# An investigation by experimentation of road lighting and the performance of typical pedestrian tasks after dark

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# ABSTRACT

The lighting recommendations and guidelines for pedestrians propose that road lighting in residential roads mainly aims to enhance the walking safety after dark. However, the lighting standards may not be supported by sufficient empirical evidence. The key visual tasks for pedestrians are obstacle detection and facial emotion recognition (FER). These have been studied in previous work but there are a number of limitations: FER studies have used 2D images and not 3D models; obstacle detection studies have used raised but not lowered trip hazards; these tasks were the sole focus of trials and hence were able to use a greater degree of cognitive resource than when in natural conditions. Further work was therefore conducted to investigate these limitations, and the implications for previous conclusions about how lighting changes affect the ability to detect peripheral objects and identify facial expressions.

Two pilot studies were conducted to test if 3D face models can be used for FER. The results confirmed that 3D face models could replace photographs by comparing the results with previous studies which were using photographs. Three experiments were carried out. Experiment 1 compared obstacle detection performance when raised or lowered obstacles: no significant difference was found. Experiments 2 and 3 followed the methods used in previous obstacle detection and FER experiments but sought performance of these tasks in parallel rather than as separate experiments, thus to explore whether multi-tasking affects the performance of obstacle detection and FER. Experiment 2 used two illuminances; experiment 3 used a similar combination of obstacle locations, obstacle heights, emotion types and task conditions but expanded to five levels of illuminance. The results revealed a plateau-escarpment relationship between both obstacle detection and FER and light level.

To consider the impact of multitasking, these results were compared with the results of previous studies where obstacle detection and FER were performed in isolation. This comparison suggests that the performance of each task was impaired when conducting multi tasks.

It is concluded that the optimal horizontal illuminance for obstacle detection is 1.0 lux, even for multi-task condition. For FER, the optimal luminance was suggested to be 0.53 cd/m$^2$ which was slightly lowered than proposed before. Further work is required to address the limitations of this research, including the impact of disability from glare, and variations in face orientation and lighting geometry.

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# GLOSSARY OF TERMS

**After dark:** the period after sunset and before sunrise

**Central vision:** 10 degrees of the central visual field and has the highest visual acuity, the ability to obtain high resolution and detailed visual information

**Cones:** one type of cells lining in the retina, sensitive at light levels typical of daylight and hence dominate vision in typical daytime conditions, including three types of cones: short-wavelength (S), medium-wavelength (M) and long-wavelength (L) cones

**Contrast threshold:** the minimum contrast of an object that can be detected at the eye, and normally refers to luminance contrast

**Contrast:** in a perceptual sense, is the difference between target and surround when seen simultaneously

**Dependent variable:** in a statistical analysis, the outcome variable(s) or the variable(s) whose values are a function of, or dependent on the effect of other variable(s) (called independent variables) in the relationship under study

**Fovea:** a small area located in the centre of the retina with the greatest concentration of cones and is responsible for central vision

**Holm-Bonferroni correction:** used to test the data and their associated *p*-value at an alpha level of 0.05 and helps to reduce the Familywise Error Rate caused by making multiple comparisons. The original *p*-values were ranked from smallest to greatest and then using H-B alpha = Target α / (n – rank + 1) to calculate the corrected *p*-value thresholds. The actual *p*-value is considered significant only if it is less than the corrected *p*-value threshold. If the two numbers are the same, it is not considered as significant. The testing stops when the first non-rejected hypothesis is reached. All subsequent hypotheses are non-significant.

**Illuminance:** the amount of luminous flux per unit area and its unit is lux

**Independent variable:** a variable that precedes, influences or predicts the dependent variable

**IpRGCs:** intrinsically photosensitive retinal ganglion cells which are only involved in non-image-forming functions such as circadian photoentrainment and the pupillary light reflex

**Light:** optical radiation or visible light, which is part of the electromagnetic spectrum that stimulates the human visual system, a range of about 380 to 780 nm

**Luminance:** the amount of light passing through a unit area in one direction, and its unit is candelas per square

**Mesopic vision:** the vision when the luminance is between 0.005 – 5 cd/m$^2$, lying between the photopic and scotopic regions

**Obstacle:** something that blocks free movement or makes the desired action more difficult or impossible

**Pedestrian:** a person who is travelling on foot

**Peripheral vision:** the vision beyond the fovea, used to gain coarser visual information about the surrounding environment and seeing large objects

**Photopic vision:** the vision when the luminance higher than about 5 cd/m$^2$ where the visual response is dominated by the cones

**Photoreceptors:** cells in the retina which respond to stimulation by radiation of wavelengths in the range 380 to 780 nm

**Relative Visual Performance (RVP):** a model which could be used to predict the visual performance change on other tasks, either changing the light condition or the task

**Road lighting:** the lamps mounted upon posts that line roads

**Rods:** one type of cells lining in the retina, sensitive to much lower light levels than the cones and dominate vision after dark

**Scotopic vision:** the vision when the luminance below about 0.005 cd/m$^2$, colour vision and discrimination ability are impaired in scotopic vision

**Spectral power distribution (SPD):** the amount of power a light contains at each wavelength

**Subjective**: influenced by or based on personal beliefs or feeling, rather than based on facts

**Visual acuity:** the ability to obtain high resolution and detailed visual information

# CHAPTER 1. ROAD LIGHTING FOR PEDESTRIANS

## 1.1 Aims of lighting for pedestrians

The research described in this thesis is about road lighting for pedestrians when walking after dark. “After dark” means the period after sunset and before sunrise the next day: in some countries such as the UK, this may be referred to as night-time, but in northerly latitudes, the 24-hour period may be in darkness for the entire period. Hence the term “after dark” is used throughout. A pedestrian is a person who is travelling on foot (Cambridge Dictionary, 2020). A pedestrians' basic desire is an ability to see their surroundings and safely move along a route (Boyce, 2014, p.427).

In order to help road users to obtain surrounding visual information after dark, road lighting was installed. Road lighting refers to the lamps mounted upon posts that line roads (Figure 1.1). In residential roads, lamp posts tend to be about 5 or 6 m high and are spaced at intervals of about 15 to 30 m (Neighbourhood Services, 2014). The lamp is usually mounted in a luminaire (or lantern) at the top of the post, protecting the lamp from weather and damage and offers optical control over light distribution (British Standards Institution (BSI), 1992). Besides the lamps mounted upon posts that line road, there are some types of lamps might be installed on different places, such as wall mounted lamp, lawn lamp and garden lamp.

**Figure 1.1.** Road lighting after dark. A photograph of a residential road in Sheffield, UK (Photograph by the author).

One way by which people gain information about the outside world is through visual perception (Baars and Gage, 2010). Vision is triggered by optical radiation reaching the photoreceptors in the eyes. Visual perception is the subsequent interpretation of the photoreceptor signals in the brain. This process enables us to make sense of changes in light intensity and colour, the contrast between objects and their background, the texture of surfaces and motion. Visual perception allows us to experience and understand the things, environment and people around us.

People could see an object when it reflects light or lit by itself. “Light” here refers to optical radiation or visible light, which is part of the electromagnetic spectrum that stimulates the human visual system, a range of about 380 to 780 nm (Commission Internationale de l'éclairage (CIE), 2014a). This radiation source may be natural, such as light from the sun and sky, or artificial, for example, light from electric light sources.

During the daytime, light from the sun and sky could (and should in most cases) meet our daily lives' visual requirements. After dark, there is no daylight, although there might be some moonlight. At low light levels, visual functions are impaired. Compared with sufficient lighting condition, when the luminance drops, the contrast threshold increased and require larger target size to see (Blackwell, 1959; Mandelbaum and Sloan, 1947). Reaction times to target detection tend to be substantially longer at a low light level than sufficient lighting conditions (Plainis *et al.,* 2006). Road lighting is installed to offset vision impairments after dark to improve road users' visual capabilities.

According to Reported Road Casualties in Great Britain: 2019 Annual Report (Department for Transport, 2020), vulnerable road users include pedestrians, pedal cyclists and motorcyclists. The casualty rates per mile travelled of these three groups were significantly higher than other road users (Figure 1.2).

Road lighting research and design are usually divided into two fields, defined by the type of roads and visual needs of certain road users in a specific environment: main roads and minor roads. According to the Manual for Streets (Department for Transport, 2007), main roads include arterial through routes and mixed-use, multi-functional high streets. On main roads, lighting is designed mainly to meet the needs of drivers of motorised vehicles (van Bommel, 2014, p.11). Lighting should maintain visual performance and visual comfort levels sufficient to keep drivers’ alert. Minor roads include residential streets, residential and service lanes, and industrial roads. On minor roads, typically in built-up and residential areas, road lighting should provide visual information for slow-moving traffic. Pedestrians and cyclists can find their path without the risk of colliding with or stumbling over potentially dangerous hazards and to discourage crime against people and property (van Bommel, 2014; BSI, 2020).

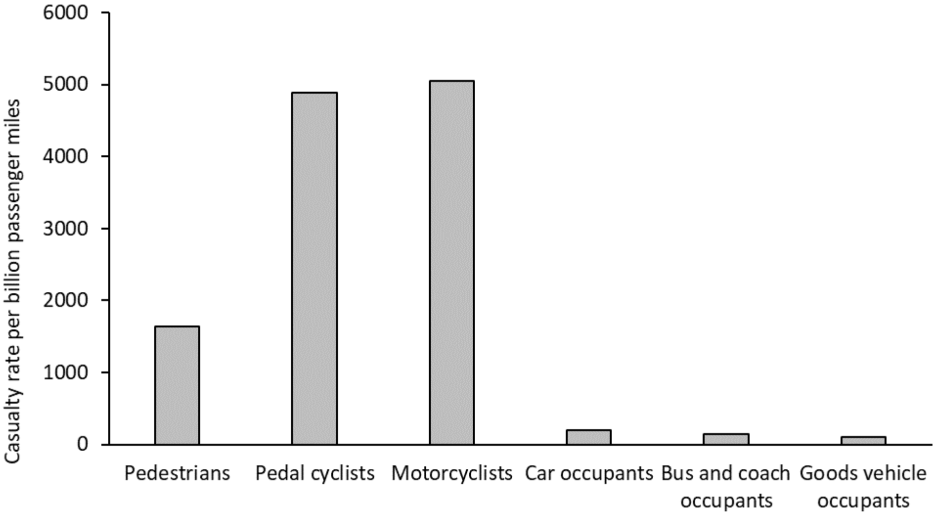


**Figure 1.2.** Casualty rate per billion passenger miles by road user type, based on the data from reported road casualties in Great Britain: 2019 annual report (Department for Transport, 2020).

## 1.2 Road lighting for pedestrians

The focus of this thesis is road lighting for pedestrians. Road lighting in minor roads is designed and installed to benefit pedestrians after dark (BSI, 2020; BSI, 2015; CIE, 2010a), especially for safety purposes.

In a residential area, the critical criteria for pedestrians will be ensuring movement safety and perceived safety after dark, such as avoidance of trip hazards, collisions or falls, being able to see the surrounding environment or the path ahead and identify the potential threats from other people (Boyce, 2014, p.455; Caminada and van Bommel, 1984). Pleasantness is another need from the pedestrians when they view the streets at home but will not be discussed here.

These assumptions have been partially validated using eye-tracking, which suggested that observing the path and observing other people are the two critical visual needs of pedestrians after dark (Fotios *et al.*, 2015a; 2015b).

Eye-tracking records gaze behaviour from which can be established the visual fixations. An attempt to identify critical fixations using the frequency by which different categories of the object were fixated is biased by the frequency with which those objects were encountered during a particular trial. The object types were not controlled in previous field studies (Foulsham *et al.*, 2011; Davoudian and Raynham, 2012). In laboratory studies (Patla and Vickers, 2003; Marigold and Patla, 2007), the allocation of fixation towards objects may be influenced by the absence of natural distractions such as dogs and by the absence of unwanted encounters.

Fotios *et al.* (2015a, 2015b) carried out a study with a concurrent dual task to investigate the key visual tasks for pedestrians after dark by using an eye-tracking device. Their test was conducted in a natural setting, and dual task was used to identify visual fixations and critical moments. Participants were asked to walk along a route in the daytime and after dark. The eye-tracking device recorded their gaze behaviour while walking. By analysing the fixation data, the results suggested that the path ahead and other people were the two most frequent items fixated, more so than other targets such as vehicles, large objects (e.g.: lamp posts or street furniture) and latent threat (hazards not visible until last moment). They further defined critical fixations as objects on the near path (a distance ahead of less than 4 m) and people at a far distance. A threshold distance of 4 m is used to discriminate near and far, which was suggested to be an important interpersonal distance (Hall, 1966).

Looking at the near path may help pedestrians detect obstacles and adjust their gait to avoid trip hazards. Previous studies have investigated the effect of illuminance, luminance, light source and age on obstacle detection task (Fotios and Cheal, 2009; Fotios and Cheal, 2013; Fotios *et al.*, 2005; Eloholma *et al.*, 2005; Uttley *et al.*, 2017; Fotios and Uttley, 2018). The obstacle detection rate tends to increase as illuminance increases. The results also suggested that light source and age only affect the performance at low light level (Fotios and Cheal, 2009; Fotios and Cheal, 2013; Uttley *et al.*, 2017).

Caminda and van Bommel (1984) mentioned that identifying a person is also one of the most important objectives of lighting relevant to pedestrian safety. It helps pedestrians make judgements on other people conveyed by their body posture or facial expressions and affect their behaviour (e.g.: orientate route). The emotion on the face affects the judgments of approachability and trustworthiness (Willis *et al.*, 2011a). By reviewing previous studies (Fotios *et al.*, 2015c; Fotios *et al.*, 2019a), the fixation duration on other people was suggested to be 500 ms and at 15 m. Lighting changes might influence the facial emotion recognition (FER) task. The recognition rate increases when at a closer distance, high illuminance or larger target size, but the light source does not reveal a difference (Fotios *et al.*, 2015d).

All of these obstacle detection and FER experiments provided suggestions on optimal illuminance or luminance. However, these results were considered on a single task condition which did not involve a secondary task. They were conducted in separate experiments for one specific task: obstacle detection or FER. It is not clear whether the performance of each task is affected when conducting an additional, concurrent task.

As mentioned above, the purpose of road lighting for pedestrians is to enhance safety after dark, including both individual and social aspects. There are suggestions that lighting after dark could reduce crime. Crime is an action or activity against the law (Cambridge Dictionary, 2020). The results of past studies about lighting and crime are mixed. The studies of Painter (1996, 1991), Painter *et al.* (1988), Painter and Farrington (1999) suggest a crime reduction after improvements to lighting, while Atkins *et al.* (1991), Morrow and Hutton (2000) and Loomis *et al.* (2002) suggest there is no effect. Brighter exterior space might also be used by criminals to judge if the target is vulnerable and valuable (Boyce, 2019, p.362).

According to the above studies, although lighting cannot directly reduce crime, it may help pedestrians identify potential threats and increase the ease of surveillance of the street like the CCTV system or other community members. More importantly, community confidence would be enhanced by road lighting instalment, contributing to informal social control (Boyce, 2019).

Compared with the relationship between crime and road lighting after dark, the effect of lighting in improving reassurance for pedestrians tends to be more certain. Reassurance is a subjective feeling provided by road lighting to pedestrians that enable them to walk on a road confidently after dark. Subjective means it is influenced by or based on personal beliefs or feeling, rather than based on facts (Cambridge Dictionary, 2020). Reassurance contains terms of perceived safety and fear of crime used in past studies (Fotios *et al.*, 2015e). A number of studies used questionnaires to investigate the effect of the lighting condition and reassurance after dark (Fotios *et al.*, 2019b; Boyce *et al.*, 2000). These studies suggested that reassurance increases significantly when illuminance increases to 10 lux, but the effect on reassurance plateaus at illuminances above 10 lux. Besides the illuminance, the illuminance uniformity and lamp spectrum (colour) also affect the perception of safety (Narendran *et al.*, 2016; Fotios *et al.*, 2019b; Rea *et al.*, 2009).

The benefits of road lighting after dark for society at large include a reduction in the risk of road traffic collisions (RTCs) (Beyer and Ker, 2009; Wanvik, 2009; Johansson *et al.*, 2009), it may encourage people to walk out and join the social activities rather than stay at home (Painter and Farrington, 1997; *Fotios et al.*, 2019a), it may improve the night-time economy (Boyce, 2019).

Road traffic collisions are a collision involving a mechanically-propelled vehicle on a road or other public area with other vehicles, pedestrians, animal or other stationary obstruction and lead to injury or damage (North Wales Police, 2020). Beyer and Ker (2009) reviewed 17 studies that compared accident ratios in the daytime and after dark and found a 55% reduction after the road lighting installed/improved though there also might be other factors that affect the results. Wanvik (2009) used the injury accidents data over 20 years on Dutch road and reported that the risk of accidents increased by around 50%, which might lead to injury after dark. Lighting after dark helps because of the visibility of the road ahead and improve the safety of road users.

Road lighting also has close relationship with walkability and in urban environment and plays an important role in urban planning. The Institute for Transportation and Development Policy (2011) affirms that great city starts with great pedestrian friendly environment. Well-lit roads play an important role in ensuring the walking safety for pedestrians. For example, pedestrians can safely cross the street only if adequate lighting is available (Moayedi et al., 2013). Kelly et al. (2011) conducted a research project in the UK to investigate what are the factors affect the walkability and pedestrian route choice. They asked the participants to rate the importance of 47 attributes when judging the walkability. Road lighting is one of the nine most important factors. Undoubtedly, the use of artificial lighting at night stimulates economic activities compared with earlier times. It encourages people to go out of home, such as going shopping, dining in a restaurant and visiting attractions (Boyce, 2019).

However, the use of artificial lighting after dark also brings some problems, such as light pollution, harm to the natural environment and the consumption of energy resources.

The sky brightness higher than 0.0006 cd/m$^2$ could be considered as polluted from an astronomical point of view (Falchi *et al.,* 2016; Luginbuhl *et al.*, 2009). The world atlas of artificial night sky brightness (Falchi *et al.,* 2016) shows that more than 80% of the world and more than 99% of the U.S. and European populations live under light-polluted skies. Almost 90% of the land surface of Europe and half of the U.S. experience light-polluted nights.

