), Person (Far), Path (Near), Path (Far)). The only significant difference was found for observations of other people at a far distance, with the daytime trial producing a greater proportion of observations (median = 13.2%, IQR = 19.3%) than the after-dark trial (median = 5.6%, IQR = 10.8%, W = 555, adjusted p-value using FDR method = 0.029). To make more meaningful comparisons between the near and far subcategories data across daytime and after-dark trials were combined, with the mean of the two trials calculated for each participant. Comparisons between the distances suggested the proportion of observations made towards other people when near (median = 6.6%, IQR = 7.8%) was significantly lower than at a distance (median = 12.1%, IQR = 8.9%, W = 271, adjusted p-value using FDR method = 0.048). The proportion of observations made towards the near path (median = 19.4%, IQR = 22.6%) was significantly higher than observations to the far path (median = 6.3%, IQR = 8.0%, W = 637, adjusted p-value using FDR method < 0.001).

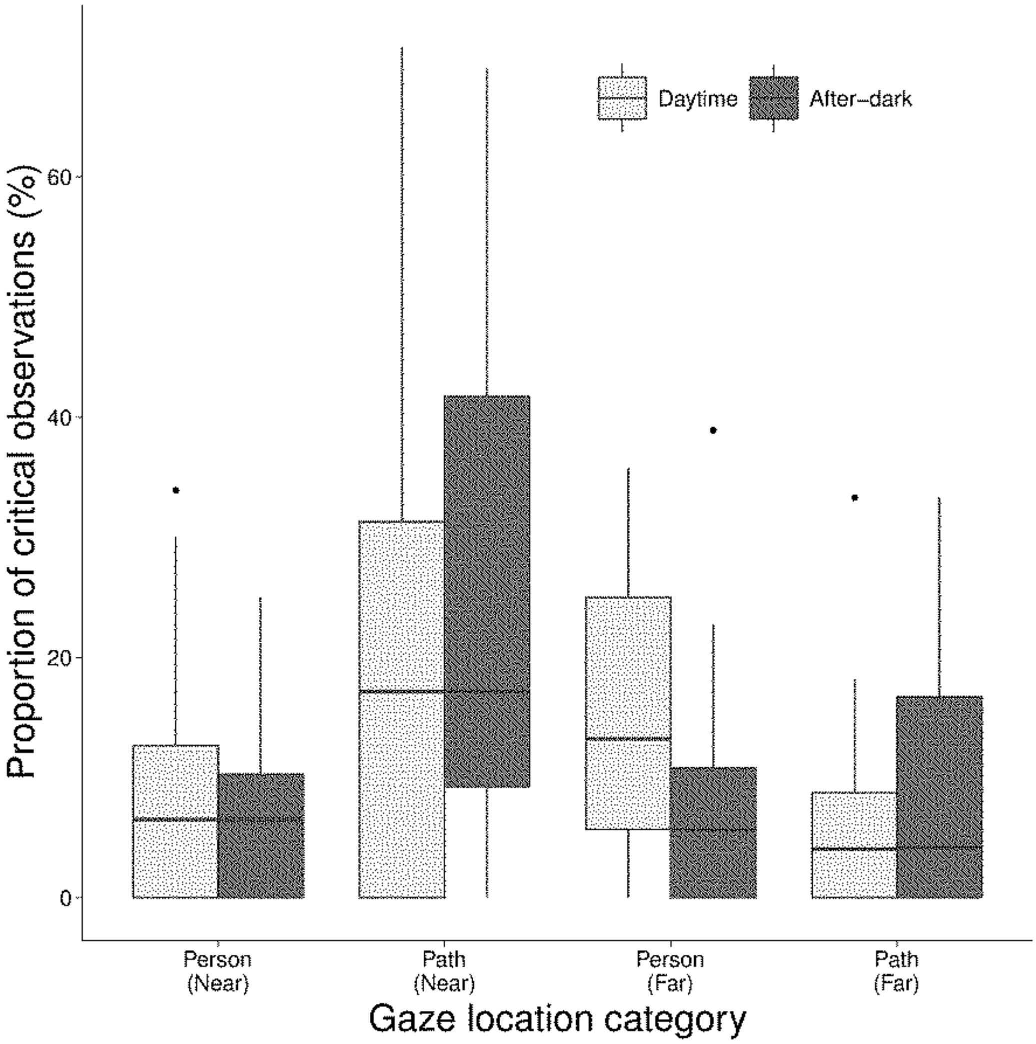


Figure 4.13. Boxplots showing proportions of critical observations in *Person* and *Path* (including *Trip Hazard*) categories at near and far distances, by daytime and after-dark trials.

4.5 Discussion

4.5.4 Critical times

The main purpose of this experiment was to identify what aspects of the environment pedestrians look at and may be important to them for safe walking. The key advantages of the experiment over previous research are that the study took place outdoors, in real pedestrian environments, and under different light conditions. It also used a dual-task approach to identify when the observer may be looking at something important to them, by highlighting instances when attention was diverted away from a concurrent auditory task and possibly towards something significant in the visual environment.

Reaction time data from the concurrent auditory task was used to define these critical times. The number of critical times showed a high degree of variance between participants, suggesting pedestrians may differ in terms of how frequently they direct attention towards potentially important elements of their environment. This variation could be caused by a number of factors. One explanation is how familiar the observer is with the surrounding environment. Greater familiarity may make it less necessary for the observer to direct attention towards areas and objects they assess as being potentially important, as decisions about the relative importance of features may have been made during previous encounters with the environment, resulting in a more targeted allocation of attention. Jovancevic-Misic and Hayhoe (2009) suggested we learn about the probabilistic nature of our environment and this influences what we look at. They found that previous exposure to the behaviour of other pedestrians influenced how long observers subsequently looked at those other pedestrians. In the current experiment, participants were asked to rate out of 5 their overall familiarity with the route and familiarity with section D. Section D was rated as significantly less familiar (median = 1.5, IQR = 1.0) than the route overall (median = 3.9, IQR = 1.0, V = 630, $p < 0.001$, Wilcoxon signed-rank test used due to non-normal data distribution). If familiarity with an environment does influence the frequency with which attention is allocated towards items in that environment, we would expect more critical times on section D compared with the other sections. This was not the case however (see Figure 4.6)

An alternative explanation for why we might see significant variation in the frequency of critical times between participants is individual ability to focus on one particular task (the auditory reaction time task) whilst limiting attentional capture by other stimuli (e.g. aspects of the visual environment). Research has shown that there is a high degree of variation between individuals in their ability to override attentional capture by salient stimuli in the surrounding environment, and this is correlated with working memory capacity (Fukuda and Vogel, 2009). Participants who were less able to ‘override’ the capture of attention by visual stimuli during this experiment would perhaps have more critical times, as their attention would more frequently be directed away from the auditory task and towards some visual stimuli or distractor. This theory is speculative however, and no data within the current experiment exists to test this theory however.

4.5.2 Critical observations – what is important to pedestrians?

Participants did not distribute their critical observations evenly across the different gaze location categories used in this experiment. There appeared to be a distinct difference between the *Person* and *Path* categories compared with other categories. These two categories had the highest proportions of critical observations and this was significantly higher than most of the other categories. The *Person* and *Path* categories were the only ones for which a daytime – after-dark difference was suggested. Although the p-values were not significant when adjusted to account for multiple comparisons, the context and nature of this experiment should be borne in mind when interpreting these results. Although adjusting the p-values for multiple comparisons reduces the risk of type I errors, it also increases the risk of type II errors. Rothman (1990) argued adjustments were not necessary or could lead to throwing out interesting findings, because the nature of experimental research involves investigating regular laws of nature and not just chance numbers. Others have also suggested that p-values should be used as a guide to interpretation of data, not a definitive conclusion (e.g. Nuzzo, 2014). The current experiment was a field study which involved exploratory investigations into a highly variable human behaviour, gaze location. The high degree of individual variation is illustrated by the relatively large interquartile ranges for critical observation proportions in each gaze location category. This noise within the data means the results of statistical tests should be interpreted alongside other information such as overall trends in the data and ecological validity. Therefore, the lack of significance between daytime and after-dark trials for the *Path* and *Person* categories when adjusted for multiple comparisons should be interpreted with caution. It may be there is a real difference between day and after-dark conditions. Looking more at the path at critical times when it is dark is a reasonable behaviour, as it may be more difficult to see potential hazards in the path and to guide foot placement. Looking more at other people during the daytime than after-dark is more difficult to explain; one might anticipate pedestrians being more wary of other people they encounter after-dark due to perceptions of safety. This should lead to greater observations of other people after-dark than during the day. However, an important factor to consider is that other people carry social implications, and looking directly at them can have social costs (Cristino and Baddeley, 2009). This may be a particularly strong consideration in deciding whether to look at another pedestrian after-dark. Social gaze can be construed as threatening or provocative in some situations (e.g. Emery, 2000) and pedestrians may seek to avoid this particularly when it is dark and the environment poses more perceived risk. Another explanation for why participants looked less at other people after-dark could be that fewer people were encountered during the after-dark trials and therefore it was a less prevalent aspect of the environment compared with during the day. This potential explanation is examined in more detail in Section 4.5.4.

The path and other people are important features of the environment that require observation at critical times by pedestrians. Observation of the path is more likely to occur at a near distance than further away. This may be because immediate information about the path in front of the pedestrian is required in order to plan foot placement and make adjustments to gait in order to walk safely and smoothly. If such information is obtained at a distance it may become redundant by the time the pedestrian reaches the path area that was fixated, due to unintentional changes to step length or travel direction. Obtaining information about the path as and when it is required would also reduce utilisation of working memory capacity. Other research has also found that the path is likely to be fixated at a near distance rather than at a far distance (e.g. Patla and Vickers, 2003), and this tendency is increased when the terrain becomes difficult or irregular (Marigold and Patla, 2007). The occlusion of the lower visual field leads to increased uncertainty in the placement of feet when stepping downwards (Timmis, Bennett and Buckley, 2009), which also supports the importance of observing the near path.

Observing other people at a distance may also be an adaptive behaviour, as this allows an assessment to be made about the person’s intentions, possible threat, or travel direction. This information is more useful when obtained at a distance so that any responding action can be planned before encountering that person. Such plans may require a more strategic approach than the direct, semi-automatic adjustments made to gait and foot placement caused by observation of the path. Looking at other people from a distance therefore allows time for these strategic plans to be made. Observing other people when close by may also have a social cost and make the observer uncomfortable (Cristino and Baddeley, 2009). Foulsham et al (2011) found that one of the key differences in gaze behaviour between real walkers compared with video watchers was that real walkers were less likely to fixate other people when nearby. They suggested this was due to the authentic social context provided by the other real person, who was able to look back at the real walker. This avoidance of looking at other people when nearby is also seen in other work (Goffman, 1963; Laidlaw et al, 2011).

4.5.3 Comparisons with other studies

Two other studies (Foulsham et al, 2011; Davoudian and Raynham, 2012) have examined fixations towards the path and other people in real outdoor settings. To enable comparison, results from the current experiment have been grouped into the *Path* category (which includes data from the *Trip Hazard* category), *Person* category, and all other critical observations have been grouped as other objects or the environment. A comparison of the data from the current experiment and the other two studies is shown in Table 4.5. Note that Foulsham et al also used a near and far distance distinction. Davoudian and Rayhnam did not include this distinction, but did include day and after-dark conditions. Both these sub-classifications have been included in the comparison table.

Table 4.5. Comparison of proportions of observations for current experiment, Foulsham et al (2011) and Davoudian and Raynham (2012). Note: *Path* category for current experiment includes *Trip Hazard* data from earlier analyses. Mean rather than median proportions are shown for current experiment for comparability with other two studies. Davoudian and Raynham did not use near/far distinction; Foulsham et al did not have an after-dark condition.

Category of object		**Current results**		**Foulsham et al (2011)**	**Davoudian and Raynham (2012)**	
		Day	After-dark	Day	Day	After-dark
Person	Near	8%	7%	7%	3%	3%
	Far	15%	8%	14%		
Path	Near	21%	24%	29%	51%	41%
	Far	6%	9%	8%		
Objects / Environment		51%	52%	37%	46%	56%

The current experiment and Foulsham et al show similar results in terms of the proportions of observations towards other people at both near and far distances. There is also similarity in terms of the proportions of observations towards the path at near and far distances. However, Davoudian and Raynham found a lower proportion of observations towards other people than both the current experiment and Foulsham et al's results, and a higher proportion of observations towards the path. This difference may reflect variations in the routes used and differences in environment and visual stimuli. It may also reflect the reduced presence of other pedestrians in Davoudian and Raynham's study, with on average only 8 pedestrians appearing during the day trial and 5 pedestrians during the after-dark trial. In contrast, an average of 43 other people were encountered during daytime trials and 29 during after-dark trials in the current experiment. An average of 10 other people were encountered during each trial in Foulsham et al., although it should be noted that Foulsham et al only analysed 90 s of eye tracking video, compared with much longer video times for Davoudian and Raynham and the current experiment. The rate of encountering another person in Foulsham et al was 1 every 9 s. If this rate persisted for 10 minutes of video, an approximately equivalent amount of time to the videos analysed in each trial of the current experiment and Davoudian and Raynham, around 67 pedestrians would have been encountered. There is clearly a large difference between the rate at which other people were encountered during the current experiment and Foulsham et al, and the rate at which other people were encountered during Davoudian and Raynham's study.

The frequency with which a category of item or environmental feature is encountered may therefore be a significant factor in explaining variations in how often these features are looked at. This is a potential limitation in any field study in an unpredictable and uncontrolled environment. Using the dual-task approach to identify only critical observations, not all observations, was an attempt to overcome this limitation. In theory, it should not matter how many times an item is encountered using this approach. If an item is not significant to the observer it should not produce a diversion of attention significant enough to be highlighted as a critical time. If the item appears frequently it may be frequently fixated but unless there was a diversion of attention away from the dual task it would not be flagged as a critical observation. However, frequency of encounters may still have some influence over the proportions of critical observations. For example, if an item is very rarely encountered but is important, it may get flagged as a critical observation every time it is encountered but the low frequency of these encounters would result in a low proportion of critical observations in that category. It is therefore important to examine whether or not the critical observations approach is insulated from limitations caused by the frequency of encounters with an environmental feature, and whether it does offer a benefit above the standard approach of categorising every fixation or gaze location, not just those identified to be important.

On a final note in terms of comparisons with other studies, the sample size used in this experiment (40 participants took part, with 28 included in the final analysis, each participant providing data on two sessions, day and after-dark) was significant relative to other eye-tracking studies carried out in real-world situations. Davoudian and Raynham (2012) for example used 15 participants in their after-dark session, and 5 participants in their daytime session. Likewise, ‘t Hart and Einhauser (2012) only used 8 participants. Foulsham, Walker and Kingstone (2011) used 14 participants, and only analysing three 30 s clips of eye-tracking data from each of these participants. The current experiment therefore provided significantly more data than previous real-world eye-tracking studies, and given the variability that was found between participants in terms of their eye movements, such a relatively large sample helps identify general trends and behaviours in terms of gaze. It may be that future eye-tracking studies should consider samples of similar size.

4.5.4 Critical observations vs other methods

Further analysis of the eye-tracking videos was carried out to compare results from the critical observations approach with two other approaches to determining whether something is important in the visual environment – the **all-fixations** approach and the **probability of fixation** approach. A sub-sample of 10 participants was selected for inclusion in this further analysis. The 10 participants all had high eye-tracking signal quality with limited missing data, and were balanced across gender, trial order and route direction. Six of the selected participants were male, 5 were aged under 30, 3 aged 30-49. A 120 s continuous sample of the eye-tracking video was selected from each of section A, B and D, giving a total of 360 s of eye-tracking that was analysed. Section C was excluded as it was a short section generally completed in less than 120 s. Data for critical observations during the 360 s of eye-tracking footage was collated for each participant. In addition the videos were analysed in two further ways:

All-fixations approach: Every fixation during the video sample was identified using the same dispersion-based algorithm as used for the earlier critical observation analysis – video frames were grouped together as a single fixation if the gaze position remained within a 15 pixel area for at least 100 ms. Remaining frames were saccades or missing data and were ignored for this analysis. Each fixation was placed into one of the eight gaze location categories described in Table 4.2. This data was converted into a proportion, calculated as the frequency of fixations in each category as a percentage of the total number of fixations across all eight categories. For example, if a participant made a total of 1,000 fixations during the 360 s sample of their eye-tracking data, and 200 of these fixations were towards the path, the *Path* category would have an all-fixations proportion of 20%. This eye-tracking metric has been used frequently in other eye-tracking research (see Holmqvist et al, 2011).

Probability approach: The dual-task approach used in the eye-tracking experiment attempted to only identify gaze behaviour that was potentially important, by highlighting critical observations rather than all observations. However, it is possible that this approach could still have been influenced by the frequency with which environmental features were encountered. An alternative analytical approach that could address this limitation or confirm / refute conclusions drawn from the critical observations data is by examining the probability with which a feature of the environment is fixated. This would in theory account for the frequency with which different features are encountered. A greater probability of fixation may indicate the observer places greater importance on that type of object or area. For example, Jovancevic-Misic and Hayhoe (2009) showed that the probability of fixating a feature increases with its importance. To calculate the probability of fixation the number of times the item is fixated is divided by the total number of times that item was encountered. This approach may only be meaningful for discrete items that are encountered irregularly. Areas such as the path or goal are almost continually present in the observer's visual field which would make it difficult and meaningless to calculate a probability of fixation. Therefore, the probability approach has only been applied to fixation of other people, as other people provide a discrete, non-continuous feature. Results from the critical observations data suggest looking at other people is important for pedestrians. If this is the case we would also anticipate a high probability of fixating other people that are encountered. The probability of fixation on other people was measured by calculating the number of times other people were fixated as a proportion of the total number of other people who appeared in the eye-tracking video during the 360 s sample. Fixation on another person was only counted once, even if that other person was fixated on more than one occasion.

Probability of fixation on other pedestrians in a real-world setting has been reported in other studies. Foulsham et al (2011) found that 83% of all pedestrians encountered were fixated by the participants at least once, and this generally happened soon after the pedestrian came into view, with 70% of pedestrians being fixated within the first 5 s of appearing. Looking at other pedestrians when they were close by or passing was relatively rare, with less than 5% of gaze being at other pedestrians in the last 3 s prior to them passing the participant. This data suggested the probability of fixating another pedestrian is high, even if overall fixation time at pedestrians is not very high. It also shows that fixation of pedestrians is likely to occur when they are further away than when they come closer, a result that is supported in other research. Jovancevic, Sullivan and Hayhoe (2006) found that fixations towards other pedestrians in their VR environment tended to happen soon after they appeared to the participant. Jovancevic-Misic and Hayhoe (2009) also found that other pedestrians in their experiment were initially fixated within 450 ms of appearing, on average. This supports the finding from the current study reported earlier (section 4.5.2) that critical observations of other people tended to occur when they were in the distance rather than when they were near.

Data from the all-fixations and critical observations approaches are compared for daytime and after-dark trials in Figures 4.12 and 4.13.

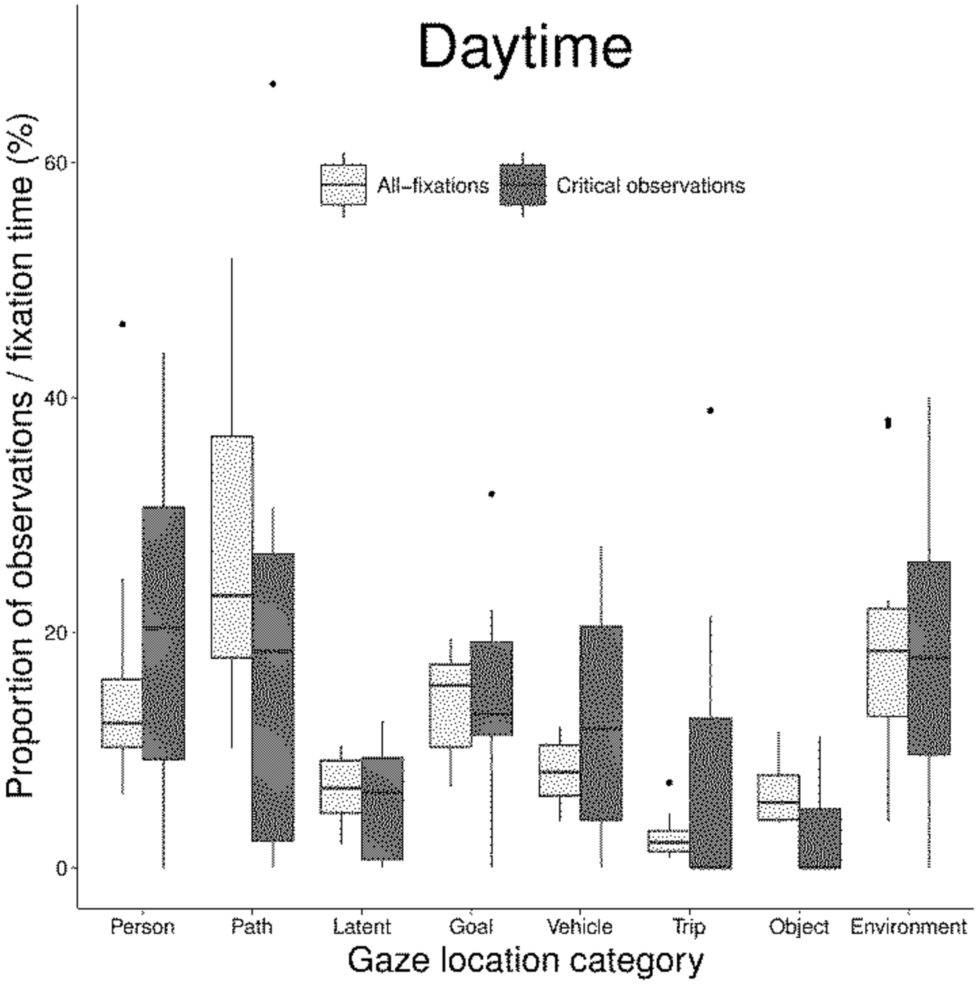


Figure 4.14. Boxplot showing proportion of critical observations and proportion of all fixation time in gaze location categories for daytime trial.

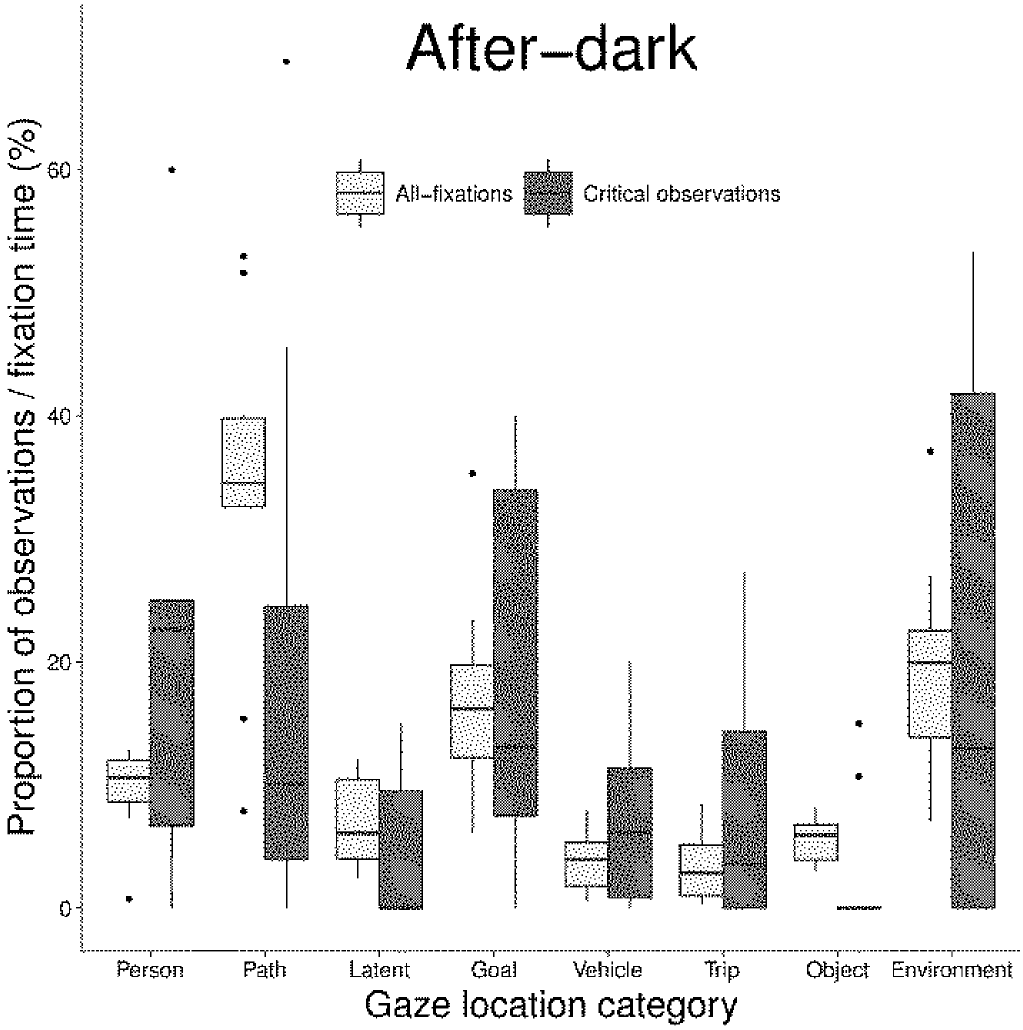


Figure 4.15. Boxplot showing proportion of critical observations and proportion of all fixation time in gaze location categories for after-dark trial.

Data about the probability of fixating other pedestrians during the 360 s samples of eye-tracking video for both trials is shown in Table 4.7. This is shown alongside the proportions of all fixations and critical observations for comparison. The probability of another person being fixated was high, with on average nearly 9 out of 10 people encountered fixated at least once by the participant. A high probability of fixation may indicate high importance of that item for the observer. This result therefore supports the conclusion drawn from the original critical observations data that looking at other people is an important task for pedestrians. Table 4.7 also highlights that the critical observations approach suggests greater importance for observing other people compared with the all fixations approach as the proportion of observations is higher using this metric.

Table 4.7. Comparison of measures of looking at other people – all-fixations vs critical observations vs probability of fixation.

	Number of pedestrians encountered – Median (IQR)	**All-fixations (IQR) on people - Median (IQR)**	**Critical-observations on people - Median (IQR)**	**Probability of fixation on people - Median (IQR)**
Daytime trials	43 (26)	15% (7%)	21% (21%)	0.87 (0.14)
After-dark trials	29 (14)	13% (5%)	23% (18%)	0.86 (0.21)
Daytime and after-dark combined	37 (16)	14% (5%)	23% (18%)	0.86 (0.17)
Correlation (r) with number of pedestrians encountered		0.59	-0.04	-0.40
Significance		P = 0.006	0.873	0.078

The number of pedestrians encountered was correlated with each method's measure, to test whether there was a relationship. To demonstrate avoidance of the influence of frequency of encounters, a method should show little or no correlation between its measure and the number of pedestrians who appear in the observer's visual field. The all-fixations and critical observations methods both use the frequency in the *Person* category as a proportion of the total number of fixations/observations as their metric. The probability method uses a different type of metric and scale – the probability of fixation is based on the number of pedestrians fixated as a proportion of the total frequency of pedestrians encountered. Therefore to make comparison between the three methods more explicable, values for each participant were converted to z-scores on each method (Rubin, 2013). Transformation to z-scores to enable better comparison between measures has been used in other perceptual research (e.g. Konar, Bennett and Sekuler, 2010). Z-scores were calculated by subtracting the sample mean from the individual value and dividing by the sample standard deviation. Transformation to z-scores results in the data distributions from all three methods having a mean of 0 and a standard deviation of 1. Transformation does not change the shape of the distribution however, meaning that the transformed data remained normal for the critical observations and probability data but not normal for the all-fixations data.

Figure 4.14 shows a scatterplot of the relationship between the number of other pedestrians encountered and the transformed measures of looking at other people for the three methods. The regression lines for the three methods suggest differences in their relationship with the number of other pedestrians encountered. The all-fixations approach produces an increasing value as the number of pedestrians encountered increases. The probability of fixation approach produces a decreasing value as the number of pedestrians encountered increases. The critical observations approach does not appear to change in response to the number of pedestrians encountered – the regression line is almost flat.

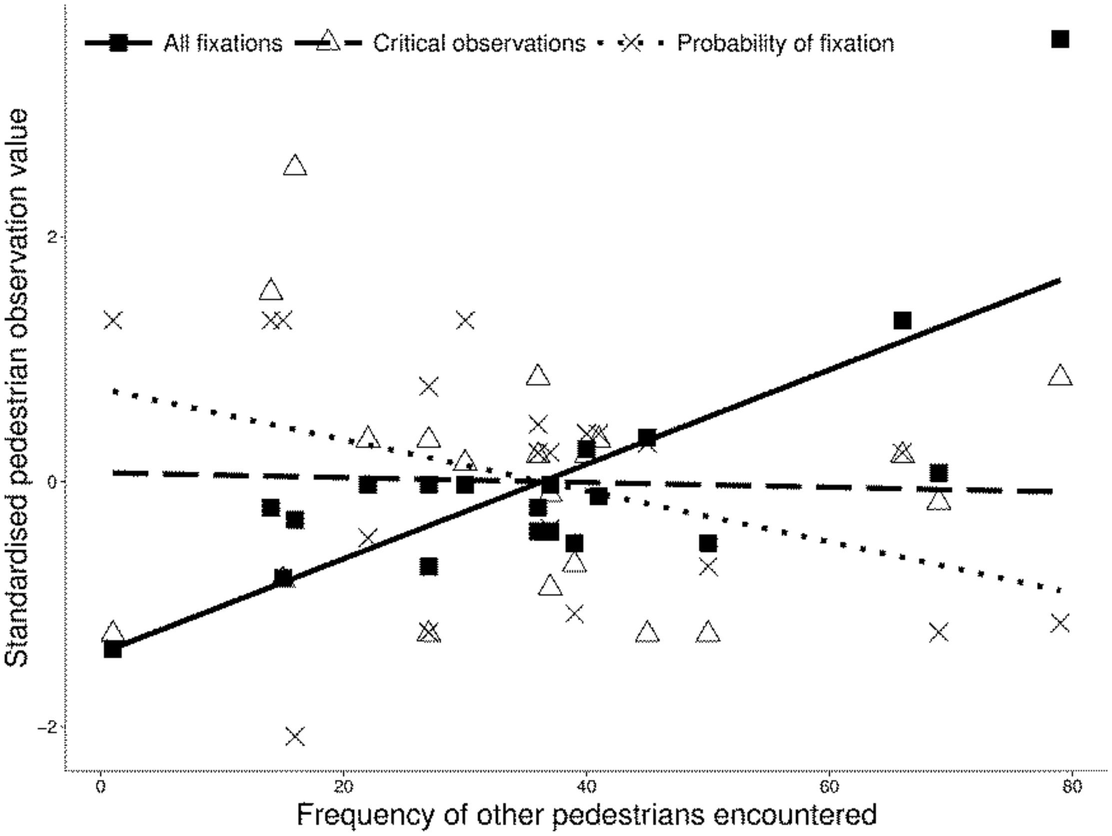


Figure 4.16. Regression of measures of pedestrian observation against the number of pedestrians encountered. Data for both daytime and after-dark trials are shown.

These trends were verified using correlation tests (Pearson's correlation for the critical observations and probability of fixation data, Spearman's correlation for the all-fixations data as it was not normally distributed). Table 4.7 shows the resulting correlation coefficients and p-value for the relationship each method has with frequency of other pedestrians encountered. For the all-fixations method the correlation is highly significant. The correlation for probability of fixation is also close to significance. The correlation for critical observation is far from significance. These results suggest the critical observations approach does not have a relationship with the frequency with which other pedestrians were encountered, unlike the other two methods. This gives some validation to the conjecture that the critical observations approach provided a more robust measure of the importance of looking at other people compared with the more standard approach of examining all fixations. Probability of fixation is an alternative method of determining importance of an environmental feature but the critical observations approach appears to offer benefit above this method also.

4.6 Summary

An eye-tracking experiment was carried out in a real outdoor environment, in which participants walked naturally on a short route through different types of urban environment. A secondary task was used to identify critical times, and reviewing the eye-tracker video at these times highlighted potentially significant visual stimuli which were defined as critical observations. The path and other people were the most frequently observed items at these critical times, with the path generally being observed at a near distance and other people being observed at a far distance. This suggests looking at the path and other people are critical visual tasks for pedestrians. One reason we can have confidence in this conclusion is that the dual-task approach to identifying critical observations appears robust against a possible confounding factor, the frequency with which types of items are encountered in the environment. This offers an improvement on an alternative method of analysis, that of recording the location of all fixations, not only those that occur at critical times. Analysis of the probability with which other people are fixated provided further confirmatory evidence that observing other people is an important visual task for pedestrians. The next chapter focuses in particular on observing the path. This behaviour is likely due to scanning the environment for potential obstacles and hazards, and obstacle detection is therefore a primary purpose of observing the path. A review is carried out of previous research that may help us understand obstacle detection under the mesopic light conditions found after-dark.

CHAPTER 5. OBSTACLE DETECTION BY PEDESTRIANS

5.1 Introduction

The experiment reported in the previous chapter suggested observation of the path was a critical task for pedestrians. A likely reason for this gaze behaviour is searching for potential trip hazards and obstacles. The detection of obstacles is an important requirement for pedestrians walking along a footpath and good road lighting should facilitate this task. Evidence is therefore required to show how lighting influences obstacle detection. This task primarily uses peripheral vision for the initial detection and previous research examining the relationship between lighting and peripheral detection is reviewed in the current chapter. These past studies show that light intensity generally improves peripheral detection, and the spectrum of the light also influences peripheral detection. However, there are discrepancies between studies in terms of the degree and nature of the effects of intensity and spectrum on detection performance. Previous studies are also limited in how applicable they are to a pedestrian context, and lack crucial mediating factors involved in obstacle detection by pedestrians such as real locomotion and concurrent cognitive tasks. Further evidence is therefore required about the effect of light intensity and spectrum on obstacle detection in a pedestrian context.

5.2 Critical visual tasks

The previous chapter presented results from an eye-tracking experiment carried out with pedestrians in a real outdoor environment. The main goal of this experiment was to identify important visual tasks carried out by pedestrians as they are walking along a street. A dual-task method was used to identify critical moments when attention may have been seized by a visual feature of the environment. Results suggested the path and other pedestrians are the two most important aspects of the environment that pedestrians pay attention to. Effective road lighting should therefore facilitate observation of these features, allowing them to be seen sufficiently well to enable safe walking. To determine how road lighting should be effective in this context data is required about how lighting influences the observation of the path and other people, and the visual tasks that are performed during this observation.

Looking at other people may serve a number of purposes, such as judging travel direction to avoid collision or out of general inquisitiveness. An important aspect for safety though is making judgements about the intent of other people and whether they pose a threat. This may be particularly pertinent after-dark. Recent research has examined how lighting influences interpersonal judgements (Fotios, Yang and Cheal, 2015; Yang and Fotios, 2014). This research has built on a large body of evidence investigating judgements about other pedestrians and the role of lighting in making these judgements (e.g. Alferdinck et al, 2010; Okuda and Satoh, 2002; Rea et al, 2009; Raynham and Saksvikronning, 2003; Lin and Fotios, 2013). There is therefore a growing set of data about lighting, observing other pedestrians and making interpersonal judgements that can be used to support the design of lighting in relation to viewing other people. This task was analysed in parallel by a colleague, Biao Yang (Yang, 2014), and is therefore not examined in further detail within this thesis.

Observing the path may also serve a number of purposes, such as planning future travel direction and wayfinding. Results from the eye-tracking experiment showed however that observation of the path at critical times was more likely to involve viewing the near path rather than the path further away. This suggests the most pressing task involved in observing the path is to obtain more immediate information about forthcoming hazards or terrain characteristics. Moving around our environment requires the negotiation of obstacles such as steps, kerbs and uneven stairs (Shumway-Cook et al, 2002). Tripping is a significant problem though. Trips, slips and stumbles on a flat surface account for 23% of all accidents outside the home that have led to a hospital visit in the UK (Department for Trade and Industry, 2003). Roads, streets and pavements are the most frequent location for such accidents. Other research has suggested that 73% of outdoor falls are caused by environmental factors such as an uneven surface or tripping over objects, and most frequently occur on pavements, kerbs and streets (Li et al, 2006). Tripping accidents are more likely to occur amongst the elderly with approximately 40% of over-65s falling at least once a year, and around 2.5% of these leading to hospitalisation (Rubenstein, 2006).

One way to limit tripping accidents on pavements and other pedestrian walking areas is to ensure obstacles and trip hazards can be seen clearly. When it is after-dark this means having suitable public lighting. Lighting guidelines have a role in determining what suitable means in this context. However, current guidelines do not appear to relate to any form of empirical evidence about enabling pedestrians to see and avoid obstacles and potential trip hazards (Fotios and Goodman, 2012; see Chapter 1). Evidence is required that can be used to optimise lighting guidelines based on the key purposes of road lighting for pedestrians, such as detecting obstacles in the path.

5.3 Lighting and obstacle detection

Two important characteristics of lighting that may influence obstacle detection are its intensity (measured as luminance or illuminance) and spectrum. As light intensity increases visual performance will increase although a plateau in performance is usually reached (Rea and Ouellette, 1991). The spectral power distribution (SPD) of light can influence visual performance because of the variable sensitivity of different types of photoreceptors (i.e. rods and cones), and these are not equally distributed across the retina (see Section 2.3). This is particularly the case with light in the mesopic range (below 3 cd/m^2), such as in road lighting. Below this luminance the eye's rod photoreceptors become increasingly dominant over the cone photoreceptors, and the rods are more sensitive to shorter-wavelength light than the cones. Furthermore, as the ratio of rods to cones increases significantly outside the fovea, spectral sensitivity increases in our peripheral vision, and peripheral visual tasks are more likely to be influenced by the light's SPD. This is relevant to obstacle detection by pedestrians, as this is likely to be primarily a peripheral vision task. The fovea is only 2° in visual angle and the vast majority of the visual field is therefore in our periphery, outside the area of highest acuity. It is unlikely that our eyes would fall upon an obstacle in our path by accident. In reality, peripheral vision is used to scan the environment for items of interest or importance (Inditsky, Bodmann and Fleck, 1982) and our eyes are moved to look directly at this area so that the high-acuity fovea at the centre of our vision can gather more detailed information about the item. Peripheral vision is more useful than foveal vision in rapidly determining the gist of a scene (Larson and Loschky, 2009) and can provide global contextual information about the scene confronting the observer which influences the direction of attention (Torralba et al, 2006). It could be argued that this presents a limitation of the eye-tracker experiment and therefore its findings, as this recorded only where foveal gaze was directed. It may be that participants initially noticed significant items whilst they were in the peripheral field-of-view. However, a saccade and fixation towards that item is likely to have occurred almost immediately. Attention in the peripheral field is inextricably linked to future saccades and fixations towards the locus of that attention (Findlay and Gilchrist, 2003). It is not possible to direct gaze towards an area that is not being attended to (Hoffman and Subramaniam, 1995). It is likely that we first notice a potential obstacle in our peripheral vision before our eyes are moved, often involuntarily, to fixate this obstacle for assessment and the determination of appropriate action. Peripheral vision is important for normal obstacle detection and avoidance, as demonstrated by the increase in bumps and trips when peripheral vision is impaired or removed, such as in patients with retinitis pigmentosa (Geruschat, Turano and Stahl, 1998; Lovie-Kitchin et al, 1990) . Indeed, obstacles do not need to be fixated to be avoided (Marigold et al, 2007; Franchak and Adolph, 2010).

5.4 Previous research

5.4.1 Driving studies

Peripheral vision is not only important for pedestrians to walk safely and detect potential tripping hazards, it is also essential to safe driving, for example by helping maintain position in a lane (Summala, Nieminen and Punto, 1996) and detect hazards (Crundall, Underwood and Chapman, 1999). A large body of research has therefore developed examining peripheral detection in a driving context. The effect of lighting has been investigated in much of this research as driving takes place in a range of lighting conditions. A number of studies have examined peripheral detection under mesopic lighting conditions, as this is the predominant level of light when driving after dark, with the only light provided by the vehicle’s headlamps and overhead road lighting where present. These studies are relevant to road lighting for pedestrians, as mesopic conditions are generally what pedestrians encounter when they are walking after-dark.

A number of studies have used driving simulators or tasks that replicate the demands found in driving. Bullough and Rea (2000) used a driving simulator task to examine the effects of luminance and SPD on driving performance and peripheral detection. Participants drove around a race course track on a driving simulator, with average speed and number of crashes used as measures of task performance. A luminance range of 0.1 to 3.0 cd/m2 was examined, and four different SPDs were used providing S/P ratios of 0.64 to 3.77. Luminance was found to have a significant effect on driving performance, but the S/P ratio of the light was not. This may have been because the task primarily involved foveal vision and under such conditions S/P ratio is unlikely to have an effect. A second experiment was carried out using the same apparatus and lighting conditions, but with an added peripheral detection task - a small target 18° off-axis would randomly appear and participants were asked to call out if they saw it. Results from this second experiment showed detection of the peripheral target improved as luminance increased, and also as the S/P ratio increased. There appeared to be a convergence in performance between the S/P ratios at the highest luminance levels, although this interaction was not significant and S/P still had an effect even at the highest luminance of 3.0 cd/m^2.

Lingard and Rea (2002) also used a driving simulator task whilst measuring peripheral detection performance under different lighting conditions. A three-dimensional roadway was projected onto a screen in front of participants. Arrow keys on a computer keyboard were used to steer through a driving course, staying within the roadway boundaries whilst avoiding other simulated traffic. The background luminance of this projected scene was varied between 0.1 and 3.0 cd/m^2, and two S/P ratios were used of 0.5 and 1.8, simulating High Pressure Sodium and Metal Halide road lighting respectively. A luminous target which subtended a 2° visual angle to participants was presented off-axis at semi-random intervals for a maximum of 1.25 s, with participants indicating detection of this target by pressing a signal switch. The target was presented at 4 eccentricities ranging between 12° and 29°, and 4 luminance contrasts of the target against the background were used ranging between 0.1 and 1.0. Performance on the target detection task was measured as the proportion of presentations successfully detected and the reaction time to detection. Results showed that off-axis detection improved as the background luminance increased, and as the target luminance contrast increased. Performance only worsened at the outer-most eccentricity of 29° off-axis. The light condition with the higher S/P ratio did improve detection performance, but only at the low background luminance levels and low target contrast.

Alferdinck (2006) used a more realistic driving simulator than that used by Rea and colleagues. Participants sat in an actual car body with real dashboard, steering wheel and instruments. A simple roadway was projected onto a large concave screen spanning 120° in width in front of the participant. The spectral radiance of the background on the screen was altered to give four different colour conditions of red, yellow, white and blue, providing four S/P ratios of 0.22, 1.39, 2.12 and 9.08 respectively. Participants had to steer along the projected roadway as it curved slightly, whilst also signalling if they saw an off-axis target that appeared at semi-random intervals. The target was a 2° circle with an average luminance contrast against the background of 0.14. The target could appear at 6 different eccentricities (± 5°, 10° and 15°) and was presented for a maximum of 3 s. The luminance level was altered by placing neutral density filters in goggles worn by participants. Four luminance level conditions were created, 0.01, 0.1, 1.0 and 10.0 cd/m^2. Performance at detecting the target was measured as the percentage of targets not detected and the reaction time to detection. Detection performance improved as luminance increased, but reached a plateau at around 1.0 cd/m^2, with luminances above this level providing no added detection benefit. In terms of eccentricity of the target, detection was only worse at the greatest eccentricity of ± 15°. The colour of the light did have an effect on detection performance, with the red light producing worse performance than the other colours, but only for the two lowest luminance levels of 0.01 and 0.1 cd/m^2. The red light also showed the biggest effect of eccentricity but again only at the lowest luminance levels.

These results suggested that S/P ratio has an effect on peripheral detection performance, although this may only be at lower luminance levels and not applicable for all S/P differences. For example, the blue light had a much higher S/P ratio than the white and yellow light, but provided no additional benefit in terms of detection performance.

The three studies of Bullough and Rea (2000), Lingard and Rea (2002) and Alferdinck (2006) all used driving simulators within a laboratory environment, and examined the overall background light of the scene. Van Derlofske and Bullough (2003) took their research outside, and examined the lighting effects of a vehicle's headlamps rather than the overall background lighting of the scene. Participants sat in a stationary vehicle whilst looking at a central target. This central target involved a foveal task, in which participants had to keep a moving LED bar centred using a control knob. Targets (flip-dot grids measuring 18 cm square) were placed 60 m in front of the participant at off-axis increments of 5° up to a maximum of 17.5°. These targets were lit by a HID lamp representing the vehicle's headlamps, and the spectral characteristics of the light produced was altered using filters to produce 4 light conditions, with S/P ratios that varied between 1.02 and 2.04. Illuminance of the targets varied depending on their location, with the most central target having an illuminance of around 14 lux whilst the most peripheral target having an illuminance of around 1.5 lux. Two target conditions were used – high-contrast target and low-contrast target. The low-contrast condition used an optical density filter over the target to reduce the contrast by 50% compared with the high-contrast, no-filter target. The targets were presented randomly and reaction time to detection was measured under each lighting condition, as was the number of missed detections. Detection performance worsened as the off-axis angle of the target increased. The low-contrast targets produced worse detection performance but only at the larger off-axis angles. At smaller angles the low- and high-contrast conditions did not differ. However, illuminance was not kept constant across the different target locations and it decreased the further from the centre the target was. It is therefore not clear whether the changes in detection performance for the two contrast conditions at greater angles is due to this change in peripheral angle or to the reduction in illuminance, or (most likely) due to a combination of these two factors. The contrast conditions also varied with the different light conditions in terms of their effect on detection performance. For the high-contrast condition no effect of light spectrum was found on performance. However, on the low-contrast condition light with a higher S/P ratio produced improved performance.

Another study in which participants sat outside in a real car was carried out by Crabb et al (2006). They had six participants sit in a stationary vehicle on a road and carry out a peripheral detection task – responding when they noticed a flip-dot panel at 15° or 25° off-axis change from black to grey. The area was lit by overhead streetlamps. Two lamp types providing different spectrums were tested – High Pressure Sodium (HPS) and Ceramic Metal Halide (CMH). The HPS lamp had a Correlated Colour Temperature (CCT) of 2000 K, and the CMH lamp had a CCT of 4200 K. S/P ratios were not given for the lamps but it is likely the CMH lamp would have a higher S/P than the HPS lamp. Unlike other research no effect of spectral differences between the lamps on peripheral detection performance was reported. However, a major limitation of this study was that the peripheral target was also lit by the vehicle headlamps which will have confounded any spectral effect from the streetlamps. In addition luminances and target contrast ratios were not tightly controlled between conditions. Therefore results from this study may not be reliable.

The driving simulator and outdoor scaled tasks used by Bullough and Rea (2000), Lingard and Rea (2002), Alferdinck (2006), van Derlofske and Bullough (2003) and Crabb et al (2006) do not present realistic driving conditions. Some do not involve an actual driving task whilst for those that do, the task is simplistic and does not present realistic levels of risk or potential danger. This may influence the allocation of attention and potentially performance in detecting peripheral targets. One study has however used a real driving task in examining peripheral target detection. Akashi, Rea and Bullough (2007) got participants to drive down a real section of road lit by street lamps and the vehicle's headlamps. A fixation target was placed at the side of the road and a detection target was placed adjacent to this but further away from the road (8.3° away from the fixation target). The target was a sequential series of squares moving either towards the road or away from it. In response to the direction of the target participants had to either accelerate or brake. The street lamps used to light the roadway were either HPS, high-luminance MH or low-luminance MH. In combination with the vehicle's headlamps the lighting measurements at the detection target for these three lamps were 0.115, 0.115 and 0.089 cd/m2 respectively, with S/P ratios of 0.91, 1.28 and 1.32. Response times to braking or accelerating appropriately were recorded as a measure of performance in detecting and responding to the off-axis target. Performance was significantly better under the high-luminance MH lighting compared with the HPS lighting even though their photopic luminance measurements were the same. Performance with the low-luminance MH lighting was not statistically different to that with the HPS lighting, despite photopic luminance with the low-luminance MH being lower than that of the HPS.

5.4.2 Non-driving studies

Studying peripheral detection within the context of driving can only provide limited conclusions when applied to a pedestrian context. The task of driving is qualitatively different to the task of walking. For example, due to the speed of travel during driving it is likely that detecting something in your periphery needs to happen at a greater distance than if you are walking. A number of studies have been carried out on peripheral detection outside a driving context that may have relevance for pedestrians.

He et al (1997) used reaction times to the onset of a peripheral target as a measure of peripheral detection performance. Participants sat at a viewing chamber and fixated a point at the centre of this chamber. A peripheral target 15° off-axis was presented at semi-random time intervals and participants had to press a button to indicate they had seen the target, with reaction time being recorded. Two lamp types, metal halide (MH) and high-pressure sodium (HPS) were compared, these having respective S/P ratios of 1.67 and 0.61, and eight luminance levels (0.003 to 10 cd/m^2) used. They found that reaction time to the peripheral target decreased as luminance increased, but there was only an effect of the lamp type (and therefore spectrum of the light produced) below about 1 cd/m^2, with the metal halide lamp producing the better performance (quicker reaction times).

In a similar experiment to that carried out by He et al, Eloholma et al (2006) examined peripheral detection at mesopic luminance levels, again using reaction times to detection as their measure of performance. Participants sat facing a uniformly-lit hemisphere, fixating a central foveal target. A peripheral target of 0.29° visual size was presented at an eccentricity of 10°. Five different colours of target were used with increasing peak wavelengths and decreasing S/P ratios (blue, cyan, green, amber and red). Three background luminances of 1.0, 0.1 and 0.01 cd/m^2 were used, with a high (3.0) or low (0.2) contrast target. As would be expected, performance became worse as the luminance decreased, and the decrement was greater for the low contrast target compared with the high contrast target. In addition, the low contrast target produced a greater effect of colour on detection, with differences between the coloured targets being present even at the highest luminance of 1.0 cd/m^2. An effect of colour was only apparent with the high contrast target at the two lower luminances of 0.01 and 0.1 cd/m^2, and the effect at 0.1 cd/m^2 was very small. This suggests that spectral effects are greater when the contrast of the target against the background is low, and you are more likely to see discrepancies in detection performance between light with different SPDs when target contrast is low, even if photopic luminances are the same between the light sources. Photopic photometry, using the $V(\lambda)$ weighting function, is therefore not a good predictor of peripheral detection performance when using light with different

SPDs and lower contrast targets. Therefore, two models of mesopic photometry (MOVE, Eloholma and Halonen, 2005, and Unified System of Photometry, Rea et al, 2004) were applied to the results and showed good prediction of the spectral effects found in peripheral detection performance.

The studies by He et al and Eloholma et al used a fundamental peripheral detection task, reacting to presentation of a light stimulus. Other studies have investigated peripheral detection using a more practical task. For example, Sammarco et al (2008) evaluated peripheral visual performance under different lighting conditions in relation to mining, using a task that had practical relevance to this context. The peripheral detection task used in this study was detecting when an off-axis disc began rotating, simulating the operation of mining machinery. The rotating targets were placed at 20°, 40° or 50° away from a fixation target at the centre of the observation station. The targets were lit by either an incandescent lamp or one of two different types of LED lamp (a commercially available LED lamp and a prototype LED lamp). Illuminance at the target varied depending on its location but ranged between 1 and 2.5 lux. The SPDs of the three lamps varied, with the two LED lamps providing more shorter-wavelength light than the incandescent lamp and having higher Colour Coordinated Temperature (CCT) values. It is likely the LED lamps had higher S/P ratios although these are not reported. Reaction time to detection was recorded as a measure of detection performance. Results showed that the prototype LED lamp provided quicker detection times compared with both the commercial LED and incandescent lamps. However, it would also have been expected that the commercial LED lamp would provide better performance than the incandescent lamp due to a greater proportion of short-wavelength light in its spectrum but this was not the case. The experiment also demonstrated that detection performance decreased as the angle between the target and current fixation increased.

Fotios and Cheal (2009) used a small-scale viewing chamber to simulate the appearance of obstacles within the visual field of a pedestrian. Participants looked at a fixation mark on the far wall of the chamber. Six cylindrical ‘obstacles’ on the floor of the chamber could be raised from the surrounding surface to different heights. These obstacle positions were at different off-axis angles within the participants’ visual field, but were obscured by a screen at the viewing aperture. When an obstacle was raised to a certain height the screen would be removed for 300 ms, to simulate the brief viewing time that pedestrians get as they scan their environment whilst walking. Participants would indicate if they saw the obstacle by calling out its position. Three different illuminances (0.2, 2.0 and 20.0 lux) within the viewing chamber were examined, and three different lamp types (one HPS and two MH lamps) were used providing three different SPDs. The S/P ratios of the three lamps were 0.57 (for the HPS lamp), 1.22 and 1.77 (for the MH lamps). Performance under each light condition was measured as the height at which a 50% detection rate was achieved, with a lower height indicating better obstacle detection performance. Results from the study suggested that detection performance improved as illuminance increased. The S/P ratio of the light was also linked with detection performance but only at the lowest illuminance level of 0.2 lux. At this illuminance, the lamp with the highest S/P ratio provided the best detection performance. At illuminances above 0.2 lux however there was no difference between the three lamps in terms of detection performance.

Most studies of peripheral detection attempt to ensure peripheral vision is used for the detection task by asking people to look at a fixation target, and presenting a peripheral target away from this central fixation point. One development of this approach is to introduce some form of task at the point of fixation. One study that has employed such a foveal task was by Akashi, Kanaya and Ishikura (2014). The foveal task comprised of a needle moving randomly either side of a central line, with participants asked to adjust the needle to keep it as near the central line as possible by turning a control knob. Two levels of foveal task difficulty were introduced by changing the contrast of the needle against the background. The lower contrast needle was assumed to be a more difficult task than the higher contrast needle. Whilst this task was ongoing, a peripheral target subtending a visual angle 0.75° was presented at 4 off-axis angles (5°, 10°, 20° and 30°) and participants had to release a button being held down by their finger to indicate detection. Performance on the foveal task was measured as the average distance the needle was away from the central line. Performance on the peripheral task was measured as the reaction time to detection. Three light conditions were used: 1) A HPS lamp, with S/P ratio of 0.44 and at photopic luminance of 0.1 cd/m^2; 2) A fluorescent lamp with S/P ratio of 1.97 and at photopic luminance of 0.1 cd/m^2; 3) A fluorescent lamp with S/P ratio of 1.97 but at a photopic luminance of 0.03 cd/m^2. However, this condition had equivalent mesopic luminance to the HPS lamp, as calculated by the Unified System of Photometry (Rea et al, 2004). The foveal task difficulty only had an influence on peripheral detection for the low luminance fluorescent lamp, with the more difficult, lower contrast foveal target producing poorer peripheral detection. Detection performance with the fluorescent lamp at low luminance and the high contrast foveal task was equal to that of the HPS lamp with both low and high contrast foveal task. Performance with the fluorescent lamp at the higher luminance was better than the HPS lamp and the low luminance fluorescent lamp. In addition to the dual task experiment, Akashi and colleagues also carried out a single task experiment in which only the peripheral detection task was carried out. Lack of a foveal task improved detection of the peripheral targets.

5.4.3 Summary of previous research

Previous research has examined the effect of a range of variables on peripheral detection, including the luminance / illuminance of the light, the spectrum of the light, contrast and eccentricity of the peripheral target, and the influence of a foveal task.

Many studies have shown that detection performance improves as luminance (e.g. He et al, 1997; Alferdinck, 2006; Elholma et al, 2006) or illuminance (Fotios and Cheal, 2009) increase. However, the relationship between luminance/illuminance and detection performance is not linear. As the light intensity increases performance may reach an asymptote. In data from Alferdinck (2006) this appears to occur at around 1.0 cd/m^2. Fotios and Cheal (2009) also found that performance tended to plateau as illuminance increased, although statistical tests suggested that all three illuminances they used produced significantly different detection performance. In follow-up work Fotios and Cheal introduced two additional illuminances within the 0.2 – 20.0 lux range in an attempt to better identify the relationship between illuminance and detection (Fotios and Cheal, 2013). Results again demonstrated the non-linear relationship, and suggested the rate of improvement in performance began to reduce when illuminance went beyond about 2.0 lux. This illuminance equated to a luminance of approximately 0.1 cd/m^2, which is an order of magnitude below the plateau point suggested by Alferdinck's data. The exact relationship between light intensity and detection performance therefore appears unclear.

Findings from previous research suggest that the light intensity may interact with other factors to produce differential performance in detecting peripheral targets, and these interacting factors could explain the differences seen between Fotios and Cheal and Alferdinck. One factor that may interact with luminance is the contrast of the peripheral target. Eloholma (2006) found that the rate at which peripheral detection worsens as luminance decreases is greater when the contrast of the target is low, compared with if the contrast is high. Data from van Derlofske and Bullough also suggested a link between the effects of target contrast and luminance, as a low contrast target only produced worse detection performance than a high contrast target when the illuminance was low (approximately 3 lux).

Another important lighting characteristic that interacts with luminance/illuminance in terms of peripheral detection is the SPD of the light. A number of studies report that SPD affects detection, with SPDs that include a greater proportion of shorter-wavelength light generally producing better peripheral detection. This is due to the increased sensitivity to short-wavelength light in rod photoreceptors, which dominate the peripheral retinal field. The S/P ratio is a commonly-used metric in studies examining effects of SPD and peripheral detection, as it characterises the stimulation of rod photoreceptors which dominate the peripheral visual field. Many studies show that peripheral detection improves as the S/P ratio increases (e.g. Akashi, Rea and Bullough, 2007; He et al, 1997; Fotios and Cheal, 2009). However, there may be a limit to the effect increasing S/P ratios can have. For example, Alferdinck (2006) used a blue light which had a much higher S/P ratio compared with white and yellow lights also used, but the blue light did not produce any better performance than the white and yellow lights. The effect of SPD and S/P ratio may also be moderated by the intensity of the light. A number of studies only found an effect of spectrum at lower luminance or illuminance levels, or found the spectral effect was greater at these lower light levels (Lingard and Rea, 2002; He et al, 1997; Alferdinck, 2006; Akashi, Rea and Bullough, 2007; Fotios and Cheal, 2009). However, there is no consensus about at what luminance (or illuminance) level spectral effects begin to be found. For example, Fotios and Cheal only found an effect of spectrum at an approximate luminance of 0.01 cd/m^2. Alferdinck found an effect of spectrum at 0.01 and 0.1 cd/m^2, but not at 1.0 cd/m^2, and He et al similarly found an effect of spectrum only at luminances below about 1.0 cd/m^2. However, Bullough and Rea (2000) found a spectral effect at all luminances they used, including the highest luminance of 3.0 cd/m^2. It may be that differences in experimental conditions, apparatus and task contribute to these inconsistencies. For example the contrast of the peripheral target can influence what effect light spectrum has on detection, with a lower contrast target producing a greater effect of spectrum (Lingard and Rea, 2002; van Derlofske and Bullough, 2003; Eloholma et al, 2006). A low contrast target may be more likely to produce spectral effects at higher light levels than a higher contrast target. Use of a foveal task, and difficulty of this task, can also mitigate the effects of spectrum (Akashi, Kanaya and Ishikura, 2014) and could lead to variations in the light levels that lead to spectral effects. The eccentricity of the peripheral target may also be a factor in whether spectral effects are seen at certain light levels; for example, Alferdinck (2006) found that eccentricity had the largest effect on peripheral detection when the S/P ratio was low.

Table 5.1. Summary of previous studies examining peripheral detection and lighting.

Study	Detection task	Foveal target / task	Lighting variables		Effect of luminance / illuminance	Effect of spectrum
			Luminance / illuminance	Spectrum		
Bullough and Rea (2000)	Small target 18° off-axis	Driving simulator	0.1 – 3.0 cd/m^2	4 S/P ratios between 0.64 – 3.77	Peripheral detection improved with luminance increase	Higher S/P produced better peripheral detection, even at highest luminance
Lingard and Rea (2002)	Small luminous target presented at 4 eccentricities between 12° and 29°	Driving simulator	0.1 – 3.0 cd/m^2	2 S/P ratios of 0.5 and 1.8	Peripheral detection improved with luminance increase	Higher S/P produced better peripheral detection, but only at lowest luminances and with low-contrast target
Alferdinck (2006)	Small circle presented at ± 5°, 10° and 15°	Driving simulator, sat in real vehicle cabin	0.001, 0.1, 1.0 and 10.0 cd/m^2	4 S/P ratios of 0.22, 1.39, 2.12 and 9.08	Peripheral detection improved with luminance increase, but reached plateau around 1.0 cd/m^2	Lowest S/P ratio of 0.22 produced worse peripheral detection than other S/P ratios, but only at lowest luminance levels
Van Derlofske and Bullough (2003)	Flip-dot grid at 5° off-axis increments between 2.5° and 17.5°.	LED bar tracking task	Illuminance varied depending on eccentricity of target, ranging between 1.5 – 14 lux	4 S/P ratios used, ranging between 1.02 – 2.04	Peripheral detection was better at higher illuminances, but this could have been due to smaller eccentricity also	Higher S/P ratio produced improved peripheral detection, but only with a low-contrast target
Crabb et al (2006)	Flip-dot panel at 15° and 25° eccentricities	Reporting the changing colour of fixation target	Luminances ranged between 0.08 – 0.67 cd/m^2 at 15° eccentricity, and between 0.05 – 0.32 at 25° eccentricity	2 lamps with differing spectrums used, HPS and MH. S/P ratios not reported.	No effect found	No effect found
Aksahi, Rea and Bullough (2007)	Flip-dot grid, moving towards or away from road. Task included decision making element – whether to brake or accelerate	Real driving; fixation target placed at side of road	Luminances of 0.115 and 0.089 cd/m^2 used	HPS and MH lamp used, with S/P ratios of 0.55 and 1.17 respectively. HPS only used at higher luminance level, MH used at both luminance levels.	Higher luminance MH lamp showed better peripheral detection than lower luminance MH, but only for task of accelerating	MH lamp (with higher S/P ratio) provided better peripheral detection than HPS lamp at same photopic luminance. Lower luminance MH lamp no worse than HPS lamp.

Table 5.1. Summary of previous studies examining peripheral detection and lighting.

Study	**Detection task**	**Foveal target / task**	**Lighting variables**		**Effect of luminance / illuminance**	**Effect of spectrum**
			Luminance / illuminance	**Spectrum**		
	depending on direction of target.					
He et al (1997)	Small luminous disk presented 15° off-axis	Fixation at a central circle	Eight luminance levels ranging between 0.003 – 10.0 cd/m^2	HPS and MH lamps used, with S/P ratios of 0.61 and 1.67 respectively	Peripheral detection improved as luminance increased	MH lamp (with higher S/P ratio) provided better peripheral detection than HPS lamp, but only below 1 cd/m^2
Eloholma et al (2006)	Small target presented 10° off-axis	Fixation at central target	Luminances of 0.01, 0.1 and 1.0 cd/m^2	Five different colours of target used, providing S/P ratios of 0.43, 0.59, 1.98, 3.44 and 11.4, for a high contrast target. Only two colours used for low contrast target, with S/P ratios of 1.35 and 5.22.	Peripheral detection became worse as luminance decreased, and decrement was greater when light was of lower S/P ratio	Low contrast target produced effect for all 3 luminances used, with higher S/P ratios producing better peripheral detection. High contrast target only produced this effect at two lowest luminances.
Sammarco et al (2008)	Rotation of disk at 20°, 40° and 50° eccentricity	Central flip-dot matrix that was continually moving up and down	Illuminance range was approximately 1.0 – 2.5 lux, varying by eccentricity of target	Three lamp types used, incandescent and two types of LED. S/P ratios not reported but LED lamps had shorter peak wavelength and higher CCT.	Illuminance not examined as variable – varied only as function of eccentricity	Peripheral detection better with one of LED lamps than incandescent, but not for other LED lamp
Fotios and Cheal (2009)	Detection of raised cylinders representing floor obstacles, at eccentricities ranging between 10 - 42°	Central fixation point	Illuminances of 0.2, 2.0 and 20.0 lux	Three types of lamp used (one HPS, two MH), providing S/P ratios of 0.57, 1.22 and 1.77	Peripheral detection improved as illuminance increased, although plateau possibly suggested around 2.0 lux	Higher S/P ratio provided better peripheral detection, but only at lowest illuminance of 0.2 lux
Akashi,	Peripheral target	Adjusting	Luminances of 0.1 and	HPS and MH lamp	Higher luminance MH	MH lamp at higher

Table 5.1. Summary of previous studies examining peripheral detection and lighting.

Study	**Detection task**	**Foveal target / task**	**Lighting variables**		**Effect of luminance / illuminance**	**Effect of spectrum**
			Luminance / illuminance	**Spectrum**		
Kanaya and Ishikura (2014)	presented at 4 off-axis angles ranging between 5° - 30°	needle to keep on central line. Two difficulties of foveal task used, by making need low or high contrast.	0.03 cd/m^2 used	used; S/P ratios not reported but MH has higher proportion of short-wavelength light. HPS only used at higher luminance level, MH used at both luminance levels.	lamp produced better peripheral detection than lower luminance MH.	luminance gave better peripheral detection than HPS lamp at same luminance. MH at lower luminance gave equal performance to HPS lamp at higher luminance, but only for high contrast (easier) foveal task.

5.5 Limitations of previous studies

The studies outlined above describe work about peripheral detection under mesopic lighting conditions. A number of limitations exist within these studies however that limit how applicable they are to peripheral detection by pedestrians, and limit what they can tell us about the influence of lighting on the critical visual task of detecting obstacles.

First, with the possible exception of Fotios and Cheal (2009), the studies do not adequately simulate the task of detecting an obstacle on the ground. This task is qualitatively different to that of detecting an illuminated peripheral disc (e.g. He et al, 1997; Eloholma et al, 2006), a peripheral target in a driving task (e.g. Bullough and Rea, 2000; Lingard and Rea, 2002; Aksahi et al, 2007), or a moving peripheral target (van Derlofske and Bullough, 2003; Sammarco et al, 2008).

Second, the tasks involved in these studies were artificial in nature and with the exception of Akashi et al did not include realistic elements of the tasks or settings that would be expected in situations involving peripheral detection. For example, many of the studies employed a static fixation mark to encourage use of peripheral vision for the detection task. However, in real situations it is highly unlikely that our gaze remains fixed on one location for an extended period of time. On average we make around 3 saccades per second (Henderson, 2003) which means we are constantly fixating on different areas of the scene in front of us. Saccadic eye movements have been shown to influence detection of changes in a scene (Henderson and Hollingworth, 1999) and are therefore likely to affect detection of a peripheral target. Some studies avoided keeping gaze static by using a driving simulation task, which required more realistic movement of the eyes (e.g. Bullough and Rea, 2000; Alferdinck, 2006). However, these driving tasks were relatively simple and did not include the distractions, visual features or element of risk that would be associated with real driving. This is illustrated by the unrealistically-high average simulated speeds reported in Bullough and Rea (2000).

Third, whilst the fixation target or foveal task in previous studies were designed to encourage use of peripheral vision for the detection task, there was no guarantee that participants did not direct their gaze towards the peripheral target and use foveal vision rather than peripheral vision. Some studies employed a foveal task to help maintain foveal vision in the desired area, such as driving (e.g. Bullough and Rea, 2000; Alferdinck, 2006). Most studies however did not use this strategy, and had no method of monitoring or checking where gaze was located. Not using a foveal task is also unrealistic – we frequently fixate areas in order to gather visual information to help us achieve some task, such as searching for something or assessing an area. Carrying out a foveal task has been shown to affect peripheral detection (Akashi, Kanaya and Ishikura, 2014; Mayeur, Bremond and Bastien, 2008).

Fourth, although some of the driving-related studies have employed a motor task, none have employed a motor task that relates to pedestrians, namely walking. Walking is a complex task (Hausdorff et al, 2005) requiring the planning of foot placement, assessment of floor surface, planning of route, maintaining posture and stability, and therefore uses attention and executive cognitive functioning in the brain (Yogev-Seligmann, Hausdorff and Giladi, 2008). It has been shown that walking speed and accuracy performance declines with the addition of a secondary cognitive task (Lindenberger et al, 2000), and avoidance of an obstacle is less likely to occur (Weerdesteyn et al, 2003). It is therefore possible that walking is an important mediator of peripheral detection performance.

Finally, previous studies have not provided a consensus about key thresholds for lighting metrics in relation to obstacle detection, which may be important for design guidance for pedestrian road lighting. It is clear that peripheral detection improves as the luminance or illuminance increases. However, the exact relationship between detection and light intensity is not clear. Most research points to there being a plateau in performance, beyond which increasing the amount of light has negligible effect on measures of detection. No consensus exists about where this plateau begins however. It would be useful to know at what light level obstacle detection by pedestrians begins to plateau, as this could provide some justification in design guidance for recommending light levels of a certain luminance or illuminance. Furthermore, previous research generally shows that SPD has an effect on peripheral detection, but again the nature of this relationship, and the interaction with light intensity, is not clear. Some research has only found an effect at lower luminances and illuminances (e.g. Alferdinck, 2006; Fotios and Cheal, 2009) whilst other research has found an effect even at higher luminances (e.g. Bullough and Rea, 2000). Sammarco et al (2008) were unable to even find an effect for one of their LED lamps. Therefore, previous research is unable to say definitively how SPD may affect obstacle detection by pedestrians and at what levels of light. In addition, previous research in this area has not isolated one specific aspect of the light spectrum when investigating SPD effects. The Scotopic/Photopic ratio is often used as a metric, but this is often varied alongside other spectrum metrics such as chromaticity or colour correlated temperature. To clarify whether S/P ratio is a valid metric it is desirable to isolate changes in S/P ratio from other variations such as chromaticity, as was done by Berman et al (1990) and Fotios et al (2015) when investigating spatial brightness.

5.6 New peripheral obstacle detection experiment

A new experiment investigating obstacle detection by pedestrians was designed to address some of the limitations with previous work highlighted in section 5.5. The goal of this experiment was to provide data about the effect of lighting on obstacle detection that would be more applicable to real pedestrian contexts.

An approach similar to that used by Fotios and Cheal (2009, 2013) was taken, using a detection task associated with a pedestrian context. However, a larger scaled set of apparatus was used, with more realistic dimensions. In addition, rather than using a static fixation mark for attracting foveal vision, a dynamic fixation task was developed. The fixation point would move randomly within the observer's field of view, requiring saccadic eye movements and simulating the visual gaze behaviour of pedestrians ('t Hart and Einhauser, 2012). The fixation point would also change, at random intervals, from a crosshair to a numeric digit, which test participants were instructed to read aloud. This created a foveal task for observers, simulating the fact that pedestrians are often likely to carry out some form of processing of their foveal stimuli. The task also aimed to promote visual attention towards the fixation point and reduces instances of looking towards the anticipated target rather than the fixation point. Performance on this foveal task also provided an opportunity to validate whether observers really were tracking the fixation point.

To further improve the realism of the experiment and make it more applicable to a pedestrian context, participants walked on a treadmill during test sessions. As discussed in section 5.5 walking is a relatively complex task and is likely to occupy a certain amount of cognitive capacity. The maintenance of balance required for walking on the treadmill together with the dynamic fixation task were intended to increase cognitive load towards that of a pedestrian. Introducing walking into the overall task would make the data collected about peripheral obstacle detection more applicable to pedestrian contexts.

The illuminance and S/P ratio of the light used in the experiment was systematically varied, to identify their effect on obstacle detection. Five illuminances and three S/P ratios were used, within ranges that were realistic for pedestrian road lighting. An attempt was made to better isolate the effect of S/P ratio on obstacle detection compared with previous work. This was done by using a tuneable LED array which enabled the S/P ratio to be varied whilst chromaticity was held constant across variations in S/P ratio.

A further variable investigated by the obstacle detection experiment was the age of the observer. The interaction of age and lighting on obstacle question is an important question. Tripping over objects on the floor is one of the most frequent causes of falls in the elderly (Campbell et al, 1990), and the elderly are less likely than young people to avoid obstacles if their attention is divided (Chen et al, 1996), a likely occurrence if walking down a street. It is therefore essential for road lighting to aid the identification and avoidance of obstacles for all age groups but particularly the elderly. Vision deteriorates as we get older, due to reduced levels of light reaching the retina, reduced contrast within the retinal image resulting from increased scattering of the light before it reaches the retina, and changes in the absorbance of the lens, particularly for shorter-wavelength light (Boyce, 2014). This not only means that obstacle detection performance in general may be poorer amongst older people, but also that the spectrum of the light may have a different effect on obstacle detection performance amongst older people compared with young people. Few previous studies of peripheral detection have examined age as a factor. Two studies that did were Sammarco et al (2008) and Fotios and Cheal (2009). Sammarco et al (2008) compared three age groups (18-25, 40-50 and 51+ years). Peripheral detection performance was significantly better in the young group compared with the mid-aged group, but surprisingly there was no difference with the oldest group. Also no interaction was found between age groups and the spectrums used. Fotios and Cheal (2009) compared younger people (mean age of 32 years) with older people (mean age of 68 years). The young group showed significantly better detection of obstacles than the old group at the lowest illuminance (0.2 lux), but there was no difference at higher illuminances. There was also no interaction between age group and spectrum reported. The age-related results from these two studies are mixed and further investigation of the influence of age on the effects of lighting on obstacle detection is useful. In particular, it is important to test the obstacle detection performance of older people under realistic pedestrian conditions, for example whilst walking, as the division of attention, dual-task situations or additional cognitive loads have greater impact on older people compared with younger people (e.g. Hollman et al, 2007).

5.7 Summary

It is important for pedestrians to adequately detect obstacles in the path. Road lighting has a role to play in facilitating this task and it is useful to know the effect of lighting on this task. Obstacle detection is predominantly carried out in peripheral vision, and a number of studies have examined detection of a peripheral target under different lighting conditions. These studies have generally found that peripheral detection improves as the illuminance or luminance increases, and as the S/P ratio of the light increases. However, there is a lack of consensus between past studies relating to the threshold of light intensity at which a plateau in performance is seen or at which the spectrum of the light no longer has an effect on performance. Furthermore, previous studies do not adequately reflect the context and concurrent tasks that occur when a pedestrian walks along a street. A new experiment was therefore designed to provide further evidence about the relationship of illuminance and S/P ratio with obstacle detection, in a pedestrian-relevant context. This new experiment planned on introducing additional elements of realism, such as engaging participants in walking and a dynamic fixation task. The following chapter describes two initial pilot studies carried out to test the general approach of the new experiment design and the additional task elements that were planned.

CHAPTER 6. OBSTACLE DETECTION PILOT STUDIES

6.1 Introduction

The previous chapter reviewed existing research about lighting and peripheral detection. This highlighted that more applicable and realistic data in relation to a pedestrian context is required, in order to draw conclusions about optimal lighting characteristics for pedestrian road lighting. A new peripheral obstacle detection experiment was therefore designed, building on the approach taken by Fotios and Cheal (2009, 2013). The key improvements made with this new experiment were: 1) Realistic scales and dimensions of apparatus used; 2) Participants walking on a treadmill to simulate a pedestrian walking down a street; 3) Tighter control of lighting parameters, specifically controlling chromaticity whilst varying S/P ratio and illuminance; 4) Use of a dynamic fixation target to increase cognitive load, simulate eye movements of pedestrians and encourage use of peripheral vision for the detection task.

Two pilot studies were carried out to ensure the new experiment apparatus adequately measured obstacle detection and provided reasonable data that would be within expectations. The pilot studies were also designed to test the effects of two of the improvements that were to be used, walking on the treadmill and the dynamic fixation target, to ensure they worked effectively and did not produce unusual results. These two pilot studies are described below. The apparatus used for the two pilot studies was near-identical, and a general description of this apparatus is given in section 6.2. Further descriptions about the method and particular aspects of the apparatus where it differed between the pilot studies is given under the sections for each study.

6.2 Apparatus – general description

The pilot tests took place in the lighting laboratory at the University of Sheffield. Within the laboratory a test area was set up. This comprised a 3-sided cubicle measuring 2.4 x 2.4 metres. At the open side of the cubicle two partition walls were placed to extend and narrow the cubicle, as illustrated in Figure 6.1. Matt black cloth was draped along all visible walls of the test area to reduce reflections. The floor was dark grey linoleum with low sheen. A treadmill was placed at the narrowed, open end of the test area. The treadmill was part of the Lifespan TR1200-DT3 Treadmill Desk but consisted of only the base walking unit and did not have side or front rails. The treadmill had a surface height of 0.19 m, and its belt length and width were 1.42 x 0.51 m. It had a maximum speed of 16.1 km/h. A black metal bar acting as a safety handhold was placed above the treadmill. When held at roughly arms-length participants were stood approximately 3.8 m from the far wall of the cubicle area. The treadmill was only in operation for pilot study one.

A simulated obstacle was placed between the participant and the far wall. This obstacle comprised a box made from cardboard walls covered in matt grey paper and an MDF top surface painted with grey paint (Munsell N5). The dimensions of the box were 600 x 450 mm, with a height of 180 mm. It housed a small servo motor attached to an MDF cylinder with a diameter of 100 mm that could be raised and lowered from the centre of the box. The top surface of the cylinder would lie flush with the top of the box when in its lowered position but could be raised to a maximum height of 50 mm above the top surface of the box, thus simulating a raised obstacle of variable potential heights. The exposed length and top of the cylinder were painted in the same grey paint as used for the top of the surrounding box. The obstacle servo motor was controlled through a computer program written in Python, via a Pololu micro-controller.

The obstacle rose at a speed of 134 mm/s. This speed meant it reached its target height very rapidly, and attempted to simulate the instantaneous appearance of the obstacle, as was the approach used by Fotios and Cheal. In their experiments Fotios and Cheal raised the obstacle to its target height out of view of the participant, before revealing the obstacle scene for 300 ms. However, at this speed the servo motor raising the obstacle produced an audible noise, measured as 34 dB at the position of the participant's head. This noise could have primed participants for when the obstacle was about to appear. Therefore, participants wore ear-surrounding headphones which played six audio clips on a randomised loop to mask the noise made by the servo motor. The audio clips were recordings of outdoor urban sounds, such as traffic noise, sirens and general city ambience, in an attempt to simulate a real pedestrian acoustic environment.