The influence of artificial lighting is not only on people. A large number of species are also affected (Longcore and Rich, 2004). The impacts include the circadian rhythms, timing and period for some organisms to capture resources and the movement patterns (Gaston *et al.*, 2013; Gaston *et al.*, 2015).

The use of artificial lighting after dark results in energy consumption and carbon emission. According to the data from International Energy Agency (Waide and Tanishima, 2006), the energy usage for grid-based lighting accounted for almost 20% of electrical power production, generated 1900 Mt of $CO_2$ annually and cost $360 billion (including energy, equipment, and labour). Light pollution often caused by excessive artificial light may lead to energy waste and high carbon emission. In the U.S., outdoor lighting consumed around 0.2 million megawatt-hours of electricity, of which an estimated 30% is wasted as light pollution, costing approximately 7 billion dollars a year (Gallaway *et al.*, 2010).

Nowadays, LEDs are replacing traditional lamp sources in road lighting. The primary reason for this transition is energy efficiency and associated cost savings (Pattison *et al.*, 2018). The energy efficiency of a light source is typically measured in lumens per watt (lm/W), which means the amount of light produced for each watt of electricity consumed (US Department of Energy, 2009). Compared with the luminous efficacies of conventional light sources such as linear fluorescent (50 - 100 lm/W), halogen (15 - 20 lm/W), and metal halide (50 - 90 lm/W), the efficacies of cool white LED has been improved up to 160 lm/W depending on its colour quality and driving conditions and the life cost drops at the same time. The energy and cost savings from LEDs in the US was estimated at approximately 30 TWh per year and 3 billion per year (Pattison *et al.*, 2018).

In 2015 the United Nations proposed 17 Sustainable Development Goals (United Nations). Improving the optimization of road lighting mainly contributes to two of these, Goal 9 (Industry, Innovation and Infrastructure) and Goal 11 (Sustainable Cities and Communities) by reducing energy consumption and carbon emission and by making cities and human settlements inclusive, safe, resilient and sustainable. The targets in the Goal 9 including upgrade infrastructure to make them sustainable, with increased resource-use efficiency. Replacing traditional lamp sources by LEDs is an example to this target. Goal 11 aims to make cities and human settlements inclusive, safe, resilient and sustainable. Improving road safety, reduce the adverse per capita environmental impact of cities, developing and planning cities sustainably are key elements in Goal 11.

Optimising the road lighting to meet the requirements of road users is therefore important. Optimal lighting is that which meets the needs of the users but no more than that: doing so means there is justification for the light pollution and energy being used. For pedestrian lighting, this meant first identifying the key visual tasks for pedestrians and then establishing the lighting characteristics which are just sufficient to ensure safe walking (physical and perceived safety). This means that any energy used (or unwanted impact imposed) in proving this optimal condition can be justified to some extent. In the reported experiments, the optimal lighting condition is the point beyond which further increase in lighting no longer brings a significant increase in benefit such as trip hazard detection.

Lighting design standards should provide optimal criteria. However, recent reviews have said this is not the case because the basis of the given criteria is not reported, until recently, the empirical evidence for design criteria was absent (Fotios and Gibbons, 2018; Fotios and Goodman, 2012).

## 1.3 Current standards

The current standard for road lighting in the UK is BS 5489-1:2020: Design of road lighting Part 1: Lighting of roads and public amenity areas – Code of practice (BSI, 2020). BS 5489-1 guides UK designers in the use of the lighting classes specified in the European standard, BS EN 13201-2:2015 (BSI, 2015). International guidance is available from CIE 115-2010 (CIE, 2010a).

BS5489-1 and EN 13201-2 offer design criteria for minor roads, including residential roads and associated pedestrian areas, foot paths and cycle tracks. In these roads, they suggest that lighting is designed for the needs of pedestrians and cyclists to get the direction of the route, detect hazards, recognise other pedestrians and discourage criminal activities.

CIE 115-2010 describes lighting criteria for users (motorists and pedestrians) rather than for road types. In all three cases, the outcome is the same: a set of six lighting classes (the P classes) where the key criteria are the average and minimum horizontal illuminance for each class. Average illuminances of the six classes, P1 to P6, range from 2 lux to 15 lux (Table 1.1).

The P-classes are used when lighting for pedestrians. There are six levels in the P-class, P1 to P6, and for each class, two criteria are specified, the minimum maintained average horizontal illuminance and the minimum point horizontal illuminance (Table 1.1).

**Table 1.1.** Minimum and average illuminances for minor roads as specified in Table 3 in BS EN 13201-2: 2015 (BSI, 2015), and in Table 7 in CIE 115-2010 (CIE, 2010a).

| **P-Class** | **Average horizontal illuminance (lux)** | **Minimum horizontal illuminance (lux)** | **Additional requirement if facial recognition is necessary** | |
|---|---|---|---|---|
| | | | **$E_{v,min}$ (lux)** | **$E_{sc,min}$ (lux)** |
| P1 | 15.0 | 3.0 | 5.0 | 5.0 (3.0)* |
| P2 | 10.0 | 2.0 | 3.0 | 2.0 |
| P3 | 7.5 | 1.5 | 2.5 | 1.5 |
| P4 | 5.0 | 1.0 | 1.5 | 1.0 |
| P5 | 3.0 | 0.6 | 1.0 | 0.6 |
| P6 | 2.0 | 0.4 | 0.6 | 0.2 (0.4)* |

$E_{v,min}$: lowest vertical plane illuminance on a plane at a specified height above the road area;
$E_{sc,min}$: lowest semi-cylindrical illuminance on a plane at a specified height above a road area.
*: the different values between BS EN 13201-2: 2015 and CIE 115-2010.

In BS5489-1:2020, a P-class is chosen according to the traffic flow and crime rate and the needs of pedestrian and cyclist in footways, residential roads and cycleways. The latest British Standard is BS5489-1:2020, which recommends a series of lighting classes according to the types of road users, traffic composition, the complexity of task and risk of crime or need for recognition of other people or their intent (Table 1.2) range from 2.0 lux to 7.5 lux (BSI, 2020).

**Table 1.2.** Lighting classes for minor roads (BSI, 2020, Table A.5)

| **Traffic composition** | **Lighting class** | | |
|---|---|---|---|
| | **Busy**[a] | **Normal**[b] | **Quiet**[c] |
| Pedestrian and cyclists only | P5 | P5 | P6 |
| Speed limit v ≤ 30 mph | P4 | P5 | P5 |
| Speed limit v ≤ 30 m | P3 | P4 | P4 |

Note: a. high traffic flow, normally near local amenities, such as clubs, shopping facilities, etc.
b. normal traffic flow, a level equivalent to a housing estate access road.
c. quiet traffic flow, a level equivalent to a residential road.

Table 1.1 also includes two further criteria for each class, minimum vertical illuminance and minimum semi-cylindrical illuminance. These two additional criteria will be required when facial recognition is necessary. The semi-cylindrical illuminance is assumed to be measured on an infinitesimal vertical half-cylinder situated at head height (1.5 m) because of the difficulty of measurement in a real situation.

Compare the guidance for pedestrians in BS EN 13201-2: 2015 (BSI, 2015, Table 3) and CIE 115-2010 (CIE, 2010a, Table 7), the content is nearly the same except the additional requirement of facial recognition necessary (Table 1.1). The selection of P lighting class is different in these two standards. For the British Standard, it is picked refer to the Table A.5 in BS5489-1:2020 (Table 1.2). The application of these classes in CIE 115-2010 (CIE, 2010a) is based on the geometry of the relevant area and the traffic and time-dependent circumstances. The number of lighting class is calculated based on the weighting system listed in Table 6 of CIE 115-2010 (Table 1.3) and equation: $P = 6\text{-}V_{ws}$.

**Table 1.3.** Parameters for the selection of P lighting class in Table 6 of CIE 115-2010 (CIE, 2010a).

| Parameter | Description | Weighting Value |
|---|---|---|
| Speed | Low | 1 |
| | Very low (walking speed) | 0 |
| Traffic volume | Very high | 1 |
| | High | 0.5 |
| | Moderate | 0 |
| | Low | -0.5 |
| | Very low | -1 |
| Traffic composition | Pedestrians, cyclists and motorized traffic | 2 |
| | Pedestrians and motorized traffic | 1 |
| | Pedestrians and cyclists only | 1 |
| | Pedestrians only | 0 |
| | Cyclists only | 0 |
| Parked vehicles | Present | 0.5 |
| | Not present | 0 |
| Ambient luminance | High | 1 |
| | Moderate | 0 |
| | Low | -1 |
| Facial recognition | Necessary | Additional requirements |
| | Not necessary | No additional requirements |
| | | **Sum of Weighting Values ($V_{ws}$)** |

As described above, the guidelines in BS EN 13201-2:2015 and CIE 115:2010 were established based on some weightings, such as travel speed, traffic volume, traffic composition, parked vehicles, ambient luminance and facial recognition needs. However, although they consider the risk of RTC, these weightings have limited relevance to the purpose of pedestrian road lighting: orientate themselves, reveal other pedestrians and vehicles and make judgements about potential threats. Additionally, there is no empirical evidence that could prove the relationship between the weighting and lighting requirement (Fotios and Gibbons, 2018; Fotios, 2020). According to Boyce (1996), the guidelines around the world are based on consensus views amongst lighting professionals and practitioners. The range of illuminance is various between different countries. For example, the illuminance requirement in British Standard now is between 2 lux to 7.5 lux, European Standard is in the range of 2 lux to 15 lux. This variation is due to different countries might consider different aspects and emphasis different factors, such as saving energy. However, defining a standard need to be more objective rather than based on consensus. Thus, consideration of the purpose of road lighting before making decisions perhaps is the most fundamental method of defining the standards compared with meeting the other requirements.

To establish optimal lighting characteristics, the effects of lighting changes of the performance on the key visual tasks need to be investigated. Therefore, firstly, it is important to identify what are the critical visual tasks for pedestrians. By reviewing previous studies, looking at the near path and observing other people in far distance were the two critical visual tasks (Section 2.2). However, previous studies about obstacle detection and FER were conducted separately while it was unclear if there is an effect when performing multi tasks simultaneously.

## 1.4 Research aims

Road lighting are related with many aspects including human, animals and plants but current research are focusing on the needs of pedestrians because pedestrians are one of the vulnerable road users as well as one of the main groups people who used the minor roads. Current standards also emphasise the importance of ensuring the walking safety of pedestrians after dark in minor roads.

Road lighting is of benefit to those who use roads after dark because it offsets the impairments to vision otherwise caused by darkness, and in doing helps to improve the physical and perceived safety of road users. However, the use of road lighting incurs some detriments, including sky glow, carbon emissions, and unwanted impact on the natural environment. Therefore, research on optimal roading lighting for pedestrians could fit in with global challenges and contribute to the sustainable development goals, the provision of road lighting should be optimised to provide for road user safety but with minimum impact. Unfortunately, current design standards may not present this optimum.

The main aim of this thesis is to test aspects of the experimental design needed to establish optimal lighting. In specific, investigate how changes in road lighting characteristics affect the ability to perform key tasks for pedestrians, detect trip hazards and evaluate the intention of other people, and synthesise the results of current work and previous studies to provide evidence or suggestions to current standards for road lighting of pedestrians.

This study is part of the MERLIN (Mesopically Enhanced Road Lighting: Improving Night-vision) project funded by EPSRC (Engineering and Physical Sciences Research Council, UK). This project was the first major study of lighting and the needs of pedestrians. It aims to validate the new design criteria for the minor road proposed by MERLIN project, thus leading towards lower lighting requirements and reduced energy consumption while maintaining visual performance.

To achieve this aim, two parts of experiments have started to explore the relationship between road lighting condition and walking safety after dark. My research focused on laboratory-based experiments carried out to test the performance of the critical visual task (obstacle detection and facial emotion recognition) under different lighting settings. Meanwhile, a colleague conducted field work on several real minor roads to evaluate the impact of lighting on reassurance after dark by doing questionnaires (Fotios *et al.*, 2019b).

## 1.5 Thesis structure

This thesis could be divided into four parts (Figure 1.3**Figure 1.3**). The first is Chapter 1 which presents background about the importance of road lighting for pedestrians and the limitations of current guidance.

Part two which is Chapter 2 reviews the literature to identify what are the critical visual tasks for pedestrians after dark - obstacle detection and facial emotion recognition (FER) and describe how visual system operate related with these two tasks. By reviewing previous studies, the limitations have been determined that need to be addressed in the following experiments.

The third part is from Chapter 3 to 7 that reported two pilot studies and three main experiments developed based on previous studies. Compared with previous studies, an attempt was made to use 3D printing in FER trials rather than photographs. Two pilot studies are reported in Chapter 3 to validate 3D models.

Three main experiments were then carried out. The aim of Experiment 1 was to compare obstacle detection performance between raised and lowered obstacle. Experiments 2 and 3 were conducted to investigate whether the performance of obstacle detection and FER were impaired when performing in parallel with different levels of variables. Chapter 4 describes the apparatus, procedure and variables used in the three main experiments. Chapter 5 demonstrates the results in Experiment 1. Chapters 6 and 7 respectively describe results of the obstacle detection and FER evaluations carried out in Experiments 2 and 3.

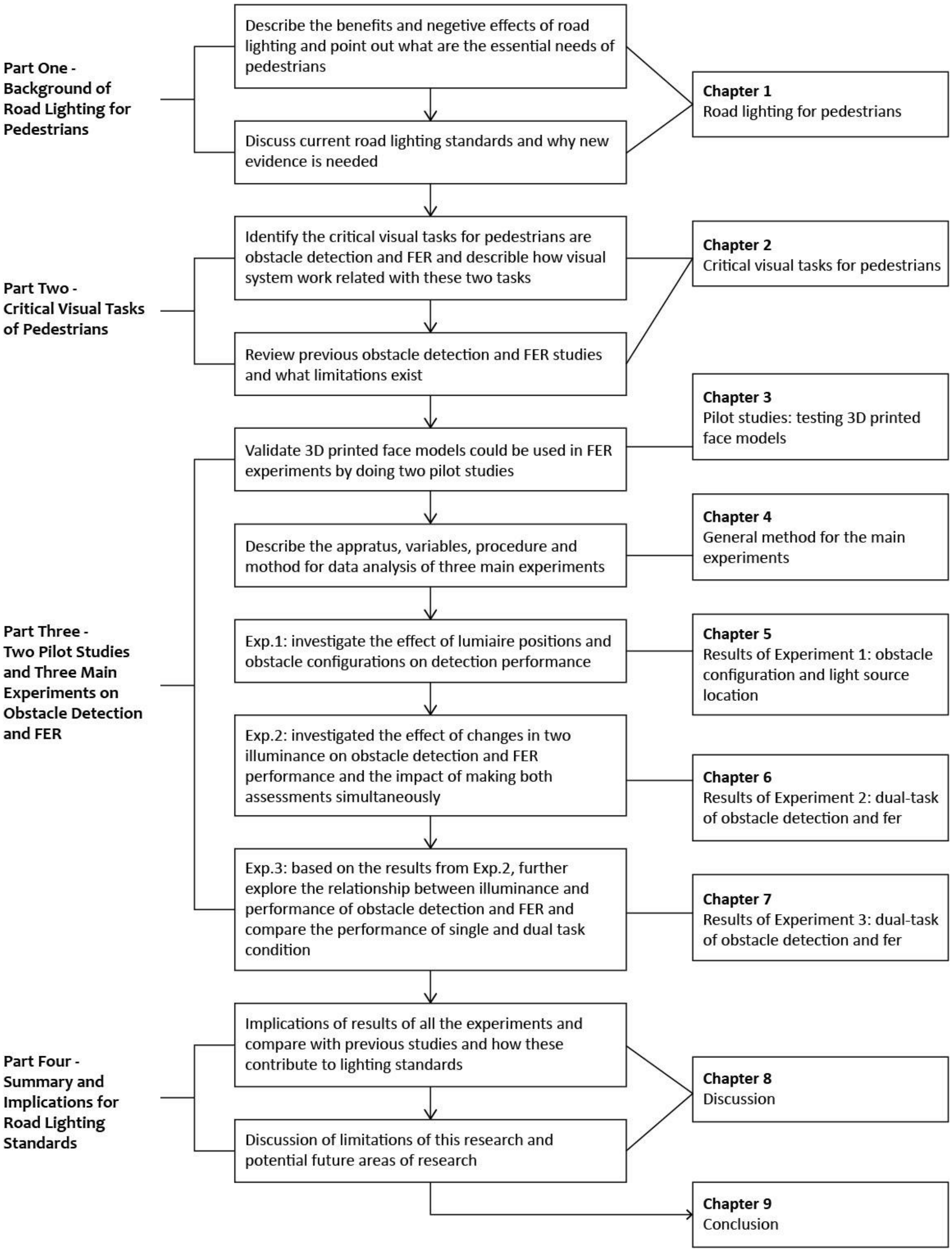


**Figure 1.3.** Summary of thesis structure and chapters relating to subject areas discussed in thesis.

The final part of the thesis includes Chapter 8 and 9. Chapter 8 summarises this research and compare the results with previous work, and discusses the limitations of the work, the need for further research and the implications for road lighting of pedestrians. The conclusions are shown in Chapter 9.

# CHAPTER 2. LITERATURE REVIEW

## 2.1 Introduction

This chapter reviews past studies about lighting for pedestrians. To measure the impact of changes in lighting, we first need to establish the critical visual needs associated with pedestrians, and this is conducted through studies, including eye-tracking. A summary of the human visual system is used to reveal why changes in lighting might have an impact on pedestrians after dark. The two critical tasks for pedestrians are suggested to be obstacle detection and interpersonal evaluations: further studies are investigated to establish the impact of changes in lighting for these two tasks. Theoretical framework was then built to guide my research and research objectives were proposed based on the limitations found from the previous studies.

## 2.2 Critical visual tasks of pedestrians

This thesis is concerned with road lighting in minor roads – also known as minor and residential roads. According to BS5489-1:2020, "*The main purpose of lighting for minor roads and areas associated with those roads is to enable pedestrians and cyclists to orientate themselves and detect vehicular and other hazards. It can allow pedestrians to recognise other pedestrians and feel more secure. It also has a wider social role, with the potential of helping to reduce the fear of crime and to discourage crime against people and property*."

In other words, road lighting in residential areas for pedestrians should provide visual information to help them to move safely and feel safe when doing so. Caminada and Van Bommel (1984) established lighting recommendations according to the visual needs of pedestrians, and there are three essential needs were detection of obstacles on the street surface, identification of persons and visual pleasantness. Obstacle detection involves detecting irregular objects lying on a path which may lead pedestrians to fall or trip, especially for the small size objects, such as holes, cracks, and kerbstones (Van Bommel, 2014, p.60). These small objects are difficult to see after dark. The ability to see other people well enough to recognise their body language and facial expression helps a pedestrian judge whether or not they will encounter a threat, and so affect their final evaluation about an area. Pleasantness involves brightness of the space, colour quality of the light source, restriction of discomfort glare and visual impact during the daytime. According to Alfonzo (2005), there are five levels of walking needs. The five levels from the most important to the least important are: feasibility, accessibility, safety, comfort and pleasurability. Safety is the third level of walking needs. The need for safety may affect the route choice of a person. As such, if a person is not satisfied with his or her need for safety, he or she may forgo the stroll. This does not mean that pleasantness is not important, but that it did not fall into the scope of the current work. Thus, pleasantness will not be discussed in this thesis.

The above recommended key needs were based on the design and applications experience of the authors but were not empirically derived. Subsequent work has attempted to validate the importance of these tasks using eye-tracking to record where pedestrians look when walking.

Before identifying critical visual tasks for pedestrians, it is essential to understand eye movements which play an important role in taking information from the outside world and interact with objects in everyday activities (Foulsham, 2015). When walking, our eyes tend to rapidly jump between different viewpoints to facilitate efficient body movements in different terrains, such as adjusting gait to avoid trip hazards or collision. Eye movements comprise a series of saccades separated by fixations, which is our main method for performing visual tasks in reality. Fixations are the period where the eye is nearly static, allowing a high resolution of the scene (Land, 1999) to be obtained. A fixation typically lasts for 300 ms or more. Saccades are movements of the eye between fixations, the rapid shift of gaze from one place to another.

Eye-tracking is a method to record these eye movements and involves two simultaneous recordings of pupil movement and of the visual field. The output is a video with the gaze direction plotted onto the visual scene. Eye movements extracted from such a recording can be used to estimate where the pedestrian looked moment by moment.

Most of the previous eye-tracking experiments investigating pedestrian fixations were conducted in a laboratory environment (Marigold and Patla, 2007; Kitazawa and Fujiyama, 2010; Jovancevic-Misic and Hayhoe, 2009), where it is easier to control variables and use non-portable devices. However, there are some inherent limitations to these experiments. First is that the simulated environment was not as real as the outdoor situation. It is normally a simple situation for participants, with targets set in advance, fewer distractors and relatively good path conditions (Marigold and Patla, 2007). In a real outdoor environment, the distractors for pedestrians are various, like other people, vehicles and constructions. Secondly, a learning effect might affect the results due to the repeated experiment process (Kitazawa and Fujiyama, 2010; Jovancevic-Misic and Hayhoe, 2009).

To address these limitations, studies using mobile eye-tracking devices have been carried out in the real world. Foulsham *et al.* (2011) recorded the eye movements of participants when they were walking to a coffee shop through a university campus, finding that 21% of fixation time was on other people, 37% on the footpath and almost 40% on other objects (objects except people and path, e.g.: lamp posts, cars and trees). Davoudian and Raynham (2012) explored the principal visual tasks of pedestrians after dark. Participants were asked to wear an eye tracker when walking three routes in a residential area. Fifteen participants completed the task after dark (five more did so in daylight) and all were interviewed afterwards. The results show that 40 - 50% of fixation time were at the footpath, but the proportion of fixations, including other people, was very low at 3% (Table 2.1).

**Table 2.1.** The measure of fixations on pedestrians using a proportion of all fixations from the work of Foulsham *et al.* (2011), Davoudian and Raynham (2012, Figure 6)

| | Proportion of all fixations (%) |
|---|---|
| Foulsham *et al.* (2011) | 21 |
| Davoudian and Raynham (2012) | 3 |

The limitations of these studies are, first, the fixated targets depend on the frequency of those types of objects which were encountered. For example, in the study of Davoudian and Raynham (2012), the number of people encountered in the test was small which leads to an extremely small proportion of fixations on people (Table 2.1). Secondly, they have not identified whether the task is relevant to walking safety after dark. Moreover, there is no evidence to prove these visual activities related to visual attention.

James (1890) describes attention 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*". When people are walking down a street continuously receiving visual information by eye saccades and fixations, the gaze might be held stationary for a period to gather more detail when an object attracts attention (Srivastava *et al.*, 2018). However, while attention is necessary for the control of saccades, saccades are not necessary for control of attention, which means a person fixating on one object may not have their attention is on it as well (Zhao *et al.*, 2012). For example, Triesch *et al.* (2003) conducted an object sorting task in virtual reality. They changed the properties of the target object when the participant was manipulating it, which assured that they were looking at the object immediately before and after the change. The results revealed that participants failed to notice changes even when they were looking at the object.

In this circumstance, further studies (Fotios *et al.*, 2015a; Fotios *et al.*, 2015b) were conducted to evaluate whether a pedestrian's fixations are critical for walking. Fotios *et al.* (2015a) carried out an experiment to investigate the critical visual tasks of pedestrians by using dual tasks. Participants had to respond to a random auditory stimulus immediately by pressing a button and the reaction time was depending on the importance of the visual task conducting at that time which may occupy participants' attention. Forty participants were asked to walk in a 900-metre route with four different sections in both daytime and night-time. The eye-tracking device recorded the specific objects which the participants fixated. Eight categories were used in the analysis of the video data: path, person, goal, the general environment, vehicle, latent threat, trip hazard and large object. The critical moment was either when the reaction time to auditory stimulus increased two standard deviations more than the average reaction time among all participants or when there was a failure to respond. The attention of participants at that moment was assumed to be diverted to something else. The results suggest looking at the path and looking toward other pedestrians were two critical tasks (Figure 2.1). In the next analysis, the distance from the participant of these fixations on the path and on other people were analysed. The threshold between near and far was set as 4 metres which is suggested to be an important interpersonal distance (Hall, 1966). The results suggest pedestrians tend to look at the path in the near field but at other people equally in the near and far fields (Figure 2.2).

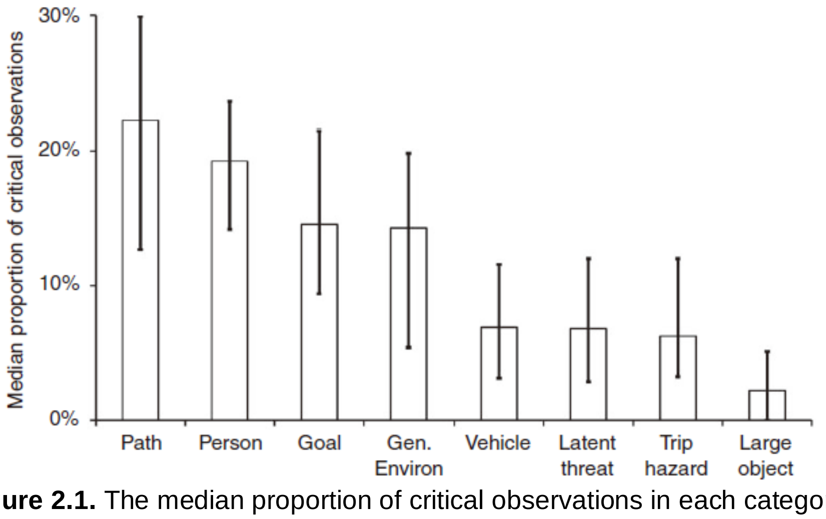


**Figure 2.1.** The median proportion of critical observations in each category, combined across both daytime and night-time trials from the work of Fotios *et al.* (2015a, Figure 4)
Note: Error bars show interquartile range.

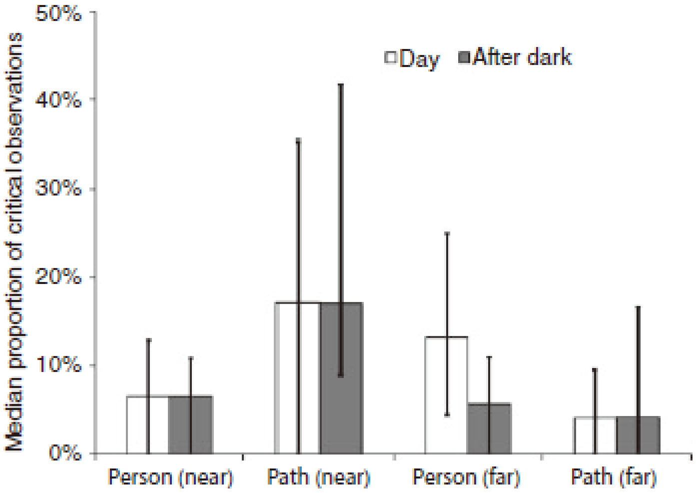


**Figure 2.2.** Median proportions of critical observations for person, path, and other categories during the day and after dark conditions, grouped by a near and far distance. From the work of Fotios *et al.* (2015a, Figure 7).
Note: Error bars show interquartile range

However, because the frequency and type of objects encountered in the real world cannot be controlled in this study, we cannot ensure the results are reliable in all circumstances. Therefore, Fotios *et al.* (2015b) further reported three approaches to interpret the eye-tracking data to address the limitation mentioned above. Data covering 360 seconds collected from 10 participants were selected for analysis based on the quality of fixations. The first method was to calculate the proportion of fixation time located on pedestrians among all fixations (14%). The fixation was defined in the experiment as when the gaze is maintained at a specific area for longer than 100 ms. The second method was to calculate the critical moments for one category as a proportion of the total number of critical moments. The critical moment was defined the same as in Fotios *et al.* (2015a), depending on a delayed or failed response to the secondary task (23%). The third method was to determine what proportion of all the people appearing in the 360-second sample were fixated at least once (86%). The results of the 1st and 3rd approach reveal the tendency that the proportion of fixation on pedestrians affected by the frequency of encountering other pedestrians but not exhibit a trend of the 2nd approach. Considering the number of fixations on individuals as a proportion of all people encountered, the method of critical moments was higher than all fixations. Thus, the method of using dual tasks could be used to identify critical visual tasks for pedestrians.

These eye-tracking experiments confirmed that looking at the path and at approaching people are two important tasks for pedestrians when walking down a street as suggested by Caminada and Van Bommel (1984). The purpose of viewing the near path is to gain immediate information about the surface that will be encountered and thus to avoid a trip hazard and to move safely. The fixations on other people refer to interpersonal judgement, which includes body posture, facial recognition or facial emotion recognition. The decision of approachability of a person is predominantly guided by facial expression and body posture (Willis *et al.*, 2011a&b).

## 2.3 The human visual system

As Figure 2.3 shows, the visual field of view is slightly larger than 180 degrees (Ware, 2013; Sardegna and Shelly, 2002, p.253) when gazing straight forward. For each eye, it extends around 94 - 104 degree laterally, 60 degrees medially, and 50 - 70 degree vertically (Walker *et al.*, 1990). Information outside of this area can be obtained only by moving the head.

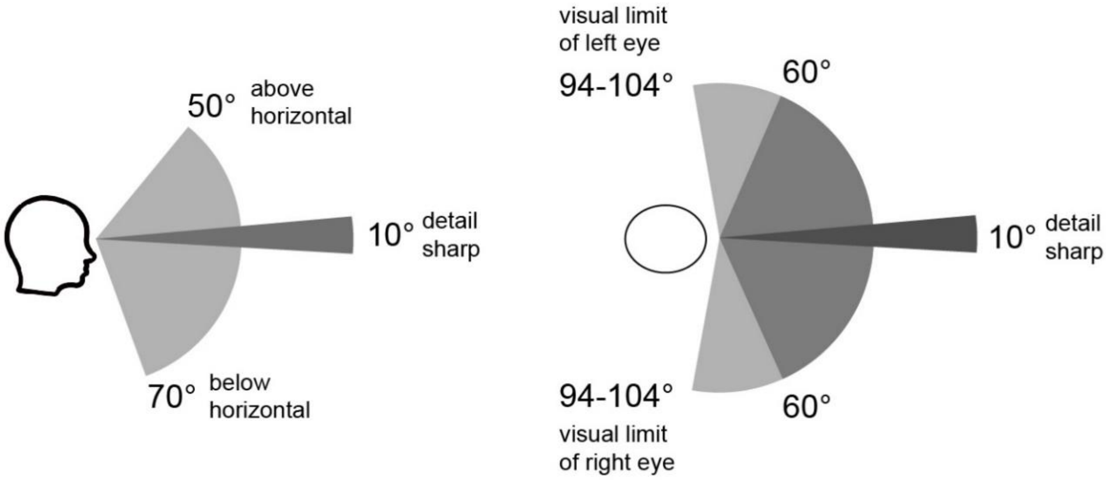


**Figure 2.3.** Visual field of human vision; vertical (left) and horizontal (right). Image is drawn based on the data from The Encyclopaedia of Blindness and Vision Impairment (Sardegna and Shelly, 2002, p.253).

The human visual system comprises the eyes and the brain. Similar to a camera, the optical components of the eye include an aperture (pupil), a layer of light sensors (the photoreceptors lining the retina) and a lens for finely focusing light passing through the pupil onto the retina (Figure 2.4). The size of the pupil and hence the amount of light entering the eye is controlled by the iris. The cornea is the outer layer that covers the pupil and iris. It refracts light and focuses on the retina to provide sharp and clear vision (Ware, 2013, pp.41-42). The retina comprises several million light-sensitive cells: photoreceptors. Then the signal transmitted to the visual cortex, which is a part of the brain processing visual information. The information is interpreted and converted into an image. For example, the brain automatically inverts the image focused on the retina.

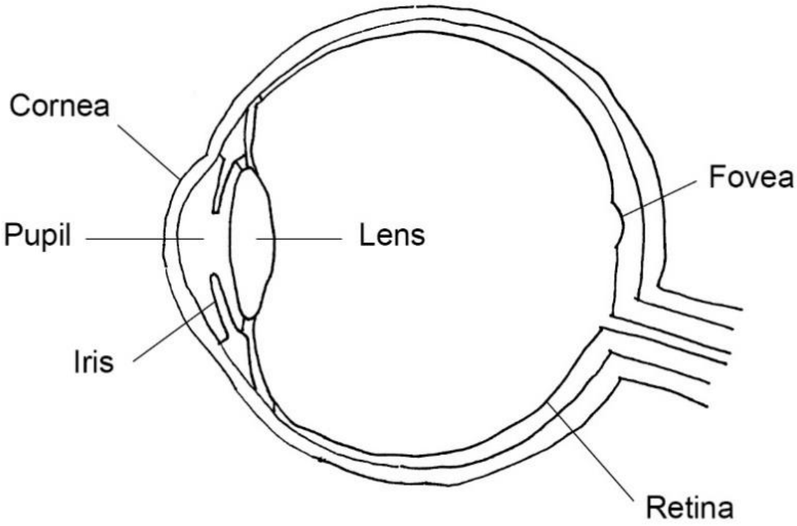


**Figure 2.4.** Diagram of the human eye (Drawn by the author based on National Institutes of Health, 2020).

Photoreceptors are cells in the retina which respond to stimulation by radiation of wavelengths in the range 380 to 780 nm (Memon and Rizzo, 2009, pp.723-742; Boyce, 2014, p.3). There are two main types of photoreceptors in the human eye, rods and cones. They are converting the light information to neural signals, which can be translated by the brain to an image (Jacobs, 2007, pp.79-85). Additionally, there is a third type of photoreceptor – ipRGCs (intrinsically photosensitive retinal ganglion cells). However, ipRGCs are not discussed here because current studies suggested that ipRGCs are only involved in non-image-forming functions, of which one is alertness (opposite of drowsiness). Alertness is defined as achieving and maintaining a state of high sensitivity to incoming stimuli (Posner, 2008). The hazards maybe easier to be detected if more alert. Additionally, the main aim of current research was to investigate the methods used when investigating the effect of changes in lighting on pedestrian visual tasks, not to establish optimal lighting. Thus, ipRGCs are not discussed in this thesis.

The fovea is a small area located in the centre of the retina with the greatest concentration of cones and is responsible for central vision (also called foveal vision) (Sardegna and Shelly, 2002). Central vision can be considered for 10 degrees of the central visual field and has the highest visual acuity, the ability to obtain high resolution and detailed visual information (Ware, 2013). Central vision is used when looking at a specific object, such as reading text and looking toward other peoples' faces.

In peripheral vision beyond the fovea, visual acuity drops dramatically as the density of photoreceptors is lower. Peripheral vision is used to gain coarser visual information about the surrounding environment and seeing large objects (Ware, 2013). It is helpful in obtaining visual information without the need to move the head or eyes to scan every part of the surroundings, such as when walking down a street and avoiding trip hazards.

The cones are sensitive at light levels typical of daylight and hence dominate vision in typical daytime conditions. There are approximately 6 million cones (Koenekoop, 2009) and these are of three types characterised by the region of the visible spectrum in which they have peak sensitivity: short-wavelength (S), medium-wavelength (M) and long-wavelength (L) cones. The different sensitivities allow interpretation of the spectral content of optical radiation and hence the colour. The peak sensitivity of each cone is at 450, 525 and 575 nm for the S, M and L-cones, respectively (Figure 2.5).