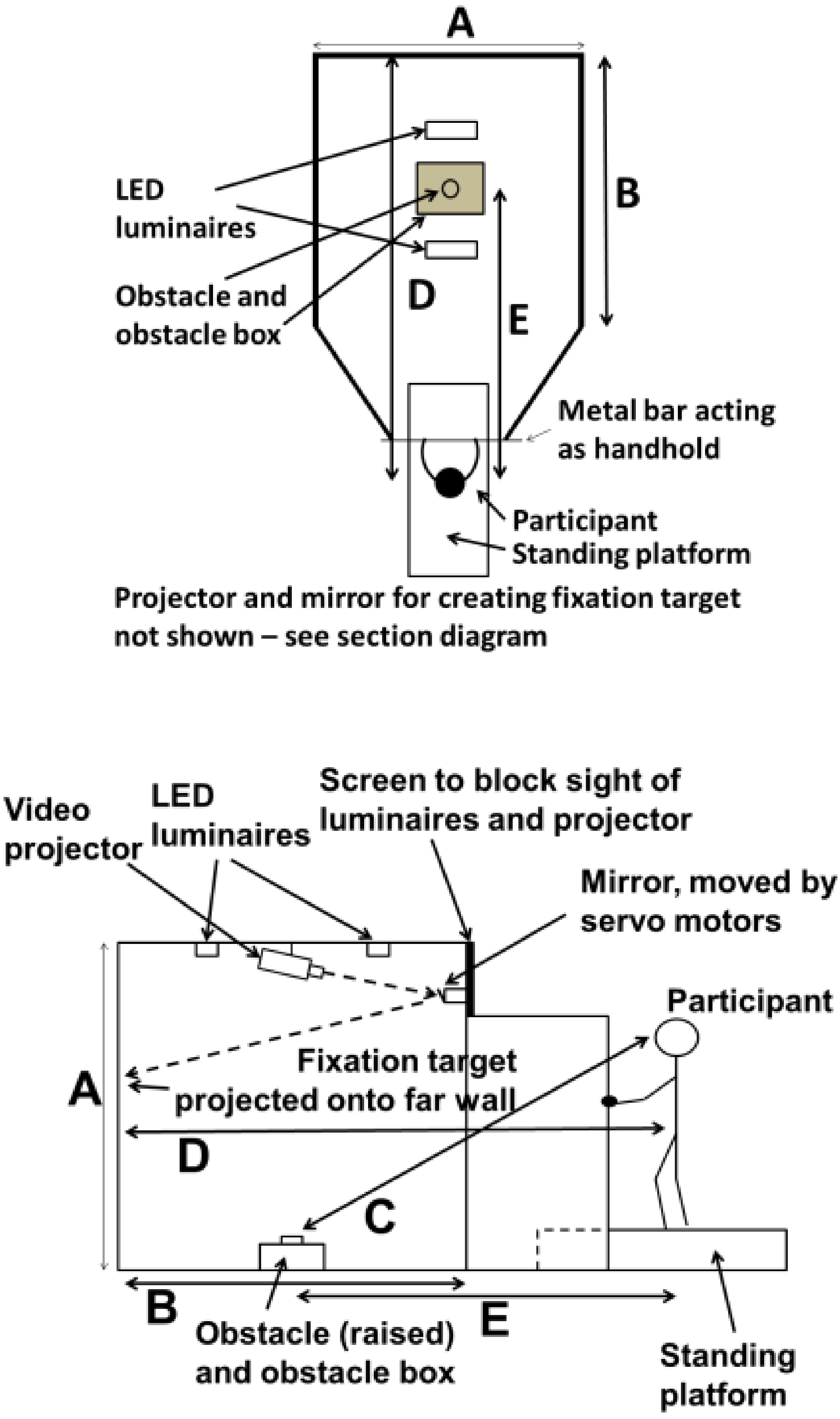


Figure 6.1. Diagram of pilot study apparatus – plan (*top*) and section (*bottom*). Dimensions: A = 2400 mm, B = 2400 mm, C= 3000 mm, D = 3800 mm, E = 2600 mm. Note: diagram shows mirror projection apparatus used in pilot study two. In pilot study one no mirror was used and the video projector pointed directly at wall opposite the participant.

The obstacle box was placed so that the obstacle at its centre was 1.7 m from the front edge of the treadmill and 1.2 m from the far wall of the semi-enclosed cubicle. The approximate distance between the participant's position on the treadmill and the centre of the obstacle was 2.6 m, although this varied slightly depending on the participant's exact position on the treadmill. The distance was kept as close to constant between participants as possible, and during trials with the same participant, by instructing them to always keep hold of the metal bar suspended over the treadmill. Assuming an average eye height of 1.5 m, the actual distance between the participant's eye and the obstacle was approximately 3.0 m. At this distance, the obstacle represented a visual size of 1.68° in width and 0.50° in height when reaching the maximum height (in these pilot studies) of 30.3 mm. Figure 6.2 shows the test area with obstacle box (obstacle not raised) from the vantage point of the participant when stood on the treadmill.

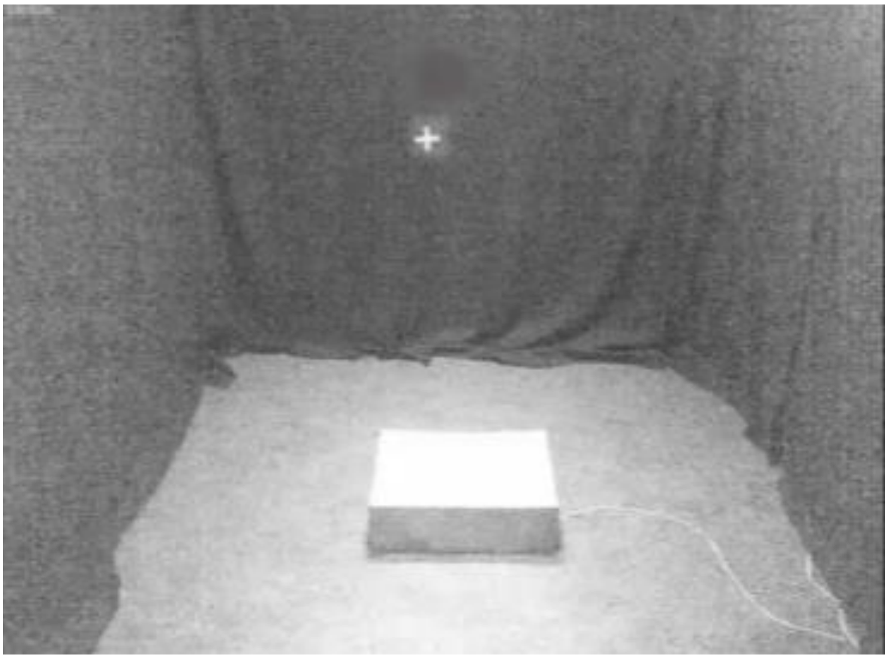


Figure 6.2. Greyscale image of test area from participant's viewpoint, showing obstacle box (obstacle not raised), fixation target and surrounding enclosed area

The obstacle box and surrounding area within the cubicle was lit by two LED arrays suspended above the test area but out of view of participants. The lighting was not a question of interest for these pilot studies so only one lighting condition was used. The illuminance on the top surface of the obstacle was 2.0 lux and the light had an S/P ratio of 1.33. Luminance values at the top surface of the obstacle, the horizontal centre of the rear wall at 1.5 m height and the centre of the fixation target were 0.13, 0.02 and

2.61 cd/m2 respectively. Further details about the lighting apparatus are given in the method description for the main obstacle detection experiment, section 7.2.2.

A fixation target was displayed on the far wall of the test area. The exact nature of this target varied within each of the pilot tests and is described in further detail within each pilot test section. The purpose of the fixation target was to hold the gaze of the participant, so that the use of peripheral rather than foveal vision was induced for detecting when the obstacle was raised.

6.3 Pilot study one – walking vs standing

The intention for the main obstacle detection experiment was to have participants walk on a treadmill whilst they carried out a detection task. A key aim of the first pilot study was therefore to check what effect, if any, walking on a moving treadmill had on the obstacle detection task compared with standing on a static treadmill. It was also necessary to check the obstacle detection task could be adequately completed whilst walking on the treadmill.

6.4 Method

A fixation target was projected directly on to the far wall by a standard data projector. The target would move in random directions and speeds across the far wall, within a rectangular area measuring 1.8 x 1.35 m, whose centre was 1.6 m above the floor. The target changed direction at randomly chosen intervals between 1 and 3 seconds. Each time the target changed direction a randomly selected speed was chosen which lay within the range of approximately 1.5 – 3.7 metres per second. This speed range equals 22° - 52° per second in terms of visual angle.

The default appearance of the fixation target was a crosshair. The crosshair was 106 mm in height and width, which subtended a visual angle of 1.6° when viewed by the participant whilst stood on the treadmill. The target would frequently but briefly change to a number between 1 and 9 before changing back to the crosshair. The interval between these changes to numbers was randomly selected from between 2 and 6 seconds. The number was shown for 0.2 seconds before returning to the crosshair. The numbers were slightly larger in height than the cross, displaying as 158 mm on the far wall or 2.4° visual angle in terms of its height. This was to account for the numbers being less wide than the cross. The width of the number varied depending on which number was displayed, but was no larger than 114 mm or 1.7° visual angle.

Two conditions were tested – standing and walking. During the standing condition participants stood on the inactive treadmill whilst holding the metal safety bar. During the walking condition participants walked on the moving treadmill whilst also holding the metal safety bar. The treadmill speed was set to a level the participant felt comfortable with prior to commencing the walking condition. This was done by incrementally increasing the speed until the participant confirmed it was comfortable and felt natural. The mean walking speed set by participants was 3.2 km/h.

Five participants took part in the pilot test (four female, mean age of 29 years). All participants had normal or corrected-to-normal vision, tested via a Landolt ring acuity test at 2 m and the Ishihara colour vision test. Each participant was tested on both standing and walking conditions, with the order in which the conditions were presented being counterbalanced to avoid order effects. For each condition the participant was instructed to stand on the treadmill whilst holding the metal handhold bar at roughly arms-length. They were told that their primary task was to keep looking at the fixation target that would appear on the far wall of the test area in front of them and whenever the target changed to a number to say this number out loud. Participants were also told that periodically the obstacle would rise up above the surface of its surrounding box, and if they noticed or thought that this had happened they were to press a handheld button as quickly as possible. They were given the button to hold in their stronger hand throughout each test. However, they were instructed that the main task was following the fixation target and reporting the numbers, and it was important for them to try and not look down at the obstacle box to verify whether the obstacle was raised or not. This instruction was an attempt to ensure peripheral vision was used for obstacle detection, as attention can be focused as a result of instruction in dual-task settings (Kelly et al, 2010).

Each condition test consisted of 18 trials, with the obstacle rising to a predetermined height (as measured from the surface of the surrounding box) at some point during each of these trials. The obstacle would remain at this height for 2 seconds before returning to its flat position. Two seconds was selected as the obstacle's exposure time as this is approximately the amount of time it would take a pedestrian to walk the 2.6 metres between the position of the participant and the obstacle (assuming an average pedestrian walking speed of 1.3 m/s or 4.68 km/h – see Bohannon, 1997, for data on adult walking speeds). Six obstacle heights were tested: 5.0, 7.9, 12.6, 15.9, 20.0 and 25.2 mm. These heights were chosen from a sequence of heights beginning at 5.0 mm that increased progressively at a ratio of 1.26 (0.1 log unit steps), the same rate of progression as used for increasing gap sizes on the Bailey-Lovie acuity chart (Bailey and Lovie, 1976).

Each obstacle height was presented 3 times, resulting in a total of 18 trials for each test. The order in which the obstacle heights were presented was randomised for each participant. A computer program written in Python and using the Psychopy library of functions (Peirce, 2007) was used to control the raising and lowering of the obstacle, and the timings of each trial. When a trial was initiated a random interval between 3 and 10 seconds was selected before the obstacle was raised. The obstacle was raised to its pre-defined height at a set speed of 134 mm/s, meaning the time taken for the obstacle to reach its height ranged between 0.037 and 0.185 seconds. Following a 2 second obstacle exposure period, the obstacle returned to its flat position. A further 3 second delay ensued before the next trial was initiated. Therefore the total time for any particular trial was between 8 and 15 seconds.

Throughout the test and continuously between trials the participant was instructed to keep looking at the fixation target and reporting numbers as they saw them. If the participant pressed the response button after the obstacle had begun to rise or when it had reached its target height but before it had started to descend this was defined as a correct detection. If the participant pressed the button at any other time this was defined as a false response. If the participant correctly detected the obstacle their reaction time to detection, starting from the point when the obstacle began to rise to the point they pressed the response button, was also recorded. This data provided two performance measures which have been used in the analysis of results. The first is the detection rate for each obstacle height, calculated as the proportion of trials for that height in which the obstacle was correctly detected. The second is the reaction time to detection, calculated as the mean reaction time to detection for all trials involving a correct detection of that obstacle height. A higher rate of detection and a lower reaction time would indicate better detection performance.

6.5 Results

6.5.1 Detection rates

Figure 6.2 shows the mean detection rates for each obstacle height in each condition, averaged across the 5 participants. First, this shows that detection is less likely with smaller obstacles, for both conditions, as would be expected. Second, it suggests there is a plateau effect for detection of the larger obstacles from the 12.6 mm or 15.9 mm height. Third, it suggests there are differences between the conditions in detection rates, with the walking condition showing higher detection rates compared with the standing condition.

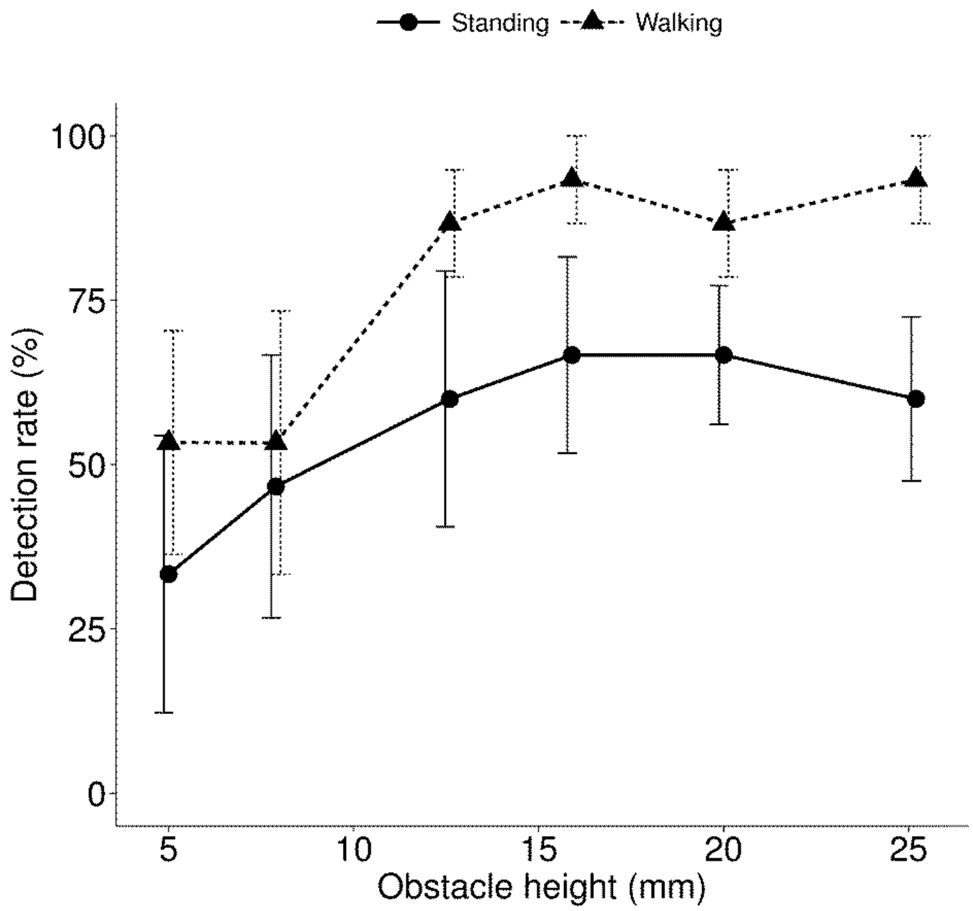


Figure 6.3. Mean detection rates by obstacle height for standing and walking conditions. Error bars show standard error of the mean.

Statistical tests were carried out to confirm whether these interpretations of Figure 6.2 were supported, although the small sample size (N = 5) means results from these tests should be interpreted with caution due to low power. The small sample size also means non-parametric tests were used as it is not possible to identify the sample's distribution characteristics and therefore confirm whether parametric assumptions about normality are met (Hill and Lewicki, 2007).

A Friedman's ANOVA was carried out for each condition testing for differences in detection rates between obstacle heights. The resulting p-values suggested no significant differences on either condition (standing condition $\chi^2 = 4.14$, p = 0.53; walking condition $\chi^2 = 10.0$, p = 0.08). To compare detection rates between the two conditions, an overall detection rate was calculated for each participant on each condition by taking the mean detection rate across all obstacle heights. This overall detection rate was used in a Wilcoxon signed-rank test. This did not suggest a significant difference between conditions though (standing overall mean detection rate = 44%, walking overall mean detection rate = 72%, V = 0, p = 0.10).

6.5.2 Reaction times

Figure 6.4 shows the mean reaction times to detect each obstacle height for the standing and walking conditions. A similar pattern to that seen with detection rates can be seen, with detection performance improving (i.e. reaction time decreasing) as the obstacle height increases, and a possible plateau in performance around 15 mm height. However no difference between conditions is apparent. Friedman's ANOVAs were carried out to compare reaction times between the different obstacle heights for the standing and walking conditions, but these found no significant differences (standing condition, $\chi^2 = 5.0$, p = 0.42, walking condition, $\chi^2 = 2.0$, p = 0.84). To compare reaction times between conditions an overall mean reaction time across all obstacle heights was calculated for each participant and used in a Wilcoxon signed-rank test. This suggested the conditions did not differ in terms of reaction times (standing mean reaction time = 1,287 ms, walking mean reaction time = 1,312 ms, V = 5.0, p = 0.63).

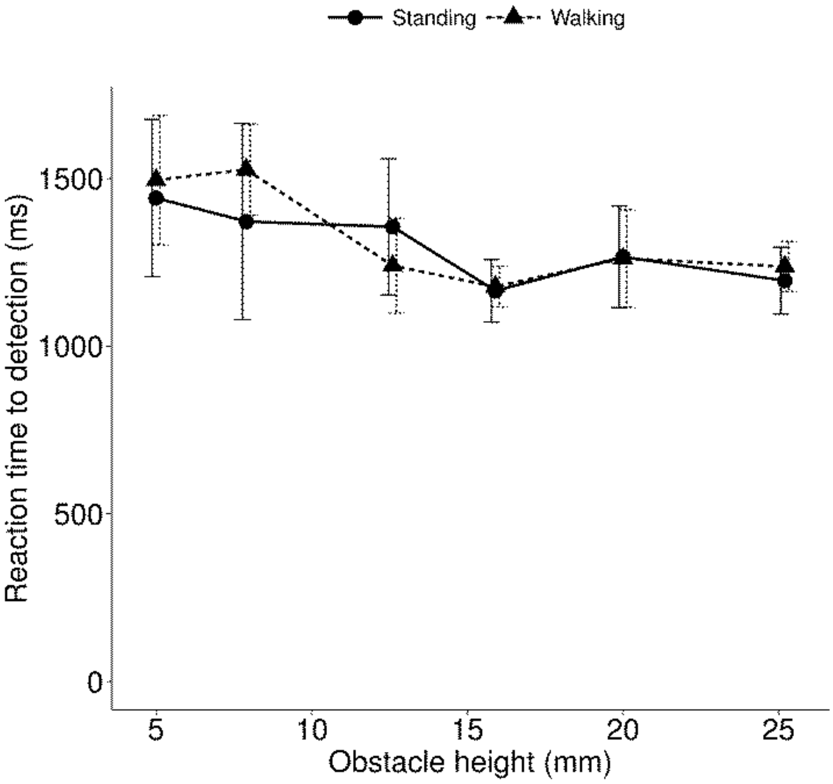


Figure 6.4. Mean detection reaction times at each obstacle height, for standing and walking conditions. Error bars show standard error of the mean.

6.5.3 Fixation target number identification

During each trial the dynamic fixation target periodically changed to a number before changing back to the default target. Participants were asked to read aloud the number if they noticed it, and their response was recorded and matched against the actual number presented. The proportion of correct responses given by participants was calculated. Any missed response, where the participant did not state anything following presentation of a number, was counted as an incorrect response. Responses from one participant were not recorded due to a failure in software, so data is reported for the remaining four participants. For the standing condition the mean proportion of correct responses was 93% and for the walking condition it was also 93%.

6.6 Conclusions – Pilot study one

The results produced during this pilot study were within expectations and demonstrated that the method and apparatus was adequately measuring obstacle detection. A trend of better detection as the obstacle became larger was seen, although statistical tests could not confirm this trend. This is likely a result of low statistical power due to the small sample size. The pilot study also showed that walking on a treadmill whilst carrying out the obstacle detection task could be successfully achieved, and the treadmill walking did not produce very unexpected results. Walking on a treadmill could therefore be used in the main experiment to improve the realism of the task without producing anomalous results. However, it was interesting to note that walking appeared to improve detection performance compared with standing. This difference was not statistically significant, possibly suggesting this apparent difference between the conditions was spurious. However, bearing in mind the small sample size for this pilot study it is perhaps unsurprising a significant difference was not found. If this effect is indeed a real one, one possible explanation lies within the action-specific perception literature. This suggests that perception is influenced by our ability to perform intended actions. For example, the throwing distance to a target appears further as the effort to throw increases (Witt, Proffitt and Epstein, 2004), and golfers perceive the hole to be larger if they are playing well (Witt et al, 2008). It is therefore possible that the action of walking, and the simulated potential that the participant would be stepping on the ground in front of them, improved their perception of this area and thus led to better detection performance. Perception of the walking environment may be influenced by the action of walking as opposed to not walking, *"…when people intend to walk, they see the world as 'walkers'"* (Proffitt, 2008, p.180).

Finally, the difficulty of the identification task appears to be about right. It is important that the task is not overly difficult, as it would then be difficult to interpret whether poor performance was due to the level of difficulty or due to participants not looking at the fixation target. Likewise, the task should not be too easy either, as this could allow participants to successfully carry out the task without having to constantly follow the fixation target. A 93% success rate at identifying the target number appears to give a good balance in terms of difficulty. This high success rate initially suggests participants were looking at the fixation target for the majority of the time, giving us some confidence that peripheral vision was being used to detect the raised obstacle. However, without monitoring the eye movements of participants we cannot know this for certain. This is what the second pilot study, described below, addresses.

6.7 Pilot study two – Effects of dynamic fixation target

This pilot study examined whether the dynamic fixation target proposed for the main test (that used in the first pilot study) would in fact hold a participant's gaze, thus ensuring peripheral not foveal vision was used for the obstacle detection task. Eye-tracking equipment was employed to monitor eye movements whilst using the proposed dynamic fixation target alongside the obstacle detection task. Three other versions of fixation target were also examined, to provide control data and investigate whether these alternatives were any better or worse at holding participants' gaze. Another question being addressed by this pilot study was whether the type of fixation target influenced obstacle detection, and performance at detecting the obstacle was measured as in the first pilot study.

6.8 Method

The same general apparatus setup used in the first pilot study was also used in this pilot study. However, a key difference was the way the fixation target was produced on the far wall. Pilot study one used a direct projection from a video projector. One limitation of this method is that light from the entire projection screen falls onto the far wall and is seen by the participant, not just the fixation target. This is not a major consideration during these pilot studies as lighting is not being investigated. However when the main test is carried out, with lighting being a key variable of interest, this projected light could have a confounding effect and may compromise conclusions drawn due to the systematic variation of the primary lighting for the experiment. Therefore a new method for creating the fixation target was developed and tested during this pilot study. The target was still produced by a data projector, but was directed in the opposite direction to the far wall on to a small mirror. The mirror reflected the target image back on the far wall, making it visible to the participant. Low-reflectance black screening was placed around the mirror so that only the light falling on the mirror was projected back on to the far wall. The mirror was mounted on a robotic two-axis gimbal controlled via a Python program, which could change the angle at which the target was reflected back on to the far wall. Thus, the redirection of the mirror meant the fixation target could move randomly around the far wall in a similar manner to that produced by the direct projection method used in the first pilot study. The mirror setup is show in Figure 6.5.

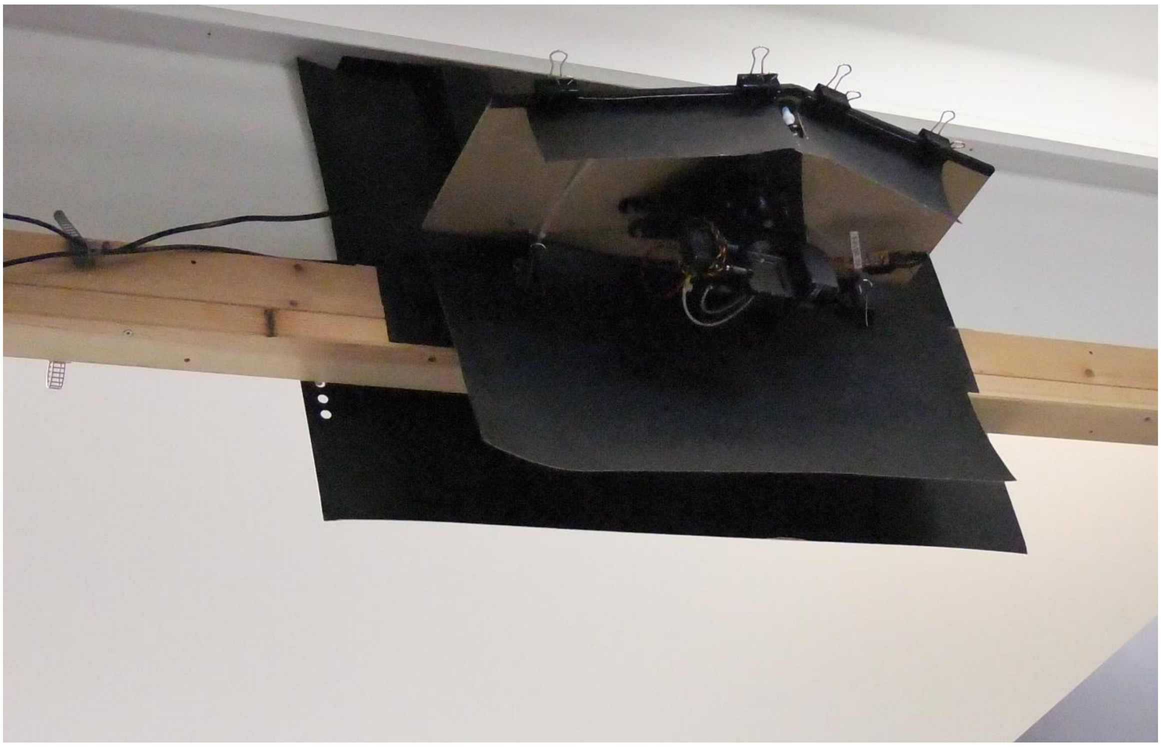


Figure 6.5. Mirror on gimbals, to redirect fixation target onto opposite wall of test area. Black screening material reduces excess light from the projector being reflected back on to the opposite wall and visible to the participant.

Six obstacle heights were used in this pilot study but they were selected from a different range of values than those used in the first pilot study. This range again followed a logarithmic progression with heights increasing at a rate of 1.26, the same as used in the Bailey-Lovie acuity chart (Bailey and Lovie, 1976). The obstacle heights selected were 3.0, 4.8, 7.6, 12.0, 19.1 and 30.3 mm. In the previous pilot test, the smallest height of 5 mm still achieved over 25% detection for the standing condition and over 50% detection for the walking condition. A smaller height, 3 mm, was therefore selected as the smallest height in the range used, in an attempt to determine at what height detection approaches 0%.

Four types of fixation target were used. The targets varied on whether they moved or not, and whether they periodically changed to a number requiring identification or not. These variations gave four conditions of fixation target: Static, Change to number (SC), Static, No change to number (SN), Moving, Change to number (MC) and Moving, No change to number (MN).

Each condition was tested with a block of 18 trials, 3 trials on each obstacle height, with a two minute gap until the next condition. The order in which the conditions were presented was counterbalanced. Participants stood on the treadmill (stationary and switched off throughout this pilot study) for each condition. The rest of the procedure was the same as that used in pilot study one. Participants looked at the fixation target, reading aloud when it changed to a number on those conditions this occurred. If they noticed a raised obstacle they pressed a handheld response button, with detection rates and reaction times to detection being recorded. Participants also wore the headphones playing urban audio clips that were used in the first pilot study. For this pilot study however participants also wore a pair of SMI eye-tracking glasses with a sampling rate of 30 Hz. The eye-tracker recorded the eye movements of the participant, producing a video output of the scene in front of the participant (recorded by a forward-facing camera on the glasses) with the position of where the eyes were looking superimposed on this. The eye-tracker also produced raw data comprising of the gaze position as an x,y coordinate centred on the video output for every eye image sample taken and details of fixations and saccades as defined by software used for processing the raw samples data.

Ten participants were recruited for this pilot test, with a mean age of 29 years. Three were female. All participants had normal colour vision and corrected acuity, as tested by the Ishihara colour vision test and a Landolt ring acuity test at 2 m.

6.9 Results

6.9.1 Eye movements

Two approaches were taken to analysing the eye movements of participants during the test. The first, The Area Of Interest (AOI) approach, was to record the amount of time gaze was located in two possible areas, the fixation target area and the obstacle area. A relatively high proportion of gaze time spent in the obstacle area would suggest participants were frequently looking down at the obstacle and thus not consistently using peripheral vision for detection. This AOI approach provides a fairly coarse level of analysis however, unable to distinguish between two different regions of the same AOI whilst at the same time creating a distinction between two AOIs that may be only a short distance apart (Hu et al, 2014). It may also be unable to highlight whether participants are making downward saccades towards the obstacle but without reaching the obstacle area. Any kind of glance downwards may improve detection ability as eccentricity is linked to visual performance (Boyce, 2014). Therefore, an additional method of analysis, the downward saccade approach, was adopted. Downward saccades were quantified as an indication of the amount of downward looking carried out by participants.

6.9.2 Area of Interest

The fixation target area was defined as the whole of the far wall onto which the fixation target was projected. The obstacle area was defined as the floor area, the obstacle box or the obstacle itself. See Figure 6.6.

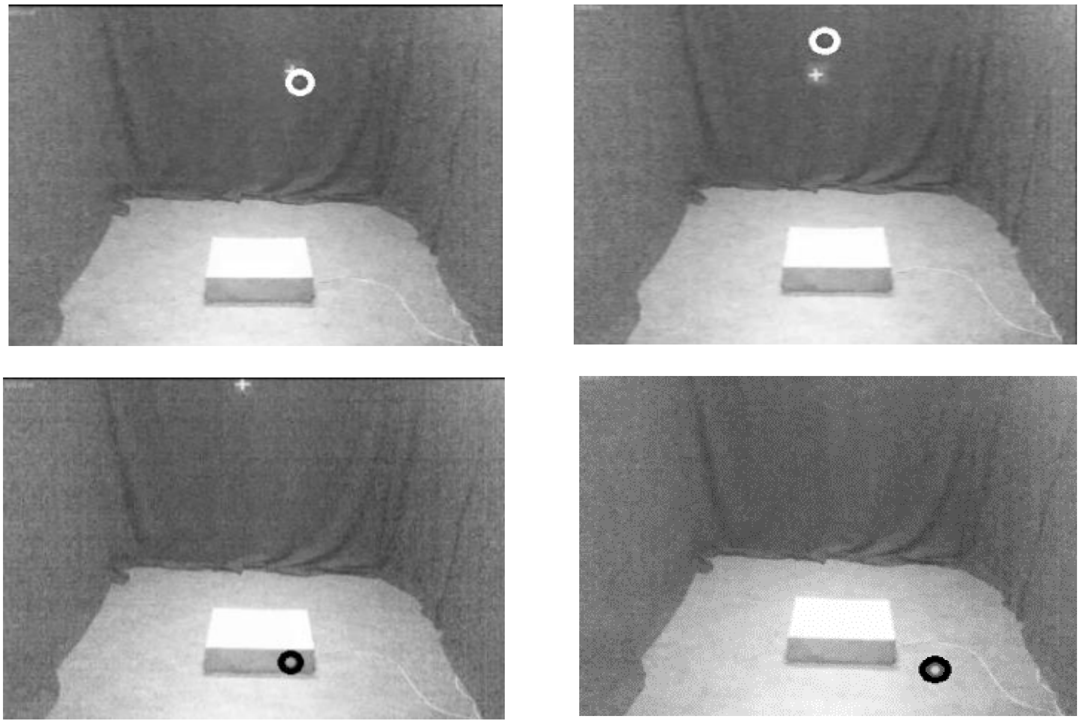


Figure 6.6. Gaze location examples. Clockwise from top left: Gaze position (white circle) on fixation target (white cross), frame classed as target area; gaze position near fixation target, frame classed as target area; gaze position (black circle) on floor near obstacle box, frame classed as obstacle area; gaze position on obstacle box, frame classed as obstacle area.

The eye-tracking video for each fixation target condition was analysed frame-by-frame. The video had a frame rate of 10 frames per second, meaning each frame represented 100 ms of time. This matches the standard assumption for minimum duration of a fixation (e.g. Marigold and Patla, 2007), meaning each frame could conceivably have been a fixation. Each frame was coded to note which of the two AOIs gaze was located in. Frames that did not show a gaze position (e.g. due to gaze located at an area off-screen, or a loss of eye-tracking signal) were coded as missing. The mean total number of frames in each condition video was 2,117, with a mean proportion of 6.0% frames coded as missing.

Figure 6.7 shows the proportion of frames gaze was located in the obstacle area for each condition. Gaze was directed towards the obstacle area for a very small proportion of frames across all four fixation target conditions (mean proportions for the four conditions were between 0.3 – 0.9%). There also appears to be little difference between the four conditions. This was confirmed with a Friedman's ANOVA ($\chi^2 = 3.15$, $p = 0.37$).

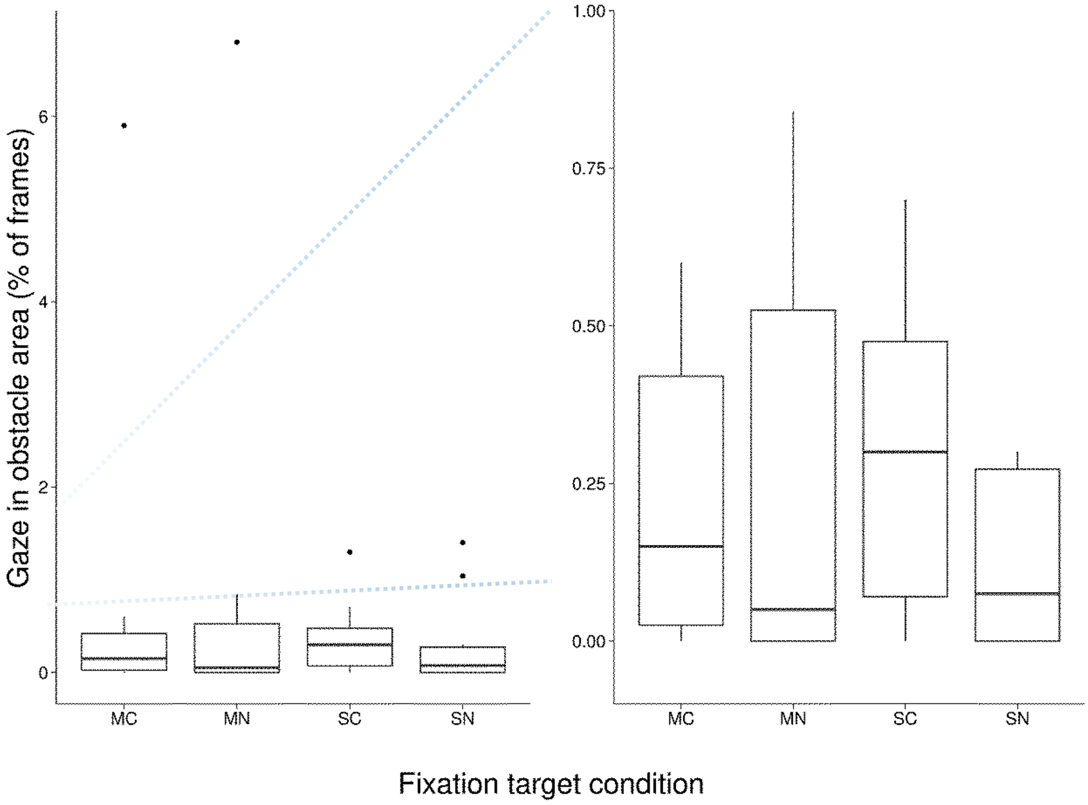


Figure 6.7. Boxplot showing proportion of frames in which gaze was located in the obstacle area AOI, by fixation target condition (MC = Moving target, Changing to number); MN = Moving target, Not changing to number; SC = Static target, Changing to number; SN = Static target, Not changing to number). Left panel shows full distribution, including all outliers, right panel shows expanded-axis view focusing on interquartile distribution.

6.9.3 Downward saccades

Data about saccades was provided by the eye-tracking software. This included a start and end position for every saccade identified, as x,y pixel coordinates relative to the top left corner of the eye-tracking video. These were used to extract all downward saccades, defined as any saccade with an end position below its start position. However, not every downward saccade is likely to have been an attempt to move gaze closer to the obstacle area, or to have had any measurable impact on detection. It should also be noted that the moving fixation target conditions (MC, MN) are likely to produce more saccades in all directions compared with the static conditions, as the eyes are moving around to follow the target. Therefore a threshold amplitude size of downward saccade is required, in order to avoid including saccades that were not potentially intended to bring the eyes closer to the obstacle area. It is difficult to know what this threshold size should be therefore a number of different thresholds have been examined. These thresholds are in video pixels, as this is the unit used by the eye-tracking software in the identification of saccades. 10 video pixels is equal to approximately 0.43° visual angle subtended at the participant's eye. Threshold sizes of 200, 250, 300 and 400 pixels were applied. These equate to approximately 8.6°, 10.8°, 12.9° and 17.2° visual angle. Saccades that moved in a downwards direction equal to or more than one of these thresholds were included in the analysis. Note that the approximate visual angle between the uppermost position, central position (used for both static target conditions) and lowermost position of the fixation target and the obstacle was 38°, 30° and 22° respectively.

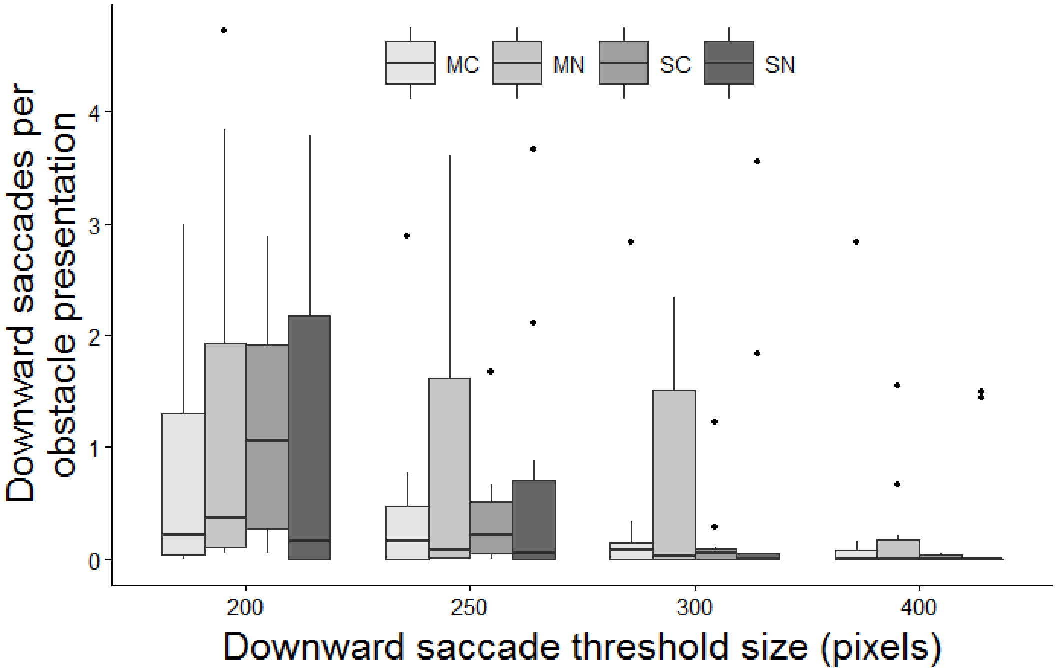


Figure 6.8. Boxplot showing rate of downward saccades per presentation of obstacle, with different size thresholds applied, for the four fixation target conditions (MC = Moving target, Changing to number; MN = Moving target, Not changing to number; SC = Static target, Changing to number; SN = Static target, Not changing to number).