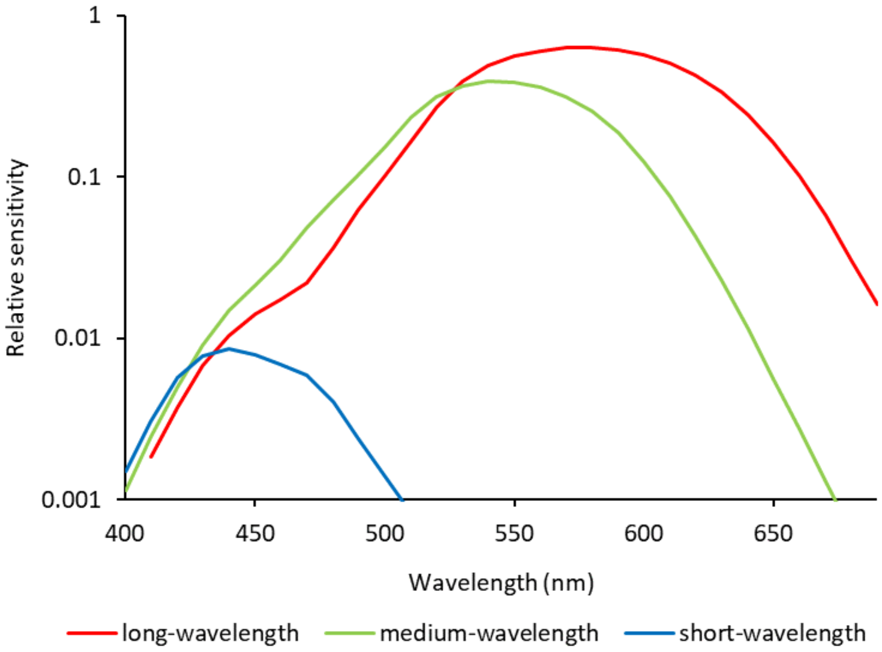


**Figure 2.5.** Relative spectral sensitivities of three types of cones. (Drawn by the author based on Vos and Walraven, 1971).

The rods are sensitive to much lower light levels than the cones and dominate vision after dark. Colour vision is limited after dark as there is only one type of rod photoreceptor (rods do not contribute to colour vision). There are approximately 100 million rods (Ware, 2013), and these are present in regions of the retina outside of the fovea, becoming most concentrated at about 20° eccentricity from the fovea (Figure 2.6).

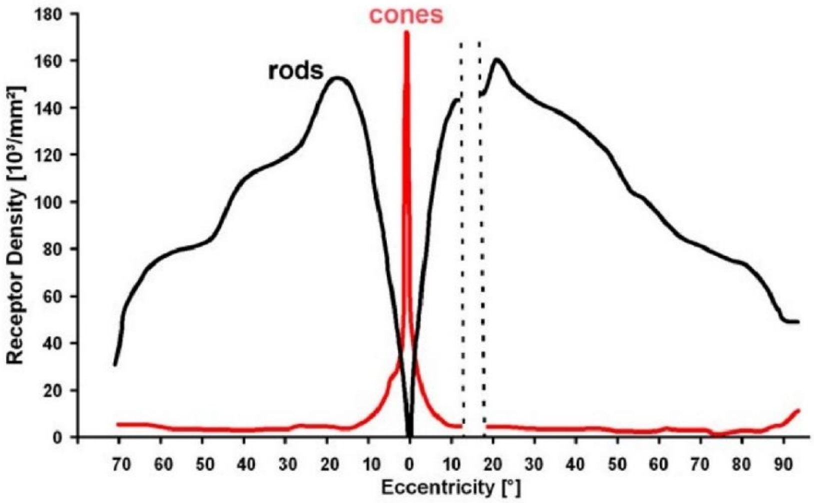


**Figure 2.6.** The density of rod and cone photoreceptors across the retina (0° represents the centre of the fovea). Image is redrawn based on Kolb e*t al.* (2005, p.80).

According to the difference of sensitivity to spectrum and the operating of cones, rods and/or other light-sensitive cells, three terms are used to define the levels of human visual adaptation: photopic, mesopic and scotopic. Photopic vision is adaptation levels higher than about 5 cd/m$^2$ where the visual response is dominated by the cones (Boyce, 2014). Photopic vision permits the colour and detail of the object to be normally discriminated. Scotopic vision is that when the luminance drops below about 0.005 cd/m$^2$, below the sensitivity of the cones and only the rods contribute to the vision. Since there is only one type of rod, and they are located beyond the fovea, colour vision and discrimination ability are impaired in scotopic vision.

This thesis is concerned with vision under road lighting, and this tends to fall into the mesopic region, a luminance range of about 0.005 – 5 cd/m$^2$, lying between the photopic and scotopic regions. Both rods and cones contribute to mesopic vision. At higher mesopic luminances, cones dominate the response: as the luminance decreases, the cone contribution gradually decreases, and the rod contribution gradually increases.

As rods and cones have different relative spectral sensitivities, CIE published the CIE standard photopic observer in 1924 and the CIE standard scotopic observer in 1951. As shown in Figure 2.7, the standard photopic observer and standard scotopic observer have peak sensitivities at 555 nm and 507 nm, respectively (CIE, 2021a). These curves are also known as 1924 CIE spectral luminous efficiency in photopic vision and 1951 CIE spectral luminous efficiency in scotopic vision (IEC, 1987).

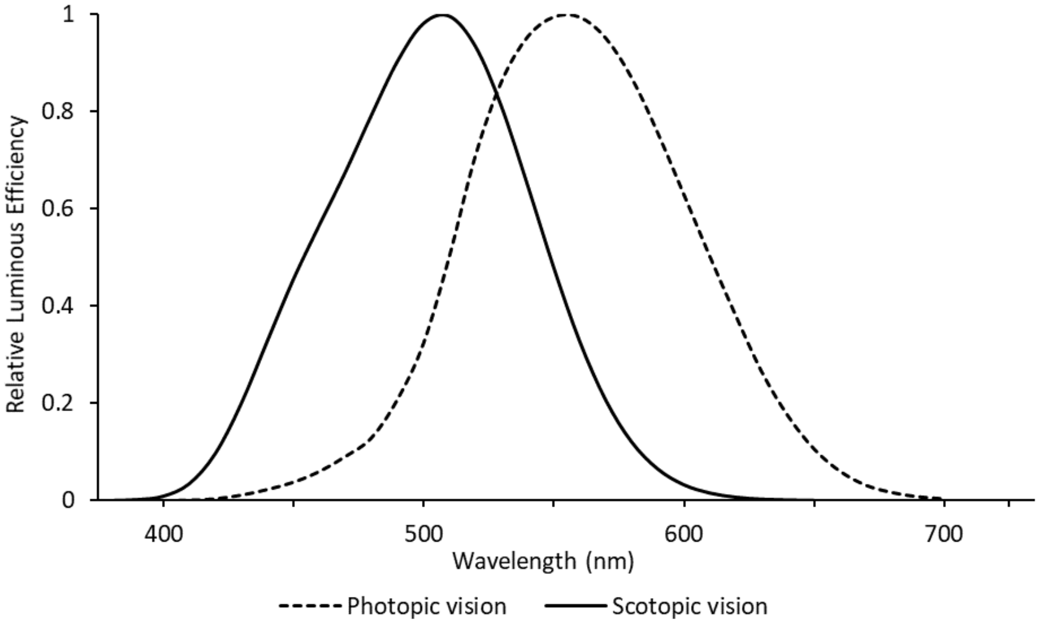


**Figure 2.7.** CIE standard photopic observers and CIE standard scotopic observers. (Drawn by the author based on Table 2.1 in CIE, 1978).

There are two terms normally used to describe the quantity of light: illuminance and luminance. Illuminance is the amount of luminous flux per unit area. It can be measured with an illuminance meter, and its unit is lux (Collins English Dictionary, 2020; CIE, 2014b). Luminance, which can be measured physically, is the amount of light passing through a unit area in one direction, and its unit is candelas per square meter (cd/m$^2$).

Spectral power distribution (SPD) describes the amount of power a light contains at each wavelength, and different light sources have different SPD (Brainard, 2001). Variations in the SPD of a light source will differently stimulate the three types of cones and the rods. In photopic conditions, this leads to variations in colour perception under different light sources. In mesopic conditions, this leads to varying degrees of relative rod and cone stimulation. This is characterised using the S/P ratio. If the photopic luminances of two light sources are the same, rods cells will be more active under the one with a higher S/P ratio, making this a useful metric for considering light sources and lighting applications in scenarios lying in the region of mesopic vision.

As mentioned above, illuminance and luminance can be measured by a photometer and, in practice, almost all measurements at all lighting levels are done using devices calibrated to the standard photopic observer. However, the lighting conditions in many scenarios correspond to the mesopic vision region, such as on parking lots and roadways, where both cones and rods cells are active (Bullough and Rea, 2004) and spectral sensitivity is changed compared with the photopic condition. It is inaccurate to apply them to mesopic conditions (CIE, 2010b). Therefore, CIE published CIE 191:2010 (CIE, 2010b) to define and recommend a system of mesopic photometry based on peripheral task performance, such as detection and recognition. In the implementation of measuring outdoor lighting by using this system, two methods were proposed, and both emphasise the measurement of lamp spectrum since SPD plays an important role in mesopic vision. Previous studies suggested that SPD does not affect foveal tasks if the stimulus not out of the fovea (Boyce and Bruno, 1999; Fotios and Cheal, 2007; Bullough and Rea, 2004). However, for an off-axis task outside the fovea in low light conditions, especially below 1 cd/m$^2$, SPD does affect visual performance (He *et al.*, 1997). For foveal tasks, which are a cone-response, we do not expect SPD to affect visual task performance. For off-axis tasks, where both rods and cones matter, we do expect SPD to matter.

A visual target can be characterised in terms of its size and its contrast with the background. Contrast, in a perceptual sense, is the difference between target and surround when seen simultaneously, such as brightness contrast, lightness contrast and colour contrast (CIE, 2021b). Whether or not an object such as an obstacle is visually distinguishable depends on the contrast. Contrast threshold is the minimum contrast of an object that can be detected at the eye, and normally refers to luminance contrast (Crumey, 2014). Changes in the target characteristics tend to change visual performance. Visual acuity increases when the luminance is higher, or the target size is larger (Shlaer, 1937). In foveal vision, the contrast threshold decreases when the light level becomes higher, and the target size becomes larger (Figure 2.8) (Blackwell, 1959). Beyond the fovea, the contrast threshold increases when eccentricity increases or the target size decreases (Blackwell and Moldauer, 1958). For both obstacle detection and facial emotion recognition tasks, we expect task performance to increase with higher light levels, although this may reach a plateau.

For the obstacle detection and interpersonal evaluation tasks suggested to be critical for pedestrians (Section 2.2), fundamental knowledge of visual performance suggests that the performance of these tasks will be affected by changes in task luminance and, for obstacle detection, by changes in lighting SPD. The next sections discuss direct evidence of changes in lighting on task performance.

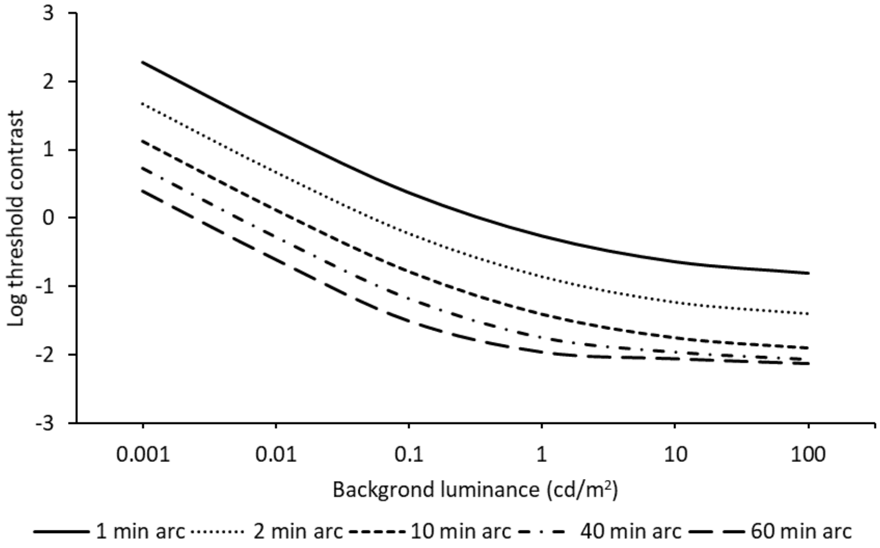


**Figure 2.8.** Threshold contrast against background luminance for different size targets within 1 second observation duration. (Drawn by the author based on Table 1 in Blackwell, 1959).

## 2.4 Facial emotion recognition

After dark, road lighting should enhance the ability for pedestrians to evaluate potential threats from other people, i.e. whether they are likely to be friendly, indifferent or aggressive. To correctly judge a person's facial expression as they approach requires sufficient vertical illuminance at the average height of the human face (BSI, 2020).

The latest two versions of the road lighting guidelines: BS 5489-1:2003 (BSI, 2003a) and BS 5489-1:2013 (BSI, 2013), indicate that lamps with good colour rendering and providing a sufficient recognition distance are necessary to take reactions if threatened. The latest CIE report 115 states that one of the targets of road lighting is allowing pedestrians to see and recognise other pedestrians and, where facial recognition is necessary, enough vertical and semi-cylindrical illuminance (CIE, 2010b). After 2015, BS EN 13201-2:2003 (BSI, 2003b) was upgraded by BS EN 13201-2:2015 (BSI, 2015), the S class was replaced by the P classes with an additional requirement if facial recognition is necessary (Table 1.1 in Chapter 1).

Previous studies have explored the effect of SPD on facial recognition. Lin and Fotios (2015) suggested that an effect of SPD on facial recognition is expected when the task is difficult, for instance, when the duration of observation is short or when the task is small. While this is not certain, two studies provided evidence. One is that the correct recognition rate of colour photographs is higher than grey when the photographs were presented blurred (Yip and Sinha, 2002). Another is that the lamp source might affect foveal acuity when the subject is small, and observers are encouraged to guess the unclear and smaller size task (Berman *et al.*, 2006).

However, compared with facial recognition, it has been proposed that FER is a suitable proxy for evaluating the intentions of other pedestrians (Willis *et al.*, 2011a; Willis *et al.*, 201b; Fotios and Johansson, 2019). This is operationalised as the ability to correctly identify the emotion portrayed by a facial expression that is helpful for pedestrians to evaluate potential threats in order to make decisions about whom to approach and trust (Willis *et al.*, 2011a).

These studies about facial recognition have not defined what is the distance for interpersonal judgement, though Caminada and Van Bommel (1980) suggested 4 m to be the minimum distance. According to different lighting conditions and methods used to measure the distance, including stop-distance, field interview and observation, past studies reported different recommended comfortable interpersonal distance range from less than 1 m to 15 m (Adams and Zuckerman, 1991; Townshend, 1997; Sobel and Lillith, 1975). Eye-tracking is another approach to explore the critical interpersonal distance. The data from Fotios *et al.* (2015a; 2015b) suggested that pedestrians tend to look at other people at a distance of around 4 – 18 m. The recognition performance drops when the distance becomes larger. When the distance is less than 15 m, the space left to pedestrians to take actions is decreased to below a comfortable level (Townshend, 1997). Thus, Fotios *et al.* (2017) suggested that 15 m is the critical interpersonal distance and appropriate to use in the experiments which investigate the relationship between lighting changes and interpersonal judgements.

The fixation duration on other people when walking down a street was investigated by Jovancevic-Misic and Hayhoe (2009). They required participants to walk along an oval path with 48 laps (four sets of 12 laps) where they met five target pedestrians following three behaviours: safe (no collisions), rogue (turning to test participant to create a potential collision) and risky (half the safe and rogue occasions). The results suggest that the duration of fixations on all types of pedestrians were around 500 ms when walking on the first four laps in each set. However, the duration increased to around 900 ms on rogue pedestrians and reduced to 200 ms on safe pedestrians eventually when the number of rogue target pedestrians increased, which means the gaze behaviour might depend on the natural environment. On the other hand, the eye-tracking records show an average duration of fixation was 480 ms which was also close to 500 ms (Fotios *et al.*, 2015a; Fotios *et al.,* 2015b; Fotios *et al.,* 2015c). Therefore, 500 ms was proposed to be the fixation duration in my work.

Table 2.2 lists four experiments of the effects of luminance and SPD on facial expression recognition (Fotios *et al.*, 2015d; Yang and Fotios, 2015, Fotios *et al.,* 2017a, Li and Yang, 2018). Fotios *et al.* (2015d) carried out a study on the ability of pedestrians to identify facial expressions and body postures under various combinations of illuminances and SPDs. Twenty-four images from four target people (a young male, a young female, an old male and an old female) were divided into six groups (anger, disgust, fear, happiness, neutrality and sadness) to keep the balance of the experiment. These six emotions were chosen because they were suggested to be universally recognised (De Gelder and Van den Stock, 2011). During the experiment, the image was presented on a non-self-luminous screen. Thirty participants were asked to identify the facial emotion, body posture and gaze direction within 1000 ms observation duration. Two lamp sources of high-pressure sodium (HPS, S/P ratio = 0.6) and metal halide lamp (MH, S/P ratio = 1.8) were used to provide three luminances of 0.01, 0.1 and 1.0 cd/m$^{2,}$ respectively, which cover the range of light levels in a residential area in the UK. The size of targets was manipulated to simulate a viewing distance at 4, 10 and 15 m. The results show a plateau–escarpment relationship between the identification rate of facial emotion and luminance (Figure 2.9). The lamp type only has effects in a few cases, and a luminance of 1.0 cd/m$^2$ is the minimum required to identify a facial expression at 10 m. For the distance of 4 m, the minimum luminance of the face suggested being in the range of 0.1-1.0 cd/m$^2$. It also showed a tendency that a closer distance, a higher illuminance or a larger target size increases the correct identification rate.