Figure 6.8 shows the rate of downward saccades per presentation of an obstacle, for each of the four fixation target conditions, with the four saccade size thresholds applied. There were 18 obstacle presentations during each condition, therefore if a single downward saccade was made to each of these 18 obstacles the resulting rate would be 1. However, the rate of downward saccades per obstacle was low, with median values generally below 1, particularly as the size of the threshold increased, suggesting downward saccades were not made towards every obstacle. There is no pattern of differences between the four conditions and this was confirmed by a Friedman's ANOVA applied to data for each of the saccade thresholds (all p-values > 0.55). Figure 6.8 shows the

6.9.4 Obstacle detection

Figure 6.9 shows the detection rates at each obstacle height under each fixation target condition. There does not appear to be any noticeable difference between the four fixation target conditions in terms of detection rates. This was confirmed by Friedman's ANOVAs comparing detection rates between conditions on each of the six obstacle heights (p-values ranged between 0.11 – 1.0). Detection increases as the obstacle height increases, but there appears to be a plateau in performance where detection reaches maximal performance above obstacle heights of 12 mm. To test this statistically an overall detection rate was calculated for each obstacle height by taking the mean value of the four conditions. A Friedman's ANOVA was then used to confirm that this overall detection rate did differ significantly between obstacle heights (χ^2 = 42.9, $p < 0.001$). Post hoc comparisons between the obstacle heights using the Nemenyi test suggested that the detection rates did not significantly improve above the 7.6 mm obstacle height (p-values for 7.6 mm vs 12.0 mm, 19.1 mm and 30.3 mm were 0.67, 0.71 and 0.36 respectively).

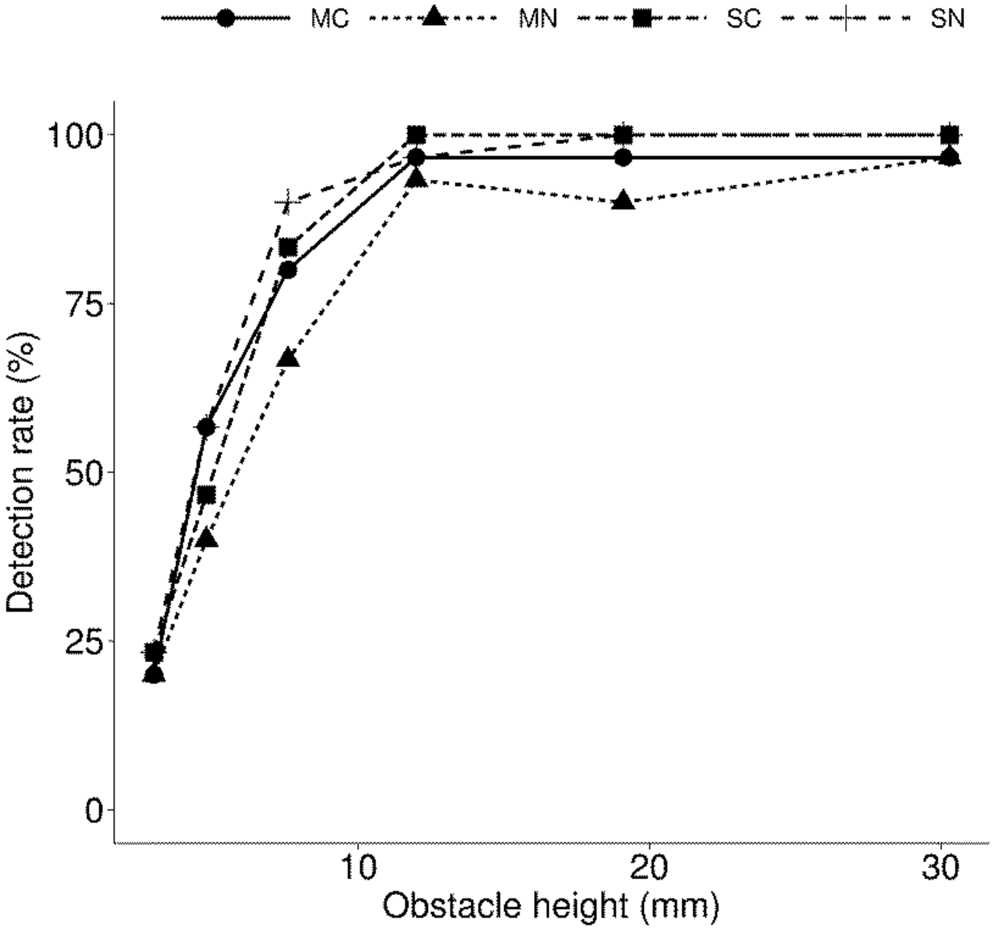


Figure 6.9. Mean detection rates at each obstacle height, by fixation target condition (MC = Moving target, Changing to number; MN = Moving target, Not changing to number; SC = Static

target, Changing to number; SN = Static target, Not changing to number). Note: Error bars are not shown to improve clarity of the figure.

Figure 6.10 shows the mean reaction time to detection for each obstacle height under each fixation target condition. Possible differences are suggested between the target conditions. Friedman's ANOVAs on each of the obstacle heights, comparing reaction times between conditions, found a significant result only for the 19.1 mm height (χ^2 = 8.9, p = 0.031). However, when p-values were adjusted to account for multiple tests, using the False Discovery Rate method, this result became non-significant (adjusted p-value = 0.19). Therefore, the fixation target conditions were combined into one overall mean reaction time for each obstacle height, as was done with the detection rate data. This was used to compare reaction times across the different heights. A Friedman's ANOVA confirmed that reaction times decreased as height increased (χ^2 = 30.0, p < 0.001). Posthoc analysis using the Nemenyi test suggested that reaction times did not significantly decrease above the 12.0 mm obstacle height (p-values for 12.0 mm vs 19.1 mm and 30.3 mm were 0.82 and 0.90 respectively).

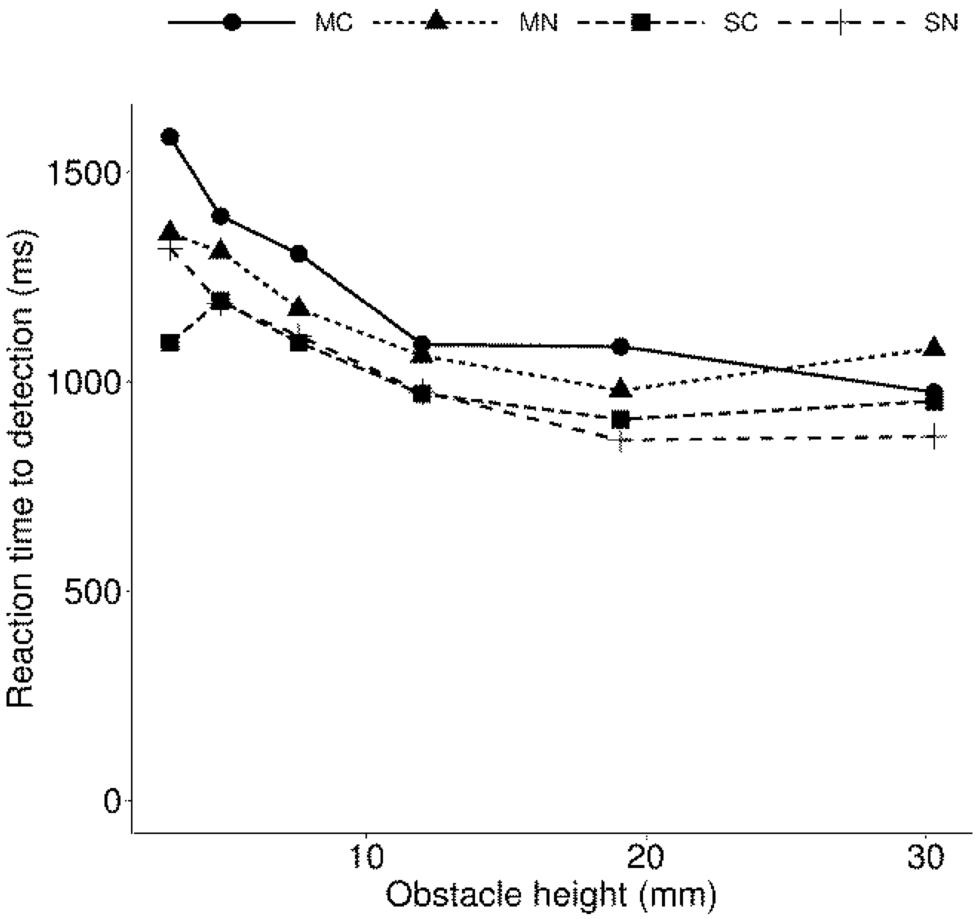


Figure 6.10. Mean reaction times to detection at each obstacle height, by fixation target condition (MC = Moving target, Changing to number; MN = Moving target, Not changing to number; SC = Static target, Changing to number; SN = Static target, Not changing to number). Note: Error bars are not shown to improve clarity of the figure.

6.9.5 Fixation target number identification

The fixation target briefly changed to a number during the Static-Change (SC) and Moving-Change (MC) conditions. The target changed to a number a mean of 49 times on each of these conditions. Participants had to respond to the number if they saw it by stating aloud what it was, with their response recorded by the experimenter. The mean proportion of correct responses was 97% in both conditions.

6.10 Conclusions – Pilot study two

The main goal of this pilot study was to determine if participants' gaze was held by the dynamic fixation target planned for the main experiment (the MC condition in the pilot), and how this compared against other types of fixation target. Results from the AOI and downward saccade analysis both suggested the dynamic fixation target was successful in maintaining foveal vision and ensuring peripheral vision was used for the obstacle detection task. Participants' gaze was directed towards the obstacle area in less than 0.8% of frames in the eye-tracking video for the MC condition. Similarly low proportions were found for the other three types of fixation target. An average fixation lasts around 300 ms (Inditsky et al, 1982). Even if participants were to look down and fixate the obstacle just once each time it rose, this would theoretically result in around 5,400 ms looking time at the obstacle, or 54 frames of the eye-tracking video. Given an average video length of 2,117 frames, this would represent around 2.6% of all frames in the video, much higher than the proportions found during the pilot test. This suggests participants were not systematically looking down at the obstacle area.

This conclusion is supported by the downward saccade analysis. This analysis showed that participants made a mean number of 9 downward saccades that were larger than the 200 pixel threshold size during the MC fixation target test session, and even fewer downward saccades of larger sizes. This was about 2.5 per minute of the test session, during which time the obstacle would have appeared at least 5 times. It is therefore unlikely that participants were looking down in order to check for or detect the obstacle.

Results from the obstacle detection task showed similar patterns to those found in the first pilot study. Detection rates increased and reaction times decreased as the obstacle height increased, indicating easier detection of larger obstacles as would be expected. Taken with the results from the first pilot study, this suggests we can have confidence the proposed method for the main experiment is appropriate for measuring obstacle detection and obtaining realistic data. One thing to note however is that detection rates appeared better in pilot study two compared with pilot study one. Although the two studies were not identical in method, e.g. they used slightly different obstacle heights, different fixation target conditions and walking/standing conditions, there is enough similarity between the two to expect reasonable similarity in detection rates. One explanation is the small sample sizes used, particularly for pilot study one (n = 5). This may have increased the random variation in the detection rates recorded. Another explanation could be the use of the eye-tracker in the second pilot study. Although the exact purpose of wearing the eye-tracker was not explained to participants before they began the experiment, it is possible or even probable that they guessed the purpose of the equipment, to monitor their eye movements. This equipment may have given participants a sense of being observed indirectly, and this may have led to increased vigilance and focus on the tasks being undertaken, leading to better detection performance. Use of an eye-tracker has been shown to influence eye-movements for example, through the implied social presence it provides (Risko and Kingstone, 2011).

The eye-tracker's use could also potentially have influenced the extent to which they kept their gaze on the fixation target and did not look towards the obstacle area. They had been instructed not to look directly at the obstacle and if they thought their eye movements were being monitored this could have disproportionately discouraged downward looks. Perhaps more downward looking would have occurred without the eye-tracker. However, if this was the case we would expect obstacle detection performance to be worse in the second pilot study, which did involve participants wearing an eye-tracker, compared with the first pilot study, in which no eye-tracker was worn. This difference was not seen, and in many cases performance actually appeared better during the second pilot study. This suggests wearing the eye-tracker did not reduce the amount of looking towards the obstacle, giving us confidence that the eye movement data obtained is reflective of eye movements in the experiment without an eye-tracker being worn.

6.11 Summary

Two pilot studies were carried out to test a proposed method and apparatus for carrying out a larger, main obstacle detection experiment. In particular the pilot studies were testing two key elements thought to be improvements on previous work. The first pilot study examined obstacle detection whilst participants walked on a treadmill and compared this with participants just standing. Participants were able to adequately complete the detection task whilst walking and performance was in line with expectations, being comparable with detection whilst standing. The second pilot study examined the eye movements of participants whilst completing the obstacle detection task to confirm whether the dynamic fixation target proposed for the main experiment did maintain gaze and limit downward glances towards the obstacle area. Results showed participants very rarely directed their gaze towards the obstacle, suggesting the dynamic fixation target was successful in ensuring peripheral vision was used for the detection task. This conclusion was supported by performance in both pilot studies in identifying the numbers when the fixation target changed. The high success rate suggested participants were visually tracking the fixation target and not looking downwards towards the obstacle. In more general terms, the two pilot studies demonstrated that the apparatus worked successfully in measuring obstacle detection and did not raise any concerns with the proposed approach for the main test. This main test of obstacle detection is described in the following chapter.

CHAPTER 7. OBSTACLE DETECTION MAIN EXPERIMENT

7.1 Introduction

Previous chapters have demonstrated that obstacle detection is an important visual task for pedestrians. From a road lighting design perspective it is therefore important to know how lighting influences obstacle detection. The task predominantly uses peripheral vision, but previous research examining lighting and peripheral detection tasks contain a number of flaws, such as a lack of relevant context and no additional cognitive load. A series of improvements were conceived to address these flaws, which included adding a walking task and using a dynamic fixation target to better simulate the visual behaviour and cognitive load of pedestrians. New experiment apparatus was designed and built, and this apparatus was tested in two pilot obstacle detection studies, reported in the previous chapter. These pilot studies confirmed that the new apparatus worked successfully in measuring obstacle detection. They also demonstrated that the new additions of a dynamic fixation target and walking on a treadmill could be successfully added to the experiment design. Data from these pilot studies also suggested we can have some confidence that the dynamic fixation target was successful in maintaining foveal gaze, giving us some confidence that the new experiment design is measuring peripheral vision for the obstacle detection task.

Based on the results from the pilot studies, a larger, main obstacle detection experiment was designed using essentially the same apparatus. Variable lighting conditions were introduced in order to investigate the effect this had on the obstacle detection task. The two lighting characteristics that were of interest were light intensity, measured as illuminance on the obstacle area, and light spectrum, measured using S/P ratio.

7.2 Method

7.2.1 Apparatus

The apparatus used was the same as used for the pilot studies but with minor variations. See Figure 7.3. The test area consisted of a 3-sided cubicle measuring 2.4 m wide, 2.4 m high and 3.8 m long. The walls were covered in black cloth on three sides with the fourth side being open. A treadmill was placed at this open end. The treadmill had a surface height of 0.19 m and a maximum speed of 16.1 km/h. A wooden bar was fixed at waist height above the treadmill to act as a handhold. The height of this bar could be adjusted to be comfortable for the participant. In front of the treadmill, up to the far wall, was a false floor constructed from MDF wood and painted in Munsell N5 grey paint (reflectance R = 0.2). Unlike in the pilot studies, in which a single box sat in the centre of the floor space in front of the treadmill, this false floor covered the entire floor area and had the same height as the treadmill, effectively creating one continuous surface in front of the participant.

At the centre of this false floor a 200 mm diameter cylinder could be raised and lowered by a servo motor, controlled via a Python program, to protrude from the surrounding surface by variable heights, up to a maximum of 50 mm. This cylinder, when raised from the surrounding surface, simulated a potential obstacle. An image of the obstacle when raised and surrounding floor surface is shown in Figure 7.1. The diameter of the cylinder was chosen to represent a typical trip hazard a pedestrian might encounter, such as a raised paving slab or ironworks. The sides and top of the obstacle were painted in the same grey paint used for the surround surface of the false floor. The centre of the obstacle was 1.2 m from the far wall, and approximately 2.6 m from the participant’s position on the treadmill, although the exact distance would vary slightly as the participant was walking. This variation was reduced by asking participants to always keep one hand on the wooden handhold bar. The 2.6 m distance between participants and the obstacle was selected as pedestrians predominantly search the path at a near distance (as demonstrated by results from the earlier dual-task eye-tracking study, see section 4.5.2), within 4 m. At this distance and for an eye-height of 1.5 m, the obstacle subtended a visual angle width of 3.81° and height of 0.47° at the maximum height used in the experiment (28.4 mm).

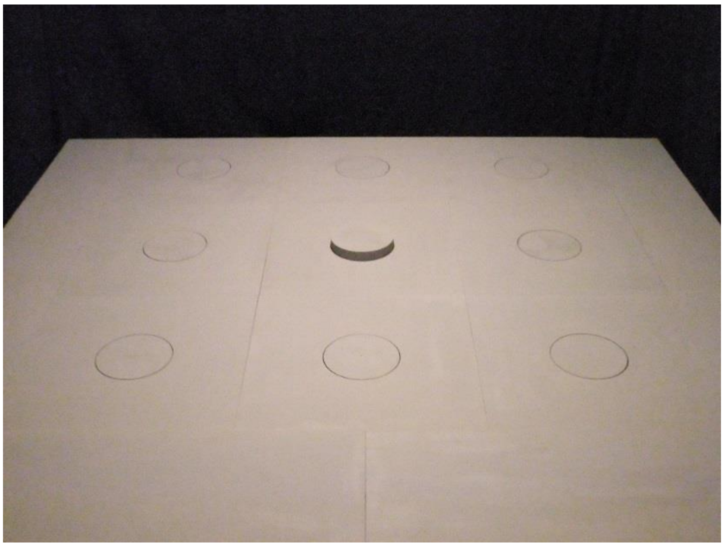


Figure 7.1. Obstacle when raised and surrounding surface. Other circles surrounding raised obstacle are other cylinders that could be raised, but were not used during this experiment.

A data projector was suspended above test area out of sight from the participant, shown in Figure 7.2. This projected a fixation target onto a small mirror, which reflected it back onto the far wall, opposite the participant when stood on the treadmill. Low-reflectance black screening was placed around the mirror, limiting the light from the projector that was projected back onto the far wall to just the fixation target that was located on the mirror. This was the same method used in pilot study two, and not the direct projection method used in pilot study one. The mirror was mounted on a robotic two-axis gimbal, controlled via servo motors using a Python program. This allowed the angle of the mirror to be continuously changed, which moved the fixation target in a random path around the far wall, simulating the gaze patterns of a pedestrian walking outdoors (e.g. ‘t Hart and Einhauser, 2012). An image of the mirror apparatus is shown in Figure 6.5, in the previous chapter.

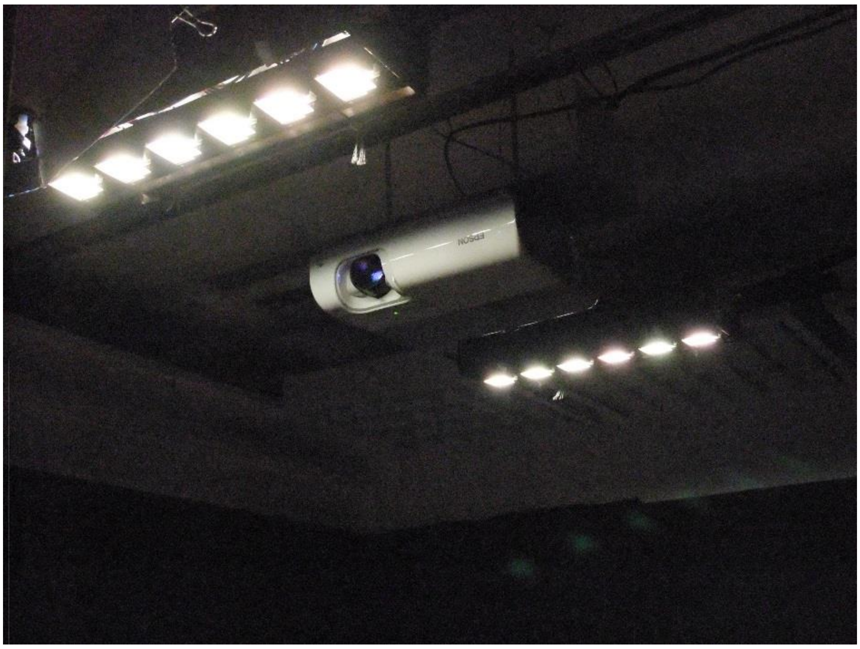


Figure 7.2. Data projector used to create fixation target image, which was projected on to pivoting mirror. Image also shows the two LED array units that were used to illuminate the obstacle area.

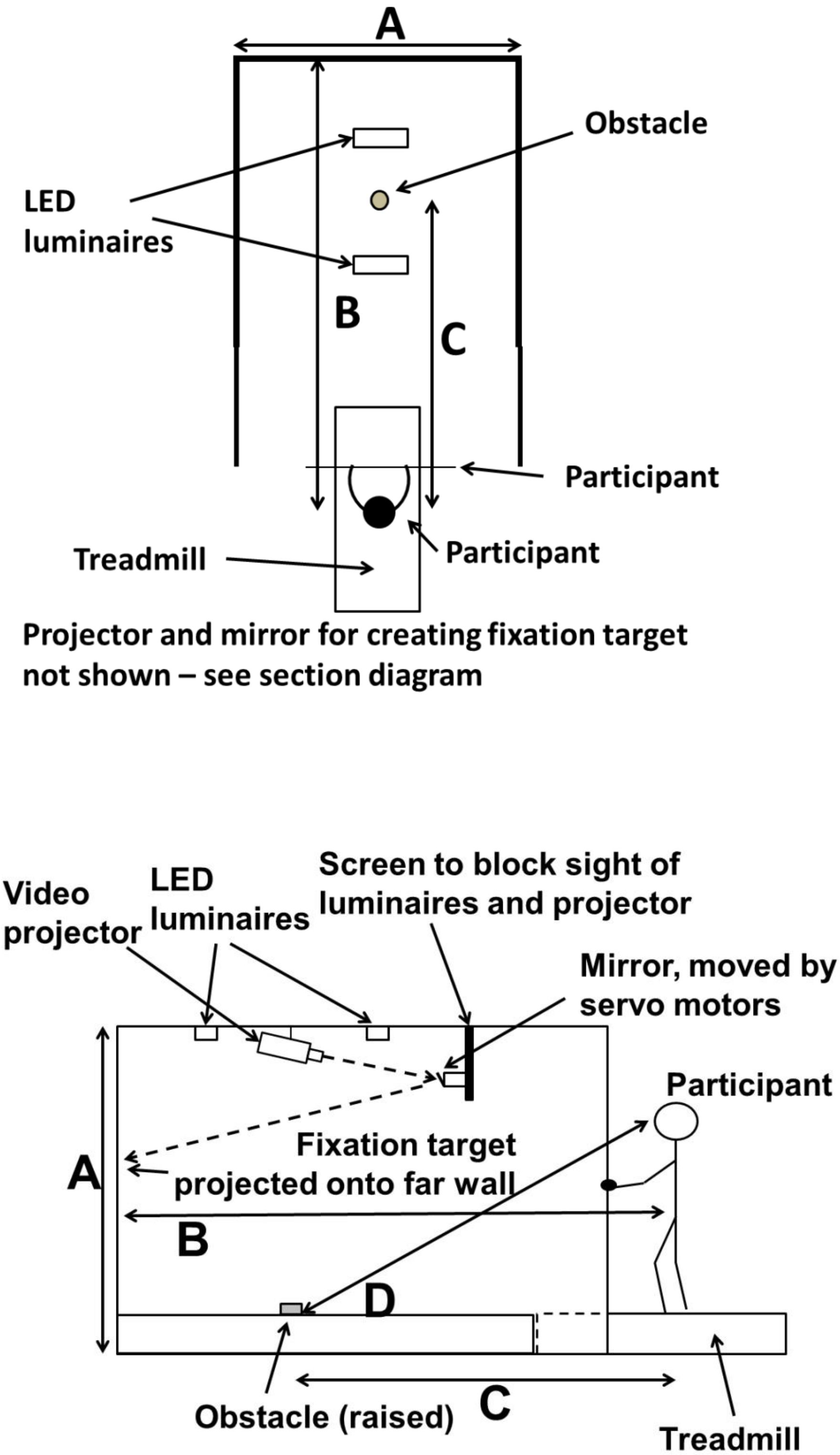


Figure 7.3. Diagram of apparatus used in main obstacle detection experiment – plan (top) and section (bottom). Dimensions = A = 2.4 m, B = 3.8 m, C = 2.6 m, D ≈ 3.0 m.

7.2.2 Lighting

The test area was lit from above by two arrays of LEDs, each containing six clusters of four types of chromatically-different LEDs. Diffusers, made from 3 mm thick cast acrylic with a light transmission factor of 70%, were placed in front of each LED cluster to increase horizontal uniformity and colour mixing of the light produced. The LED arrays were controlled through software written in MATLAB. This allowed the illuminance and spectrum of the light produced by the LEDs to be altered, which meant a range of different light conditions could be produced. In particular, it enabled the S/P ratio to be varied whilst the chromaticity was kept constant. This was desirable as it allowed a step towards isolating the effect of S/P ratio, as a metric of spectrum, on obstacle detection. Three S/P ratios were selected as variables: 1.2, 1.6 and 2.0. This S/P range was partly dictated by what the LEDs could produce within other parameters of the experiment, i.e. maintaining constant chromaticity and providing different illuminance levels. However, this range is realistic in terms of S/P ratios of commonly used road lighting lamps (Boyce, 2014). The range is also smaller than that used in many other studies that have examined the effect of S/P ratio on peripheral detection (e.g. Fotios and Cheal, 2009; van Derlofske and Bullough, 2003; Alferdinck, 2006) so an important question for the experiment to answer is whether an effect of S/P ratio will still be seen given the smaller range under investigation. Further discussion of this is given in section 7.4.5. The S/P ratios of 1.2, 1.6 and 2.0 are subsequently referred to in this chapter as *low, medium* and *high*. The chromaticity coordinates at these three S/P ratios are given in Table 7.1. Example spectral power distributions for three S/P level light conditions are shown in Figure 7.4.

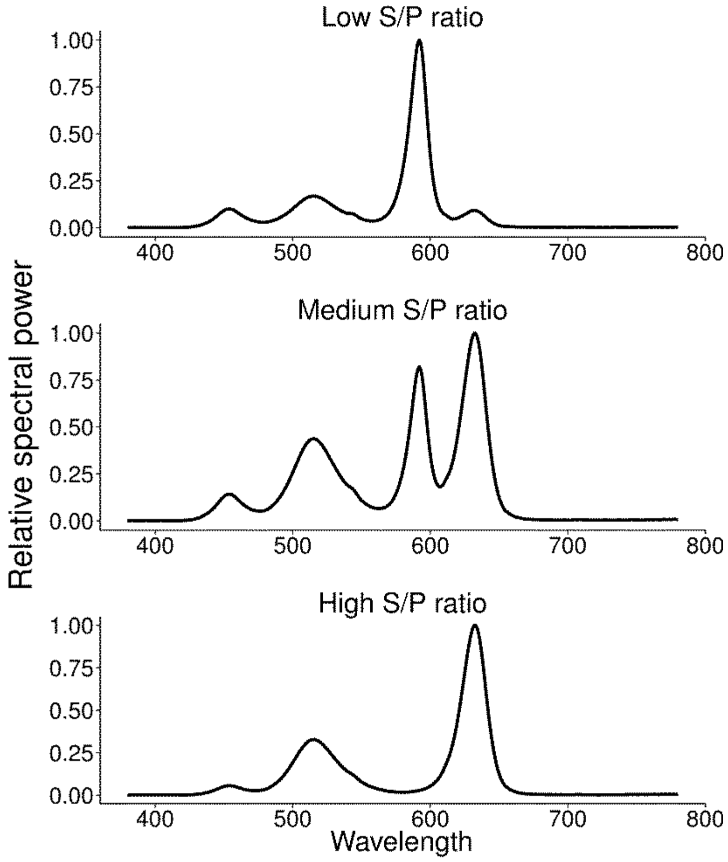


Figure 7.4. Relative spectral power distributions for low, medium and high S/P ratio lighting conditions, as measured at 2 lux illuminance on top of obstacle.

Illuminance was also varied during the experiment. Illuminances investigated were 0.2, 0.6, 2.0, 6.3 and 20.0 lux, as measured at the centre of the obstacle’s top surface. Horizontal illuminance on the obstacle itself was chosen as the variable of interest, rather than another metric such as luminance, semi-cylindrical illuminance or illuminance at the observer’s eye, because this is the metric currently used in specifying road lighting criteria (e.g. BS 5489-1:2013). A key goal for this research is to assess these existing guidelines in terms of their effect on obstacle detection, and potentially provide evidence contributing towards revised recommendations if required. The illuminance range chosen for this experiment increases in steps of 0.5 log units and brackets the illuminances recommended in the UK road lighting guidelines, allowing comparison between the results and these guidelines. In addition, the illuminance range is the same as that used in a previous peripheral detection study (Fotios and Cheal, 2013), enabling direct comparison with past results.

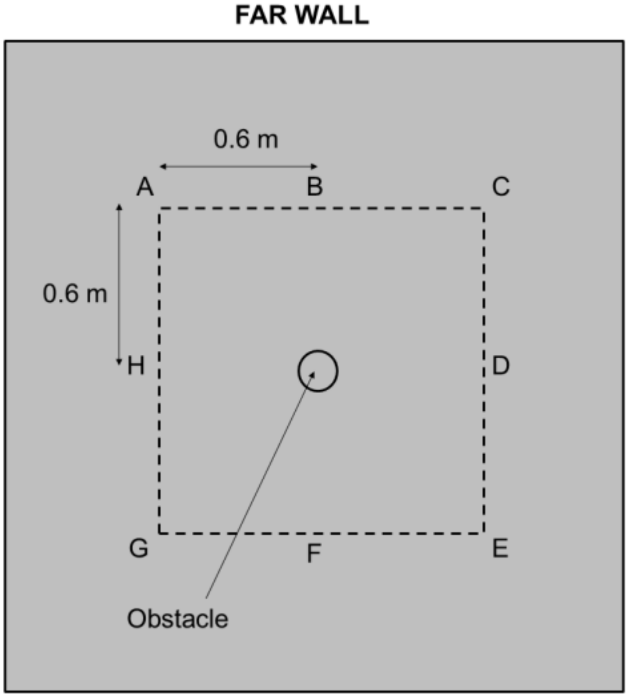
Table 7.1. Chromaticity coordinates for illuminance and S/P lighting conditions used in experiment. Note: Chromaticity at 0.2 and 0.6 lux not calculated due to insufficient amount of light for spectrometer to function correctly. Settings used for LED arrays at 2.0 lux also used for 0.2 and 0.6 lux, so chromaticity coordinates at these illuminances assumed to be same as for 2.0 lux.

S/P ratio	**Illuminance (lux)**		
	2.0	**6.3**	**20.0**
1.2	0.463, 0.418	0.462, 0.416	0.462, 0.416
1.6	0.462, 0.416	0.462, 0.416	0.461, 0.416
2.0	0.465, 0.419	0.461, 0.415	0.461, 0.415

The illuminance was as measured at the centre of the top surface of the obstacle. To check the distribution and uniformity of lighting in the area surrounding the obstacle eight measurements were taken at equally-spaced locations along the perimeter of a 1.2 m square surrounding the obstacle – the four corners and four edge centres of the square. These measurements were taken with an obstacle illuminance of 20 lux and 2 lux. See Figure 7.5. This provides a minimum overall uniformity value of 0.73 (calculated as the ratio between the minimum illuminance measurement and the average illuminance measurement, including that taken at the obstacle centre). This is well within the recommended uniformity levels outlined in existing road lighting guidelines (BS-EN 13201-2:2003). Illuminance at the approximate eye position of the participant was 1.18 lux when directed towards the obstacle surface and 0.55 lux when directed towards the far wall, at the 20 lux obstacle illuminance level. Luminance measurements were also taken in the area surrounding the obstacle and are included in Figure 7.5. Luminance at the top of the obstacle was measured at the five illuminance conditions and these are given in Table 7.2. Luminance at the front side of the obstacle when raised was also measured. This gave a luminance contrast against the background luminance of the top of the obstacle and surrounding surface of approximately -0.7, using the formula $C = (L_t – L_b)/L_b$, where C = contrast ratio, L_t = Luminance of the target and L_b = Luminance of the background.

Table 7.2. Luminance measurements at top and side of obstacle with contrast ratios, for the five illuminance levels used in experiment. Note that variation in contrast ratios for the two lowest illuminances may be due to limitations with the precision of the luminance meter at these lowest light levels.

Illuminance - top of obstacle (lux)	**Luminance – top of obstacle (cd/m^2)**	**Luminance – side of obstacle when raised (cd/m^2)**	**Contrast ratio between luminance of top and side of obstacle ((L_t – L_b)/L_b)**
0.2	0.011	0.005	-0.54
0.6	0.040	0.012	-0.70
2.0	0.127	0.033	-0.74
6.3	0.430	0.112	-0.74
20.0	1.220	0.314	-0.74



Location	Illuminance (lux)	Luminance (cd/m²)
A	13.3 1.31	0.820 0.007
B	16.4 1.59	0.991 0.008
C	13.6 1.32	0.821 0.007
D	15.9 1.59	1.046 0.009
E	15.6 1.57	1.020 0.009
F	19.5 1.94	1.337 0.012
G	16.1 1.59	0.981 0.009
H	16.0 1.57	1.005 0.009

Figure 7.5. Plan view of illuminance and luminance uniformity measurements in area around obstacle. Top values are for obstacle illuminance of 20 lux, bottom values for obstacle illuminance of 2 lux.

7.2.3 Task details

The obstacle was raised to seven different heights – 0.5, 2.8, 4.5, 7.1, 11.3, 17.9 and 28.4 mm. The sequence of the six largest heights (2.8 – 28.4 mm) followed a geometric progression ratio of 1.59 (0.2 log unit steps). The smallest height of 0.5 mm was used as a control condition to test for false positives – accidental or random responses from the participant. The probability of detecting this height was expected to be close to zero. At this height the obstacle subtends a visual angle of 0.5 arc minutes at the eye but average visual acuity at 20° eccentricity (approximately the eccentricity between the fixation target used in the experiment and the obstacle) and in the mesopic luminance range is above 10 arc minutes (Boyce, 2014). In addition the luminance contrast of the obstacle side against the surrounding surface (approximately 0.7) was below threshold contrast for the size of the obstacle at off-axis viewing (Boyce, 2014). It is therefore highly unlikely participants would be able to detect this 0.5 mm obstacle using peripheral vision and any responses to indicate detection would either indicate guessing or use of foveal vision.

The seven heights were presented in a randomised order. For a precise detection task the obstacle should appear near-instantaneously, as was done in the two pilot studies (Chapter 6). However, in order to do this the obstacle had to be raised rapidly. This provides two unintentional primes for the participant to indicate appearance of the obstacle. First, raising the obstacle at high speed produced an audible noise from the servo motor controlling the obstacle. Second, the rapid movement of the obstacle could activate motion detection systems within the participant, influencing detection responses and providing inaccurate data, given that motion detection was not something the experiment aimed to measure. Therefore the obstacle was set to rise at 1 mm/s or 2 mm/s. Two speeds were used rather than one so that comparisons could be made to determine whether the speed influenced detection performance. If there was a difference in performance this might suggest an element of motion detection was taking place. The rising height of the obstacle means the visual angle it subtends increases in a manner similar to the increasing size of a static obstacle as a pedestrian walks towards it. The two rise speeds were selected as they fall within the range expected for typical walking speeds and obstacle sizes. Rising at speeds of 1 mm/s and 2 mm/s the obstacle will increase in visual angle subtended at a rate of 1 arcmin and 2 arcmins per second. This is the same mean increase in visual angle of a static obstacle of size 9 mm or 18 mm, approached from 10 m away at a speed of 1.3 m/s, estimated to be an average walking speed based on data from Bohannon (1997).

If participants detected the raised obstacle they were instructed to press a handheld response button, shown in Figure 7.6. If this occurred before the obstacle reached its maximum height it would immediately return to its ‘home’ position, lying flush with the surrounding surface, and a successful detection would be recorded. Assuming detection had not already occurred, when the obstacle reached its predetermined height for that trial it would stop rising and remain at that height for 2 s, or until the detection button was pressed, whichever was sooner, before returning to its home position. If the button was pressed within this 2 s period a successful detection was recorded, otherwise a failed detection was recorded. The 2 s exposure time at the predetermined height was selected as this represented approximately the amount of time the participant would have before reaching the obstacle if they were not on the treadmill, based on average walking speeds (Bohannon, 1997). If detection did not occur within this 2 s period, or whilst the obstacle was still rising, then the obstacle could potentially have tripped the participant. The smallest obstacle height being used, 0.5 mm, was designed as a null condition to capture false positive responses due to guessing or pressing the response button randomly. Therefore the exposure time at this height was increased in order to simulate the full length of time obstacles at other heights could be detected. This included the rise time and the 2 s exposure time when the predetermined height had been reached. The 8 s exposure time for the null condition height represented a typical average time for other trials, from starting to rise to the end of the 2 s exposure time.

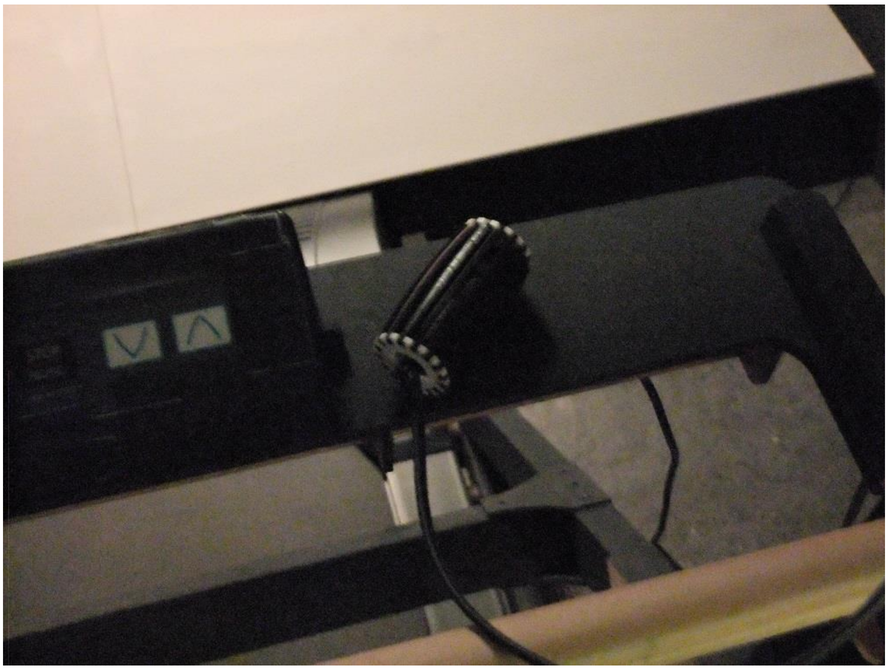


Figure 7.6. Handheld button used by participants to indicate detection of the raised obstacle.

The dynamic fixation target that was tested and validated in the two pilot studies was also used in this main experiment, to maintain foveal vision and encourage use of peripheral vision for the obstacle detection task. The fixation target was projected onto the far wall of the test area via the data projector and mirror apparatus described in section 7.2.1. The target moved randomly within an ellipse measuring 1.05 m high and 2.0 m wide (subtending 15.7° x 29.5° visual angle at the participant’s eye), with its centre 1.5 m above the false floor. The largest visual angle between the target and the obstacle was 37.9° when the target was at the top of this ellipse, and 22.1° when the target was at the bottom of this ellipse. The speed at which the target moved across the far wall varied randomly between 14.7° and 36.4° visual arc per second, changing every time the target changed direction. An example path taken by the fixation target during the first minute of a full condition is shown in Figure 7.7.

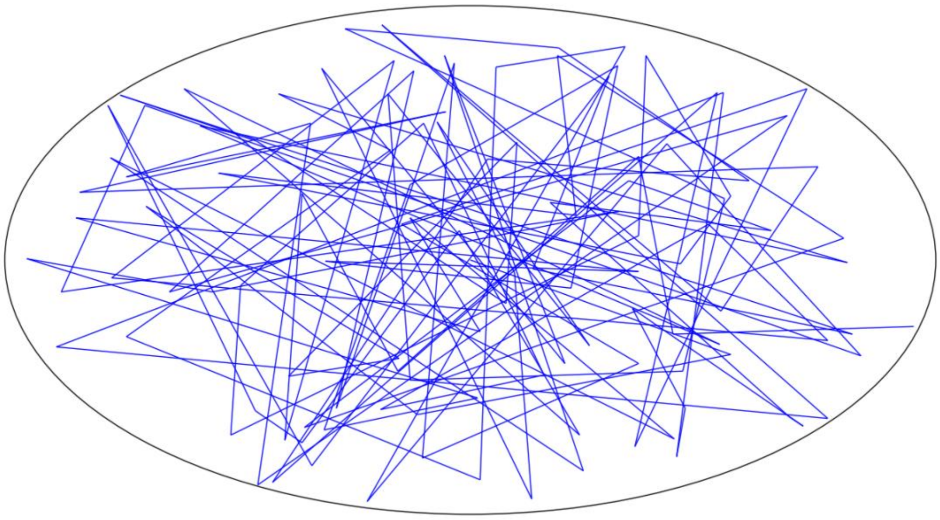


Figure 7.7. Example path taken by fixation target within ellipse of possible locations. This example is taken from the first minute of a session with one of the lighting conditions. It demonstrates the random nature of the target's movements.

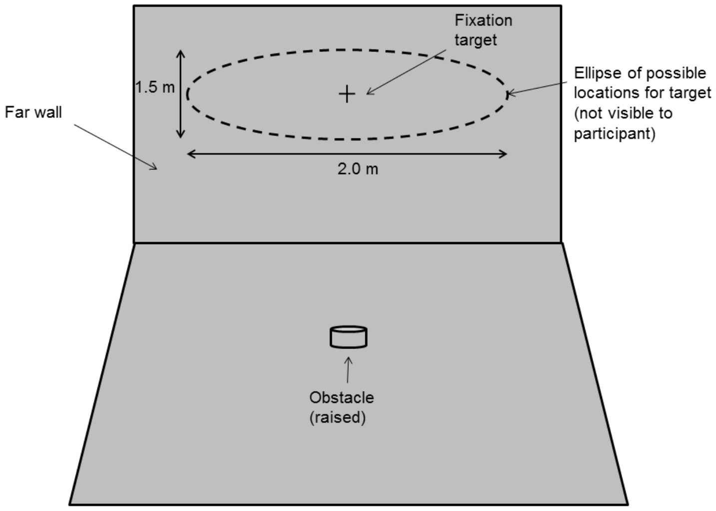


Figure 7.8. Schematic diagram of view from participant. Fixation target could move to any location within ellipse shown, although this ellipse was not visible.

The default shape of the target was a crosshair. At semi-random intervals between 2 and 6 s the target would change to a digit between 1 and 9 for 0.2 s before changing back to the crosshair. Participants were instructed to continually follow this target with their eyes and read aloud the digit when it changed, if they saw it. A schematic diagram of the apparatus as seen from the view of the participant is shown in Figure 7.8.

7.2.4 Procedure

Thirty participants took part in the experiment, 15 in a *young* age group (all aged < 35 years, mean age = 26.3 years) and 15 in an *older* age group (all aged > 50 years, mean age = 62.5 years). This sample size was estimated to be sufficient to reveal an effect size of f = 0.4. This effect size was anticipated based on data from a previous study (Fotios and Cheal, 2009). The required sample size power calculations were carried out using the G*Power software package (Faul et al, 2007). Eight of the young group were females and 4 of the older group were females. Participants received £20 for taking part, upon completion of the experiment. Normal colour vision was confirmed in all participants using the Ishihara test under a D65 daylight-simulating fluorescent lamp. Participants wore their normal corrective lenses if required (25% of the young group, 60% of the old group) and normal visual acuity (minimum 6/6) was confirmed using a Landolt ring acuity test at 2 m.

Upon completion of the colour and acuity vision tests the laboratory room lights were switched off and the LED lights used in the experiment were switched on at the 2.0 lux, medium S/P ratio setting. Participants were given 20 minutes adaptation time to become accustomed to the mesopic light conditions, this being an adequate adaptation time for the light levels being used in this experiment (Boyce, 2014). During this adaptation time participants were given instructions. They were told that their primary task was to follow the fixation target with their eyes and read aloud the number when it changed. The secondary task was to press the response button, which was to be held in their strongest hand, as soon as they noticed that the obstacle was raised. It was expected that given these instructions the participants primary attentional focus would be on the target-following task and not the detection task (Kelly, Janke and Shumway-Cook, 2010), simulating how the primary focus of pedestrians is likely to be on cognitive tasks other than looking out for obstacles. Participants were also given time to become accustomed to walking on the treadmill and find a speed they were comfortable with. This speed would be used in the actual experiment. Individual walking speeds were used for each participant rather than setting the same speed for all participants to use because asking participants to walk at unnaturally slow or fast speeds may have added additional task difficulty (e.g. Abernethy, Hanna and Plooy, 2002) not found in a real pedestrian setting. During the 20-minute adaptation time participants also completed a practice session to familiarise themselves with the fixation and detection tasks. This involved 12 practice trials of progressive difficulty, in which the obstacle was raised to gradually decreasing heights and the fixation target became increasingly difficult, changing from a static target to a moving target and to a moving target that also changed to a number.

Following completion of the 20-minute adaptation period participants began the main experiment. During a trial within the main experiment participants fixated the fixation target, stating aloud any digits that appeared, whilst walking on the treadmill at their self-selected speed and pressing the response button to note detection of a raised obstacle. Each of the seven obstacle heights was presented twice, once at each obstacle rise speed, with each presentation being defined as one trial. Trials were separated by a random interval between 5 and 8 s. Fourteen trials took place for each lighting condition, with the trial order being randomised. There were 15 lighting conditions in total, each condition a combination of one of the five illuminance levels and one of the three S/P ratios. The lighting conditions were presented in a randomised order, although it was ensured that each condition was presented once as the first condition in each age group. This first condition was repeated as a final 16th condition which allowed direct comparison of responses collected at the beginning and end of the experiment, to test for practice or fatigue effects.

Each lighting condition took approximately 3 minutes to complete. If the participant requested a break or if four consecutive conditions had been completed a short rest period of approximately 3-4 minutes was taken. Overall the experiment took approximately 2 hours to complete for each participant, including instructions, adaptation and completion of all lighting conditions.

7.3 Results

The experiment was a mixed-measures design, with one between-subjects factor (age group, having two levels, *young* and *old*), and two within-subjects factors (illuminance, having five levels, and S/P ratio, having three levels). Two dependent variables were recorded. The first was whether the obstacle was detected; the second was the height of the obstacle when detected. For this second measure only results obtained from the largest obstacle height of 28.4 mm have been used. This is because the detected height of the obstacle was limited by the maximum height the obstacle could go to for any particular trial. This could produce a floor effect, where no detected height is recorded at the lower heights if the obstacle is not detected. Using only the trials with the largest obstacle height reduces the likelihood of producing this floor effect.

All groups of data were tested for normality by inspecting histogram distributions, measures of central tendency and the Shapiro-Wilks test. Except where otherwise stated it was considered that these data were drawn from normal distributions and parametric statistical tests have been used.

7.3.1 Fixation target number identification

The fixation target changed to a number a mean of 40 occasions (sd = 5) during each condition. Overall the number was correctly identified in 91.8% (sd = 4.1%) of presentations. The young age group had a slightly higher rate of correct identification than the old age group (94.3% vs 89.5%, confirmed as statistically significant using a between-subjects t-test, $p < 0.001$). Given that around 9 out of every 10 digits were successfully identified this suggests we can have confidence that participants were looking at and following the fixation target throughout the experiment, and that peripheral vision was being used for the obstacle detection task.

7.3.2 Obstacle speed

Two different speeds were used to raise the obstacle (1 and 2 mm/s) with each obstacle height being repeated twice in each lighting condition, once at each speed. To check whether the obstacle speed influenced detection performance a series of paired comparisons were made between the two speeds for detection rate and detection height. These data were not normally distributed. For detection rate, comparisons were made across all obstacle heights and lighting conditions (a total of 112 comparisons) using the McNemar test. For detected height, paired comparisons were made using the Wilcoxon signed-rank test. All lighting conditions were compared but only for the largest obstacle height trials, resulting in 16 comparisons. Both tests were applied repeatedly to the data: to account for increased chance of Type 1 errors we used p-value adjustment using the false discovery rate (FDR) control method (Benjamini and Hochberg, 1995).

For detection rate, differences between the two different speeds were not suggested to be significant. However, for detection height, all 16 comparisons of obstacle speed were significant. The slower obstacle speed produced a lower mean detection height (5.63 mm, averaged across all conditions) than the faster speed (7.73 mm).

This difference can be explained by the latency between an obstacle being detected and the response button being pressed to indicate detection: the obstacle will travel a greater distance in this latency period for the faster speed. In the pilot study tests described in Section 6 the obstacle rose almost immediately (<0.1s) to a range of different heights. The resulting reaction times to detection data suggested a mean latency between the obstacle becoming noticeable and the response button being pressed of approximately 1.25 s (see Figures 6.4 and 6.10 in the previous chapter). Given such a reaction time, at a speed of 2 mm/s the obstacle would travel 1.25 mm further than at 1 mm/s when the response button was pressed. If this latency distance is subtracted from the detection heights for the 2 mm/s presentations the effect of obstacle speed in all 16 conditions is no longer suggested to be significant.

It was concluded that any differences in detection height between the two obstacle speeds is a function of the extra distance travelled in the period between detection and response, rather than the speed affecting detection performance itself. The lack of any significant differences between the speeds when comparing detection rates also supports this conclusion. Thus in subsequent analyses we used the mean detection rate and detection height for each participant as averaged across the two obstacle speeds.

7.3.3 False responses

False responses were recorded to determine whether participants were pressing the response button incorrectly or randomly. A false response was defined as a button press (or multiple button presses) at any point on each trial before the obstacle began rising. A maximum of 14 false responses could therefore be recorded for each condition. The mean number of false responses was very low, 0.08 per condition for the young group and 0.27 per condition for the old group.

As a further check on whether participants were responding randomly or incorrectly during the experiment, the probability of pressing the response button during the ‘null’ trials in which the obstacle height rose to only 0.5 mm was calculated. This probability was again very low, the response button was pressed in only 4% of trials involving the 0.5 mm height in the young group and 5% of trials in the older group.

These results suggest that random or ‘false alarm’ responding by participants was very low during the experiment and the data collected is therefore of good quality – participants tended to only press the response button to indicate detection when the obstacle was actually present.

7.3.4 Detection rates

Mean detection rates were calculated for each obstacle height presented under each lighting condition. These are shown in Figure 7.9 for each age group. As expected, the plots show that detection rate increases as the obstacle height increases. The plots also show a rapid increase in detection rate from the smallest obstacle height, until a plateau of maximal performance is reached, usually before the largest obstacle height used in this study (28.4 mm).

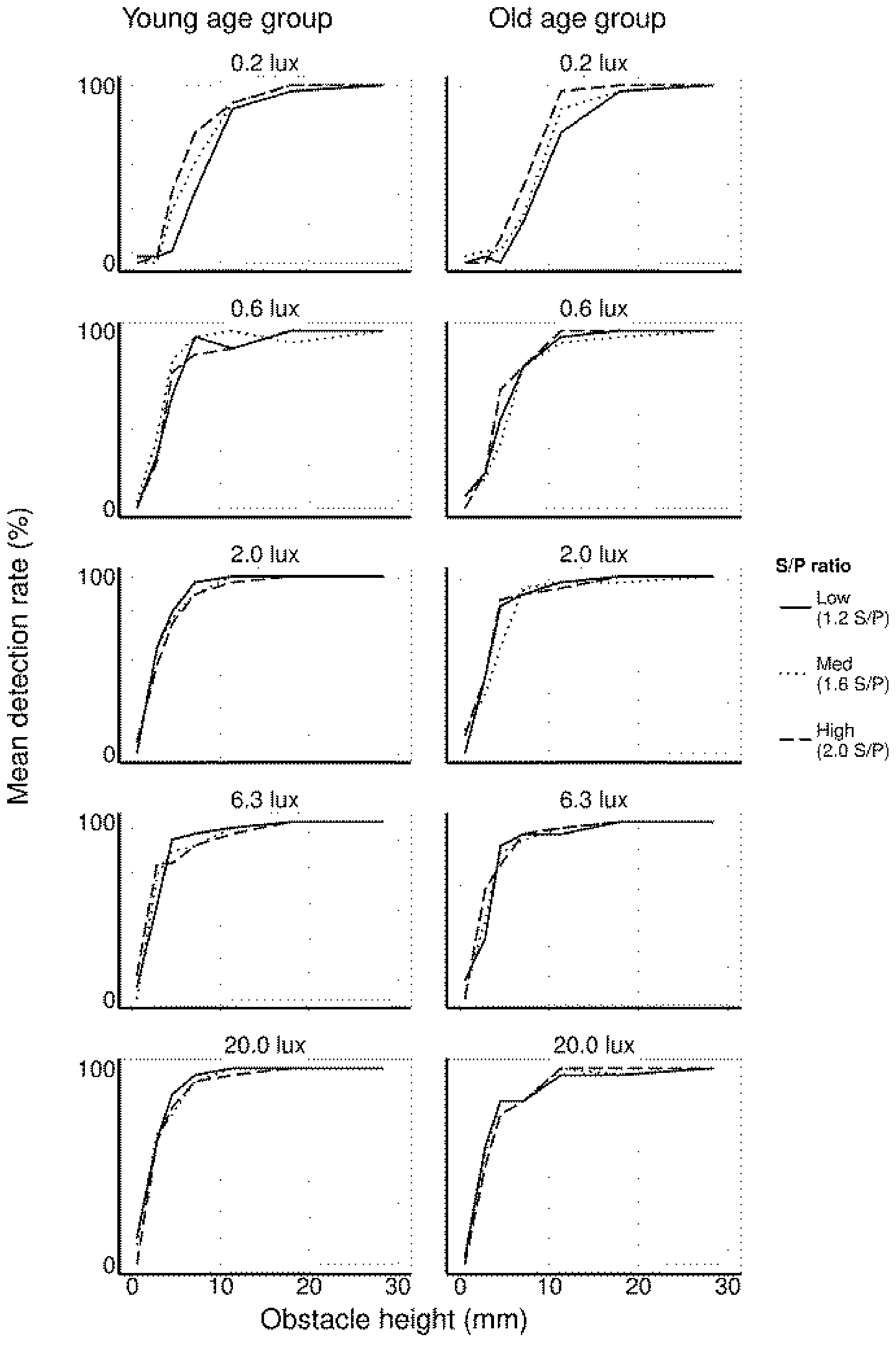


Figure 7.9. Mean detection rates by obstacle height, for each illuminance and S/P ratio lighting condition and young and old age groups.

Initial analysis of detection rates was carried out comparing detection performance across age group, illuminance and S/P ratio using the obstacle height at which a 50% detection probability is achieved (h_{50}). This was calculated using the four parameter logistic equation (4PLE), as has been used in previous lighting research (e.g. Harris, 2006; Fotios and Cheal, 2009, 2013). The 4PLE creates a line of best fit using as data points the detection rates for each obstacle height on each combination of illuminance and S/P ratio. An example is shown in Figure 7.10. The 4PLE can be expressed as:

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

Equation 7.1. Detection rate calculated from four parameter logistic equation.

with y as the detection rate, h as the height of the obstacle, h_{50} as the height of the obstacle when detection rate is 50%, and s is the slope of the curve. Best-fit lines and values for h_{50} were calculated using the *drc* package and *drm* function in the statistical computing language *R* (Ritz and Streiberg, 2005).

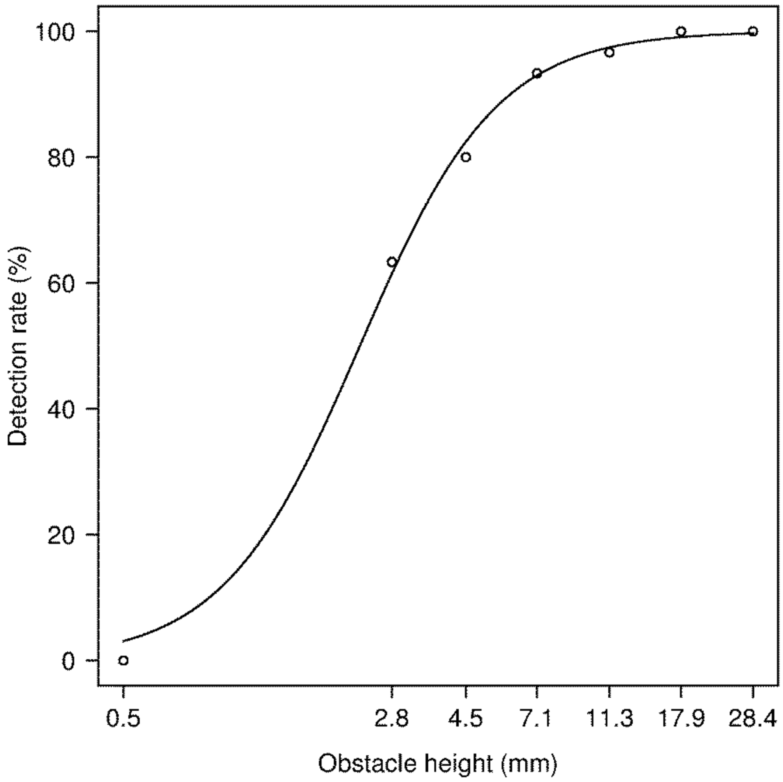


Figure 7.10. Example of 4PLE best-fit curve, for 0.2 lux, high S/P ratio and young age group. Data points show actual mean detection rates at each obstacle height. A $\log_{10}$ scale is used for the x-axis.

Obstacle heights for a 50% detection rate (h_{50}) based on the 4PLE curves for each condition are shown in Figure 7.11. Smaller values of h_{50} indicate better detection performance: Figure 7.11 shows that detection performance improves as illuminance increases. However, performance appears to approach a plateau before the highest illuminance is reached, somewhere between 0.6 and 6.3 lux. There is also a suggestion that detection performance may vary between S/P levels, particularly at the lowest illuminance, as there are systematic differences between the levels: at the lowest illuminance the high S/P gives the best performance and the low S/P the worst in both age groups. Table 7.3 shows the obstacle heights for 50% detection rate, as predicted by the 4PLE, for each illuminance and S/P combination. The value for each age group is shown, as well as a combined value.

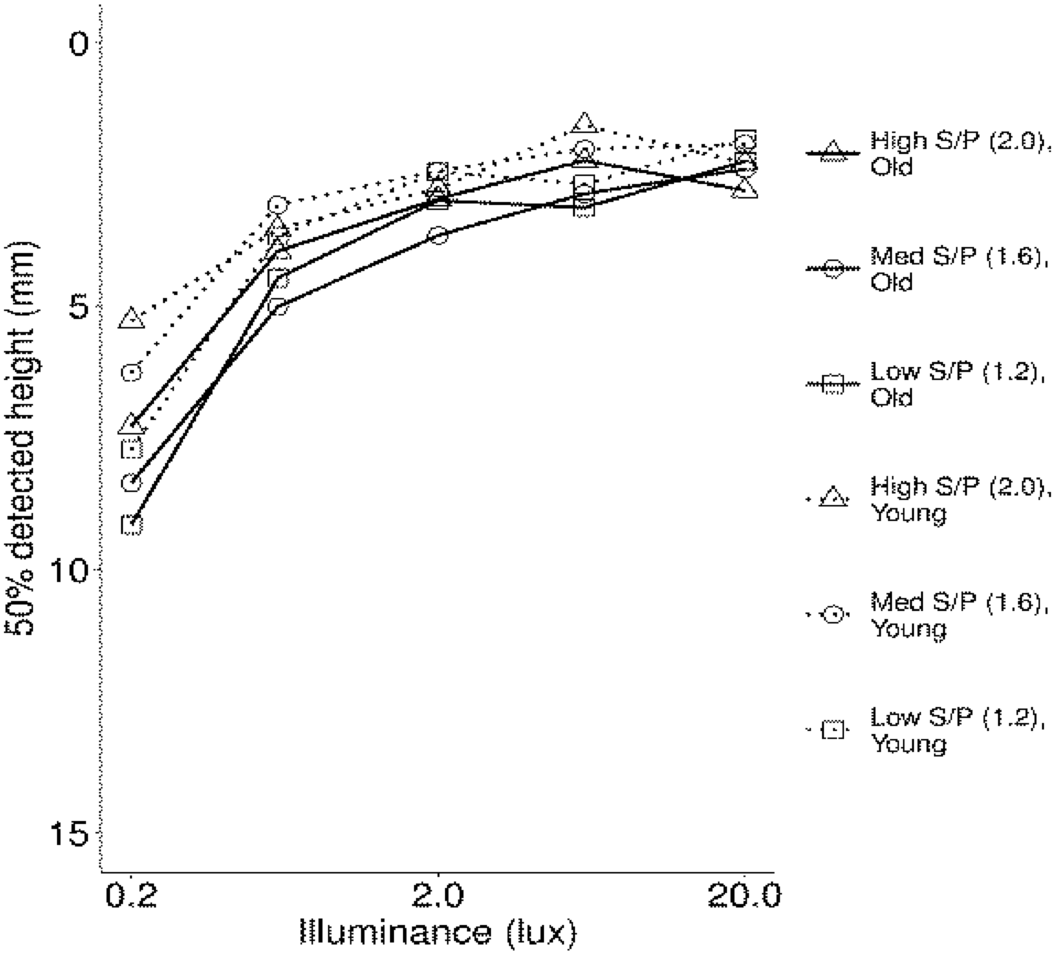


Figure 7.11. Obstacle heights for 50% detection probability, as calculated by 4PLE, plotted against illuminance for each combination of S/P ratio and age group.

Table 7.3. Obstacle heights (mm) for 50% detection probability, as calculated by 4PLE, for each illuminance, S/P ratio and age group. Low S/P = 1.2; Med S/P = 1.6; High S/P = 2.0.

Illuminance (lux)	**Obstacle height (mm) for 50% detection (h_{50}) according to age group and S/P ratio**								
	Young (<35 years)			**Old (>50 years)**			**Combined**		
	Low	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
0.2	7.72	6.26	5.28	9.15	8.35	7.28	8.40	7.35	6.23
0.6	3.67	3.08	3.53	4.46	5.01	3.96	4.04	3.85	3.74
2.0	2.45	2.43	2.77	2.99	3.66	2.96	2.73	3.01	2.85
6.3	2.68	2.02	1.57	3.13	2.86	2.23	2.92	2.36	1.87
20.0	1.82	1.93	2.28	2.25	2.40	2.80	2.07	2.17	2.53

Comparison of differences between conditions using statistical tests was not possible for the h_{50} values as these values were already a summary statistic based on the combined data of all participants. Therefore an alternative approach to analysing detection rates was also adopted that would allow statistical analysis to be carried out. In this approach a mean detection rate across all 7 obstacle heights was calculated for each participant and used as a metric. This has been plotted against illuminance in Figure 7.12, with separate lines showing each level of S/P ratio for the young and old age groups. This illustrates the trend for increasing detection performance with illuminance, and also how this performance begins to plateau beyond 2.0 lux. Detection rates generally seem lower for the older age group compared with the younger age group. Any influence of S/P ratio on detection performance is less clear, but there is a suggestion a higher S/P may result in better performance at the lowest illuminance level.

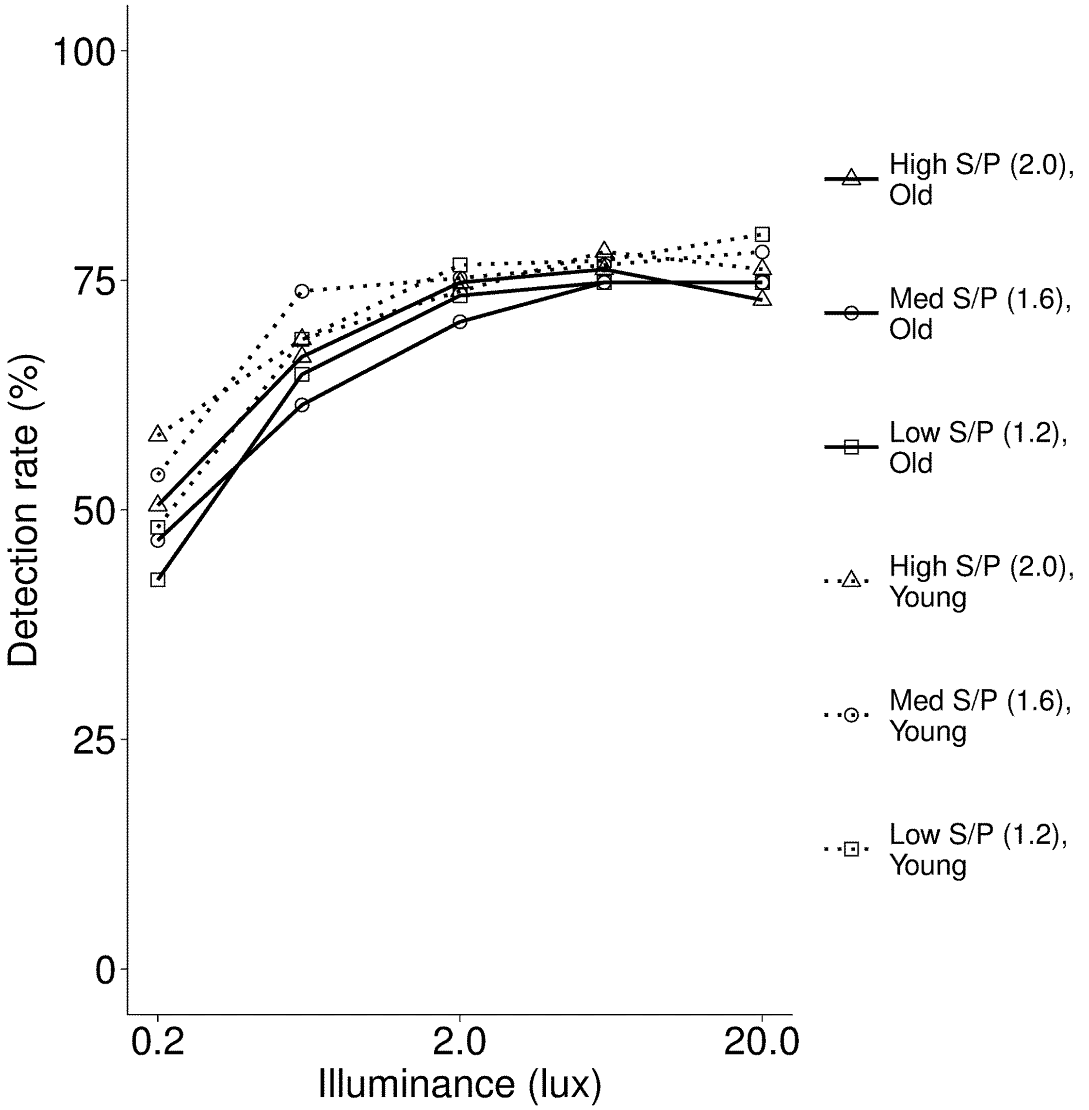


Figure 7.12. Combined detection rate across all obstacle heights by illuminance, for each S/P ratio and age group. Log_{10} scale used on x-axis.

The overall detection rate was used as a dependent variable in a mixed-model ANOVA, with the age group as a between-subjects factor and illuminance and S/P as within-subject factors. Results from this test indicated there was no significant difference between age groups in terms of their detection performance ($p = 0.173$). There was also no significant main effect of S/P ratio ($p = 0.366$). The main effect of illuminance was highly significant ($p < 0.001$), with detection performance increasing as illuminance increased. There was also a significant interaction between illuminance and S/P ratio ($p = 0.008$), but no significant interaction between age group and S/P ratio ($p = 0.353$), age group and illuminance ($p = 0.422$), or between age group, illuminance and S/P ratio ($p = 0.504$).

Post-hoc contrasts were carried out using Tukey's HSD to further investigate the main effect of illuminance. This suggested that at 0.2 lux overall detection rates were significantly worse than all other illuminance levels, and at 0.6 lux overall detection rates were worse than the three higher illuminance levels (all p-values < 0.001). From 2.0 lux upwards however, detection rates did not significantly alter, confirming that a plateau in performance had been reached at this illuminance.

Post hoc contrasts were also carried out to investigate the interaction effect between illuminance and S/P ratio (again using Tukey's HSD test). These tests suggested the interaction was due to the S/P ratio only having a significant effect on overall detection rates at the lowest illuminance level, 0.2 lux. At this illuminance the high S/P ratio produced significantly better detection rates than the low S/P ratio (0.54 vs 0.45, p < 0.01) but there was no difference between the medium S/P ratio and the other two S/P levels. At all other illuminance levels the S/P ratio had no effect on overall detection rates. This effect of S/P at the 0.2 lux was confirmed with a post-hoc one-way repeated-measures ANOVA (p < 0.001). One-way repeated-measures ANOVAs on the other four levels of illuminance confirmed there was no effect of S/P ratio on detection rates at these levels (p-values ranged between 0.297 and 0.902).

7.3.5 Detected heights

This section analyses data about the height the obstacle reached when it was detected. Only data for trials involving the largest obstacle height (28.4 mm) are used. The mean detected height on these trials was calculated across the 2 obstacle speeds used. When the distributions of detected heights within each combination of illuminance and S/P ratio were inspected for normality, some were positively skewed due to outlying data points at the higher end of the detected height range. Outliers were identified and deleted from the dataset. Inspection of these outliers showed that performance on these outlying trials was not consistent with performance on the majority of other trials for the individual participants involved, and no systematic pattern was seen in the conditions that produced the outliers. It was therefore concluded that outliers were likely due to participant error, for example loss of concentration on a particular trial. Removal of outlying values was therefore justified (Osborne and Overbay, 2004).

Identification of outlying values for removal was done by converting detected heights for each participant within each lighting condition to a z-score. Values with a z-score above a recommended threshold z-score of 2.576, (Cousineau and Chartier, 2010) were deleted. This resulted in the deletion of one data point from 9 conditions and two data points from one condition. The outlying values came from 8 of the participants (4 in each age group). After removal of outliers the datasets for all conditions approximated a normal distribution.

Figure 7.13 shows the mean detected height at each illuminance level, for each S/P ratio and age group. As illuminance increased participants detected the obstacle at lower heights. There is a possible suggestion that this performance plateaus before the maximum illuminance is reached but this is not as apparent as the trend in overall detection rates shown in Figure 7.12. There is a possible difference between age groups suggested, with detected heights being generally larger for the older participants. There appears to be little relationship between S/P ratio and detected height, with the exception of the lowest illuminance level (0.2 lux), where the pattern of higher S/P ratio, lower detected height is repeated for both young and old age groups.

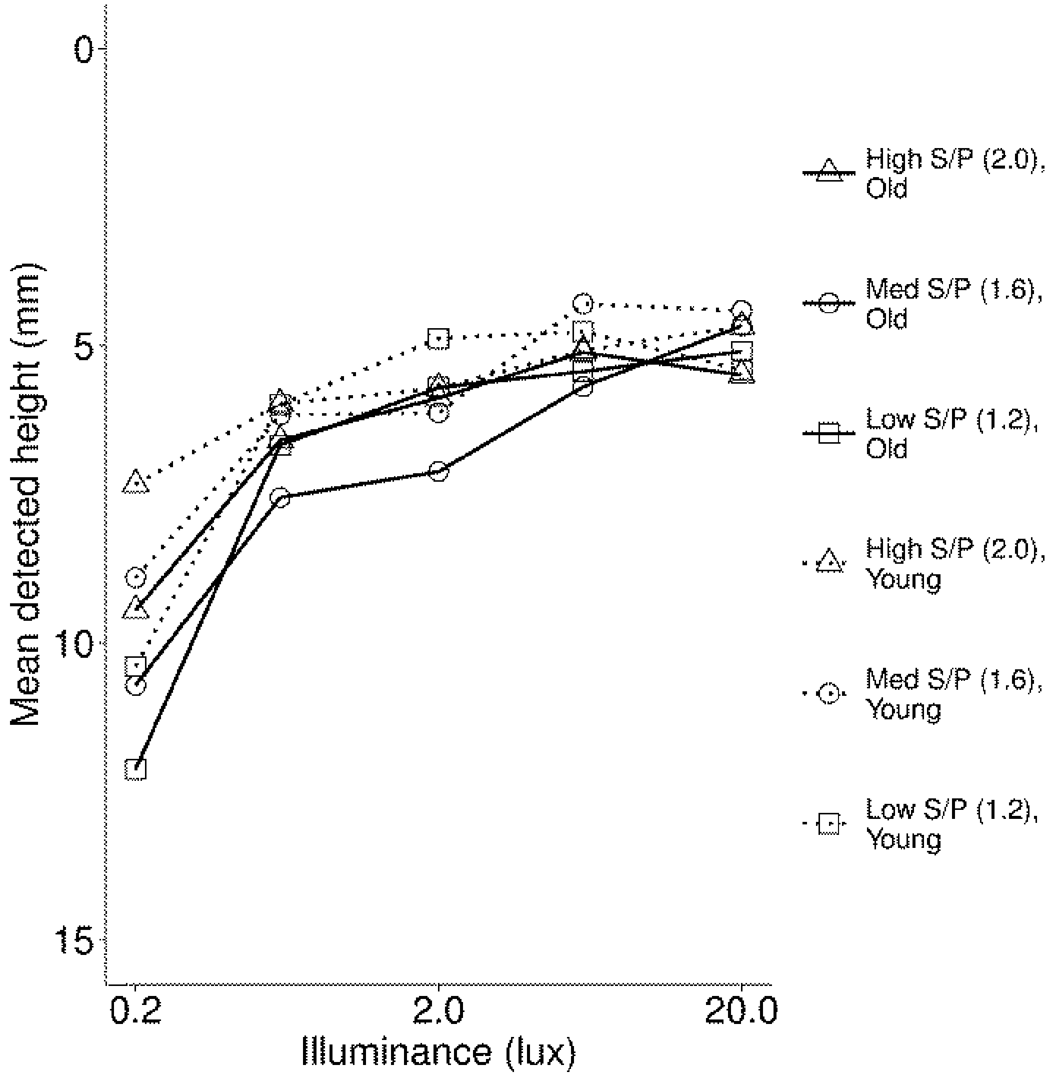


Figure 7.13. Mean detected height by illuminance, for each S/P ratio and age group. A $\log_{10}$ scale is used for the x-axis.

A mixed-model ANOVA was carried out to examine the relationships between age group, illuminance and S/P ratio, and detected height of the obstacle. The detected height was used as the dependent variable, with age group as a between-subjects factor (2 levels) and illuminance (5 levels) and S/P ratio (3 levels) as within-subject factors. The ANOVA found a significant main effect of illuminance (p < 0.001). Post hoc tests using the Tukey HSD test suggested the detected height at 0.6 lux (mean = 6.75mm) was significantly greater than at higher illuminances, and the detected height at 0.2 lux (mean = 9.94 mm) was significantly greater than all other illuminances (p < 0.001 in all cases). The height of the obstacle when detected at 2.0 lux upwards did not significantly differ (means for 2.0, 6.3 and 20.0 lux = 6.07, 5.24 and 5.37 mm respectively, p-values ranged between 0.083 and 0.994).

The model suggested there was no significant main effect of age group on detected height (p=0.123), and no significant interaction between age and S/P level (p=0.68). However, there was a significant interaction between age group and illuminance (p=0.014). Post hoc comparisons using the Tukey HSD test gave a suggestion that detection performance, as measured by the mean detected height, may have been better in the young age group compared with the old age group at the lower illuminance levels, but not at higher illuminance levels. For example, there was no significant difference between detected height for the young group at 0.6 lux and detected height for the old group at 6.3 and 20.0 lux, suggesting detection performance for the young group at this lower illuminance was equal to detection performance at the higher illuminances for the old group. This effect was confirmed by independent t-tests comparing the two age groups on each level of illuminance, using the FDR method of controlling for multiple comparisons. These showed that the young age group had significantly better performance at 0.2 lux compared with the old age group (means = 8.9 vs 11.0 mm, p = 0.04). At 0.6 lux and above performance did not differ significantly between age groups (p-values of 0.14, 0.39, 0.77 and 0.98 at 0.6, 2.0, 6.3 and 20.0 lux respectively).

The ANOVA suggested a significant main effect of S/P ratio (p = 0.004). Post hoc tests using the Tukey HSD test suggested the differences between S/P ratios may have lay between the high and low levels and the high and medium levels, but p-values did not reach significance (p = 0.09 and 0.12 respectively). Additional paired t-tests with FDR adjustment comparing the three combinations of S/P ratio (high vs medium, high vs low, medium vs high) suggested the high S/P ratio produced a significantly lower detected height than the medium or low S/P ratios (p = 0.012 in each case, means for high, medium and low = 6.24, 6.87 and 6.91 mm respectively).

The interaction between illuminance and S/P ratio was significant ($p = 0.001$). Post hoc tests using the Tukey HSD test suggested the detected height differed significantly by S/P ratio at 0.2 lux (specifically, the high S/P resulted in significantly lower detected height than the low S/P, means = 8.39 vs 11.26 mm respectively, $p < 0.01$), but not at any other illuminance. This was further confirmed by repeated measures ANOVAs at each level of illuminance with FDR adjustment. Detected height varied significantly with S/P ratio at 0.2 lux ($p < 0.001$), but not at any other illuminance (p-values ranged between 0.131 and 0.858). The interaction between illuminance, age and S/P was not significant ($p = 0.79$).

7.3.6 Practice or fatigue effects

It is possible that performance changed for each participant as the experiment progressed, due to practice effects with the participant becoming more proficient at the task through learning, or fatigue effects with the participant becoming less proficient at the task as they become more tired or concentrate less on the task (Wesnes & Pincock, 2002; Ackerman & Kanfer, 2009). To check whether any such effects occurred during this experiment the first lighting condition used for each participant was also repeated at the end of the experiment. This allowed direct comparison of the same condition at the beginning and at the end of the experiment.