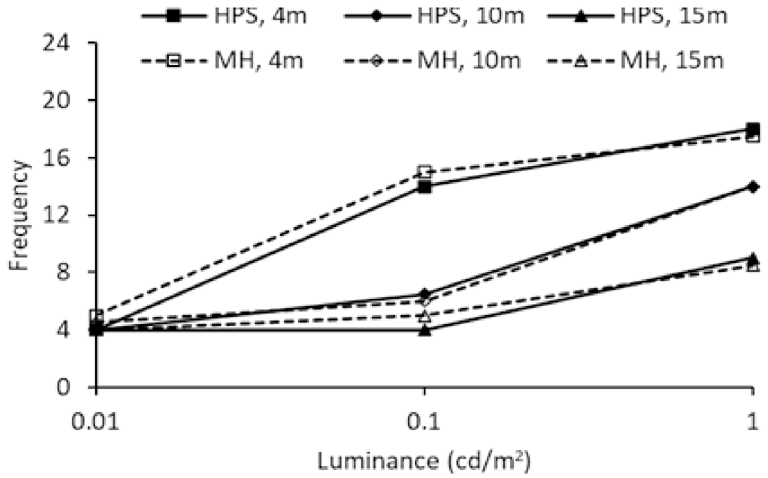


**Figure 2.9.** Results of facial emotion recognition from Fotios *et al.* (2015d). These results combined both young and old age groups, and 24 is the maximum frequency.

**Table 2.2.** Past studies on the effects of luminance and SPD on facial expression recognition.

| Study | Experimental design | | | | | Sample | Lighting conditions | |
|---|---|---|---|---|---|---|---|---|
| | Task | Observation period | Target distance | Target type | Facial expression * | | Luminances (measured on the face) | SPD |
| Fotios *et al.*, 2015d | Forced-choice judgements of emotion and gaze direction | 1000 ms | 4, 10 and 15 m | Images (very little colour) | 6 emotions * | 15 young<br>15 old | 0.01, 0.1, 1.0 cd/m$^2$ | Two types of lamp (HPS and MH) (S/P = 0.6 and 1.8) |
| Yang and Fotios, 2015 | Forced-choice judgements of emotion | 500 and 1000 ms | 4 and 15 m | Images (very little colour) | 6 emotions * | 20 young | 0.01, 0.03, 0.1, 0.33, 1.0, 3.3 cd/m$^2$ | Two types of lamp (one HPS and two types of MH) (S/P = 0.6, 1.2 and 1.8) |
| Fotios *et al.,* 2017a | Forced-choice judgements of emotion | 500 ms | 4 and 15 m | Images (in grey scale and colour versions) | 6 emotions * | 18 young | 0.1, 0.33, 1.0 cd/m$^2$ | Two types of lamp (HPS and MH) (S/P = 0.6 and 1.8) |
| Li and Yang, 2018 | Forced-choice judgements of emotion | 4000 ms | 4 m | Static 3D terracotta head models | 4 emotions ** | 30 young | 0.33, 1.0, 2.0, 3.0, 10.0, 30.0 lux*** | Three types of lamp (HPS, MH and LED) (S/P = 0.6, 1.8 and 25.13) |

Note: * In all cases the six emotions were anger, disgust, fear, happiness, neutrality and sadness, displayed by 2D photographs. ** In Li and Yang (2018), four emotions were happy, angry, sad and surprise, displayed by 3D terracotta head models. *** Li and Yang report illuminance rather than luminance.

In order to explore a clearer relationship between lighting condition and FER performance, Yang and Fotios (2015) extended their work by adding three luminances (0.03, 0.33 and 3.3 cd/m$^2$), a shorter observation duration (500 ms) and one more MH lamp type in different S/P ratio (CPO, S/P ratio = 1.2). The simulated target distance was reduced from three to two (4 m and 15 m). The procedure of this experiment was similar to the previous one, but participants were only required to identify the emotion on the face. The results also show an escarpment-plateau relationship between the correct identification rate of facial emotions and luminance (Figure 2.10). It indicates the optimum luminance was 0.33 cd/m$^2$ at 4 m distance which validate the conclusion from the previous study, in the range of 0.1-1.0 cd/m$^2$. For the typical interpersonal evaluation distance of 15 m, performance under luminance of 3.33 cd/m$^2$, the highest luminance used in these trials, did not suggest the plateau had been reached. Whilst this or increased luminance on the face may improve FER performance, and it also might cause glare. Hence, it may be unrealistic to expect an optimal FER performance. Therefore, a 50% correct identification rate was proposed as another benchmark to interpret the results. It suggested 0.03 cd/m$^2$ at 4 m and 1.0 cd/m$^2$ at 15 m to achieve 50% correct identification rate. The observation durations only affect the judgments in the escarpment region but not apparent in the plateau region.

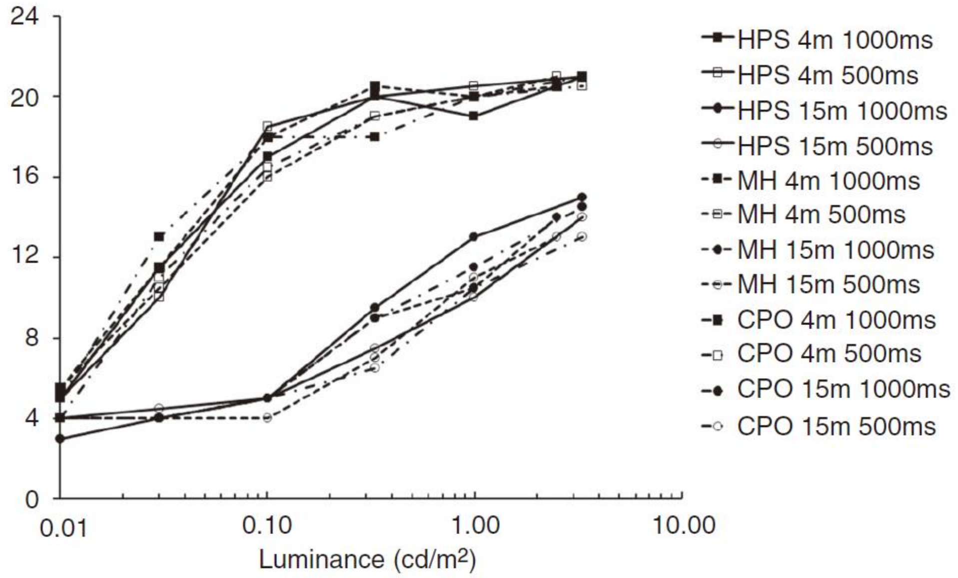


**Figure 2.10.** Results of facial emotion recognition from Yang and Fotios (2015). The frequency of 24 is the maximum score.

By comparing the results from these two studies (Fotios *et al.*, 2015d; Yang and Fotios, 2015), the data suggest a luminance of 0.1 cd/m$^2$ at 4 m and 1.0 cd/m$^2$ at 15 m is required for FER (Fotios *et al.*, 2015d). In the following experiment (Yang and Fotios, 2015), the optimum luminance was suggested to be 0.33 cd/m$^2$ at 4 m, and 1.0 cd/m$^2$ when observing at 15 m distance for 50% correct identification rate. The light source type did not show any effect on the final results of both studies, although the reason might be the images displayed in the two experiments were almost in greyscale due to the low light level. Therefore, Fotios *et al.* (2017) set up an investigation on whether the colour and greyscale images affect the performance under two SPDs. Same with previous studies (Fotios *et al.*, 2015d; Yang and Fotios, 2015), twenty-four images with six expressions from four actors (a young male, a young female, an old male and an old female) were presented to 28 participants (13 male, 15 female aged between 18-34 years). Six lighting conditions have been used in total, including two SPDs (HPS, S/P = 0.6 and MH, S/P = 1.8) and three luminances (0.1, 0.33 and 1.0 cd/m$^2$) which is the average luminance measured on the whole face area. These 24 images were displayed in both coloured and grey scale for observing 500 ms duration in each trial. Similar to the previous experiments, the results indicated there is no significant effect of SPDs on judgments of facial expression slightly.

Previous studies have investigated the light effects on interpersonal judgement conveyed by facial expressions. The results suggest that the ability to discriminate facial expressions increases when the viewing distance is shorter, and luminance is higher. The fixation duration only has an influence on identification performance before reaching the plateau region, while SPD has not revealed a significant difference.

## 2.5 Obstacle detection

The previous section reported on previous eye-tracking experiments and suggested that path and other people are the two most important visual targets for pedestrians to pay attention to when walking down a street.

Peripheral vision acquires visual information about the surrounding environment (Inditsky *et al.*, 1982) and is sufficient for avoiding obstacles to movement. Fixations do not always have to be redirected to an obstacle or the foot landing area (Marigold *et al.*, 2007).

By observing the path, a pedestrian gains visual information to perform locomotion, such as maintaining the walking direction, avoiding trip hazards and getting the direction (Foulsham, 2015). The data have also shown that pedestrians spend more time looking at near path than at far distance (Fotios *et al.*, 2015b), suggesting they require immediate information about the surrounding terrain and incoming hazards to avoid obstacles. For a pedestrian, an obstacle is something that blocks free movement or makes the desired action more difficult or impossible (Cambridge Dictionary, 2020). A pavement obstacle or uneven pavement surfaces, such as a raised paving slab or kerb, can occur unexpectedly and may cause a pedestrian to trip or fall if not detected (Figure 2.11) (Frith and Thomas, 2010).

**Figure 2.11.** Uneven surface on the pavement may lead to a trip or fall. (Photographs by the author).

Obstacle detection is an important task for pedestrians if they are to avoid accidents like a trip, fall or slip by changes in gait or direction. In England from 2007-2009, almost 25,000 pedestrians were injured from car accidents. In comparison, over 75,000 pedestrians were hospitalised from falls on the highway (Mindell *et al.*, 2012). An investigation involving postal delivery officers from the Royal Mail in the UK found that 86% of them believed that damaged walking surfaces and similar obstacles are the main risks for their job (Bentley and Haslam, 2001). It is not only a problem in the UK. Research in New Zealand found that around 700 pedestrians were admitted to hospital each year as a result of slips, trips and stumbles in the road environment (Frith and Thomas, 2010). Apart from physical damage, economic loss is also brought to both national and personal finance. In 2007, the average cost due to a fall on a footway was estimated to be £6,046 in England and Wales (Bird, 2008). A survey in Melbourne found that less than one hundred incidents were reported due to car crashes, but around 1,680 hospital admissions and 3,545 emergency department presentations were caused by pedestrian falls in the road environment, and the number is still increasing (Oxley *et al.*, 2017). The tendency of older people to fall or collide with something is higher than for young people, especially if they have a long-term health condition (NHS, 2018). Talbot *et al.* (2005) reported that the fall rates become higher with increasing age. These examples suggest that adjacent pavement surfaces with a discrepancy in elevation are responsible for most pedestrian accidents on the highway. Detecting obstacles successfully is useful to provide a conducive, friendly and safe environment for pedestrians walking outside (Abley, 2005).

Detecting obstacles reliably and accurately in advance is a crucial task for elderly people. The visual system deteriorates with age, especially in spatial vision: the contrast sensitivity function is lower in elderly people (Guirao *et al.*, 1999). Retinal image quality shows a nearly linear decline with age because of the increasing optical aberrations of the eye (McLellan *et al.*, 2001). Another problem is stray light increases remarkably among old people. Stray light reduces the retinal contrast and might cause glare (IJspeert *et al.*, 1990).

As mentioned above, road lighting normally falls within the mesopic vision region, which is around 0.005 cd/m$^2$ to 5 cd/m$^2$ (Bullough and Rea, 2004). In the mesopic state, both cone and rod photoreceptors are active and leading to changes in spectral sensitivity with changing light level throughout this region. When the lighting level is changing, the performance of peripheral vision might be affected, including the abilities to discriminate the colour and visual acuity. Therefore, this work investigates how changes in lighting affect the detection of obstacles in peripheral vision.

Previous studies suggest that luminance and light source type influence the results of peripheral visual tasks. According to the results of these studies, SPD only slightly affects obstacle detection at photopic conditions, but when the luminance drops from the photopic to scotopic region, the effect becomes stronger. Additionally, the detection probability of peripheral targets increases if the luminance or S/P ratio of a light source increases. In an experiment concerning the ability to move in an obstructed environment, the escape speed and the number of collisions were found to be related to the light source type (Fotios and Cheal, 2009; Fotios *et al.*, 2005; Eloholma *et al.*, 2005). At the same photopic illuminance, blue lamps (S/P ratio = 14.0) had better performance than red lamps (S/P ≈ 0.06) (Mulder and Boyce, 2005). Fotios and Cheal (2009) studied obstacle detection in peripheral vision under mesopic visual conditions and found that the light source types only affect the detection height of obstacles significantly at low illuminance (0.2 lux), lamps with higher S/P ratio allowed better obstacle detection ability. Other peripheral visual tasks show the same effect (Lewis, 1999; Rea *et al.*,1997).

A recent paper from Fotios and Uttley (2018) studied the minimum height of an obstacle and the minimum distance to detect it under five illuminances (0.2 - 20.0 lux). It was found that 10 mm is the critical height instead of 25 mm used before, and 1.0 lux is sufficient for pedestrians to avoid any trip hazards regardless of light source type at 3.4 m distance.

Table 2.3 shows previous studies of the effects of the illuminance and step height on peripheral obstacle detection based in a laboratory. These experiments tested peripheral detection in the context of pedestrians. Fotios and Cheal (2009) studied the effects of lamp type, illuminance and age on obstacle detection in peripheral vision. The obstacles were in six different positions below the fixation point, which makes it more realistic. The HPS (S/P ratio = 0.6) and two MH (S/P ratio = 1.2 and 1.8) lamps used in this experiment are still used widely for road lighting in the UK. Three illuminances were projected from the ceiling of the booth in order to diffuse the light, 0.2 lux, 2.0 lux and 20.0 lux, and this range covers the recommended light level for minor streets in the UK (BSI, 2015). Younger (<45 years) and older (>60 years) groups were tested to compare the results. The obstacle was presented for 300 ms each time randomly from 0.40 mm to 7.94 mm for observing to simulate a real height of 1.8 to 28.7 mm in the eye at the height of 1.5 m (0.40, 0.50, 0.63, 0.79, 1.00, 1.26, 1.58, 2.00, 2.51, 3.16, 3.98, 5.01, 6.31 and 7.94 mm). The exposure time was chosen because a fixation typically lasts for at least 300 ms (Land, 1999). Twenty-one participants in two age groups (young and old) were required to report which obstacle was raised or "none" if no obstacle appeared. The results revealed a plateau-escarpment relationship between obstacle detection probability and illuminance. Plateau-escarpment is used to describe the tendency of detection performance here. When the detection performance changed from escarpment to plateau, the illuminance at the transition point is the optimal light level in this case. The performance increases as the illuminance become higher, while the difference between 0.2 lux and 2.0 lux was larger than 2.0 lux to 20 lux. The transition point was 2.0 lux, illuminance higher than 2.0 lux reduced effect on detection. The influence of SPD on the visual performance in the photopic region was weak but increased when the light level drops thought mesopic to scotopic. At 0.2 lux, the light source with a higher S/P ratio has the better performance, and the detected obstacle height in the younger group was lower than the older group.

A repeat experiment that used the same apparatus and methodology was done by Fotios and Cheal (2013) to validate the plateau-escarpment relationship in the previous study and further establish the appropriate illuminance for road lighting. The number of obstacles reduced from 6 to 4 while using only one lamp source (HPS, S/P = 0.6) with five illuminances (0.20, 0.63, 2.0, 6.32 and 20 lux). The plateau-escarpment relationship was shown in this experiment as well; the transition point is around 2.0 lux.

Uttley *et al.* (2017) set up an experiment to test peripheral obstacle detection based on the previous works with a larger visual field and dynamic visual fixation. Both young and old age groups participate in this experiment. One of the obstacles that appeared

**Table 2.3.** Past studies on the effects of the illuminance and step height on peripheral obstacle detection.

| Study | Method | Observation | Participant motion | Participants | Illuminances | SPDs | Obstacle configuration | Heights of obstacle | Results: optimum illuminance |
|---|---|---|---|---|---|---|---|---|---|
| Fotios and Cheal, 2009 | forced-choice; which of 6 obstacles was raised; single booth | 300 ms | Seated | N = 21<br>11 young (<45 yo) and 10 old (>60 yo) | 0.2, 2.0 and 20.0 lux | 3 (One HPS and two MH lamps) | Raised | 8 (between +0.40 and +7.94 mm) | 2.0 lux |
| Fotios and Cheal, 2013 | forced-choice; which of 6 obstacles was raised; single booth | 300 ms | Seated | N = 4<br>(18-34 yo) | 0.20, 0.63, 2.00, 6.32 and 20.0 lux | 1 (one HPS lamp) | Raised | 6 (between +0.40 and +6.31 mm) | 2.0 lux |
| Uttley *et al.,* 2017 | Reaction time to detection of a slowly rising obstacle | Continuous | Treadmill walking | N = 30, 15 young (<35 yo) and 15 old (>50 yo) | 0.2, 0.6, 2.0, 6.3 and 20.0 lux | 3 (two LED arrays) | Raised | 7 (between +0.5 and +28.4 mm) | 2.0 lux |
| Cheng *et al.,* 2018 | Eye-tracking on ascended or descended step | Continuous | Walking along a 13.2 m walkway | N = 31, 16 young (25-34 yo) and 15 old (65-74 to) | 4 and 200 lux | 2 (4 lux provided by HPS lamps; 200 lux provided by fluorescent lamps) | Raised and lowered | 8 (± 125 mm) | 4 lux |

in each trial ranged from 0.5 to 28.5 mm. Three S/P ratios (S/P ratio = 1.2, 1.6 and 2.0) were provided by tuneable LED arrays from above. A dynamic fixation mark was projected onto the wall ahead, and it changed from a crosshair to random digits for participants to read out. This reading task was to ensure participants were using peripheral vision to detect the obstacle. The participants were asked to identify the raised obstacles while walking on a treadmill in order to simulate the situation of walking down a street. The results were similar to previous work (Fotios and Cheal, 2009; Fotios and Cheal, 2013). The detection rate for the younger group was higher than the older group. Different light source and observer age only affect detection performance at the lowest light level. A plateau-escarpment relationship appeared in this test as well, and the plateau was reached at 2.0 lux.