The obstacle height for 50% detection probability, based on the 4PLE, was compared for the first condition and the repeat condition. The obstacle height for a 50% detection rate on the first condition (h_{50}) was 4.50 mm, compared with 2.69 mm on the repeat condition. The overall detection rate combined across all obstacle heights was better during the repeat condition (mean = 0.73) than the first condition (0.62). A paired samples t-test confirmed that this difference was significant ($p < 0.001$).

Considering the mean detection height, a paired samples t-test suggested the mean height at which the obstacle was detected was significantly higher on the first condition compared with the repeat condition (means = 7.76 vs 5.20 mm, $p < 0.001$).

These results suggest there was a practice effect during the experiment: obstacle detection performance was better at the end of the experiment than at the beginning. However, this should not create a bias within the current results as the order in which conditions were presented to participants was counterbalanced, ensuring each condition appeared an equal number of times at the beginning, middle and end of the experiment (Cozby, 2009).

7.4 Discussion

This experiment examined peripheral obstacle detection under different lighting conditions by young and older people. The experiment improved on previous research in this area by increasing the realism of the task through introduction of walking on the treadmill and use of a dynamic fixation target to both better encourage and test for use of peripheral vision for the detection task and add an additional cognitive task to the paradigm. The headline results from the experiment are presented in Table 7.4, and are discussed below in terms of the main variables of age, illuminance and S/P ratio that were being examined. A comparison with previous results is also presented.

Table 7.4. Summary of main findings from obstacle detection experiment.

Dependent variable	**Main graph**	**Effect of illuminance**	**Effect of SPD**	**Effect of Age**
H_{50}	Fig 7.11	H_{50} value reduces as illuminance increases, although apparent plateau at around 2.0 lux	Possible effect of S/P ratio at lower illuminances, with higher S/P producing lower H_{50} value	Possible effect of age with younger group generally having lower H_{50} value than older group, particularly at lower illuminances
Overall detection rate	Fig 7.12	Significant main effect of illuminance ($p < 0.001$), with detection rate increasing as illuminance increased. Detection rates do not significantly improve beyond 2.0 lux however.	No significant main effect of S/P ratio ($p = 0.366$). However, significant interaction with illuminance. Higher S/P ratio produced better detection rates, but only at lowest illuminance of 0.2 lux.	No significant main effect of age ($p = 0.173$), and no interaction with S/P ratio or illuminance
Mean detection height	Fig 7.13	Significant main effect of illuminance ($p < 0.001$), with mean detected height decreasing as illuminance increased. Mean detected height does not significantly decrease beyond 2.0 lux however.	Significant main effect of S/P ratio ($p = 0.004$), with high S/P producing lower mean detected heights than medium and low S/P. Also, significant interaction between S/P ratio and illuminance, with mean detected height varying significantly between S/P ratios at 0.2 lux but not at higher illuminances.	No significant main effect of age ($p = 0.123$), and no significant interaction with S/P ratio. However, interaction between age and illuminance was significant, with mean detected height being lower for the young than old group at 0.2 lux, but no differences between age groups at higher illuminances.

7.4.1 Age effects

The mean age of the two age groups recruited for this experiment differed by 36 years (young group mean age = 26.3 years, old group mean age = 62.5 years). This difference was anticipated to be large enough to reveal any effects of age, if such effects existed. A difference between age groups was only found at the lowest illuminance level used of 0.2 lux. At this illuminance the older group performed significantly worse than the younger group at detecting the obstacle. No difference was found between age groups at illuminances of 0.6 lux and greater. This should perhaps be expected as visual performance deteriorates with age, and such deterioration is likely to be most evident when the visual system is operating near its limits (Boyce, 2014). The lowest illuminance level is likely to bring the detection task closest to threshold levels, resulting in the largest differences between age groups. It appears that at illuminances above 0.2 lux the visual system within the older participants is still capable of performing on a par with that of the younger participants.

It was anticipated that an interaction between age and S/P ratio would be apparent, as spectral absorbance of the lens increases with age and this is particularly so at shorter wavelengths (Weale, 1988). However, no interaction was found when looking across all 5 illuminance levels. This lack of interaction may be due to a sufficient amount of light falling on the participants' eyes to outweigh any differences resulting from increased spectral absorption. Examination of the data at the lowest illuminance level, 0.2 lux, suggests an effect could be starting to occur. The difference in performance between the young and old age groups is largest at the high S/P level. For example, the young-old difference in detection rates for the high S/P is 0.076, compared with 0.057 for the low S/P. Similarly, the young-old difference in detected heights for the high S/P is 2.16 mm, compared with 1.82 mm for the low S/P. We would expect the high S/P light condition to provide a greater improvement over the low S/P condition for the young group compared with the old group, as the high S/P light has greater power at short wavelengths which better stimulate the peripheral rod photoreceptors, but this short wavelength light is absorbed to a greater extent by the lens in the eyes of the older group.

The older group performed slightly worse at identifying the fixation target digit when it changed compared with the young group, although success rates were still high (almost 90% for the older group). This difference may reflect the increased difficulty with which dual task situations are completed as age increases, as has been shown in past studies (Verhaeghen et al, 2003).

7.4.2 Illuminance effects

The three metrics of obstacle detection performance used in this experiment (obstacle height for a 50% detection probability, overall detection rates and mean detected height) all showed improvement as illuminance increased. This is as would be expected given that greater illuminance means more light falling on the retina and increased stimulation of the photoreceptors in the eye. However, it is perhaps surprising the level of performance that is still possible even at the lowest illuminance of 0.2 lux. Analysis of detection rates using the 4PLE revealed that participants could detect an obstacle height between 5.28 and 9.15 mm with 50% probability, depending on S/P ratio and age group. The 4PLE also revealed participants could detect an obstacle height of 9.79 – 14.32 mm with 90% probability. The minimum obstacle size that local authorities should ensure can be seen has been suggested to be 25 mm (Fotios and Cheal, 2013). Therefore, even at 0.2 lux participants in this experiment were able to detect obstacle heights well below this end-user threshold with a high degree of probability.

Performance in detecting the obstacle showed an escarpment-plateau relationship with illuminance – relatively small increases in illuminance initially lead to large increases in performance – the escarpment. However a point is reached at which increases in illuminance lead to no, or negligible, improvements in performance – the plateau. This can be seen in different aspects of visual performance and with different visual variables such as luminance contrast or visual size of the target (Boyce and Rea, 1987). The escarpment-plateau relationship between performance and illuminance found in this experiment is illustrated by all three of the detection performance metrics used (height for 50% detection probability, overall detection rate and mean detected height – see Figures 7.11, 7.12 and 7.13). The point at which the plateau begins is around 2.0 lux. Statistical tests suggested detection performance at 2.0 lux was no worse than at 6.3 lux and 20.0 lux. An increase in illuminance by an order of magnitude from 2.0 lux did therefore not bring any tangible benefit in terms of being able to detect the obstacle. This finding has implications for current recommended illuminance levels for pedestrian road lighting, given that five of the six types of road or area in existing guidelines have recommended average horizontal illuminances above 2.0 lux (BS EN 13201-2: 2003; see Table 1.2). These implications are discussed in more detail in Chapter 8.

7.4.3 Spectrum effects

The spectrum of the lighting was varied in this experiment to investigate its effect on peripheral obstacle detection. We used the S/P ratio as a metric of spectrum as it provides a simple yet effective measure of the efficacy of a light source in stimulating the rod photoreceptors that will be dominant under the mesopic conditions and peripheral detection task used in this experiment. We attempted to control other aspects of the lighting spectrum such as the chromaticity, in order to isolate any effect of S/P ratio.

The S/P ratio was found to have an effect on performance in the obstacle detection task but only at the lowest illuminance of 0.2 lux. At this illuminance a higher S/P led to better performance. Based on the mean detected height of the obstacle, participants were able to detect an obstacle that was 2.6 – 3.1 mm smaller under the high S/P condition compared with the low S/P condition, depending on whether they were young or old. This may seem an insubstantial improvement but it could potentially be important considering the average toe clearance when walking is only around 15 mm (Mills, Barrett and Morrison, 2008). Therefore relatively small obstacles can still potentially trip a pedestrian, and small improvements in detection performance offered by higher S/P lighting could make more trip hazards detectable. Furthermore, the S/P range investigated in this experiment was relatively small (a difference of 0.8 between the low and high levels). It is possible that a larger effect of S/P would be witnessed if a larger range had been investigated. For example, Bullough and Rea (2000) used an S/P range of 0.64 – 3.77 and found an effect at higher luminances than were used in the current experiment.

7.4.4 Comparison with previous research

A number of studies have previously demonstrated that peripheral detection improves as the luminance / illuminance increases (e.g. Bullough and Rea, 2000; Lingard and Rea, 2002; He et al, 1997). This effect is obvious and not in doubt. However, what is more debateable and of greater note is the nature of the relationship between light intensity and detection performance. Results from the current experiment suggest a plateau is reached at around 2.0 lux illuminance on the target. This corresponds well with other work that has used illuminance as the metric of choice, for example Fotios and Cheal (2013) also suggested a plateau in performance was reached at around 2.0 lux. Alferdinck (2006) measured background luminance rather than illuminance, but also suggested that “for high luminances at photopic light levels it [detection performance] approaches an asymptotic level” (p. 271). Examining Figure 6 in

Alferdinck (2006) suggests this asymptote is reached at around 1 cd/m^2. An equivalent illuminance is not given, but this appears to be almost an order of magnitude greater than the point of plateau found in the current experiment. The luminance of the obstacle at 2.0 lux illuminance was 0.127 cd/m^2. Data from Eloholma et al (2006) also suggested there was a plateau in the relationship between peripheral detection performance and light intensity. Eloholma et al used 3 luminance levels of 0.01, 0.1 and 1.0 cd/m^2 and measured reaction times to detection of a peripheral target. Performance appeared to level off at the 0.1 cd/m^2, with no great improvement seen when luminance was increased to 1.0 cd/m^2, although the conspicuousness of this plateau depended on the spectrum of the light source, being more obvious with light of a lower S/P ratio. However, other studies have not appeared to show the escarpment-plateau relationship between detection performance and light intensity demonstrated in the current experiment. For example, Bullough and Rea (2000) and Lingard and Rea (2002) both examined a luminance range of 0.1 – 3.0 cd/m^2 and found no suggestion of a plateau in performance at the greater luminances. He et al (1997) examined a luminance range of 0.01 – 10.0 cd/m^2 and again did not find an obvious escarpment-plateau relationship with detection performance.

To compare results between the six different studies referred to above and the current experiment, normalised performance values (NPVs) have been estimated for each study and plotted against luminance in Figure 7.14. The NPV at each luminance is calculated as the ratio of the difference between the value of the performance measure used in the study (e.g. reaction time, detection height of obstacle) for a particular luminance and the worst performance measure across all luminances, and the overall difference between the best and worst performance across the luminances used. This can be expressed in the following equation:

$$NPV_i = \frac{|P_i - P_w|}{P_b - P_w}$$

Equation 7.2. Cacluation of Normalised Performance Value.

Where for a particular luminance of i, NPV_i = Normalised Performance Value, P_i = Performance at luminance i, P_w = Worst performance across all luminances tested, and P_b = Best performance across all luminances tested.

For example He et al used reaction time to detection, in ms, as their performance measure. The best performance was approximately 215 ms, given at 10 cd/m^2. The worst performance was 288 ms, given at 0.01 cd/m^2. The difference between these best and worst values is 73 ms. If a particular luminance gave performance at 240 ms the difference between this and worst performance would be 48 ms, and the NPV would be 48/73 = 0.66. Note that the worst performance will always have an NPV of 0 and best performance will always have an NPV of 1. The value in calculating NPV for different studies is that it allows comparison between those studies, regardless of the type of measure used, and it illustrates the relationship between luminance and performance. The calculated NPVs for the seven studies, including the current experiment, are shown in Figure 7.14. This shows the distinction between those studies that show an escarpment-plateau relationship between detection performance and light intensity, shown as luminance in Figure 7.14 (Alferdinck, 2006; Eloholma et al, 2006; Fotios and Cheal, 2013; and the current experiment), and those that do not (Bullough and Rea, 2000; Lingard and Rea, 2002; He et al, 1997). Figure 7.14 also shows a high degree of consistency in the intensity-performance relationship when data from the supporting studies is normalised.

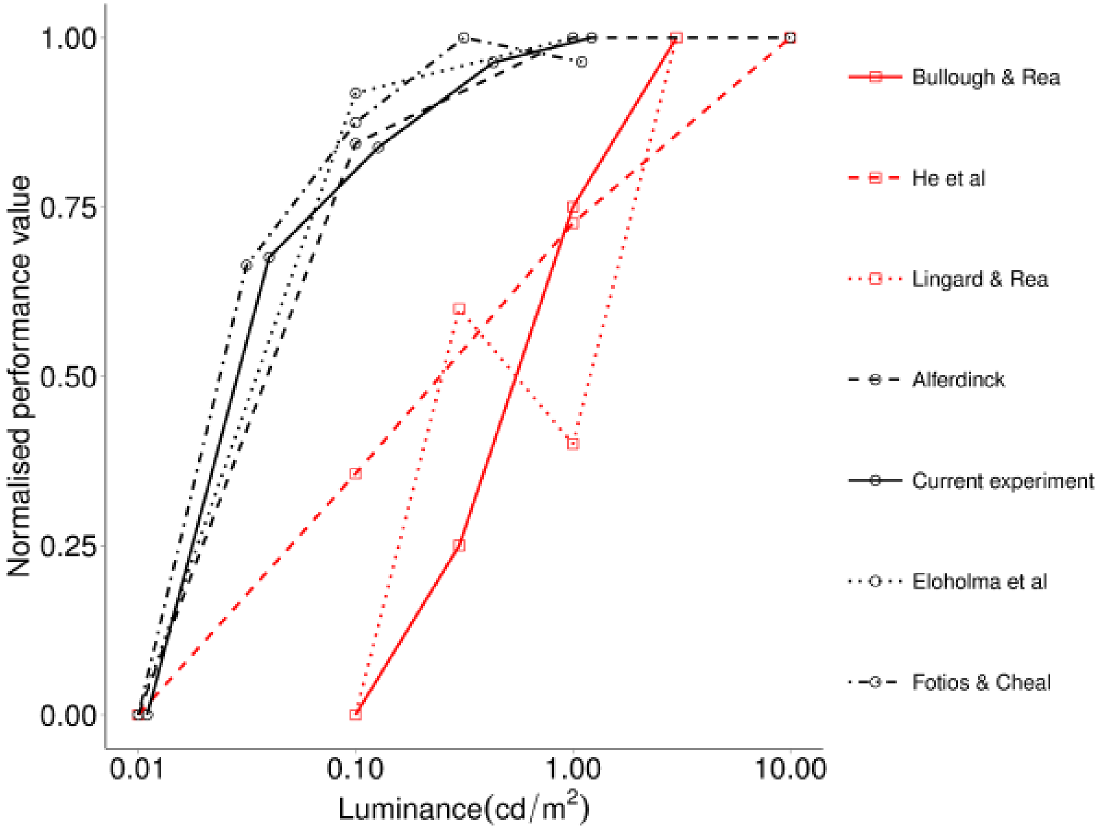


Figure 7.14. Normalised performance values by luminance for Bullough & Rea (2000), He et al (1997), Lingard and Rea (2002), Alferdinck (2006), Eloholma et al (2006), Fotios and Cheal (2013) and the current experiment. Black lines represent those studies that indicate an escarpment-plateau relationship between luminance and detection performance, red lines indicate those studies that do not suggest such a relationship.

The current experiment found an effect of spectrum but only at the lowest illuminance of 0.2 lux, with a higher S/P ratio resulting in improved obstacle detection. Many other studies have found a similar effect of higher S/P improving peripheral detection, but this effect is influenced by different factors such as the illuminance or luminance, the contrast of the peripheral target, and the eccentricity of the peripheral targe. Bullough and Rea (2000) for example found an effect of S/P even at the highest luminance used in their study of 3.0 cd/m^2. Lingard and Rea (2002) used the same luminance range as used by Bullough and Rea (0.1 – 3.0 cd/m^2) but in contrast only found an effect of S/P at the lower luminances used. This finding is more in line with other studies that have shown an improvement in peripheral detection is induced by a higher S/P ratio only at luminance levels around 1.0 cd/m^2 and below. Alferdinck (2006) used a luminance range of 0.001 – 10 cd/m^2 and an S/P range of 0.22 – 9.08 but found the S/P only influenced peripheral detection below 1 cd/m^2. Likewise, He et al (1997) used luminances up to 10 cd/m^2 but only found a difference between the two light sources used, each having different S/P ratios, below 1 cd/m^2. In Eloholma et al's study (2006) the maximum luminance used was 1.0 cd/m^2. An effect of S/P ratio was found at this highest level but only when the contrast of the peripheral target was low. The current experiment only found an effect of S/P ratio at the lowest illuminance of 0.2 lux. This illuminance was equivalent to a luminance value of 0.01 cd/m^2. Luminances for the 0.6, 2.0 and 6.3 lux were all still below 1.0 cd/m^2 but S/P did not affect detection of the obstacle. This result is similar to that found by Fotios and Cheal (2009), who only found an S/P effect at 0.01 cd/m^2 and not at 0.12 and 1.2 cd/m^2.

What can explain these differences in the light intensity levels at which S/P begins to have an effect? One factor that is likely to be important is the difficulty of the task or tasks participants are being asked to complete. Bullough and Rea (2000) suggest that the closer a visual task is to threshold levels of vision the more magnified the effect of spectrum. Therefore we might expect a more difficult detection task to elicit spectral effects at higher light levels than an easier task, all other things being equal. With an easier task, increasing the light level may take the visual task far enough away from threshold levels for the spectrum of the light to not have an effect. However, a more difficult task may still be near to threshold levels even when light levels are increased. The difficulty of the visual task can be increased in a number of ways, such as by reducing the luminance contrast of the target, increasing visual background 'noise' or introducing additional visual tasks. Bullough and Rea (2000) suggest that they found spectral effects at higher luminance levels than other studies because they used a naturalistic and visually noisy environment (a driving simulator). The task used by He et al (1997) for example, who only found an effect at luminances below 1 cd/m^2, was relatively simple and with little visual noise. Studies that have varied the luminance contrast of the peripheral target have also shown that a lower contrast target is more likely to produce an effect of spectrum and at higher luminances than a higher contrast target (e.g. van Derlofske and Bullough, 2003; Eloholma et al, 2006). Similarly, introducing a more difficult foveal task can also increase the likelihood of seeing an effect of spectrum (Akashi, Kanaya and Ishikura, 2014). These findings can be explained by the hypothesis that a more difficult visual task will magnify any effect of spectrum, meaning spectral effects may be witnessed at higher light intensity levels.

Applying this hypothesis to results from the current experiment it is possible that the detection task used was not as difficult or did not involve as much visual noise as tasks used in other studies. The raised surface in front of participants, out of which the obstacle rose, was smooth and uniform in colour and texture. The surrounding walls were also uniform and of low reflectance, with no distracting features. The obstacle always appeared in the same location, and was always within the visual field of the participant. These factors may have resulted in the task being relatively simple to complete, hence why the S/P ratio only influenced detection performance when the illuminance was at its lowest level, at which point the task may have been approaching visual threshold levels. Evidence for this interpretation can be seen in the fact that detection rates approached 100% for the obstacle height of 11.3 mm and above even at the lowest illuminance level (see Figure 7.9). With smaller obstacle heights we can assume the task was more difficult, and therefore we might expect to see a greater effect of spectrum. To examine this, the spectrum effect has been quantified as the percentage difference between the detection rates on the high and low S/P ratios (combined across all illuminance levels) and plotted against obstacle height, see Figure 7.15. A greater positive difference indicates a larger improvement in detection rate offered by the high S/P light level over the low S/P light level. It shows the difference in detection rates between the S/P levels decreases as the obstacle height increases. This offers support to the idea that a greater task difficulty is more likely to result in an observed effect of spectrum; the smaller obstacle heights are likely to present a more difficult detection task and therefore a greater difference in performance is seen between the high and low S/P levels at these smaller heights.

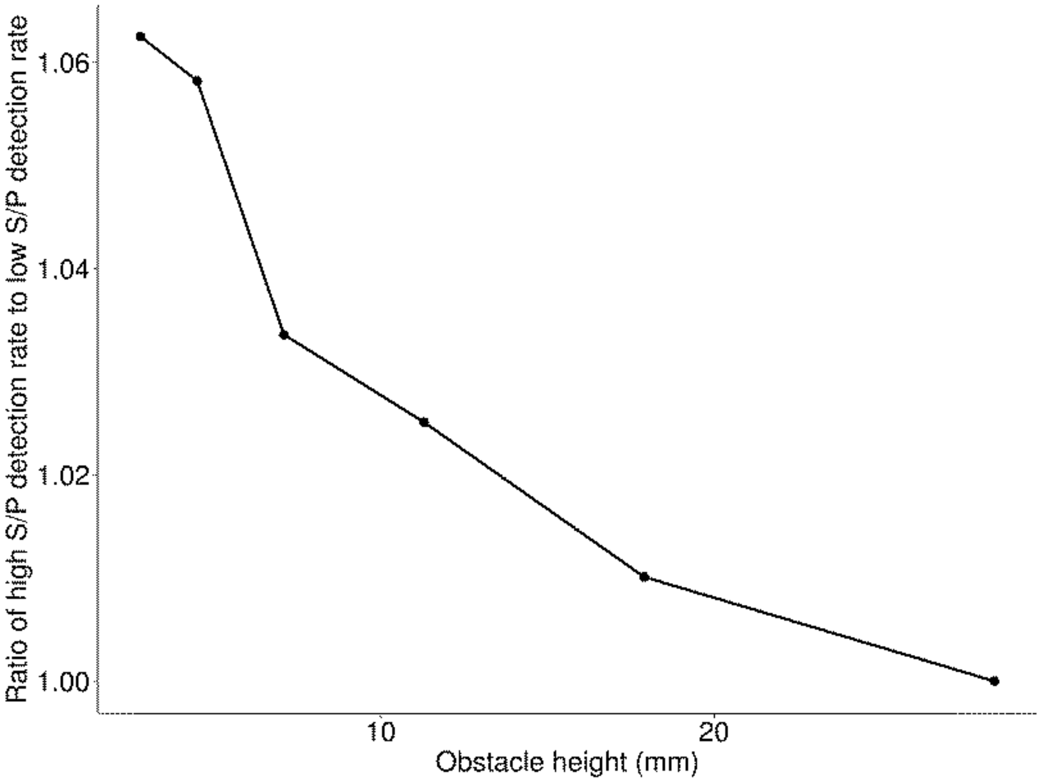


Figure 7.15. Detection rate at high S/P light condition as ratio of detection rate at low S/P light condition, by obstacle height. Detection rates combined across all luminances.

The current experiment only found an effect of age at the lowest illuminance used, 0.2 lux, with younger participants performing better at the obstacle detection task than older participants at this light level. No age differences were found above 0.2 lux, and there was no interaction between age and S/P indicating the age groups were not affected in different ways by the spectrum of the light. These results are similar to those found in previous work (Fotios and Cheal, 2009). This study compared younger people (mean age of 32 years) with older people (mean age of 68 years). The young group showed significantly better detection of obstacles than the old group at the lowest illuminance (0.2 lux), but there was no difference at higher illuminances (2.0 and 20 lux). Age did not appear to influence the degree to which spectrum affected detection ability, as no interaction was found between age and S/P in this study. Both old and young participants were affected in the same way, with S/P only having an effect at 0.2 lux for both age groups.

7.4.5 Mesopic system of photometry

Data from this experiment confirms the effect of spectrum on obstacle detection that has been shown by other studies of peripheral detection under different SPD conditions (e.g. Fotios and Cheal, 2009; He et al, 1997). This effect is a result of the variable stimulation of the rod photoreceptors by light with different SPDs. Light with a higher content of short-wavelength light better stimulates the rod photoreceptors, resulting in a brighter appearance (e.g. Houser, Fotios and Royer, 2013; Fotios and Cheal, 2011) and improved visual performance (e.g. Walkey et al, 2007; He et al, 1997) at low light levels. The S/P ratio is commonly used as an indication of the relative stimulation of the rods compared with the cone photoreceptors. This spectral sensitivity means different perceptions of the light and different visual performance can be produced from light with the same photopic illuminance, but different SPDs. Therefore a system of photometry designed for the mesopic light range (0.01 – 3.0 cd/m^2), in which spectral variation has the greatest influence on vision, has been developed by the International Commission on Illumination, the CIE (CIE, 2010). This system enables calculation of a mesopic luminance, based on the photopic luminance and the S/P ratio of the light in question. The mesopic luminance provides an indication of the efficacy of the light within the mesopic range, taking account of the light's spectral qualities. Light with a higher S/P ratio will generally have a higher mesopic luminance, reflecting the fact it is perceived as brighter than lower S/P light. The CIE model for calculating mesopic luminance uses an iterative approach as follows:

$$
\begin{aligned}
&m_0 = 0{,}5\,,\\
&L_{\mathrm{mes},n} = \frac{m_{(n-1)}\, L_{\mathrm{p}} + (1-m_{(n-1)})\, L_{\mathrm{s}}\, V'(\lambda_0)}{m_{(n-1)} + (1-m_{(n-1)})\, V'(\lambda_0)}\,,\\
&m_n = a + b \log_{10}(L_{\mathrm{mes},n}) \qquad \text{for } 0 \le m_n \le 1\,,
\end{aligned}
$$

Equation 7.3 CIE mesopic luminance calculation.

Where L_p = photopic luminance, L_s = scotopic luminance, $V'(\lambda_0)$ = 683/1699 (value of scotopic spectral luminous efficiency functions at λ_0 = 555 nm), a = 0.767, b = 0.333, n is the iteration step. Given the S/P ratio and photopic luminance of a given light condition it is possible to calculate its mesopic luminance. Light with similar mesopic luminances should in theory give similar perceptions of brightness and visual performance. Using this model of mesopic photometry it is possible to calculate the photopic luminances for any of the S/P ratios used in the current experiment that would give equivalent mesopic luminances to the other S/P ratios. This enables an evaluation of how well the CIE mesopic photometry system predicts the performance of obstacle detection at different S/P ratios and luminance levels. It also allows an understanding of the potential differences in performance that might have been predicted based on the S/P range used in this experiment and the relative mesopic luminances.

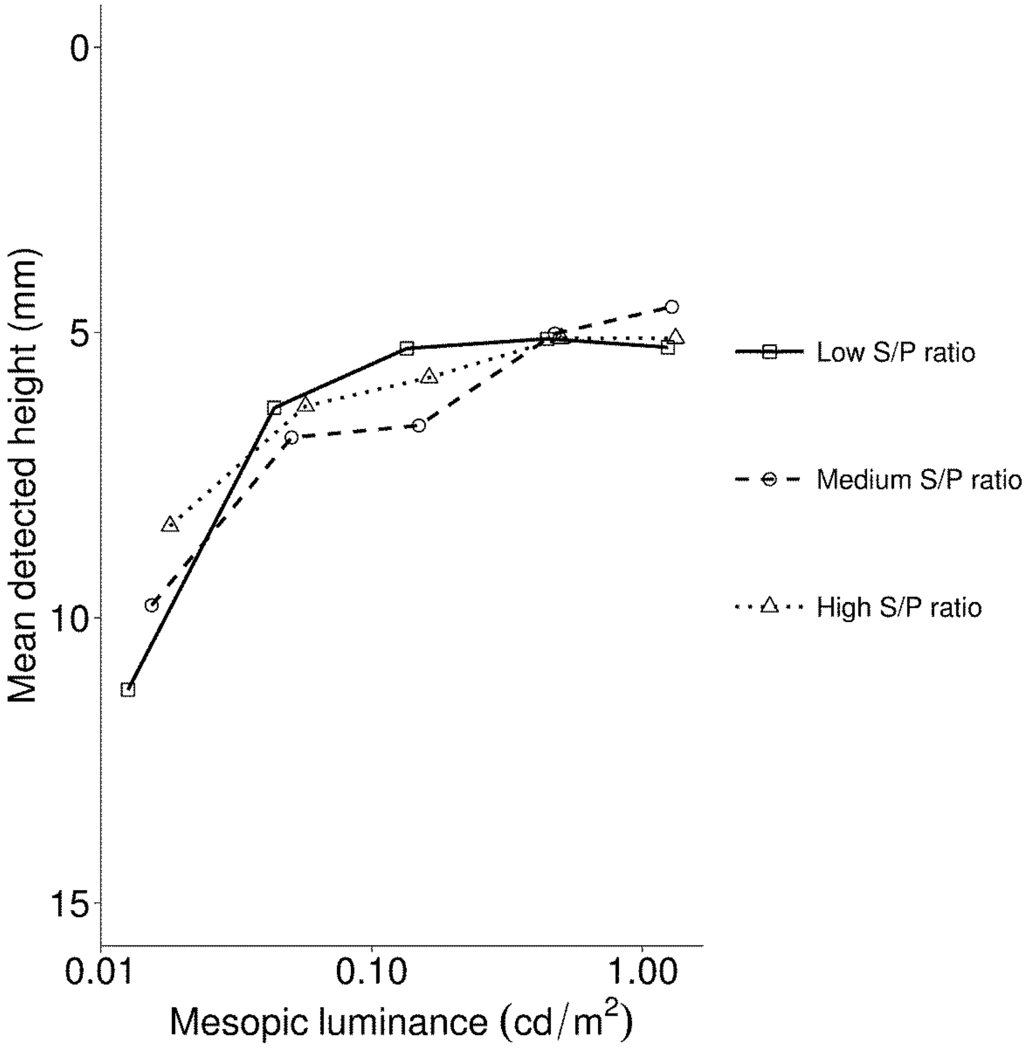
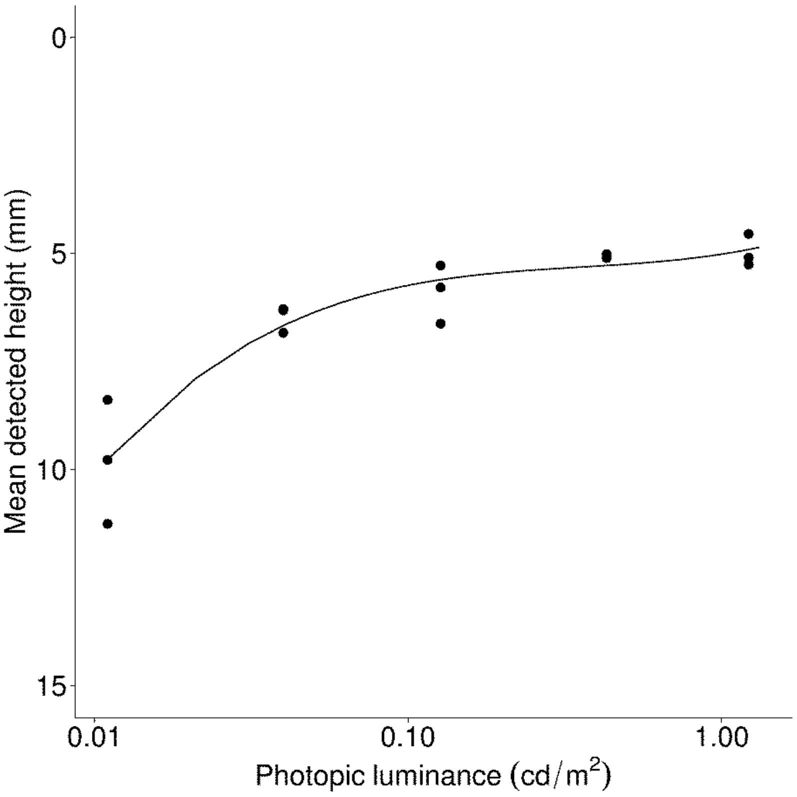


Figure 7.16. Mean detected height (both age groups combined) by S/P ratio, plotted against mesopic luminances as calculated using the CIE mesopic photometry model (CIE, 2010)

The luminances for each illuminance and S/P condition in this experiment have been converted to mesopic luminances using the CIE model and are shown in Table 7.5. The mesopic luminances for each S/P ratio condition have been plotted against the mean detected height at those luminances (combined across both age groups) and is shown in Figure 7.16. If the CIE mesopic system perfectly predicted obstacle detection performance under lighting with different S/P ratios we would expect all mean detected height values to converge on a single curve indicating performance. This is not the case however. For example, a clear difference can still be seen between the S/P ratios at the lowest luminance level. This suggests the CIE model does not perfectly predict the effect of spectrum on obstacle detection. However it does offer a small improvement in prediction compared with photopic luminance alone. This is demonstrated through the fitting of a regression curve to the mean detected height for photopic luminances and comparing this against a regression curve fitted to mesopic luminances. A third order polynomial model has been used to create the best-fit curve for both photopic and mesopic luminances. The predictive models along with actual datapoints are shown in Figures 7.17 and 7.18. The polynomial model for photopic luminance has an adjusted R-squared value of 0.85, compared with an adjusted R-squared value of 0.92 for the mesopic luminance model. Although the R-squared value for the mesopic predictive model is higher than the photopic model, the photopic model is still high and is therefore capable of explaining much of the variance in mean detected height values found in this experiment. However, this should be expected as the S/P ratio only had an effect at the lowest luminance. At the four other luminance conditions, spectrum had no effect and the photopic luminance could satisfactorily account for changes in mean detected heights. At the lowest luminance the photopic model is inadequate however, and it is at this lowest luminance condition that the mesopic predictive model shows the greatest improvement over the photopic model. This is demonstrated by the residuals in the photopic model (see the three leftmost datapoints in Figure 7.17) at the lowest luminance compared with the residuals in the mesopic model for the lowest luminance condition (see the three leftmost datapoints in Figure 7.18).

Table 7.5. Mesopic luminances for each S/P ratio and luminance condition, as calculated by CIE mesopic photometry model (CIE, 2010). Luminance is as measured at top surface of obstacle. Equivalent illuminance condition is given in brackets.

	S/P ratio		
Luminance, cd/m^2 (illuminance, lux)	**1.2 (low)**	**1.6 (medium)**	**2.0 (high)**
0.011 (0.2)	0.0126	0.0154	0.0180
0.040 (0.6)	0.0437	0.0506	0.0570
0.127 (2.0)	0.1348	0.1494	0.1630
0.430 (6.3)	0.4453	0.4744	0.5018
1.220 (20.0)	1.2425	1.2856	1.3264



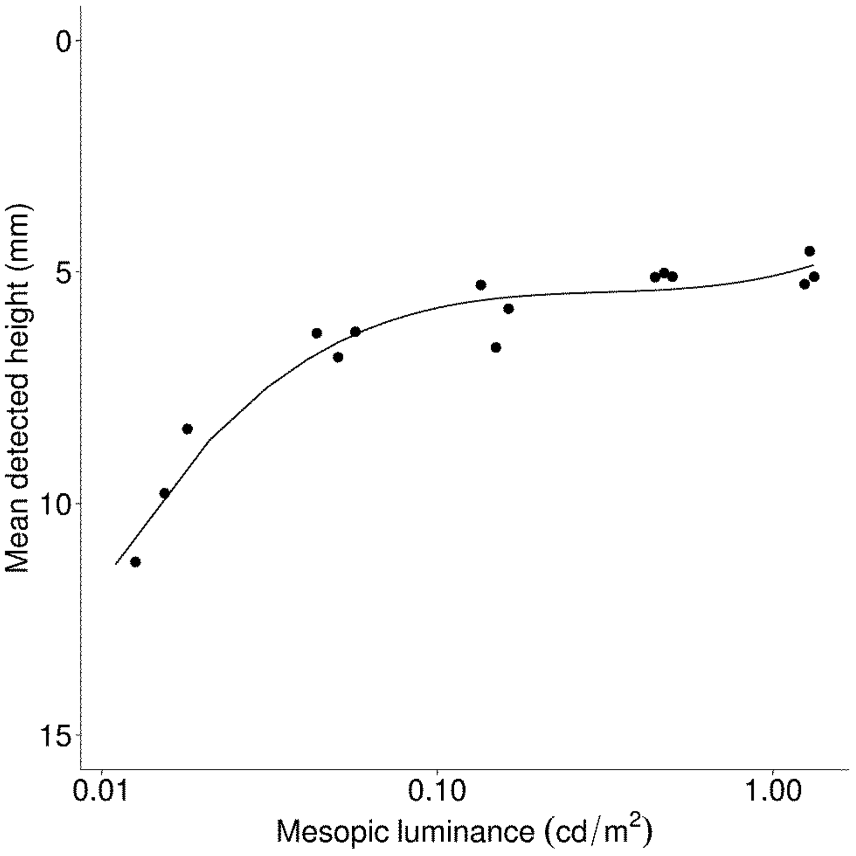


Figure 7.17 (top) and **Figure 7.18 (bottom)**. Mean detected height for all three S/P ratios plotted against photopic luminance (top) and mesopic luminance (bottom). Third order polynomial models are fitted to the data.

It is possible to estimate the predicted differences in mean detected height resulting from the S/P range investigated, based on the polynomial model fitted to the mesopic luminances as calculated by the CIE mesopic model. Does the CIE model predict that the S/P range selected for this experiment (1.2 – 2.0) would only show differences in mean detected height between the S/P ratios at the lowest luminance, as was actually found in the collected data? Also, what range of S/P might we reasonably expect to find a difference in mean detected heights at higher luminances? Table 7.6 shows the predicted mean detected heights for the 3 S/P ratios at each of the 5 luminances used in the experiment, based on the polynomial regression line fitted to the equivalent mesopic luminances (shown in Figure 7.18). The equation for the polynomial model is:

$$\mathrm{y} = 5.08 - 1.60\, Log_{10}(L_{mes}) - 2.71\, Log_{10}(L_{mes}^{2}) - 1.79\, Log_{10}(L_{mes}^{3})$$

Equation 7.4 Polynomial regression equation for best-fit line between mesopic luminance and predicted mean detected height.

where y is the predicted mean detected height and L_{mes} is the mesopic luminance as calculated by the CIE mesopic model.

Table 7.6 Predicted mean detected heights (mm) by photopic luminance and S/P ratio, based on polynomial model fitted to mesopic luminance for each lighting condition.

	S/P ratio		
Photopic luminance, cd/m^2 (illuminance, lux)	**1.2 (low)**	**1.6 (medium)**	**2.0 (high)**
0.011 (0.2)	10.65	9.78	9.17
0.040 (0.6)	6.77	6.52	6.34
0.127 (2.0)	5.61	5.57	5.55
0.430 (6.3)	5.39	5.38	5.37
1.220 (20.0)	4.91	4.87	4.84

The predicted difference in mean detected heights between the low and high S/P ratios at the lowest luminance condition (0.011 cd/m^2, 0.2 lux) is 1.48 mm. This compares with predicted differences of 0.43, 0.06, 0.02 and 0.07 mm for the four other luminance conditions. This suggests the CIE mesopic model predicts a clear distinction between the lowest luminance condition and the other luminances, reflecting the results that were actually found. To obtain a predicted difference between high and low S/P ratios at the next highest luminance level as large as that found at the lowest luminance (1.48 mm), an S/P range of 0.4 – 2.0 would be required. These S/P values would give predicted mean detected heights of 7.90 and 6.34 mm respectively. Examining the next highest luminance level condition (0.127 cd/m^2, 2.0 lux), it was not possible to achieve a difference in predicted mean detected height equal to 1.48 mm with any realistic range of S/P ratios. This data therefore suggests that, based on the CIE mesopic model, an effect of S/P could have been found at the second lowest luminance level (0.040 cd/m^2, 0.63 lux) if a larger S/P range had been used (0.4 – 2.0). However, an effect of S/P should not have been expected at luminances equal to and above the middle level used in this experiment, 0.127 cd/m^2 (2.0 lux), regardless of the S/P range used.

7.5 Summary

The obstacle detection experiment described in this chapter built on previous research that has examined peripheral detection under different lighting conditions by introducing task elements that made it more representative of a pedestrian walking in a real environment. The results showed that illuminances above 2.0 lux appear to offer no improvement to detection of an obstacle on the floor, demonstrating an escarpment-plateau relationship between peripheral detection and light intensity that has been shown in a number of other studies. Light with a higher S/P level improved detection performance but only at the lowest illuminance level of 0.2 lux. Other studies have found an effect of S/P ratio at different light intensities but these differences can perhaps be explained by the difficulty of the tasks involved. The detection task involved in the current experiment may have been relatively simple and therefore an effect of S/P was only seen when the visual task approach threshold levels, at the lowest illuminance. Had a more complex detection task been used, such as introducing variable locations of the obstacle or a less uniform visual environment, S/P may have influenced detection of the obstacle at higher illuminances. The CIE system of mesopic photometry was applied to the data to determine how well it predicted the results, and to gain an understanding of whether a larger S/P range would have elicited significant spectrum effects at illuminances greater than 0.2 lux. The mesopic system provided an improvement in predicting obstacle detection performance compared with using photopic luminance alone, particularly at the lowest light level used. The system also suggested a size of effect equivalent to that found at 0.2 lux could also have been found at 0.63 lux if an S/P range of 0.4 – 2.0 had been used, but it predicted that no range of S/P could have produced an effect of spectrum at illuminances above this.

The next chapter discusses the implications of the findings from this experiment in terms of road lighting guidelines for pedestrians, and future areas of research required.

CHAPTER 8. SUMMARY AND IMPLICATIONS

8.1 Introduction

The previous chapters in this thesis have reported research that is relevant to pedestrian road lighting. My first aim was to identify the important visual tasks of pedestrians and my second aim was to investigate how lighting influences one of these visual tasks, obstacle detection. My third aim is to draw conclusions from the research about the implications for pedestrian road lighting, and these implications are described in this final chapter. The chapter begins with a summary of the research carried out before outlining the implications of my findings, particularly for defining optimal illuminances and spectral qualities for pedestrian road lighting. I conclude with a discussion about the limitations of my research and some suggestions about future areas of research that would continue to improve the fields of eye-tracking and lighting for pedestrians.

8.2 Summary of thesis

Chapter 1 highlighted that existing guidelines for pedestrian road lighting are not based on robust evidence. Further evidence is required to either confirm that current guidelines are appropriate, or contribute to the development of new guidelines. To ensure road lighting guidelines are effective and fit-for-purpose an understanding of the primary goals of pedestrian road lighting is required. This requires awareness of the critical visual tasks performed by pedestrians after-dark.

An objective way to identify these visual tasks is through eye-tracking. The second chapter reviewed previous eye-tracking literature about visual behaviour and what it can say about where a pedestrian might look whilst outside. Although some common themes emerged, such as looking at areas important in motor-planning or areas learned to be important or unpredictable such as other pedestrians, there are major limitations with previous research. First, the number of studies carried out in real-world, naturalistic environments is limited, and findings from lab-based studies or studies using video footage may not reflect gaze behaviour in the real world (Foulsham et al, 2011). Second, previous studies have not identified whether participants were directing attention towards what they were looking at, or whether what they were looking at was important for safe walking. The locus of our gaze is frequently disconnected from the locus of our attention so to identify gaze behaviour important for safe walking it is necessary to identify instances when gaze and attention are connected. Therefore a dual-task approach was developed which used eye-tracking alongside a secondary, concurrent reaction time task to identify moments when attention may have been directed towards something important in the visual environment. This method was investigated and validated in a pilot study, described in Chapter 3.

Using this dual-task method an eye-tracking experiment, described in Chapter 4, was carried out to identify what pedestrians looked at during these critical moments when attention may have been directed towards something visually significant. Participants walked a short route during the day and after-dark whilst wearing an eye-tracker and carrying out the secondary reaction time task. Critical moments were identified as instances when performance on the secondary task was significantly worse than average, and whatever the participant was looking at during these critical moments was placed into a gaze location category. Results suggested looking at the nearby path, and other pedestrians at a distance, were the two most significant visual behaviours of pedestrians.

The implication from the eye-tracking experiment was that road lighting should facilitate the observation of the near path and other pedestrians. This doctoral research focused on one of these visual behaviours, observation of the path, and in particular detecting obstacles in the path. Obstacle detection is likely to be an important reason for looking at the path and it is therefore important to know how road lighting influences obstacle detection. This task involves peripheral vision, and Chapter 5 reviews previous investigations into the relationship between lighting and peripheral detection. Most of the literature showed effects of light intensity and spectrum on peripheral detection, but there is little consensus on the nature and thresholds of these effects. In addition, most of the previous studies did not realistically reproduce the task elements of obstacle detection by pedestrians in a real street environment. Therefore a new obstacle detection experiment was designed to address these limitations. The new apparatus was tested in pilot studies described in Chapter 6. These pilots also tested key improvements that were planned, such as use of a dynamic fixation target to simulate eye movements of a pedestrian, better maintain and test for foveal vision on the fixation target, and introduce an additional cognitive task. Results from these pilots showed that the new apparatus and its improved elements worked successfully.

The tested apparatus was then used in a full obstacle detection experiment, described in Chapter 7. Participants walked on a treadmill whilst visually tracking the dynamic fixation target. Performance in detecting an obstacle on the floor in front of the participant was measured, whilst the illuminance and spectrum (S/P ratio) of the light in the test environment was systematically varied. Two age groups were recruited, a young (< 35 years) and older (> 50 years) group. Results showed that obstacle detection improved as illuminance increased, but only up to 2.0 lux. Illuminances above this level offered no improvement in obstacle detection, suggesting a plateau had been reached in the relationship between illuminance and performance. Light with a higher S/P ratio led to better obstacle detection but only at the lowest illuminance of 0.2 lux. Above this level, S/P had no effect on detection performance. Likewise, the age of the participant only influenced obstacle detection at this lowest illuminance. Above 0.2 lux both young and old participants performed equally well at detecting the obstacle. The results from this experiment were compared with those from previous studies. The escarpment-plateau relationship between illuminance and peripheral detection performance found in this experiment is consistent with a number of other studies, although the exact point at which the plateau occurs is not consistent. Similarly, the interaction effect between S/P ratio and light intensity varies between studies. These differences can perhaps be explained by the task difficulties involved in the different studies, and how close the detection task is to threshold levels.

This final chapter discusses the implications of the findings collected during this research, in particular what they may mean for pedestrian road lighting guidelines. Some of the limitations with the work are also discussed, and potential future areas of research are highlighted for real-world eye-tracking and to gather appropriate evidence to inform road lighting guidelines.

8.3 Implications of research

8.3.1 Eye-tracking studies

Studying eye-movements in laboratory settings provides important data about fundamental parameters involved in vision and visual behaviour. However it is sometimes difficult to apply these fundamental findings to real, natural situations. One of the strengths of laboratory studies is the control they offer over variables that are not under investigation. This leads to a relatively noise-free environment, where the only variations in stimulus are those controlled and known about by the experimenter. However, the real world is a very noisy environment. We constantly encounter changing scenery, new people, unpredictable events, attention-grabbing images. We are also engaged in a variety of tasks, such as planning our route, looking for hazards, walking and placing our feet appropriately, engaging in internal thoughts. We may also be experiencing different affective states, or being influenced by social contexts, that are difficult to reproduce in lab settings. For example, walking alone on a dimly-lit footpath at night may induce feelings of anxiety or fear; walking towards other pedestrians may make us avoid eye-contact, or conversely look directly towards them. It is therefore difficult to reproduce in laboratory conditions this range of factors we experience as pedestrians in the real world. Generalising visual behaviour from lab studies to the real world is not always appropriate, as demonstrated by differences in visual behaviour between viewing video footage compared with real walking (Foulsham et al, 2011). More studies of eye movements in real-world settings are required in order to develop a more accurate understanding of what we look at and why in normal situations. The review of previous eye-tracking literature presented in Chapter 2 only found 4 studies carried out in natural outdoor settings. Using real-world trials to validate ideas and theories developed in laboratory experiments is a useful approach to combining the merits of both types of study (‘t Hart and Einhauser, 2012).

A major difficulty with real-world eye-tracking studies is being able to discern the signal from the noise – distinguishing visual behaviour that is of note and caused by something of interest from the noise of all other visual behaviour. Stimuli in the real world, and our visual responses to these stimuli, are continuous and non-discrete. It is therefore difficult to isolate significant visual behaviour and their causes, where this is more achievable in a laboratory. A method is required to identify the signal of important gaze from the noise of other gaze, and this is what the dual task approach used in the main eye-tracking experiment attempted to do. One manifestation of the uncontrolled stimuli present in real-world settings is the frequency with which items are encountered. This can lead to noisy data in terms of how often such items are fixated. The dual-task approach for identifying critical observations was shown to be robust against such variations in real-world stimuli however (see Section 4.5.4, Figure 4.12). Identifying critical observations therefore offers potential for reducing the noise within data collected through real-world eye-tracking studies. We used reductions in performance on a secondary task to indicate potential direction of attention to something significant in the external world. However, this is only a proxy measure of attention allocation to visual stimuli. It is very possible that performance on the secondary task is influenced by factors other than whether attention is diverted towards the visual environment. Sounds can be significant distractors and lead to changes in task performance, as can internal thoughts, losses of concentration and mind-wandering (e.g. Barron et al, 2011; Forster and Lavie, 2009). A more direct way of linking attention to gaze location would improve the critical observations method.

8.3.2 Visual tasks of pedestrians

The main eye-tracking experiment used the critical observations approach to identifying significant visual behaviour. The results suggested looking at the path and at other people were important for pedestrians. This supports previous suggestions about what the critical visual tasks of pedestrians are (Caminada and van Bommel, 1984), and provides the first objective corroboration of these previous propositions.

Observation of the path is likely for identifying potential trip hazards or other items on the floor that require negotiation. Observation of other people may have a similar role in terms of planning future walking direction, e.g. in order to avoid walking into the other person. However it is very likely that after-dark pedestrians may look at other people in order to make judgements about their intentions and whether they pose a threat or not. This is the type of task for which consideration of the lighting is important. Seeing another person in silhouette or just as a vague shape is likely to be adequate if the task is just to avoid a collision. However, making a judgement about the other person's intentions may require more visual detail, and the lighting in the area becomes a greater consideration. This leads to the conclusion that in terms of road lighting considerations the visual task pedestrians need to perform when looking at other people is to make a judgement about the intentions of that person and whether any new action is required in response.

A third role for pedestrian road lighting that has been suggested (e.g. Caminada and van Bommel, 1980) and referenced as a consideration in road lighting guidelines (BS 5489-1:2013) is the requirement to provide an environment that is perceived as safe. Feeling safe may be important for pedestrians and if road lighting does not help achieve this it may be less likely to encourage people to walk after-dark, a raison d'etre for pedestrian road lighting. The eye-tracking data collected is not able to confirm whether this is an important consideration for pedestrians. The critical observations data relates to specific categories of item, object or area, whereas the judgement about whether an area feels safe is likely to come from multiple observations of different parts of the scene (Fisher and Nasar, 1992). Other methods of research however have suggested perceived safety is very important to pedestrians, and is influenced by the lighting conditions (Loewen, Steel and Suedfeld, 1993; Boyce et al, 2000).

8.3.3 Pedestrian road lighting guidelines – obstacle detection

A main aim of investigating the effects of lighting on obstacle detection was to provide evidence that can be used to either support existing guidelines for pedestrian road lighting or develop new guidelines that are better based on objective data. The two key lighting characteristics under investigation were:

1) Light intensity – characterised as horizontal illuminance as this is the metric currently specified in guidance documents (e.g. BS 5489-1:2013 and BS EN 13201-2:2003) and will be familiar to road lighting practitioners

2) Spectral Power Distribution – characterised using the S/P ratio as this gives a simple measure of a light source's mesopic efficacy and can be easily applied by road lighting practitioners, and is also currently referred to in guidance documents

Other lighting factors that are also of relevance in terms of road lighting guidelines include the spatial distribution of lighting, the glare properties of the light source and the colour appearance of the light. Light intensity and spectrum were selected for investigation as these are two fundamental properties of the light that may take primacy over these other characteristics in terms of their influence on the performance of visual tasks carried out by pedestrians.

To determine the optimal illuminance road lighting should provide for pedestrians three approaches to applying the obstacle detection experiment data are now examined:

1) The legal liability approach

2) The plateau approach

3) The toe clearance approach

The legal liability approach suggests that road lighting should provide enough light to enable detection of an obstacle size that could otherwise place a tripping liability on those responsible for maintenance of the footpath, usually Local Authorities. Fotios and Cheal (2013) review evidence about what obstacle size could place liability on Local Authorities, such as policy documents and information from solicitors, and suggest 25 mm as the critical height. What illuminance is required to detect an obstacle of this size? A high probability of detection would be required to minimise any potential liability. Figure 7 shows the heights for a 50% detection probability, estimated using the 4PLE. This probability of detection is too low if the aim of lighting is to minimise the risk of liability on Local Authorities. The four parameter logistic equation (4PLE) can be used to estimate heights for different probabilities of detection. The obstacle heights for a 95% detection probability are shown in Table 8.1 for the different conditions used in the obstacle detection study.

Table 8.1. Obstacle heights (mm) for 95% detection probability, as calculated by 4PLE, for each illuminance, S/P ratio and age group. Low S/P = 1.2; Med S/P = 1.6; High S/P = 2.0.

Illuminance (lux)	**Obstacle height (mm) for 95% detection (h_{95}) according to age group and S/P ratio**								
	Young (<35 years)			**Old (>50 years)**			**Combined**		
	Low	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
0.2	14.29	14.81	12.08	16.68	13.86	12.51	15.71	15.68	13.75
0.6	8.87	6.22	7.78	11.61	12.00	9.42	10.34	10.27	8.72
2.0	7.52	9.24	10.67	7.12	10.03	6.57	7.47	10.55	8.94
6.3	5.88	8.29	11.83	5.82	7.65	9.49	5.86	9.08	10.90
20.0	9.05	10.34	8.31	10.55	9.98	10.27	9.52	10.23	9.38

The largest obstacle height with a 95% detection probability is for the old age group at 0.2 lux illuminance at the low S/P level, this being 16.68 mm. This obstacle height is still well below the 25 mm height defined as threshold for legal liability. This suggests an illuminance of 0.2 lux would be sufficient as a recommended guideline if these guidelines were based on the legal liability approach. Fotios and Cheal (2013) also use the 4PLE to estimate obstacle heights for a 95% detection probability. Their data suggests an illuminance of 0.13 lux would be required for detecting a 25 mm obstacle at a distance of 2.4 m, approximately the same distance as used in the current experiment. This data is based on performance by young people, so we might expect detection by an older person to require an illuminance closer to 0.2 lux as suggested by the current experiment's data.

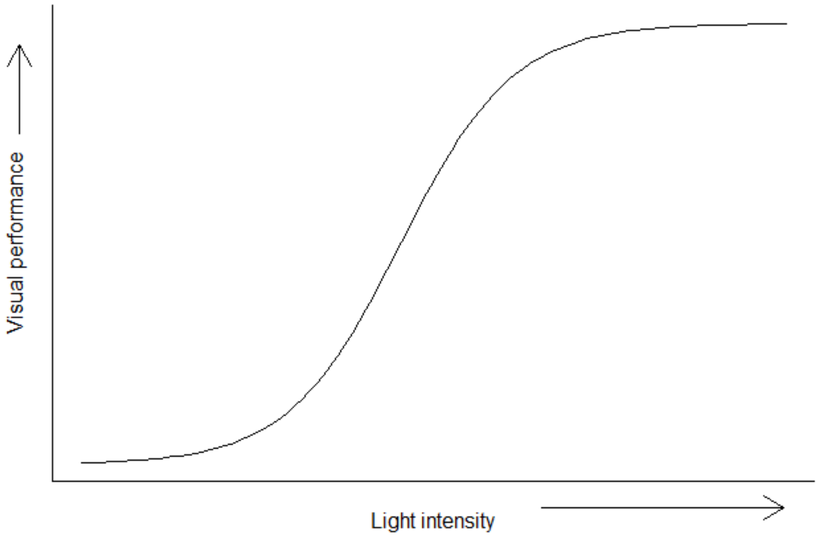


Figure 8.1. Illustrative example of escarpment-plateau relationship between visual performance and light quantities, such as light intensity (e.g. illuminance).

Visual performance often shows an escarpment-plateau relationship with lighting quantities, such as illuminance (Boyce and Rea, 1987). An illustration of this relationship is shown in Figure 8.1. As can be seen, visual performance is low at low illuminance levels, increasing rapidly in the escarpment region of the relationship pot, before reaching a plateau of maximal performance. The plateau approach to defining road lighting guidelines asks at what illuminance level obstacle detection performance plateaus, at which point providing additional illuminance gives no added benefit to the ability to detect obstacles in the path. In the main obstacle detection experiment this point of plateau was suggested to be at 2.0 lux. No difference was found in detection performance between the illuminances of 2.0, 6.3 and 20.0 lux, suggesting performance had plateaued at 2.0 lux. This plateau approach would suggest the guidelines for pedestrian road lighting should recommend an illuminance of 2.0 lux, as this is the lowest illuminance that provides optimal obstacle detection performance. Illuminances that were higher than this would potentially be wasting energy, as no obstacle detection benefit would be gained. This point of plateau is similar to that found in Fotios and Cheal (2013). They suggest detection performance begins to plateau at around 2.0 lux. Alferdinck (2006) and Eloholma et al (2006) both report data suggesting a plateau in performance as light intensity increases. They both used luminance rather than illuminance, and reflectance properties of surfaces are not reported so illuminance values cannot be calculated. Alferdinck’s data suggests a plateau is reached at around 1 cd/m^2. This would be equivalent to approximately 16 lux in the current experiment, based on the linear correlation between illuminance and luminance measurements at the top of the obstacle (see Table 7.2). Eloholma et al’s data suggest a plateau at about 0.1 cd/m^2. This would be equivalent to an approximate illuminance of 1.5 lux in the current experiment. This is more in line with the plateau suggested by my data, and by that of Fotios and Cheal.

The toe clearance approach asks what illuminance is required to ensure obstacles large enough to trip a normal walker are detectable. Toe clearance is the term used to describe the vertical distance between the toe and the floor during the swing phase of walking. Tripping occurs when the swing foot contacts the floor or an object (Tinetti, Speechley and Ginter, 1988), and the greatest risk of a trip occurring is when the toe clearance distance is at its lowest (Begg, et al, 2007). This is known as *minimum toe clearance*, or MTC. Obstacles that are larger than the MTC have the potential to trip a pedestrian. The toe clearance approach to defining road lighting guidelines would stipulate what illuminance is required to allow detection of obstacles that are as large as or larger than the MTC of pedestrians. The average MTC of normal walkers has been estimated as 15 mm, and no difference is found between young and older adults (Begg et al, 2007). However, older people tend to have greater variability in their MTC, and a larger variability may make tripping more likely as there will be more instances when the MTC during a stride approaches critically low levels (Mills, Barrett and Morrison, 2007). The variability of MTC is estimated at between 2.5 – 4.0 mm (Begg et al, 2007), depending on the measure of variability used and whether the walker is young or old. Taking the maximum estimate of MTC variability and subtracting it from the average MTC gives a height of 11 mm. This can be seen as a critical height in terms of potential tripping hazards. Obstacles larger than this will have significant potential for tripping a pedestrian if not seen. Therefore according to the toe clearance approach to defining optimal illuminance levels for road lighting, the illuminance should be enough to allow regular detection of an 11 mm obstacle. Revisiting Table 8.1, which shows the obstacle heights with 95% detection probability for the different lighting conditions and age groups, an illuminance somewhere between 0.6 and 2.0 lux would be sufficient for regular detection of an 11 mm obstacle, based on data from the current experiment. Detection of an equivalent-sized obstacle in Fotios and Cheal (after converting sizes to visual angle subtended, as the viewing distance was much closer in Fotios and Cheal compared with the current experiment) at 95% detection probability required an illuminance of approximately 2 lux.

A summary of the three different approaches to defining optimal illuminances for pedestrian road lighting is given in Table 8.2.

Table 8.2. Summary of different approaches to defining optimal illuminance for pedestrian road lighting, based on current results and other results where applicable.

Method	**Description**	**Optimal illuminance – current results**	**Optimal illuminance – other results**
Legal liability approach	Local authorities, who are responsible for installing and maintaining road lighting, could reduce legal liability for trips if lighting allows detection of 25 mm obstacle. Therefore illuminance required to detect obstacle of this size can indicate optimal illuminance.	< 0.2 lux	0.13 lux – Fotios and Cheal (2013)
Plateau approach	Obstacle detection performance plateaus as illuminance increases. Identifying point of plateau can indicate optimal illuminance.	2.0 lux	1.5 lux – Eloholma et al (2006) 2.0 lux – Fotios and Cheal (2013) ≈16 lux – Alferdinck (2006)
Toe clearance approach	Obstacles that are larger than minimum toe clearance (MTC) during walking have the potential to trip pedestrians. Identifying illuminance required to see obstacles of this size can indicate optimal illuminance.	0.6 – 2.0 lux	2.0 lux – Fotios and Cheal (2013)

Turning now to what the evidence says about optimal SPD characteristics for pedestrian road lighting, the current experiment only showed an effect of spectrum at the lowest illuminance used, 0.2 lux. Lighting with an S/P ratio of 1.2 – 2.0 was used in this experiment and a higher S/P ratio enabled better detection of an obstacle. Data suggested the high S/P ratio allowed detection of an obstacle that 2 mm smaller than under the low S/P lighting, at the 0.2 lux illuminance. This may sound a fairly insignificant improvement but considering an obstacle size of only 11 mm can potentially offer a tripping hazard for pedestrians based on average variability in minimum toe clearance distances, this improvement could be critical in supporting detection of a trip hazard. The implication of this for pedestrian road lighting guidelines is that light with a higher S/P ratio should be used in areas where low illuminances (< 0.6 lux) are provided, in order to improve a pedestrian's ability to see potentially dangerous obstacles. This could be an important tool in the lighting designer's toolbox if they want to reduce energy consumption of road lighting by reducing illuminance levels – a reduction to illuminances below 0.6 lux could be offset by an increase in S/P ratio. If illuminances above 0.2 lux are used the current data suggests S/P ratio may not need to be a consideration for the lighting designer, in terms of enabling adequate obstacle detection. However, it is worth noting that other studies have found an effect of S/P ratio at higher light levels than that found in the current experiment (e.g. Bullough and Rea, 2000; He et al, 1997; Alferdinck, 2006). The influence of S/P on obstacle detection and the light level at which this influence occurs may be a function of the difficulty of the task involved and the visual environment. As these factors will constantly vary for pedestrians it may be beneficial to err on the side of caution and assume an effect of S/P at higher illuminances than that suggested by the obstacle detection experiment presented in this thesis.

To summarise the implications of the findings presented in this thesis for pedestrian road lighting guidelines, three approaches could be used to define optimal illuminance values – the legal liability approach, the plateau approach and the toe clearance approach. These three approaches lead to recommended illuminances of between 0.2 and 2.0 lux. In terms of the S/P ratio of the road lighting, the current data alongside findings from other studies suggest a higher S/P should be used particularly at lower illuminance levels, although what illuminance levels this may be, and what S/P ratio should be used, is not yet known.

8.4 Pedestrian road lighting guidelines – other considerations

Section 8.3 describes implications for pedestrian road lighting guidelines based on how the lighting influences a critical visual task of pedestrians, detecting obstacles. However, as discussed in section 8.3.2 other factors are likely to be important when considering the characteristics of road lighting for pedestrians, such as how they facilitate interpersonal judgements and how they influence perceptions of safety. These two factors have been investigated alongside the obstacle detection work presented in this thesis, as part of the MERLIN project (see section 1.6). Findings from this other work in relation to optimal lighting characteristics for pedestrian road lighting are summarised here and compared with conclusions based on obstacle detection.

Fotios, Yang and Cheal (2015) investigated the influence of spectrum and luminance on judgements about the emotion and gaze direction of people, based on their facial expressions and body postures. Images of faces and body postures showing different recognised emotions (e.g. fear, happiness, anger) were presented for 1000 ms to participants under different lighting conditions, and performance in correctly recognising the displayed emotion was recorded. Two light sources were used, a High Pressure Sodium and a Metal Halide lamp with S/P ratios of 0.57 and 1.77 respectively, and three luminance levels, 0.01, 0.1 and 1.0 cd/m^2. The images were presented on a non-luminous screen positioned within a viewing chamber, with the size of the image varied to simulate a range of viewing distances between 2 and 135 m, based on visual angle subtended. Results showed correct identification of emotion and gaze direction improved as luminance increased, and as the simulated distance decreased. For the facial expression and body posture tasks an escarpment-plateau relationship was suggested between luminance and performance, with a luminance of 0.1 cd/m^2 required for adequate recognition of facial expressions at a distance of 4 m and of body posture at a distance of up to 30 m. Increasing the viewing distance of facial expressions to 10 m meant a luminance of at least 1.0 cd/m^2 was required, and a luminance of at least this amount was required for recognition of gaze direction at 2 m distance above chance levels. The lamp type was not found to have a conclusive effect on judgements in any of the tasks.

This study was further developed in an additional investigation (Yang and Fotios, 2014) in which more luminance levels were included creating a luminance range of 0.01 – 3.33 cd/^{2}. A third type of lamp was also introduced, with an S/P ratio of 1.22, and an additional level of difficulty was included for the viewing task by including a condition in which images were viewed for 500 ms, as well as the 1000 ms viewing time used in the original experiment. This latter addition was included as analysis of the eye-tracking videos recorded during the pedestrian eye-tracker experiment (presented in Chapter 4) suggested pedestrians fixate other people for an average of 500 ms (Fotios, Yang and Uttley, 2015). Only the facial expression task was carried out in this new study, and at simulated distances of 4 and 15 m. Luminance was again shown to have a significant effect on successful judgements of emotion. At the 4 m distance the effect of luminance plateaued, with the plateau occurring at around 0.33 cd/m^2. However at a distance of 15 m a plateau in performance did not appear to have been reached even at the highest luminance of 3.33 cd/m^2. This suggested luminances greater than this could still bring improvements to performance in terms of judging the emotions of other pedestrians on the street. As with the first study however, no effect of lamp type was found, suggesting the S/P ratio of a light source may not influence judgements of emotion under the conditions examined in these two studies.

Conclusions from the above two studies about the optimal luminance levels for making judgements about the emotions of other pedestrians depend on the distance assumed for making such judgements. A lower optimal luminance is required if this distance is assumed to be 4 m compared with 15 m, for example. It is therefore important to know at what distance pedestrians do indeed need to make these judgements. Results from the eye-tracking experiment carried out in Chapter 4 suggested that other pedestrians were more likely to be looked at during critical times at a far distance (> 4 m) as opposed to a near distance (see Figure 4.10). The eye-tracking videos have been analysed in further work (Fotios, Yang and Uttley, 2015). This involved estimating the distance at which every fixation of another pedestrian occurred. Based on this analysis a distance of 15 m was suggested as being a useful distance on which to base assumptions about the interpersonal distance at which judgements of other pedestrians are made. At this distance a luminance above 3.33 cd/m^2 would be required in order to reach a plateau in performance. An alternative approach to specifying an optimal light level is to set a probability of correct detection and estimate the luminance required to meet this probability. For example, assuming a 50% probability of correct identification data from Yang and Fotios (2014) suggested a luminance of approximately 1.0 cd/m^2 would be required. This represented an illuminance of approximately 20 lux at the surface of the screen displaying the facial images.

Alongside obstacle detection and interpersonal judgements, a third consideration for lighting and its role for pedestrians after dark that is often cited as being important (e.g. Caminada and van Bommel, 1984; BS 4589-1: 2013) is the effect it has on the perceived safety or assessment of risk in a street or area. A study of the role of road lighting in perceptions of safety, also termed a feeling of reassurance, was carried out by Fotios, Unwin and Farrall (2014). Participants in the study were asked to provide photographs of streets they felt confident walking along alone at night, and streets they did not feel confident walking along alone at night. Participants were subsequently interviewed and asked to comment on their choices of street, giving reasons for choosing the locations. However, the interviewer did not make any reference to lighting, or to fear, crime or other such primed terms, to avoid biasing the comments made by participants. The resulting discussions were analysed and reasons for feelings of reassurance or lack of reassurance were placed into categories. One of these categories was road lighting, and this had the second most frequent mentions, behind only the ‘Access to help’ category. This was taken as evidence that road lighting does indeed influence perceptions of safety and feelings of reassurance, supporting other research that has shown a similar link (e.g. Loewen, Steel and Suedfeld, 1993; Painter, 1994, 1996).

Having established the link between road lighting and reassurance, Fotios, Unwin and Farrall go on to review research about the relationship between road lighting illuminance and spectrum and levels of reassurance. They suggest a higher illuminance does lead to improved feelings of reassurance, although they highlight a study by Boyce et al (2000) that suggests an optimal illuminance is around 10 lux, with increases beyond this amount bringing little added benefit to feelings of reassurance. Fotios and colleagues also suggest the spectrum of the light, specifically the S/P ratio, influences perceptions of reassurance. Light with a higher S/P ratio tends to be perceived as brighter than light with a lower S/P ratio, and brightness appears correlated with feelings of safety (Blobaum and Hunecke, 2005). This connection between spectrum and reassurance is confirmed by a number of field studies (Knight, 2010; Morante, 2008; Akashi, Rea and Morante, 2004), leading Fotios, Unwin and Farrall (2014) to conclude that light with a higher S/P ratio will usually lead to increased feelings of reassurance.

8.5 Summary of pedestrian road lighting implications

Obstacle detection is a critical task for pedestrians. Three possible approaches to defining a recommended illuminance level for pedestrian road lighting based on enabling satisfactory obstacle detection are the legal liability approach, the plateau approach and the toe clearance approach. For the legal liability approach, data reported in this thesis suggests an illuminance of 0.2 lux would be sufficient. This is similar to the illuminance suggested by data from Fotios and Cheal (2013). For the plateau approach, an illuminance of 2.0 lux would be sufficient, with greater illuminances providing no additional benefit. This threshold illuminance is also suggested by Fotios and Cheal (2013), and is close to the 1.5 lux threshold suggested by the data of Eloholma et al (2006). For the toe clearance approach an illuminance somewhere between 0.6 and 2.0 lux would be sufficient for seeing an obstacle large enough to be a potential trip hazard with 95% certainty. Data from Fotios and Cheal (2013) agrees with the upper value of this range, suggesting the illuminance required is approximately 2.0 lux. Based on these conclusions, a minimum illuminance of 2.0 lux would be sufficient for adequate obstacle detection by pedestrians, regardless of which approach is selected for defining this value.

However, if other tasks or purposes of road lighting are to be considered in defining a recommended illuminance level, a higher value may be required. Considering the task of making judgements about the intentions of others for example, the work of Yang and Fotios suggested an illuminance of 20 lux would be required for pedestrians to achieve reasonable success in making interpersonal judgements about other pedestrians, this being the threshold value for achieving 50% probability of correct identification of the emotions used in their studies at 15 m. An even higher illuminance than this could offer further improvements in this task, as 20 lux appeared below the point of plateau in performance. Now, considering the role of road lighting in making pedestrians feel safe and reassured, Fotios, Unwin and Farrall suggest a minimum illuminance of at least 10 lux could be an optimal value, as based on the work of Boyce et al (2000) this represented a plateau point, above which feelings of reassurance no longer increase.

It is therefore apparent that defining recommended illuminances in pedestrian road lighting guidelines based purely on being able to detect obstacles would lead to a much lower illuminance than if it is based on other purposes of the lighting such as enabling satisfactory interpersonal judgements to be made and endowing feelings of reassurance. The existing guidelines for pedestrian road lighting (see Table 1.2) provide recommended average horizontal illuminances for six classes of road or area. Five out of six of these classes have recommended illuminances above the 2.0 lux suggested to be a suitable illuminance for obstacle detection purposes. These recommendations therefore need to be justified with reasons other than obstacle detection. Such justification perhaps requires an acknowledgement of the relative weighting or importance that is placed on different pedestrian tasks or requirements, i.e. obstacle detection, interpersonal judgements and reassurance in different types of road or environment. The evidence presented in this thesis suggest it is not acceptable to justify illuminance levels above 2.0 lux based on obstacle detection goals alone – other justifications need to be sought.

Table 8.3 provides a summary of the optimal illuminances suggested by the three different visual tasks or purposes of road lighting for pedestrians, discussed above.

Table 8.3. Summary of suggested optimal illuminances and supporting evidence, based on different visual tasks or purposes of road lighting.

Visual task / purpose of road lighting	Suggested optimal illuminance	Supporting research
Obstacle detection	2.0 lux	Current results Fotios and Cheal (2013) Eloholma et al (2006)
Interpersonal judgements	20.0 lux	Fotios, Yang and Cheal (2013) Yang and Fotios (2014) Fotios, Yang and Uttley (2015)
Reassurance / perceived safety	10.0 lux	Fotios, Unwin and Farrall (2014) Boyce et al (2000)

8.6 Research limitations

8.6.1 Defining visual tasks of pedestrians

The eye-tracking experiment reported in Chapter 4 was designed to identify what the critical visual tasks of pedestrians are. It did this by recording the eye movements of pedestrians walking in a real environment to determine what they looked at during significant, potentially important times. One possible criticism of this approach is the method of recording the eye movements, the eye-tracking apparatus, may have influenced the wearer’s eye movements, resulting in artefactual data being produced. The purpose of the eye-tracking equipment was not specifically explained to participants until after they had completed both trials, but there was no avoiding some reference to eyes and vision, as the equipment necessitated placement of a mirror to capture an image from the eye and also visual calibration, both of which required the participants’ cooperation. It is therefore probable that many of the participants were able to guess the purpose of the equipment, and that it was recording something to do with their gaze and where they were looking. This may have created an implied ‘social presence’, resulting in a consciousness about where they looked, as people often behave differently when they know they are being observed (e.g. Bond and Titus, 1983). This effect has previously been demonstrated. Risko and Kingstone (2011) showed that wearing an eye-tracker produced an implied social presence which altered looking behaviour – wearers of the eye-tracker avoided looking at particular stimuli. However, eye movements are often involuntary and even though wearers of the eye-tracker may be conscious about where their eyes are pointing, this may not influence the type of automatic shifts of gaze and attention that occur when something of significance becomes visible in the environment. The dual task approach used during the eye-tracker experiment attempted to identify when participants were looking at something visually important, and gaze at these critical moments may have been less likely to be influenced by awareness of the eye-tracker and the implied social presence it represented.

The method used to define critical moments in the eye-tracker experiment was to identify responses to the secondary reaction time task that were significantly worse than average. The threshold for defining ‘significantly worse’ was 2 standard deviations above the participant’s mean reaction time. This threshold was selected due to statistical distribution properties, with 2 standard deviations representing ‘outlying’ values by standard conventions, but it may represent a relatively arbitrary measure. It is possible that responses beyond this threshold may not have been due to a diversion of attention away from the reaction task. Likewise, it is also possible that diversion of attention away from this task could result in responses that were less than 2 standard deviations above the mean. The 2 standard deviations threshold was selected as a first approach to identifying critical moments, and this threshold may require further justification. One result that can give some confidence however that the 2 standard deviations does not greatly miss the mark are the standard deviations in reaction times recorded during the pilot study used to justify reaction to an auditory stimulus as an appropriate task (see section 4.4.3). For example, in task one of the pilot study (section 3.3.1) the mean reaction time to the auditory stimulus when no distractors were present was 241 ms (combined across before and after stages), with a standard deviation of 49 ms. The mean reaction time during the distraction stage was 388 ms, which is 3 standard deviations above the mean reaction time with no distractors, only one standard deviation greater than the threshold used for identifying critical moments in the main eye-tracker experiment.

Once critical moments had been identified, critical observations were defined by making a judgement about what was the most significant category of item or area within a 2-second window around this critical moment. The 2-second window was a relatively arbitrary length of time within which to identify the thing that may have caused the diversion of attention, and was partly dictated by the potential length of time between beeps on the reaction time task. However, a 1-second period before and after the instance of delayed response appears appropriate. It is possible that whatever caused the poor response occurred more than a second before the button press. If this was the case, there is a good chance it would have been captured by response on the preceding beep and therefore the significant item still recorded as a critical observation. It is unlikely that participants diverted their gaze to whatever caused the diversion of attention more than a second after the poor reaction time was recorded. If something visual grabs our attention there is no obvious reason not to divert our gaze towards it.

Latencies between the direction of our attention and the direction of our gaze are generally below 500 ms (e.g. Hoffman and Subramaniam, 1995; Posner, 1980) and so it is unlikely it would take more than a second for someone to direct their gaze towards a visual stimulus that grabbed their attention.

In the eye-tracker experiment, a slow response to the auditory beep was interpreted as being a result of a diversion of attention away from this response task and towards something else. This ‘something else’ was always assumed to be something visual, as every critical moment was included for determination of a critical observation. However, it is possible that the slow response was caused by the redirection of attention towards something non-visual, for example some internal thought or a sound. It is also possible that yes, something visual was the cause for a redirection of attention, but this visual stimulus had no relevance to the task of walking safely. This was the task I aimed to investigate with the eye-tracking experiment, and it was observations of types of object or area that facilitated this safe walking that I hoped to identify. However, redirection of attention due to seeing a funny advertising slogan or piece of graffiti, or seeing someone you know on the other side of the street, is not the visual behaviour the dual task was aiming to identify. However, it is very difficult to separate these types of instance, which we can call ‘task-irrelevant’ critical moments (the task of interest being walking safely), from the critical moments we are interested in, when attention is directed towards something in the visual environment that is significant for a pedestrian walking safely. This perhaps has to be accepted as a limitation of the dual task method, but we should at least acknowledge even with this limitation the approach offers an improvement on merely using all fixations at all times, throughout the participant’s walk.

The categorisation of the critical observation within the 2-second window was a subjective judgement made by the coder viewing the videos. During this time a number of fixations are likely to have occurred, given that the average duration of a fixation is around 330 ms (Henderson, 2003). It is possible that all fixations during the 2-second window were on the same object or item, in which case no decision was required. However, the fixations could have been on more than one category of item / area. In this case the coder would have to judge which fixation was the most important, most likely to have caused the diversion of attention. This was a subjective decision, and with a different coder a different set of results could have occurred. To check this a second coder was used to analyse a portion of the videos, and there was 63% agreement between the two coders on the allocation of critical observations to one of eight categories. However, this agreement increased to more than 90% when the number of categories were reduced to three, Person, Path and Other, the categories used in past studies of outdoor fixations (Foulsham et al, 2011; Davoudian and

Raynham, 2012). The critical observations data was used to conclude that the path and other people were the two most significant types of things pedestrians look at, and the high agreement between coders when using just these two categories and a third category suggests the subjectivity that may be present in the judgements about critical observation categorisation is less apparent when categorising observations at path and people.

As discussed in section 4.5.4, one limitation of using an eye-tracking field experiment to determine what may be visually important to pedestrians is that the frequency with which different items or objects may influence the extent to which those things are looked at. If a particular category of item, such as a vehicle, never appears throughout a participant's trial, that category of item can never be looked at. It does not mean to say it is unimportant to pedestrians. Likewise, an item category that is frequently visible to the participant may be looked at numerous times simply because it is often in the participant's field of view, regardless of how important the pedestrian perceives it to be. The critical observations approach attempted to address this limitation by only examining what pedestrians looked at during critical moments, not throughout their journey. Using observations of other pedestrians as an example, the critical observations approach was shown to be robust against changes in the frequency with which other pedestrians were encountered (see Figure 4.12). However this does not rule out the possibility that data from the critical observations approach could still be influenced by how frequently different items are encountered. It may be that the method is not robust to changes in the frequency of other item categories, and frequency of encounters is still likely to influence critical observations data if it is at an extreme value, e.g. close to or at zero encounters, or a very high number of encounters. This has to be accepted as one of the potential negative aspects of a field experiment, in which the stimuli encountered by participants cannot be tightly controlled and may influence resulting visual behaviour.