Fotios and Uttley (2018) investigated the critical height of an obstacle, the distance ahead and illuminance required for pedestrians to avoid trip or fall by reviewing previous experiments. They proposed 10 mm is the critical height for pedestrians to detect obstacle because the obstacle lowered than 8 mm unlikely to cause a fall or trip while higher than 15 mm may increase the probability to fall. The analysis of previous eye-tracking data suggested the fixation point tend to locate at 3.4 m ahead of walking direction. Considering previous results from obstacle detection experiments and Boyce (1985), a photopic illuminance of 1.0 lux is sufficient for all age pedestrians to avoid trip hazards under all lighting conditions.

This section provides evidence other than eye-tracking data to emphasise the importance of obstacle detection for pedestrians walking after dark. By reviewing previous studies, it was found that SPD and age can affect peripheral detection performance but only in low light levels. A critical obstacle size and illuminance for obstacle detection task after dark is proposed to be 10 mm under 1.0 lux.

## 2.6 Theoretical framework

My research considers the events in the pedestrian environment, the occurrence of an obstacle or encounter with another person as stimuli. People perceive to a varying degree these events, in my case visually, process the information with the outcome that they can correctly or incorrectly define the occurrence of an obstacle or recognition of emotion. Environment conditions (lighting) and the presentation of the stimuli (event) are varied in my studies.

In a theoretical perspective, Lewin's equation, *B = f (P, E)*, could be used here to explain what determines behaviour. It stated that behaviour is a function of the person and environment (Lewin, 1936). *B* is the behaviour, *P* is person, and *E* is the environment. In my case, *B* here refers to the walking activity after dark (Figure 2.12). The behaviour is affected by the performance of a specific activity, such as obstacle detection and FER. *P* refers to pedestrians and could be reduced to the function of visual system. As mentioned above, obstacle detection and FER are an activity which triggered by visual system after obtaining the visual information from outside. *E* is the environment, including physical environment and social environment in my case. The lighting condition (such as illuminance, luminance, SPD and luminaire position) and the obstacle characteristics (such as obstacle location, size, and configurations) are all a part of physical environment. Another aspect is social environment, including the people being encountered when waling down a street. Both *P* and *E* have impact on *B* and this relationship is revealed in previous studies.

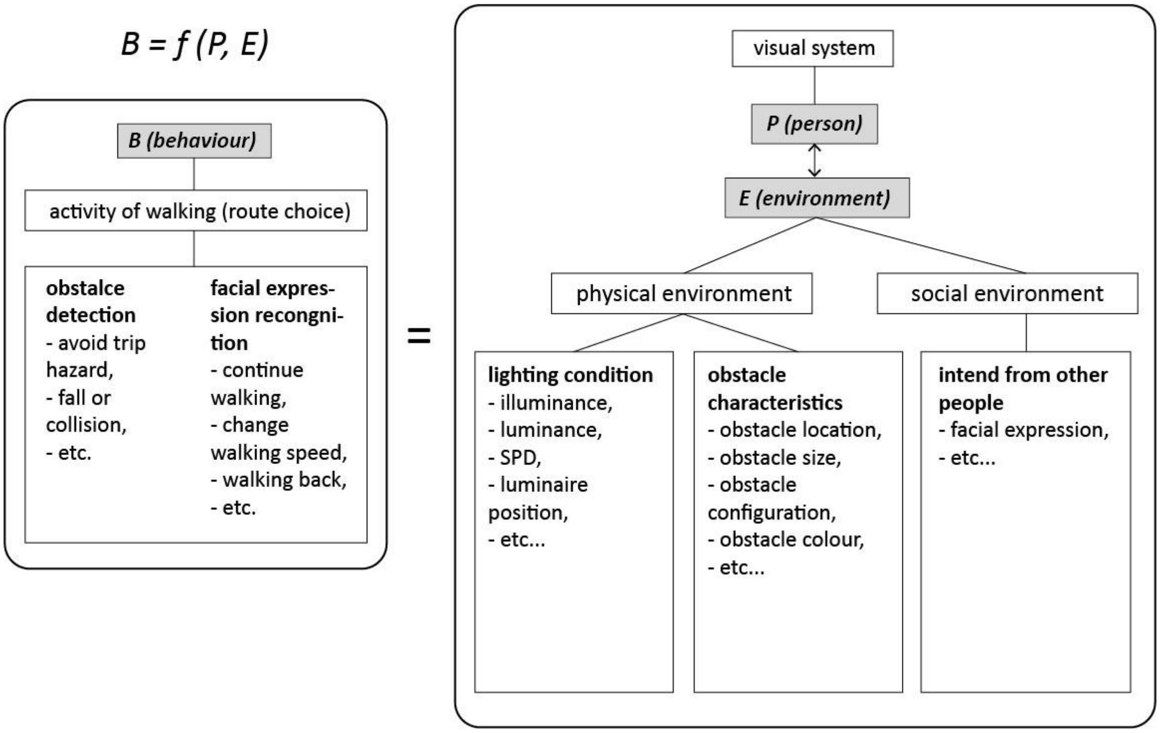


**Figure 2.12.** Theoretical framework in my research.

## 2.7 Limitations of past studies

Sections 2.4 and 2.5 review previous experiments that measured obstacle detection and FER. One shared limitation in all of these studies is that the performance in either FER or obstacle detection experiments was measured whilst instructing test participants to focus on one specific task. In the real street environment, pedestrians have to deal with multiple parallel tasks that reduce their attention toward any one task, such as avoiding collisions with vehicles, trip hazards on the ground and judging approaching people in case they present a threat (Figure 2.13). However, in a laboratory setting, these distractors are excluded to control the variables. As mentioned in section 2.2, attention is the information processing capacity of an individual. Its capacity is limited, and each task being conducting requires a proportion of that capacity (Woollacott, Shumway-Cook, 2002). When two tasks are performed at the same time, the performance for both or one task is likely to be impaired if the available attention is insufficient (Pashler, 1994). If either of these issues is significant, it may affect the relationship between lighting conditions and task performance. Dual task performance has been used in two studies related to driving. Bullough and Rea (2000) examined peripheral target detection in parallel while playing a video driving game. They comment on the effect of lighting changes but not the effect of dual task performance itself. Fotios *et al.* (2020) tested peripheral target detection with simultaneous distraction tasks. The results revealed a significant increase in reaction time to detection. It also shows a significant increase in missed targets in trials with distractions than a distraction-free control trial. However, they did not account for the effect of changes in lighting. The effect of dual task performance on those tasks pertinent to pedestrians is unclear.

**Figure 2.13.** Comparison of a real street condition with a laboratory setting environment. Left: street view after dark; right: photo of experiment setting (Photograph by the author).

Another limitation for FER is that only 2D images of faces have been used in previous studies. These photographs of actors were displayed on a screen. Although the emotions on the images were presented to participants constantly without changing and already with shadow on the face, there might be systematic deviation compared with the real condition.

Figure 2.14 shows an example of a comparison between 3D moulded copies of hand-carved face models and 2D photographs. Comparing the photographs and 3D face models, photographs and 3D face models should look the same if the target face and observation point are static. However, if the illuminance or the relative position of the face and luminaire was changed, the shadow may vary on the face while photographs cannot reflect this change. One approach to address this is to hire actors to present the emotions, but the expressions and intensity of emotion presented by actors cannot be kept constant during the experiment process and for all participants, and the expense of hiring them might be unaffordable. Thus, the use of 3D face models instead of photographs was proposed for future research, especially for studying FER when the target (head/people) is moving or rotating.

The performance of FER when using 3D faces was still uncertain (Li and Yang, 2018). The shadow and shading information might be elements that affect the results. Li and Yang (2018) conducted a FER experiment by using 3D target stimuli, but the results might have a bias because of the material used for face models (Table 2.2). Additionally, the face models used in their experiment were not chosen from a validated database that had been pre-tested to ensure a satisfying correct identification rate. Therefore, further work of testing 3D face models for FER has to be carried out.

In addition to the dual task issue described above, there are two further uncertainties of the past obstacle detection studies: obstacle direction and position relative to the light source.

**Figure 2.14.** Comparison of 3D face model under experiment lighting setting condition (Photograph by the author) and the sample of the 2D photograph used in Yang and Fotios (2015) from FACES database (Ebner *et al.*, 2010).

In past studies (Fotios and Cheal, 2009; Fotios and Cheal, 2013; Uttley *et al.*, 2017), only raised obstacles were presented during the experiments. In the real situation, besides raised obstacles, trip hazards can also be found as depressed areas, like potholes. (Figure 2.11). The raised and lowered obstacles may lead to different detection performances because we tend to observe them in different ways. Cheng *et al.* (2018) conducted an experiment to investigate this by using an eye-tracking device. Participants were asked to walk towards a pavement hazard in a 13 m corridor. The hazard might be either a raised or lowered step. The eye-tracking data were analysed by two methods: the number of fixations and fixation duration on the step (Table 2.4). Raised to lowered hazard ratios show a difference between the two obstacle configurations, and an effect was found between younger (25–34 years) and older groups (65–74 years). The ratios are all above 1.0 for the young participants, indicating they devote more attention and longer fixations towards raised hazards than lowered hazards, while nearly all the ratios for the older group were less than 1.0.

**Table 2.4.** Characteristics of gaze behaviour toward an approaching obstacle, for younger and older test participants. These data were estimated from Figures 5 and 6 of Cheng *et al.* (2018)

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

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

Secondly, in the previous experiments, the obstacle was always positioned directly underneath the light source. The luminance of the facing side of the obstacle will be changed if the relative position between luminaire and obstacle were varied to the observer. As a result, the contrast and shadow pattern will be changed and may lead to different detection performance.

## 2.8 Research objectives

By reviewing previous studies on obstacle detection and FER, the limitations have been defined. Therefore, the aim of this thesis is to test aspects of the experimental design needed to establish optimal lighting, investigate how changes in road lighting characteristics affect the ability to perform key tasks for pedestrians, detect trip hazards and evaluate the intention of other people. This main research aim could be answered by three research questions:

1. Since only photographs have been used in previous FER studies, could 3D printed face models be used in FER experiment? It was hypothesised that 3D printed face models can replace photographs in FER experiment.
2. In the previous obstacle detection experiments, the obstacle has only been moved in one direction – lowered. Is there any difference on detection performance if the

obstacle could be raised? It was hypothesised that there is no difference on detection rates between raised and lowered obstacle.

3. Previous obstacle detection and FER experiments were conducted separately, will the performance of each task be affected when they were performed simultaneously compared with individually? It was hypothesised that the performance in dual task condition should be worser than single task condition.

It was considered to synthesise the results of the current work and previous studies to provide evidence or suggestions to current standards for road lighting of pedestrians. An effective experimental design strategy is expected to be proposed after the whole research. Moreover, new experiments could be proposed and designed based on the findings together with previous studies in order to further explore the relationship between road lighting and obstacle detection and FER performance.

The expected theoretical contributions including find out the effect of multi tasks condition on the performance of obstacle detection and FER tasks, and the effect of obstacle configurations (raised/lowered) on detection performance. From methodological aspects, hoping to test if the occlusion glasses could be used for controlling the observation duration time in laboratory-based experiments. Secondly, if the participants can recognise the facial expressions on the 3D face models in a satisfied rate (comparing with previous studies using photographs from a validated database), then 3D face models could replace photographs in future FER studies. Thirdly, if there is no performance difference between raised and lowered obstacle, future experiment could use one direction instead of two.

The reason for choosing experimental research is due to its advantages (Mildner, 2019). The experimenters could manipulate the variables they interested in, exclude other factors which may affect the results to test the hypotheses. In an experimental research, people could easily understand the relationship between the variables and find out which variable cause the effect. If other researchers hope to replicate the research, it is easy to repeat the studies, confirm the results or test other variables based on the findings. However, experimental research also has some disadvantages. First, the experiment setting is an artificial situation although the experimenter aims to simulate a real-world scenario. Secondly, it may take very long time and money to conduct if many variables are included. According to my research aim, it is to investigate how changes in road lighting characteristics affect the ability to detect trip hazards and evaluate the intention of other people. Thus, doing laboratory-based experiments is appropriate in my case.

## 2.9 Summary

Road lighting in minor roads plays an important role in ensuring the walking safety of pedestrians during night-time. British Standards and Caminada and Van Bommel (1984) proposed that lighting in a residential area should meet the requirements of pedestrians to feel safe and move safely after dark, and these have been validated by reviewing the eye-tracking experiments. The results of these studies suggest that looking at the near path and other people in the distance are two main visual tasks for pedestrians.

Reviewing previous studies concerning obstacle detection and FER have proposed 1.0 lux is the critical illuminance for obstacle detection in 3.4 m distance, and a minimum luminance of 1.0 cd/m$^2$ and 0.33 cd/m$^2$ at 10 m and 4 m distance for FER respectively. The SPDs only have slight effects on an obstacle detection task when the illuminance is below 0.2 lux but no effect for a FER task.

There are limitations of past studies which will be addressed in this research. First is both obstacle detection and FER studies were implemented separately, but it should happen simultaneously in reality which possibly influences the performance of each task. The performance of each task is expected to decrease compared with single task condition. Secondly, all FER experiments have been conducted recently only used photographs. 3D face models can provide realistic and adjustable shadow patterns on the face depending on the luminaire positions. For obstacle detection, only raised obstacles have been tested directly under the lamp source in previous experiments, which means spatial variations and potholes have not been considered.

# CHAPTER 3. PILOT STUDY: TESTING 3D PRINTED FACE MODELS

## 3.1 Introduction

Chapter 2 reviewed eye-tracking experiments that demonstrated looking at other people is one of the critical visual tasks for pedestrians (Fotios *et al.*, 2015a; Fotios *et al.*, 2015b), confirming the applications-based proposal of Caminada and van Bommel (1984). Some experiments have been conducted to explore the effect of changes in the luminance and SPD of lighting on interpersonal judgments, specifically a FER task (Fotios *et al.*, 2015d; Yang and Fotios, 2015; Fotios *et al.*, 2017a).

However, these experiments were conducted using photographs of the face targets, 2D images rather than a 3D object, which may have some limitations compared with using three-dimensional models (Li and Yang, 2018). Therefore, two pilot studies were carried out to explore the use of 3D models. These two pilot studies were designed with the main purpose of testing whether the facial expressions on the 3D face models could be recognised in a high correct identification rate and replace photographs in future studies.

## 3.2 Apparatus – general description

A series of 3D models were presented, one at a time, inside a booth, as shown in Figure 3.1. The interior was painted with Munsell N5 neutral grey paint (reflectance = 0.2) and lit from above by a light source at the centre of the ceiling of the booth. The light source was a 4-colour (RGBW) tuneable LED module producing a white light of S/P ratio 1.4, CCT around 2700 and chromaticity coordinates (x,y) of 0.46, 0.41. Two light levels were used in these trials, named Bright (98 lux) and Dim (2.8 lux). These illuminances were as measured at the centre of the floor of the booth. The Bright condition was the full power mode of the LED for this spectrum; the Dim condition was chosen to represent a typical road environment after dark. These two light levels were used in both pilot studies.

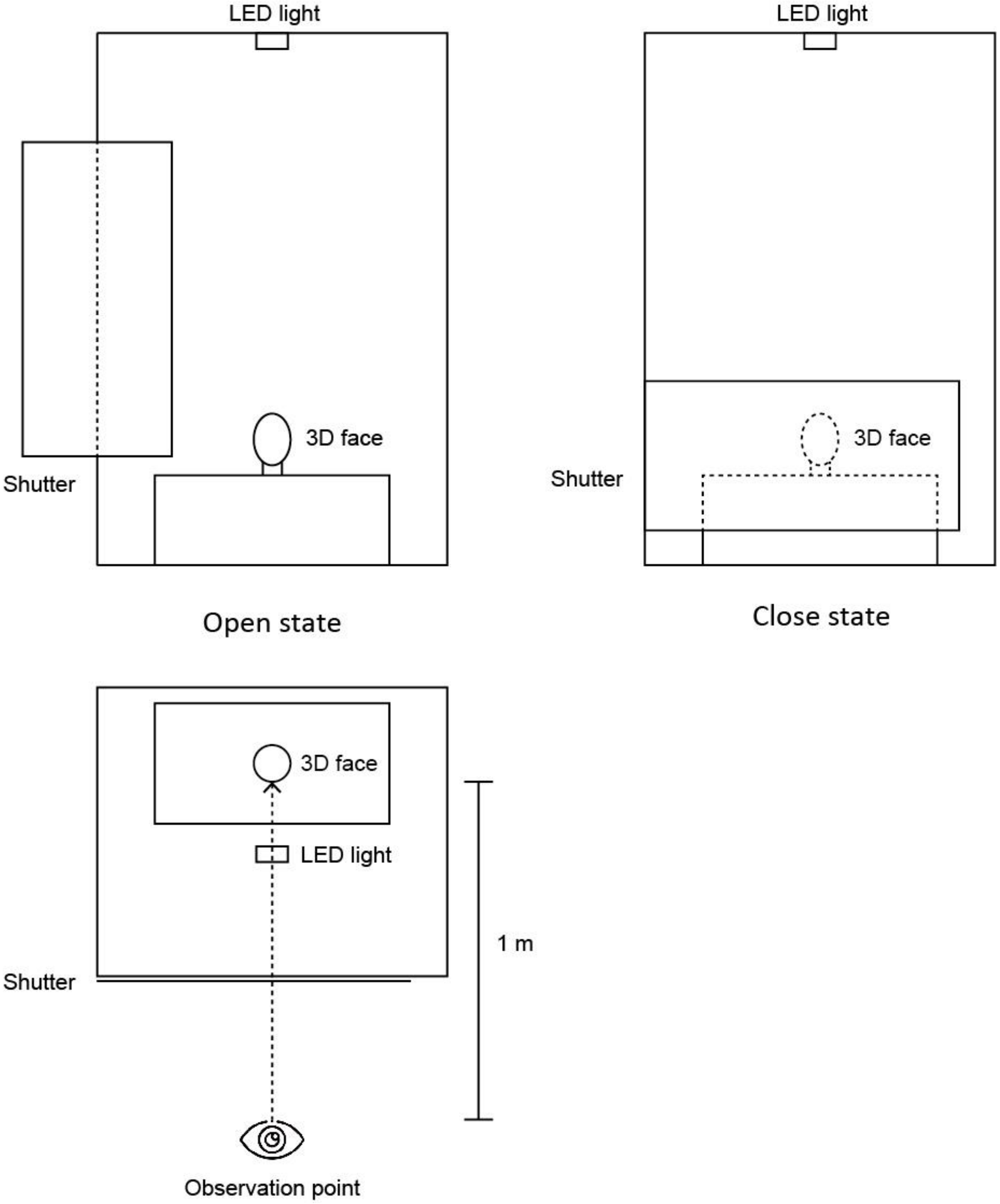


**Figure 3.1.** The apparatus used for the pilot study. Top: Front view of the shutter open and shutter close; Bottom: Top section.