8.6.2 Obstacle detection and lighting

The effect of lighting on the ability to detect obstacles was investigated in a laboratory experiment which used a dynamic fixation target and walking on a treadmill to introduce improvements to experimental designs of previous peripheral detection research. One of the purposes of the dynamic fixation target was to hold the foveal gaze of participants, so that peripheral vision was being used to detect the obstacle in its position on the floor. However, as eye-tracking was not used during the main experiment, it cannot be guaranteed that peripheral vision was always being used when the obstacle was detected by the participant. One attempt at testing whether the fixation target was indeed holding foveal vision was instructing participants to read aloud the number each time the target changed. It was assumed that a high proportion of correct identifications would indicate participants were generally looking at the fixation target and not at the obstacle. At 92%, correct identification of the digit was high. It is possible participants correctly identified the digit whilst not looking directly at it although this would be a difficult task, as visual acuity decreases rapidly with eccentricity from the fovea due to the lack of cone photoreceptors in the peripheral retina (see Boyce, 2014). The minimum visual angle between obstacle and fixation target was 22.1°, and would almost always be larger than this. It is also possible that participants may have been using their foveal vision to correctly identify the digit, but in the interval between two changes to digits may have glanced downwards to use foveal vision to confirm whether the obstacle was present or not. Results from the pilot study using eye-tracking, reported in section 6.9, did not suggest this was likely. However, wearing the eye-tracker may have altered participants looking behaviour and given them a greater obligation not to look towards the obstacle than if they were not wearing the eye-tracker. If this was the case, we might expect obstacle detection performance when not wearing the eye-tracker to be better than when it was being worn, if it meant participants felt less obligated to maintain foveal vision on the fixation target. However, detection results whilst wearing the eye-tracker were very similar to those when not wearing it – mean overall detection rate without the eye-tracker (from pilot study one) was 72%, on the walking condition, and with the eye-tracker (from pilot study two) this was 74% for equivalent conditions. In conclusion, whilst it is possible participants occasionally used foveal vision for detecting the obstacle and so this has to be recognised as a potential limitation of this experiment, data from the correct identification of the dynamic fixation target when it changed to a digit, and data from the eye-tracking pilot study, suggest this was unlikely to have occurred frequently.

The fixation target used in the obstacle detection experiment was constantly moving within an elliptical area on the far wall of the test environment. This was intended to simulate the real eye movements of a pedestrian. However, a limitation of this approach was that the angle between the fixation target and the obstacle was always changing. The possible angle between target and obstacle at any one time lay in the range 22.1° - 37.9°. The probability of the actual visual angle between target and obstacle at any point in time was not evenly distributed within this range however, given the elliptical shape of the area of possible locations. The exact position of the target was recorded by the experiment program every 12 ms, and from this it is possible to calculate the visual angle between target and obstacle at every 12 ms instance, for all conditions and all participants. This allows creation of a probability curve for what the target-obstacle visual angle was at any point during a trial, shown in Figure 8.2. This shows how the target is most likely to be at an eccentricity of around 30° from the obstacle, with the probability of a larger or smaller eccentricity progressively decreasing. The target spent over half (52%) the time it was visible within the visual angle range of 27-32° from the obstacle. Therefore, although it was possible for the target to be at the extremes of the range of potential visual angles when the obstacle appeared, it was most likely that it was within a smaller range of possible angles. This may have helped minimise the influence eccentricity of target to obstacle had on detection performance, although an effect cannot be excluded completely.

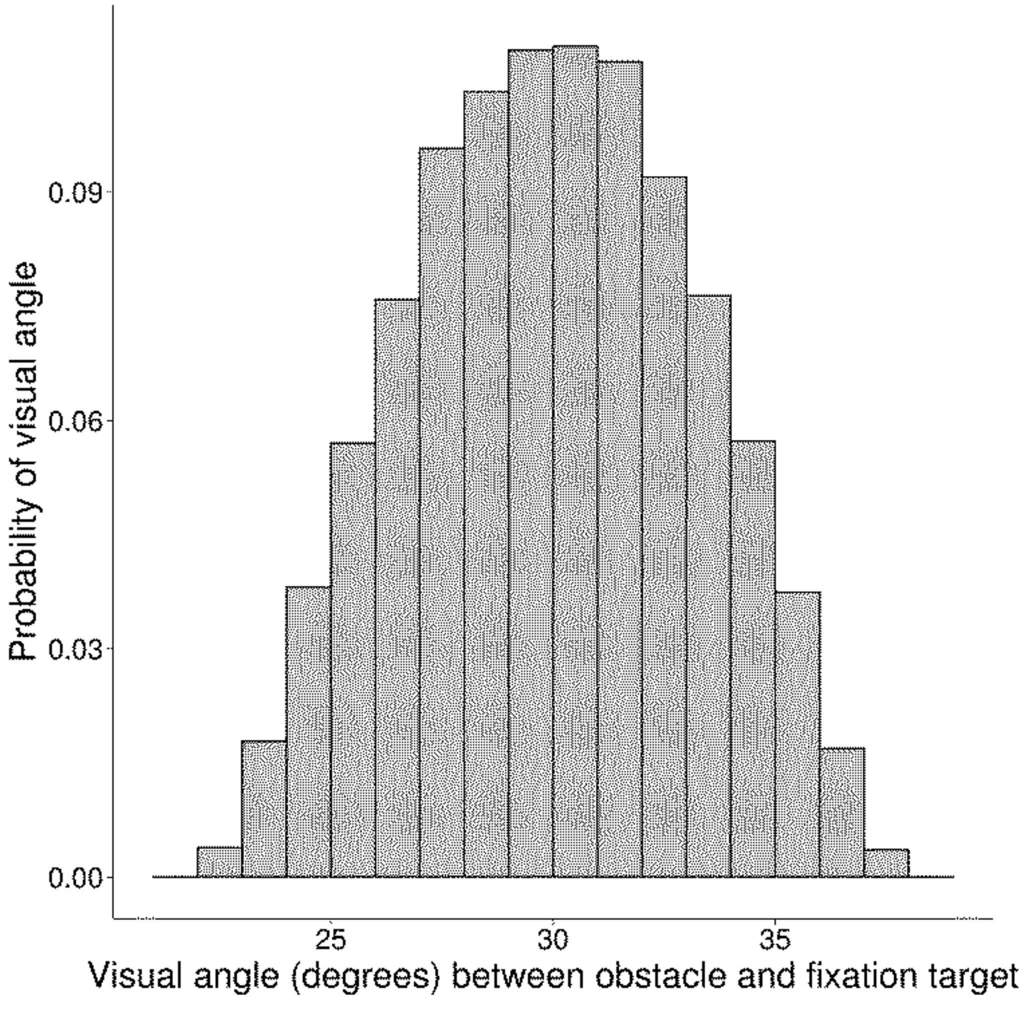


Figure 8.2. Probability of visual angle between fixation target and obstacle at any instant during an experiment trial. Calculated from records of target position every 12 ms. Based on eye-height of 1.5 m.

The obstacle detection experiment reported in this thesis attempted to improve the applicability of findings to the pedestrian context compared with previous studies of peripheral detection by introducing elements that increased the realism, such as the dynamic fixation target and walking on the treadmill. However, certain aspects of the apparatus remained relatively abstract and unrealistic, which was a potential limitation of the study. For example, the surface of the floor out of which the obstacle rose was smooth and uniform in colour and texture. This is unlike the pavements and paths that pedestrians might experience in the real world. The front edge of the obstacle when raised presents an area of higher contrast that is dissimilar to the rest of the floor surface. On a real pavement with a less uniform surface there are likely to be other areas of higher contrast which may act as visual distractors or 'noise', disrupting the signal from a real obstacle or trip hazard and making it more difficult to detect (Duncan and Humphreys, 1989). Furthermore, the rest of the visual environment in the experiment was plain and, with the exception of the moving and changing fixation target, contained little to distract or capture the attention of the participant. This again is not reflective of a real pedestrian environment, which might contain buildings, vehicles, other people, notices or billboards, wildlife and so on. Although the dynamic fixation target attempted to create a distraction and occupy some cognitive capacity in the participant, it is unlikely to have adequately replicated the diversionary qualities of a natural outdoor environment. This fact may explain why an effect of S/P ratio was only found at the lowest illuminance. Bullough and Rea (2000) suggest that visual noise and the amount of distraction in a visual environment is a factor in determining the threshold of light intensity at which spectrum begins to influence peripheral detection. Increased visual distraction brings the peripheral detection task closer to threshold levels, enabling spectrum to influence performance. The influence of visual distraction and noise on detection performance is also relevant when considering the obstacle detection experiment was laboratory-based with tightly controlled conditions. As already discussed above, despite efforts to improve the representativeness of the paradigm in comparison to previous similar studies, the fact remains that there were limitations in terms of how realistic the task and situation was. In the real world there will be significant visual distractions and environmental features to attract attention away from a potential obstacle, and this needs considering when interpreting the results from the current experiment. It is possible that detection performance in a real-world setting may not be as good as found in this laboratory setting. However, it is also worth noting the results from the obstacle detection pilot study one (see Section 6.3). Detection performance was actually better when walking compared with standing, and this may have been due to improved perception of the environment due to the action of walking (see results from action-specific perception literature, discussed in that section). It is therefore just as possible that when out in the real world our perception of the environment and features that we may need to respond to, such as obstacles in our path, our detection performance may be heightened due to the action-specific nature of the task, compared with when in a laboratory setting. This may counteract to some extent any effect of the additional visual noise and distractors that are present. However, until this concept is investigated it remains conjecture, and the 2 lux threshold for detection identified in the current results should be viewed with some caution, perhaps as a minimum illuminance required rather than a maximum.

A further limitation of the obstacle detection study was that the obstacle always appeared in the same location. This will have created an expectation in the participant which may have influenced their performance in detecting the obstacle, for example by participants covertly attending to the obstacle area (Posner, 1980). It should be noted however that the relative position of the obstacle in relation to where they were currently fixating was constantly changing due to the random movements of the fixation target.

The obstacle area was lit from above by two LED arrays. The position of the arrays was fixed, to always create the same distribution of light on the obstacle and the surrounding surface. In real pedestrian situations however the direction of light from road lighting in relation to the pedestrian will constantly change as they move through the environment. This will create variation in the manner in which obstacles are illuminated which could have differential effects on the ability to detect them. Consider for example if the light source was positioned further away from the pedestrian than the obstacle. This would create a shadow in front of the obstacle, from the perspective of the pedestrian, and would also result in a greater luminance contrast between the top and front surfaces of the obstacle compared with if lit from directly above. Both these facts would in theory lead to easier detection of the obstacle. In contrast however, if the light source was positioned closer to the pedestrian than the obstacle, the shadow created would be behind the obstacle and potentially not visible to the pedestrian. The contrast between top and front surfaces would also be lower than if lit from directly above, meaning detection of the obstacle may be more difficult. The static position of the light source in the obstacle detection experiment means it was not possible to replicate the changing directions of light for pedestrians and this may influence obstacle detection.

The lighting provided by the LED arrays allowed investigation of an illuminance range between 0.2 and 20.0 lux. The upper limit of this range appears to have been suitable for the task investigated, as a plateau in performance was reached at illuminances below this level. However, it may have been useful to investigate an illuminance below 0.2 lux, to determine at what light level performance becomes virtually zero. Detection rates at this illuminance were still around 50% (see Figure 7.12), suggesting the illuminance could have gone lower still before participants were unable to detect the obstacle. The range of S/P ratios investigated was 1.2 – 2.0. This range was in part limited by the capabilities of the LED arrays and software system controlling them, particularly as the chromaticity of the light at the three S/P ratios used was being kept constant. This range was relatively small, for example in comparison to other studies (e.g. Bullough and Rea, 2000; Eloholma et al, 2006). Although it was within the range of S/P ratios expected from different types of road lighting lamps it did not completely bracket this potential range. For example, a High Pressure Sodium lamp might be expected to have an S/P ratio of around 0.6 whilst new LED lamps on the market can have S/P ratios above 2.0. Using a larger S/P range would have better simulated the range of potential S/P ratios pedestrians might experience when walking on streets in the UK. It may also have elicited a more obvious and extensive effect of S/P on obstacle detection. The CIE mesopic photometry model (CIE, 2010) predicted that an S/P range of 0.4 – 2.0 could have elicited an effect of spectrum at 0.6 lux, based on results found in the current study. However, it also predicted that no realistic range of S/P could have elicited an effect at 2.0 lux and above.

The LED arrays that provided the lighting during the experiment were not directly visible to participants, thus preventing any glare. However, glare may be a likely occurrence in real situations, with pedestrians unprotected from direct sight of the road lighting luminaire. The advent of LED road lighting may possibly increase the likelihood of glare for pedestrians due to the point-like nature of this type of lighting. Glare has previously been shown to influence peripheral detection in a driving context. For example Theeuwe, Alferdinck and Perel (2002) investigated the effects of discomfort glare on driving behaviour, and found that even low levels of glare significantly reduced the detection of a simulated pedestrian at the side of the road and also caused slower driving speeds. Results from Aksahi and Rea (2001) also suggested that mean reaction times to detection of a peripheral target increased when a glare source was present, although only when the target was 23° off-axis, not at 15° off-axis. Clearly glare is likely to influence peripheral detection, and this effect can not be accounted for by the results of the obstacle detection experiment presented in Chapter 7. However, previous research on glare and peripheral detection has been done in a driving context, with the glare source generally representing the oncoming headlights of another vehicle. To my knowledge know study has been done examining glare from road lighting in a pedestrian context. It is possible that the effect of glare in such a context may not be as great as compared to the effect in driving studies. The glare source in these driving studies is close to being on-axis, whereas the glare from road lighting will be at a greater visual angle relative to the average gaze position of pedestrians. Glare sensation decreases with eccentricity of the glare source, therefore the effects of glare could be surmised to be less for pedestrians and road lighting compared with drivers and oncoming headlights. This means we perhaps need not expect the results from the current obstacle detection experiment to alter drastically with the introduction of a glare source, although it is a research avenue that needs pursuing. The introduction of glare as a variable would potentially worsen detection performance, if it has any effect (glare is unlikely to improve detection), therefore the current set of results can be seen as being at the upper end of performance, as no glare source is present.

8.7 Future areas of research

The research presented in this thesis has attempted to provide new and informative evidence about the visual behaviour of pedestrians, and the influence of lighting on a critical pedestrian visual task, detecting obstacles. This research highlights a number of potential future areas of research that would add further to our knowledge in these two areas, and beyond. Further investigations may also be required to address some of the limitations that existed and emerged in the work carried out.

The review of previous eye-tracking literature reported in section 2.6 highlighted that very few studies have been carried out in real, outdoor environments, despite the potential lack of transferability between findings in laboratory studies and such environments. The rapid development of mobile eye-tracking technology allows the use of this method in a range of different environments and for different population groups. Further studies investigating eye movements and gaze behaviour in natural environments and under natural conditions would enhance what we know about how and why people look where they do, and could help prove or disprove theories about human vision based on laboratory studies of eye movements (‘t Hart and Einhauser, 2012). There is variability in the findings of the few eye-tracking studies conducted in outdoor environments (for example, compare the distribution of fixations to different areas of the environment in Davoudian and Raynham, 2012, with Foulsham et al, 2011 – see Table 4.5) which highlights the need for further work in this area to find the common factors that influence gaze behaviour.

One approach that could reduce the variability that might be found between different studies in different outdoor environments is by focusing only on visual behaviour that is significant or important to the task under investigation. I attempted to do this by introducing a secondary reaction time task to identify ‘critical observations’. This method appears to have had some success, for example by being robust to changes in the frequency with which certain things such as other pedestrians are encountered. However, further work investigating, validating and refining this method would be useful. It would be valuable to know how replicable this approach is – would we find a similar distribution of critical observations between categories if another sample of participants or a different environment were used, or what effect would using different categories have? How would the conclusions be affected if some of the thresholds used in the method were changed, for example defining critical moments as 3 standard deviations above the mean reaction time rather than 2, or using a 1-second window around the critical moment rather than a 2-second window? The critical observations approach may be a useful tool in the toolbox of eye-tracking researchers, but further refinements and validation are required. A useful piece of work would be to compare identification of critical moments using the dual-task method with other potential methods for identifying critical or important times when attention may be focused on something significant. Such comparator methods could include measuring pupil dilation as an indicator of cognitive activity (e.g. Privitera et al, 2010) or electrodermal response as an indicator of emotional arousal or perceived risk (e.g. Jones, Chapman and Bailey, 2014).

The data produced by the critical observations approach and analysis confirmed that obstacle detection is likely to be a key visual task for pedestrians. Previous research about peripheral detection and lighting did not provide adequate evidence to allow robust conclusions to be made about the influence of lighting characteristics on the task of detecting obstacles by pedestrians. The obstacle detection experiment reported in Chapter 7 attempted to provide more appropriate evidence, although this was a step towards conclusions rather than providing a definitive answer to questions about the appropriate illuminance and spectrum of road lighting for pedestrians. Therefore further work to clarify the optimal lighting parameters for obstacle detection is required, addressing some of the limitations highlighted in section 8.6. An important factor that could potentially modify the results found is the level of distraction and visual noise that is present. This should be increased to adequately simulate a real pedestrian environment, for example by introducing real, dynamic images of street environments into the visual field of the participant, and by making the floor surface less uniform. Using multiple obstacle locations as opposed to just one constant location would also make the experiment more realistic, preventing participants from predicting where the obstacle would appear next. Introducing a task of not only indicating detection of the obstacle but also its location would again increase the realism of the experiment and potentially influence the resulting data collected. This additional task would require a decision to be made by the participant based on additional visual information from the scene, which is similar to what a pedestrian might be required to do when confronted with a real obstacle – is the obstacle 20 cm or 2 m in front, and what mitigating action should be taken? Making a decision (e.g. deciding whether the obstacle was to the right, centre or left) rather than simply responding (pressing a response button regardless of the location of the obstacle) is likely to lead to longer reaction times (Hick, 1952) which may influence the results about the height of obstacle capable of being detected. Lighting may also interact with the decision process, with the delay produced by making a decision potentially having a greater effect under certain lighting conditions than others (Akashi, Rea and Bullough, 2007).

The obstacle detection experiment investigated two aspects of lighting, illuminance and spectrum. However, there are other factors that could also influence the ability to detect obstacles. Two such factors are the uniformity of the light and glare from a light source. Although the uniformity of the illuminance on the obstacle and surrounding area was not spatially constant (see Figure 7.5), it was temporally constant, i.e. the distribution of light did not change throughout each condition tested. If a pedestrian is walking along a real street they will however experience constant variations in the spatial distribution of the light they encounter. For example, when passing directly underneath a road lighting fixture they will experience a brighter illuminance than if they are at the midpoint between two road lighting fixtures. Exposure to different light levels over short timescales may affect the luminance they are adapted to, and this in turn will affect their ability to see obstacles. Glare from road lighting luminaires may also adversely affect obstacle detection performance by reducing the contrast between the obstacle and its surrounding surfaces, making it less visible. Current guidelines (e.g. BS 5489-1: 2013) specify requirements for the control of glare in road lighting but it is not clear whether these guidelines adequately reflect the impact glare could have on important visual tasks. Local Authorities are increasingly installing LED road lighting and whilst these offer benefits in terms of energy use and control, they may also produce more glare for the pedestrian at ground level, due to high luminances from the point-like sources of the luminaire. Therefore, glare is likely to be an important consideration for investigating lighting and the visual tasks of pedestrians, even more so in the future than it currently is. Future research could include glare as variable to determine how it interacts with other lighting parameters such as illuminance and spectrum to influence obstacle detection.

The ultimate aim of the obstacle detection experiment and the previous eye-tracking experiment that confirmed obstacle detection was an important visual task is to provide evidence to inform guidelines for pedestrian road lighting. As discussed in section 8.4 however, helping pedestrians detect obstacles in the footpath is not the only purpose of road lighting, and the different purposes may require different amounts and qualities of light. Empirical evidence about the relative weighting of these different purposes would be useful to help inform which purpose the lighting in a particular area should primarily address. It is likely that the purpose may differ between different types of environment, and the visual tasks performed by pedestrians may equally differ. This is demonstrated by the variation between different sections of the route used in the eye-tracker experiment, in terms of the distribution of critical observations amongst the item categories (see Figure 4.9). Therefore, a useful research area would be to investigate how important the three purposes of obstacle detection, interpersonal judgement and reassurance are to pedestrians in different environments and street types, to determine which of these purposes should be used to define optimal road lighting parameters.

8.8 Summary

This final chapter of the thesis summarises the research carried out and its implications for pedestrian road lighting, whilst highlighting some of its limitations and potential future areas of research that could address these limitations. The research used eye-tracking with a novel dual task paradigm to confirm that obstacle detection is an important visual task for pedestrians. The task of obstacle detection was then investigated under variable lighting conditions. The results from this investigation suggested an illuminance of 2 lux would be sufficient for pedestrians to adequately detect obstacles, and that a higher S/P ratio could improve obstacle detection if lower illuminances are used. However, obstacle detection is not the only purpose of pedestrian road lighting. Two other important reasons are enabling interpersonal judgements to be made and providing a feeling of reassurance. Other research suggests illuminances above 2 lux may be required to adequately fulfil these purposes. Although the research reported in this thesis offers new evidence in the areas of pedestrian eye-tracking and peripheral detection under mesopic conditions that may be more ecologically valid than previous research, a number of limitations exist. Future research should address these limitations for example by validating the dual-task method for identifying critical observations with alternative methods and investigating the relationship between lighting and obstacle detection using a less uniform and more distracting test environment.

APPENDIX A. EYE-TRACKING EXPERIMENT RAW DATA

Table A.1. Participant data for eye-tracker experiment. F = Female, M = Male, AC = Anti-clockwise, C = Clockwise.

Participant ID	Gender	Day route	After-dark route	Day mean reaction time	After-dark mean reaction time	Day frequency of critical times	After-dark frequency of critical times
1	M	AC	C	197.8	189.1	14	10
2	F	C	AC	281.6		17	NA
3	F	C	AC	240.5	207.5	10	10
4	F	C	AC	368.1	328.8	19	21
5	M	AC	C	402.4	355.2	40	40
6	M	C	AC	329.4	309.6	NA	11
7	F	C	AC	277.1	302.4	21	16
8	F	AC	C	427.8	494.3	11	20
9	F	AC	C	512.8	496.6	15	23
10	F	C	AC	568.8	413.8	29	14
11	F	AC	C	459.5	527.9	11	16
12	F	AC	C	315.3	371.7	14	21
13	M	AC	C	435.9	359.6	22	20
14	M	AC	C	340.2	352.8	18	16
15	M	C	AC	245.5	215.5	9	9
16	F	AC	C	235.5	243.3	14	17
17	F	C	AC	410.3	408.6	8	11
18	M	AC	C	342.9	307.2	6	8
19	F	C	AC	299.1	316.4	26	18
20	F	C	AC	262.2	279.8	14	20
21	F	AC	C	334.5	328.8	8	13
22	M	AC	C	363.0	289.0	8	10
23	M	C	AC	362.5	326.4	20	14
24	F	AC	C	335.3	442.5	6	17
25	F	C	AC	230.8	251.4	11	11
26	M	C	AC	219.4	251.9	17	10
27	M	C	AC	334.2	320.1	19	18
28	M	AC	C	270.9	264.3	9	13
29	M	AC	C	364.3	358.7	10	11
30	F	AC	C	372.6	316.0	10	13
31	M	AC	C	438.2	375.1	16	20
32	M	C	AC	309.4	301.6	14	9
33	M	AC	C	243.1	330.2	19	28
34	F	AC	C	401.0	365.8	12	8
35	F	C	AC	428.8	467.1	24	11
36	M	C	AC	381.2	377.4	14	11
37	M	C	AC	446.2	392.0	20	20
38	M	C	AC	454.0	565.5	30	42
39	M	AC	C	216.6	266.0	10	12
40	M	C	AC	336.4	448.7	16	19

Table A.2. Participant critical observation frequencies in each gaze category, daytime session

Participant ID	Person	Path	Latent threat	Goal	Vehicle	Trip hazard	Large object	General environment	Unknown
1	3.5	3.0	1.0	1.5	3.0	1.0	0.0	1.0	0.0
2	1.5	1.5	0.0	1.0	7.0	2.5	0.5	1.0	2.0
3	0.5	1.5	0.0	0.0	0.0	0.0	0.0	0.0	8.0
4	2.0	1.0	0.0	3.5	2.5	0.0	0.0	4.0	6.0
5	9.0	4.0	1.0	1.5	0.5	2.0	1.0	4.0	17.0
6	NA	NA	NA	NA	NA	NA	NA	NA	NA
7	2.5	1.5	2.5	3.5	1.0	0.0	2.5	0.5	7.0
8	2.0	5.0	0.0	0.0	2.0	2.0	0.0	0.0	0.0
9	0.0	4.0	1.0	1.0	0.0	4.5	0.5	1.0	3.0
10	4.5	4.0	3.0	9.5	3.0	0.0	0.0	4.0	1.0
11	3.3	1.0	0.5	0.8	1.8	1.5	1.0	1.0	0.0
12	0.5	3.5	3.0	5.0	0.5	0.0	0.0	1.5	0.0
13	8.5	0.0	1.5	4.0	1.0	0.0	0.5	2.5	4.0
14	2.0	0.5	0.0	1.0	1.0	0.0	0.0	4.5	9.0
15	0.0	0.0	2.0	0.0	0.0	0.0	0.0	1.0	6.0
16	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.0
17	1.5	0.0	1.0	1.5	0.0	0.0	0.0	1.0	3.0
18	0.0	1.0	0.0	0.0	1.0	1.0	0.0	0.0	3.0
19	0.0	0.0	0.0	2.0	0.0	0.0	1.0	0.0	23.0
20	2.5	2.5	0.0	1.5	1.0	2.0	0.5	0.0	4.0
21	1.0	1.5	2.0	1.5	1.0	0.0	0.0	0.0	1.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0
23	3.0	6.0	1.5	3.0	3.0	2.5	1.0	0.0	0.0
24	2.0	2.0	0.5	0.5	0.0	1.0	0.0	0.0	0.0
25	0.0	1.0	1.0	3.5	1.5	1.0	0.0	0.0	3.0
26	4.5	0.0	2.0	1.0	0.5	2.0	2.0	0.0	5.0
27	4.0	2.5	0.0	7.0	0.5	3.0	0.0	1.0	1.0
28	2.5	1.0	1.0	0.0	1.0	1.0	0.0	1.5	1.0
29	0.5	1.8	1.3	1.0	0.0	1.0	0.0	2.3	2.0
30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.0
31	1.5	1.0	2.5	1.0	1.0	0.0	0.0	3.0	6.0
32	0.5	3.0	0.0	0.0	4.5	0.0	0.0	1.0	5.0
33	3.0	2.0	1.0	0.5	1.0	0.0	1.0	2.5	8.0
34	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.0
35	6.0	4.5	0.0	1.5	0.5	4.5	0.0	1.0	6.0
36	1.0	2.0	1.0	0.0	0.0	0.0	0.0	0.0	10.0
37	1.0	4.0	0.0	3.5	0.5	0.0	1.0	7.0	3.0
38	17.0	0.0	2.0	4.0	4.0	0.0	0.5	0.5	2.0
39	0.0	3.0	2.0	0.5	0.0	0.5	0.0	0.0	4.0
40	3.5	0.0	0.0	2.0	0.5	0.0	0.0	1.0	9.0

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Table A.3. Participant critical observation frequencies in each gaze category, after-dark session

Participant ID	Person	Path	Latent threat	Goal	Vehicle	Trip hazard	Large object	General environment	Unknown
1	2.0	2.0	0.0	1.0	0.0	0.0	0.0	4.0	1.0
2	NA	NA	NA	NA	NA	NA	NA	NA	NA
3	1.5	1.5	0.0	0.0	0.5	1.5	1.0	2.0	2.0
4	4.5	1.0	1.0	1.0	2.5	2.0	0.0	6.0	3.0
5	4.0	4.5	0.5	11.0	5.5	1.0	3.0	6.5	4.0
6	0.5	3.5	0.5	1.5	0.0	0.0	0.5	0.5	4.0
7	2.0	5.5	0.5	1.5	1.0	1.0	3.0	1.5	0.0
8	2.5	2.5	0.0	5.0	1.0	0.5	2.5	6.0	0.0
9	1.5	9.5	0.5	2.5	1.0	5.0	0.0	1.0	2.0
10	2.5	4.0	1.0	1.0	1.5	1.5	0.5	2.0	0.0
11	2.5	0.5	1.5	8.0	1.0	1.0	1.5	0.0	0.0
12	1.0	3.0	1.0	0.0	1.0	0.0	0.0	3.0	12.0
13	0.0	3.0	1.5	8.0	0.0	1.0	1.5	5.0	0.0
14	3.0	2.0	2.0	0.0	2.5	2.0	1.0	3.5	0.0
15	3.5	2.0	1.0	1.5	0.0	1.0	0.0	0.0	0.0
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	16.0
17	0.0	1.0	3.0	1.0	0.0	0.0	0.0	1.0	5.0
18	0.0	0.0	2.0	2.5	0.0	1.0	0.0	0.5	2.0
19	2.5	4.3	1.0	1.0	1.8	4.0	2.3	1.0	0.0
20	0.5	1.0	0.0	1.0	2.0	1.5	0.0	1.0	13.0
21	2.0	0.0	4.0	2.0	1.0	0.0	0.0	0.0	4.0
22	1.0	4.5	0.0	0.0	1.5	0.0	0.0	1.0	2.0
23	3.5	5.5	0.0	0.0	2.0	0.0	0.0	1.0	2.0
24	1.5	8.0	0.0	1.0	0.0	2.5	0.5	1.5	2.0
25	1.0	0.5	0.0	0.0	0.0	0.0	0.0	2.5	7.0
26	1.0	3.0	0.0	1.0	1.0	0.0	0.0	4.0	0.0
27	0.5	7.0	0.0	2.0	0.0	2.5	0.0	3.0	3.0
28	1.0	5.0	1.0	0.5	0.0	1.5	0.0	3.0	1.0
29	4.5	0.0	2.5	1.0	1.0	0.0	0.0	0.0	2.0
30	0.0	1.5	1.0	1.5	0.0	1.0	0.0	0.0	8.0
31	1.0	7.0	2.5	2.5	0.5	2.5	1.5	0.5	2.0
32	2.0	5.5	0.0	0.5	0.0	0.0	0.0	1.0	0.0
33	1.0	7.0	1.0	6.0	4.0	5.5	0.0	1.5	2.0
34	1.0	2.0	0.0	2.0	0.0	1.0	0.0	1.0	1.0
35	3.5	4.5	0.0	1.0	0.0	1.5	0.0	0.5	0.0
36	1.0	5.3	1.3	2.0	0.5	0.0	0.3	0.5	0.0
37	0.0	0.5	1.0	6.0	0.5	1.0	0.0	8.0	3.0
38	4.5	12.0	4.0	6.0	0.5	3.0	1.0	5.0	6.0
39	1.0	2.0	3.0	2.0	1.0	0.0	1.0	0.0	2.0
40	3.5	2.0	1.0	2.5	1.0	1.0	0.0	4.0	4.0

APPENDIX B. OBSTACLE DETECTION EXPERIMENT RAW DATA

Table B.1. Participant overall detection rates (%), averaged across all obstacle heights, for each S/P ratio and illuminance condition. F = Female, M = Male, Y = Young age group, O = Old age group.

Participant ID	Gender	Age	Age group	Low S/P ratio					Medium S/P ratio					High S/P ratio				
				0.2 lux	0.6 lux	2.0 lux	6.3 lux	20.0 lux	0.2 lux	0.6 lux	2.0 lux	6.3 lux	20.0 lux	0.2 lux	0.6 lux	2.0 lux	6.3 lux	20.0 lux
1	M	25	Y	43	71	71	71	79	43	64	79	86	79	57	79	79	86	79
2	M	25	Y	43	86	64	79	79	64	86	86	86	93	71	71	93	93	86
3	F	25	Y	64	86	86	93	86	71	86	79	86	93	71	79	86	93	86
4	F	23	Y	43	57	79	71	64	43	71	71	64	64	43	64	71	64	57
5	F	24	Y	64	57	86	71	86	57	86	86	86	86	57	79	79	93	86
6	F	29	Y	57	79	86	86	93	71	86	86	86	86	71	79	79	86	79
7	M	33	Y	36	50	86	71	79	29	57	71	57	79	43	43	71	79	71
8	M	24	Y	50	86	86	86	86	57	79	86	86	93	64	79	86	86	86
9	F	30	Y	36	71	71	57	86	43	64	57	79	71	57	36	64	57	71
10	F	32	Y	36	71	71	86	79	43	71	79	86	79	50	79	79	86	79
11	M	24	Y	50	50	79	79	86	50	71	71	43	86	50	79	71	86	86
12	M	24	Y	50	71	64	64	86	71	71	64	71	64	50	71	36	50	57
13	F	26	Y	36	50	50	71	50	50	64	57	64	50	57	57	50	50	57
14	M	24	Y	57	64	86	86	71	57	71	79	86	64	64	71	71	79	79
15	F	27	Y	57	79	86	86	93	57	79	79	86	86	64	64	93	86	86
16	M	58	O	50	64	79	79	71	64	79	79	86	71	64	79	79	86	71
17	F	72	O	36	64	71	57	57	50	64	71	71	57	57	71	71	64	71
18	M	69	O	50	86	71	71	86	50	71	71	86	86	50	71	79	86	79
19	M	72	O	50	64	86	79	71	36	57	64	71	50	43	57	71	86	71
20	M	61	O	21	36	43	64	50	21	36	57	64	79	43	50	57	64	50
21	F	62	O	43	57	79	64	57	43	64	57	57	71	50	57	36	64	50
22	M	54	O	36	71	64	86	79	50	71	79	79	86	50	71	71	86	86
23	M	61	O	36	57	71	64	79	43	50	64	71	71	43	57	79	86	86
24	F	78	O	43	57	86	79	86	43	64	57	93	79	50	79	93	79	64
25	M	55	O	57	79	57	79	86	57	71	71	71	86	71	71	86	86	71
26	M	61	O	43	64	86	79	86	36	57	64	86	79	43	57	79	71	79
27	M	61	O	43	71	71	86	86	43	57	86	71	71	43	57	71	71	86
28	M	65	O	36	71	79	86	86	50	29	79	79	86	43	79	86	79	79
29	M	55	O	43	57	79	64	57	50	57	64	43	64	50	57	71	50	64
30	F	53	O	50	71	79	86	86	64	93	93	93	86	57	86	93	86	86

Table B.2. Participant mean detected height (mm), for 28.4 mm obstacle height trials, for each S/P ratio and illuminance condition.

Participant ID	Low S/P ratio					Medium S/P ratio					High S/P ratio				
	0.2 lux	0.6 lux	2.0 lux	6.3 lux	20.0 lux	0.2 lux	0.6 lux	2.0 lux	6.3 lux	20.0 lux	0.2 lux	0.6 lux	2.0 lux	6.3 lux	20.0 lux
1	12.6	7.0	4.9	5.3	4.6	10.2	7.9	6.3	4.4	5.7	6.4	5.5	5.1	3.3	5.5
2	9.8	4.0	3.0	3.9	5.2	6.8	4.2	2.5	4.1	3.4	7.2	6.7	3.2	2.0	3.5
3	4.6	3.6	1.6	4.1	2.9	5.6	4.1	5.7	1.6	3.5	5.3	4.9	3.5	3.9	3.8
4	12.7	7.2	7.4	8.5	5.2	8.9	6.3	7.3	6.6	6.7	8.3	5.1	6.8	6.5	7.6
5	8.5	8.3	3.2	2.9	3.2	8.2	6.8	6.3	5.0	2.5	7.3	4.6	2.1	4.0	3.5
6	6.3	3.4	3.2	2.5	2.9	5.7	6.1	3.1	2.9	2.6	5.4	3.7	4.2	3.5	3.2
7	12.3	9.0	7.0	5.1	6.6	17.1	7.0	12.3	5.2	4.6	11.7	7.6	4.6	7.2	12.2
8	9.7	5.6	3.6	4.0	4.8	8.5	3.2	4.6	2.7	4.0	5.3	4.6	3.4	2.6	1.2
9	15.9	4.4	9.5	13.0	5.4	7.2	10.1	9.8	3.8	12.5	6.9	7.4	13.6	8.9	4.1
10	16.6	6.1	3.8	3.7	5.0	8.6	6.8	4.0	2.9	4.6	8.2	5.6	4.2	4.0	2.9
11	10.6	7.5	5.5	4.2	5.3	13.1	6.7	5.0	12.2	5.5	10.7	5.4	5.4	3.5	4.7
12	7.8	5.4	5.6	5.0	9.0	6.9	5.3	8.3	6.0	5.8	7.0	10.7	8.5	8.7	8.3
13	11.1	8.4	7.9	10.5	9.3	9.5	8.5	9.4	7.4	13.0	8.3	9.3	12.7	8.3	8.0
14	8.3	6.5	4.2	3.7	7.7	8.7	4.9	4.6	4.4	6.0	7.6	4.1	4.8	5.6	6.3
15	9.7	3.8	3.2	3.7	4.5	8.9	5.1	3.2	3.4	3.0	4.8	4.8	4.1	4.5	3.1
16	10.6	6.9	4.7	4.6	5.2	9.8	5.1	4.6	4.5	3.1	6.8	4.8	3.9	5.5	4.0
17	14.0	9.4	12.5	6.2	3.0	11.6	9.4	12.5	7.6	3.0	12.1	5.5	4.4	6.0	6.8
18	11.7	6.3	7.7	3.1	6.4	13.3	7.5	5.8	4.2	2.5	8.8	5.2	5.5	2.9	5.8
19	11.2	6.1	7.1	4.0	5.5	10.8	7.8	7.2	8.4	5.3	12.6	7.0	6.5	4.3	4.0
20	17.6	18.2	7.2	5.7	8.2	14.2	9.9	8.0	6.2	4.9	13.2	10.5	14.1	7.8	7.9
21	10.6	7.4	6.3	10.6	18.4	21.2	13.6	10.7	7.4	6.2	7.8	8.0	7.8	6.8	10.5
22	10.1	5.1	5.3	3.9	3.2	10.9	5.7	4.4	5.9	5.6	7.9	5.3	4.9	4.0	4.0
23	15.3	8.9	5.6	4.2	5.0	11.5	9.1	7.5	8.9	7.1	10.0	8.5	7.7	6.4	3.7
24	14.9	5.6	3.9	4.8	4.0	13.1	4.9	8.2	2.7	2.5	9.2	4.1	4.7	2.7	6.5
25	7.0	4.4	4.4	7.6	4.8	9.2	4.8	5.5	3.9	5.3	8.4	4.1	7.6	2.8	8.1
26	5.9	5.7	8.1	3.4	3.9	11.9	6.0	10.2	3.3	3.3	7.8	8.3	8.5	4.7	4.3
27	10.8	7.3	5.1	6.0	3.8	11.1	8.4	4.8	6.1	7.8	11.1	6.7	5.1	6.5	4.1
28	14.0	6.4	5.4	8.2	5.7	7.6	19.0	6.1	4.0	4.4	9.7	5.3	4.9	3.5	3.4
29	11.9	8.4	6.4	4.6	7.4	8.3	8.6	7.1	10.0	6.0	9.6	9.5	7.0	10.9	5.4
30	16.6	5.8	3.0	5.0	5.7	7.2	5.3	4.7	2.7	3.5	6.9	6.4	4.1	2.3	4.3

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