During the experiment, the 3D face model was located in the centre of the box inside the booth in order to keep the face (fixation point) and the observation point at the same height. The observation of the interior was controlled by the experimenter using a servo mounted shutter which was installed in front of the booth. Normally, the shutter was in the closed position to shield the face model inside the box and control the target exposure time.

Target 3D face expressions were chosen from the Binghamton University 3D Facial Expression (BU-3DFE) database, created by the University of Binghamton in the United States (Permission was obtained for use in the current work) (Yin *et al.*, 2006). The BU-3DFE is a 3D facial expression database, including 100 actors (56% female, 44% male), ranging in age from 18 years to 70 years. Each actor performed seven expressions which can be considered as one positive emotion (happiness), two ambivalent emotions (surprise and neutral) and four negative emotions (anger, sadness, fear and disgust) (Yin *et al.*, 2006). Furthermore, each emotion has four levels of intensity which is the degree to which the emotion is expressed from low to high (level 1 to level 4). The raw data for each emotion and intensity is provided in a 3D polygon surface mesh (.3dm file) taken along with an image (.bmp file) taken from the same viewpoint.

The selected face models were printed in a white colour UPFila PLA (polylactic acid) material and sprayed painted in pale flesh colour (Tamiya TS-77 Flat Flesh) (Figure 3.2). All printed by using UP Box 3D printer. As there is no thickness of the 3D polygon surface mesh from the database, a thickness of 0.15 mm was applied to the object (face part) using Rhino to make it printable.

Figure 3.2 shows two examples of face models. The height of each face is 55 mm: when observed at a distance of 1 m, this simulated observation of a full-size face at a distance of 4 m. The primary purpose of the pilot studies was to test whether the 3D printed face models could replace photographs in FER experiments. Thus, the experiment setting was set to an ideal condition. The distance between the face model and observation point was 4 m instead of 10 m which suggested by eye-tracking data (Fotios *et al.*, 2015a).

Sixteen face models were created to use in the two pilot studies. Thirteen expressions were chosen from one actor (young male), with six expressions other than neutral being used in both expression intensities (level 2 and level 4). One expression from three other people was picked as distractors (three in total). Besides, three expressions from other actors were picked in order to distract participants during the experiment and used as compare group in the analysis.

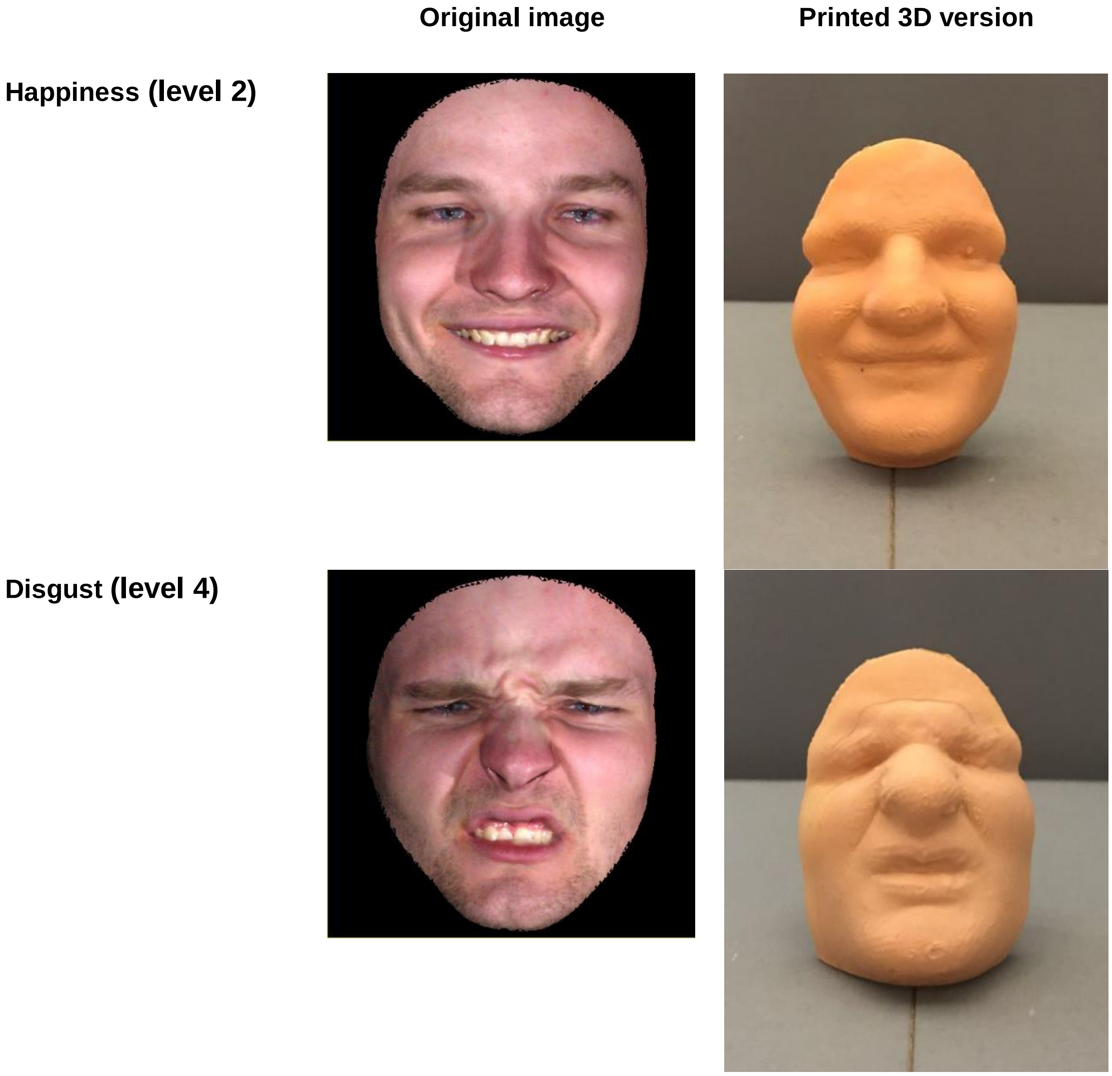


**Figure 3.2.** Two examples of the 3D printed face models used in the pilot study.

## 3.3 Pilot Study 1

The aim of the first pilot study was to test whether the expressions of the 3D printed face models could be identified in ideal conditions by comparing the identification performance of Bright condition and Dim condition both with unlimited observation duration.

### 3.2.1 Method

The apparatus used is described above. There were three independent variables: light level (Bright condition and Dim condition); face emotion (happiness, surprise, neutral, anger, sadness, fear and disgust); lighting combination (two different orders of the two light levels in subsequent presentations). Six of the emotions are universally recognised facial expressions (Etcoff and Magee, 1992). There were 80 trials in total for each participant, which were divided into four blocks. One block contains 20 trials, including thirteen expressions from one person (6 expressions × 2 intensities + 1 neutral expression), four repeated faces were randomly chosen from the thirteen, and three distractors from other actors. The presentation order of face models was randomised in each group. Two lighting combinations luminance sequence were set as Order 1: bright-dim-bright-dim and Order 2: dim-bright-dim-bright (BDBD and DBDB, respectively).

Each test session commenced with 10 minutes of dark adaptation, during which time the test procedure was explained to the participant. Each combination (Order 1 and 2) was presented to five different participants to counterbalance between subjects. Breaks of approximately 2 minutes were included when changing light levels. Participants were asked to identify the emotions presented by the 3D-printed faces but were not required to identify the intensity of expression. The observation duration in pilot study 1 was unlimited because the aim was to validate whether the expressions can be recognised in favourable lighting and viewing conditions with a high accuracy rate.

Ten young participants aged 23 to 30 years were recruited from the students inside the School of Architecture for pilot study 1. Each participant saw all conditions (facial expressions and illuminances) in a 30-minute test session.

Ethical approval was obtained because this experiment involved data collection from human participants. All participants read the Information Sheet about the experiment and then signed a Consent Form. They were free to stop at any time during the experiment. The data for each participant was kept securely and anonymised.

### 3.2.2 Results

The dependent measure analysed here is the percentage of facial emotions that were correctly identified. A high percentage means that an expression was correctly identified in a large proportion of those trials in which it was the target expression.

Within each block of 20 trials, four faces were repeated twice. The percentage of correct identification given in the first and second responses ranged from 55% (2nd response in the Bright block 1 of Order 1) to 90% (1st response in the Dim block 2 of Order 1). These differences did not appear to follow any trend according to light condition or trial number (Figure 3.3). There was an overall accuracy of 75.6% for the first response to a target face and 76.3% for the second response to the same target face. Thus, there were no strong order effects that might be associated with learning or fatigue. These repeated target face responses were then removed for subsequent analyses.

After removing the target faces that were repeated twice, and three additional faces used as distractors during trials, thirteen target faces were left. A second analysis was carried out to further check for order effects. The results of Block 1 and 2 (i.e. the first Bright and Dim conditions) was combined as Session 1, while Block 3 and 4 (i.e. the second Bright and Dim conditions) was combined as Session 2 in the following analysis. The results are shown in Figure 3.4. For Order 1 (BDBD), there does not appear to be a trend: 1st and 2nd sessions led to a higher percentage of correct responses for similar numbers of expressions. For Order 2 (DBDB), the results were higher (or the same) for the second session. This suggests a learning effect – test participants' performance improved with experience. One reason for the difference between the two Orders is the first condition experienced: for Order 1, it was bright lighting, and this bright light may have offset any initial lack of familiarity or experience, but for Order 2, the first condition was dim, and this may have compounded the initial lack of experience. These results confirm it was correct to counter-balance the dim versus bright starting condition. An equal number of dim and bright conditions will be retained in subsequent experiments.

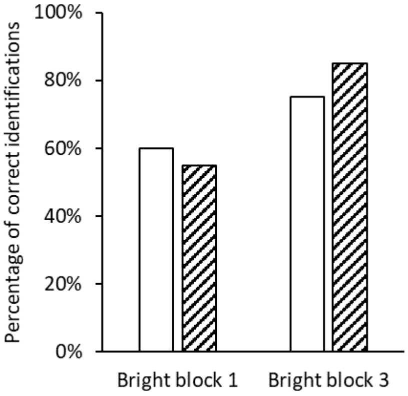
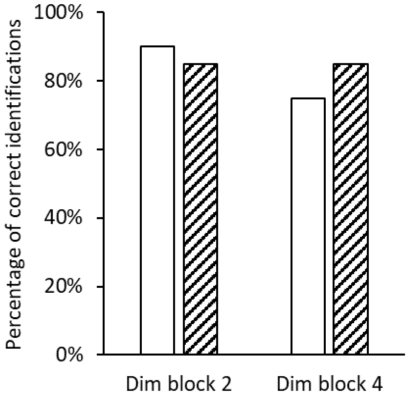
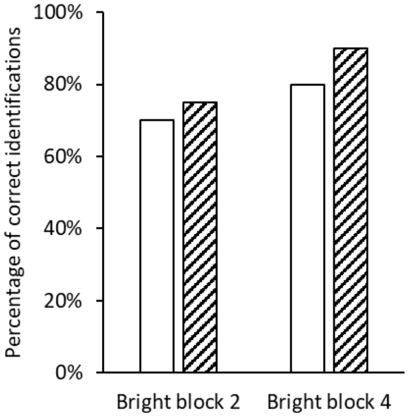
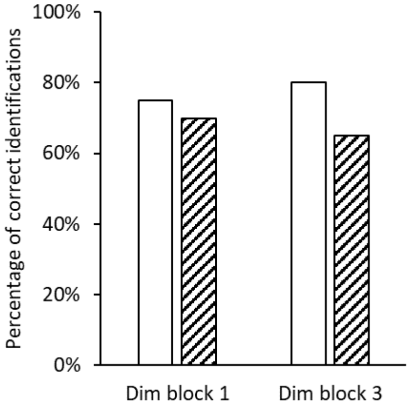
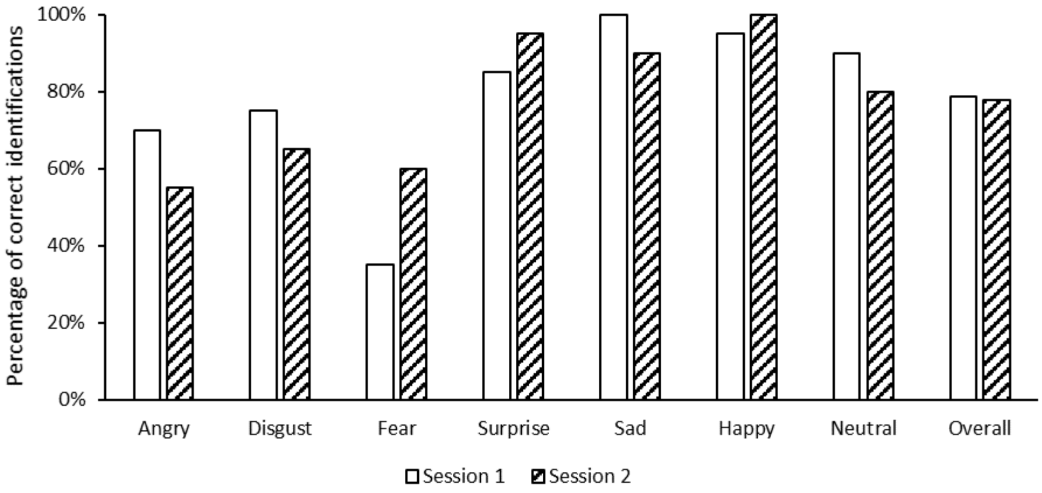
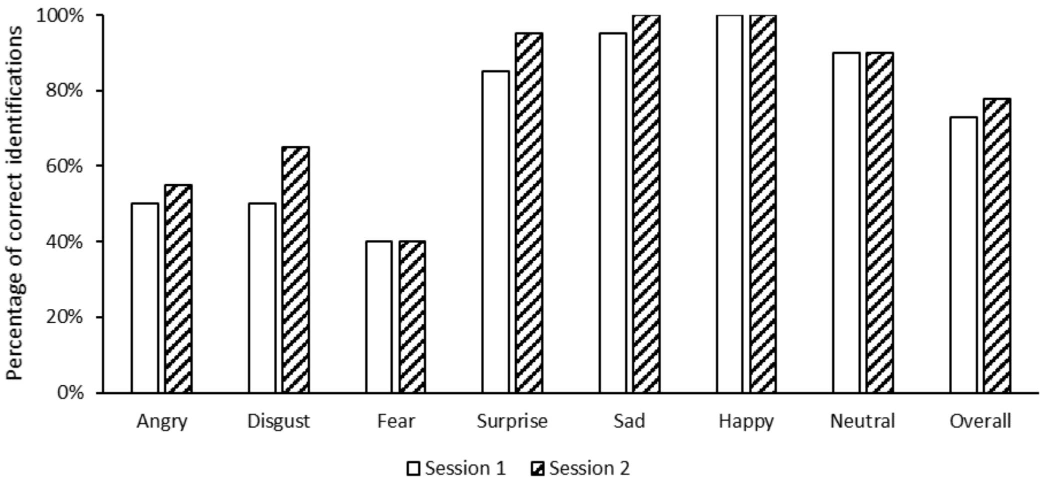
| Block presentation order | Light level | |
|---|---|---|
| | Bright | Dim |
| **Order 1: BDBD**<br>☐ 1st Response<br>▨ 2nd Response |  <br>Bright block 1: Bright block 3<br>**B**DBD: BD**B**D |  <br>Dim block 2: Dim block 4<br>B**D**BD: BDB**D** |
| **Order 2: DBDB**<br>☐ 1st Response<br>▨ 2nd Response |  <br>Bright block 2: Bright block 4<br>D**B**DB: DBD**B** |  <br>Dim block 1: Dim block 3<br>**D**BDB: DB**D**B |

**Figure 3.3.** Comparison of the percentage of repeated faces correctly identified.



Order 1 (BDBD)



Order 2 (DBDB)

**Figure 3.4.** Comparison of the percentage of each emotion correctly identified in two sessions.

This pilot study used two combinations of light conditions, but the different presented orders of light conditions did not reveal any trend due to that (Figure 3.5). Order 1 (with BDBD) shows a slightly better performance than Order 2 (with DBDB), but this is not expected to be a significant difference (average correct identification rate = 78.2% in Order 1, 75.4% in Order 2). The seven facial expressions per target lead to a 1/7 (0.14) probability of correctly identifying the expressed emotion by chance. However, under the

Bright condition in the 1st Session of Order 1 (Bright block 1 in Order 1), the correct identification rate for the fear expression is very low, approximately 10%, which is around the chance response. A possible reason to explain this is: the test participants forgot that fear was an option due to a lack of characteristics to remember before the test. Besides, some expressions are quite similar in appearance that enhanced the difficulty for participants to distinguish the expressions by detail, such as anger and disgust. It is suggested that we should check and confirm that the test participants are familiar with all seven expressions in future experiments.

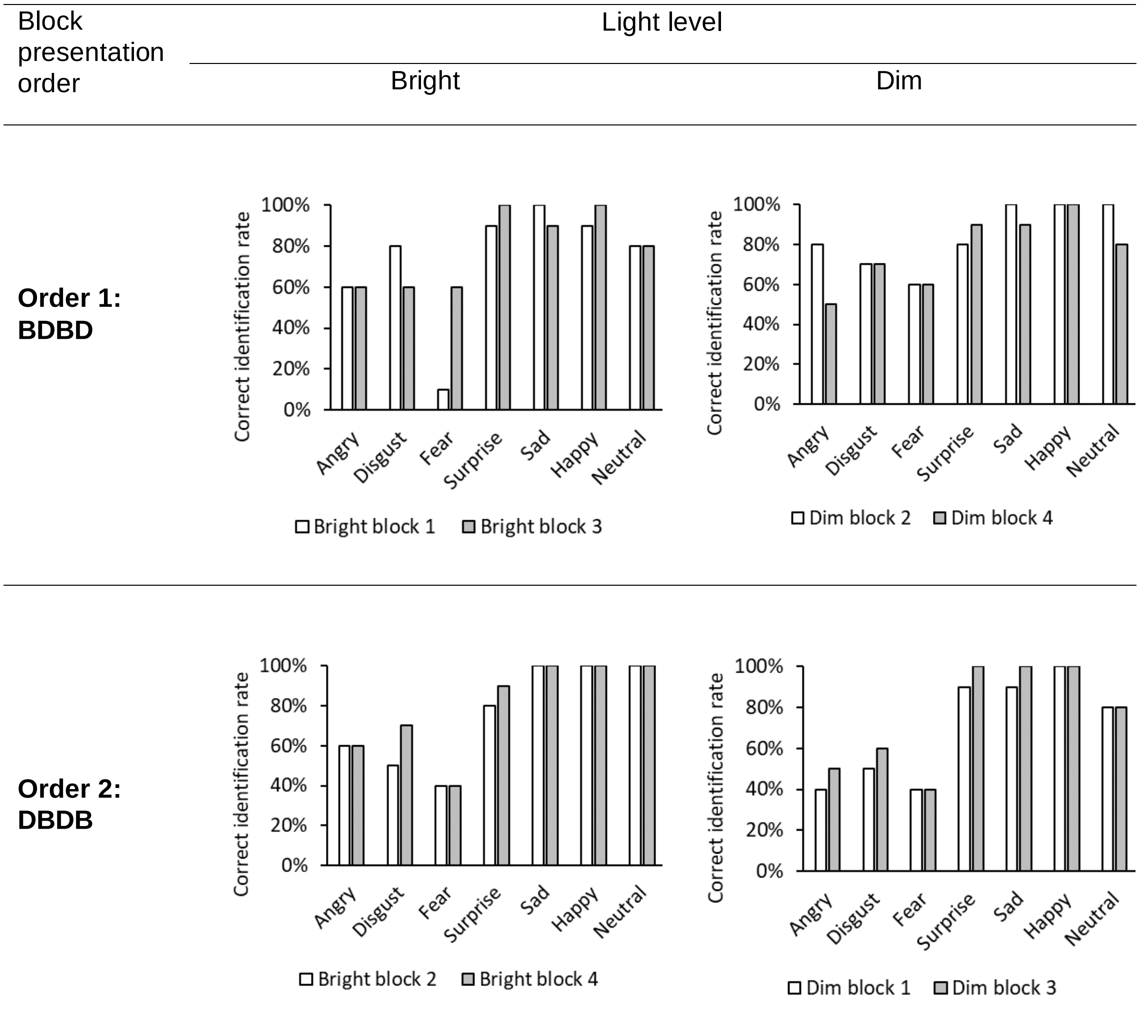
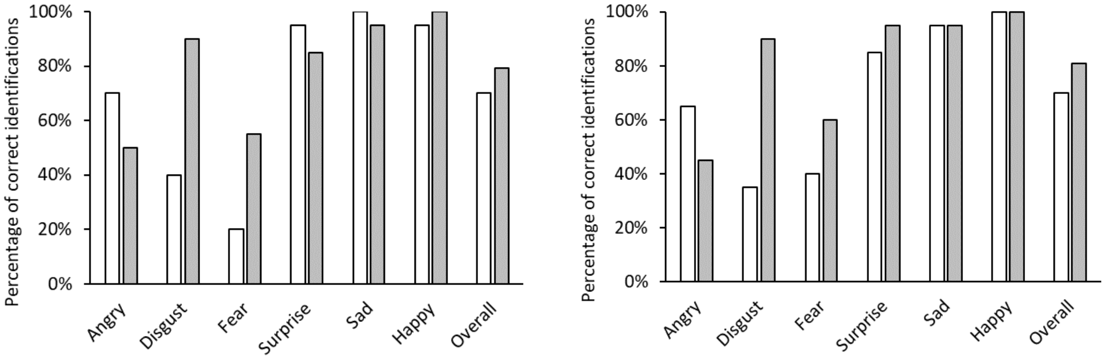


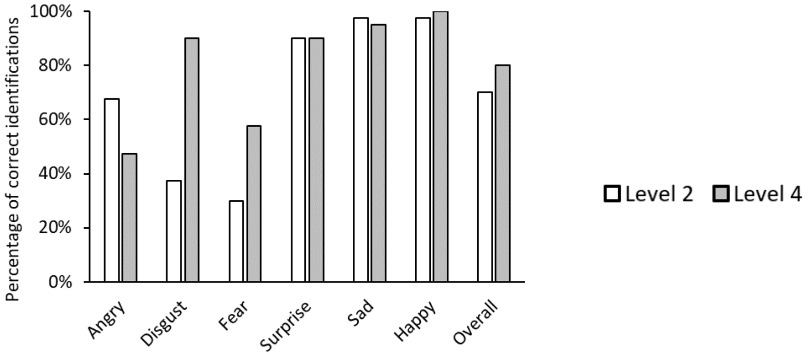
**Figure 3.5.** Comparison of the correctly identified expression rate under two lighting condition presentation orders.

Two different intensities of facial expressions were used in this test: half intensity (level 2 in the original database) and full intensity (level 4). Note that the neutral expression cannot be portrayed with different intensity and excluded from this particular analysis. The results are consistent for the bright, dim, and overall comparisons (Figure 3.6). Only the surprise expression performed opposite trends under two lighting conditions: half intensity has a better identification rate than full intensity under the Bright condition but worse under the Dim condition. For the other expressions, the higher expression intensity (level 4) tends to lead to the higher of correct responses, other than for the angry expression. The overall accuracy of the full intensity expressions is 80.0%, while the half intensity is 70.0%. Therefore, the performance of level 4 (full intensity) shows a better performance than level 2 (half intensity). Given that we expect the higher expression intensity to be more frequently correctly identified, the experiment confirmed this suggests some validation of the target faces used and the experimental design.



Bright condition

Dim condition



Overall

**Figure 3.6.** Comparison of correct identification rate under two intensities of emotions.

All seven expressions were tested under the two light levels (Figure 3.7). The performance under higher illuminance was expected better than lower illuminance, but no apparent tendency can be concluded. The overall accuracy of approximately 77% was found for both Bright and Dim conditions.

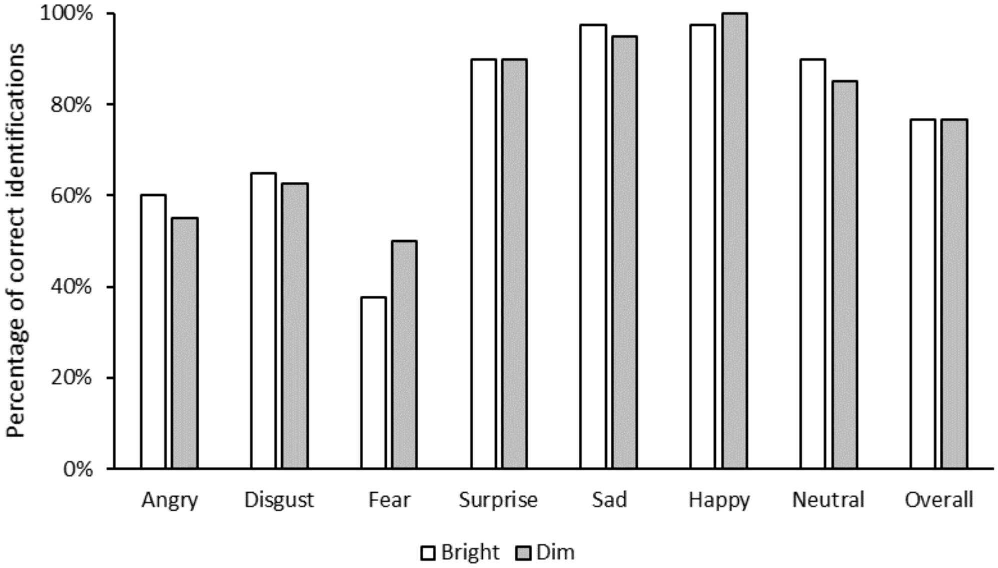


**Figure 3.7.** Comparison of correct identification rate under two light conditions.

### 3.2.3 Discussion

These results demonstrate that the ability to recognise emotions from facial expressions is affected by the intensity of expressions: higher intensity tends to increase the frequency of correct judgments. The presenting order of light conditions and repeated target faces did not show a sequence effect that causing bias.

For the facial expression tests, all the target faces were of an apparent white Caucasian origin. However, the BU-3DFE database contains other three-dimensional face files from different ethnicities, leading to different interpretations of emotions.

Figure 3.8 shows the results of this pilot study compared with those from two previous studies (Ebner *et al.*, 2010; Yang and Fotios, 2015). The percentage of correct identification is similar for four expressions (happiness, neutral, sadness and disgust), but the pilot study revealed much fewer correct identifications for fear and anger. All are, however, above the chance level (25%) of the correct response. However, the two light conditions have not revealed the expected difference in the rate of correct identification. Yang and Fotios (2015) used six light levels: 0.01 cd/m$^2$, 0.03 cd/m$^2$, 0.10 cd/m$^2$, 0.33 cd/m$^2$, 1.00 cd/m$^2$ and 3.33 cd/m$^2$ (measured on the display screen) and found that changes in light level could affect the proportion of correctly identified expressions. Two possible reasons could explain this disagreement with the current findings. The first is the illuminances reported here have not been mapped to the luminances reported by Yang and Fotios (2015). If the current test used higher light levels, we might be on the plateau where no effects are expected. The second reason is the current test used longer target exposure than Yang and Fotios (2015) (500 ms and 1000 ms). With longer duration, performance increases (Dong *et al.*, 2015) and may have reached the plateau of performance.

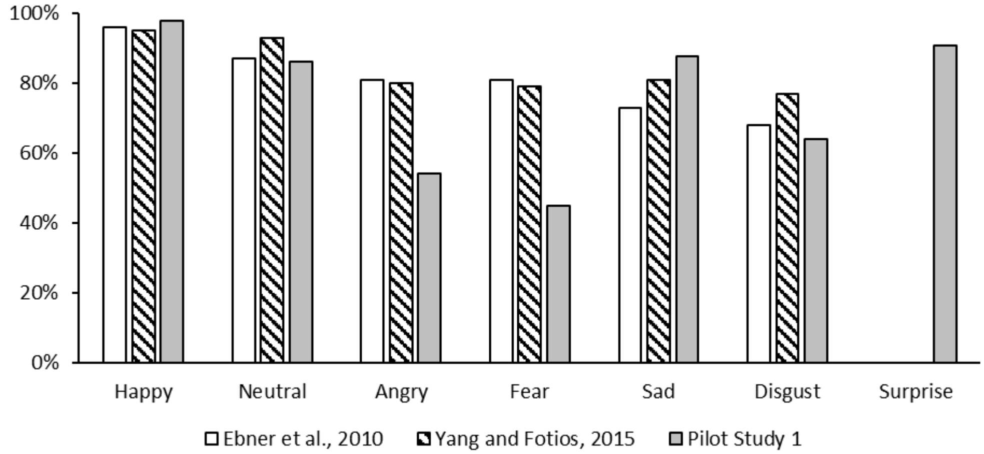


**Figure 3.8.** Comparison with the studies from Ebner *et al.* (2010), and Yang and Fotios (2015).

Thus, luminances on the faces need to be measured before further experimental work. Short exposures can be used to investigate whether there is any effect on facial expression recognition. Additionally, of the seven expressions used in this pilot study, some might lead to misunderstanding (e.g. anger, fear and surprise). One reason for this is the 3D printed face models did not have sufficient resolution to provide subtle differences for recognition. Another reason is different people may have different opinions on what an emotion looks like. It might be helpful to pick the most salient expressions for interpersonal evaluations or try to decrease the number of emotions used based on the performance of this experiment.

### 3.2.4 Conclusions – Pilot study 1

The aim of pilot study 1 was to validate the 3D printed faces for replacing the two-dimension photographs in further experiments. The results suggest these 3D printed face models could possibly replace photographs in the following experiments. The correct identification rates were nearly 80% for both Bright and Dim conditions. A further test needs to be carried out to validate whether the result of this study is repeatable. Repeating this experiment using shorter observation durations, fewer facial expressions and adjustment of face luminances if needed, may affect the results.

Besides, this work was conducted to better understand the relationship between lighting and expression recognition by examining how performance changes with variation in lighting parameters and the task.

The results suggest that task performance was influenced by the intensity of emotions, with higher intensity tending to lead to higher correct identification rates. The presenting order of light conditions, repeated target faces, and different light levels did not exhibit a relationship with task performance.

## 3.4 Pilot Study 2

This second pilot study was carried out to validate whether the results from the first pilot study are repeatable and continuously test if the three-dimensional face models could replace photographs in future experiments based on suggestions listed above. Two facial expressions were excluded (surprise and disgust) in this study. The observation duration was changed from unlimited in the previous study to four different durations: 0.5 s, 1.0 s, 5.0 s and 10.0 s. Two lighting conditions were unchanged, but luminances on face models have been measured in advance to compare the performance with previous studies.

### 3.3.1 Method

The apparatus employed in this experiment was the same as that used in the first pilot study. The apparatus is described in Section 3.2.

This test was developed from the first pilot study based on the suggestions given (Table 3.1). There were four independent variables: emotion (happiness, neutral, anger, sadness and fear), light level (Bright condition and Dim condition), observation duration (0.5 s, 1.0 s. 5.0 s and 10.0 s) and lighting combination (order of the light levels in subsequent presentations).

**Table 3.1.** Comparison of 1st and 2nd pilot study.

| | **Procedure** | **Illuminances** | **Observation durations** | **Number of facial expressions** | **Distance** |
|---|---|---|---|---|---|
| Pilot study 1 | 4 groups (20 faces each group);<br>test order (BDBD or DBDB) | 2 (98 lux and 2.8 lux; equal to 0.22 cd/m2 and 8.3 cd/m2 on the face) | Unlimited | 7 (happiness, fear, anger, sadness, surprise, disgust and neutral) | 4 m |
| Pilot study 2 | 3 group (24 face each group);<br>test order (BBD or BDB, first Bright condition not included in the analysis) | 2 (98 lux and 2.8 lux; equal to 0.22 cd/m2 and 8.3 cd/m2 on the face) | 4 (0.5 s, 1.0 s, 5.0 s and 10.0 s) | 5 (happiness, fear, anger, sadness and neutral) | 4 m |

Target 3D-printed faces were again those derived with permission from the BU-3DFE database. Some expressions might be more difficult to discriminate than others because they are more ambiguous or complex (Adolphs, 2002). Therefore, in contrast with the previous experiment, five emotions conveyed by facial expression were used as anger, fear, happiness, sadness and neutral, surprise and disgust were excluded. These were chosen based on the performance of the first pilot study. Happiness and sadness got the highest scores in the first test while anger and fear had the worst performance. They were all required to be tested again in the second test in order to validate if the results can be repeated or tend to have a better performance. As there was an effect of the intensity of emotions, only the highest intensity (level 4) was used in pilot study 2.

Two light conditions were set as same as the first test in relation to measured luminances on the forehead of the face, 0.22 cd/m$^2$ for the Dim condition and 8.3 cd/m$^2$ for the Bright condition. Fotios *et al.* (2017) used three different luminances in their test as 0.1, 0.33 and 1.0 cd/m$^2$. The expected plateau-escarpment relationship between size, luminance and performance was confirmed at 4 m distance, though the effect was not suggested to be significant. Hence, the light setting was kept as in the first experiment.

The luminance of 0.22 cd/m$^2$ was in the middle of the escarpment while the 8.3 cd/m$^2$ was on the plateau.

Pilot study 1 used an unlimited observation duration. Eye-tracking records have shown that only a short observation is used in natural settings, typically about 500 ms (Jovancevic-Misic and Hayhoe, 2009; Fotios *et al.*, 2015a; Fotios *et al.*, 2015b; Fotios *et al.*, 2015c). Therefore, pilot study 2 used four different observation periods, 0.5 s, 1.0 s. 5.0 s and 10.0 s. The different observation durations were controlled by the experimenter using the shutter in front of the booth, as shown in Figure 3.1. Three blocks of trials were implemented consisting of 24 target faces with five emotions, which include anger, fear, happiness, sadness and neutral (4 duration x 5 emotions + 4 distractors). Four additional face models from other actors were included within trials as distractors but were not analysed. Every expression was presented for participants to identify within four observation durations separately. In each group, both the presentation order of face models and observation durations were randomised.

Two lighting combinations were set as Order 1: bright-bright-dim and Order 2: bright-dim-bright (BBD and BDB respectively). The aim of the first block (Bright condition) in both orders was to enable participants to become familiar with the emotions and the test procedure. Therefore, these data were not analysed.

The whole test for each participant took around 45 minutes, including an initial 10 minutes for dark adaptation and explanation. During the trial, the participants were required to judge the emotions conveyed by the target faces during the observation duration. The response was reported orally by participants.

Ten participants were recruited for pilot study 2, none of whom had participated in pilot study 1. All were students at the School of Architecture and aged under 25 years. Ethical approval was obtained together with pilot study 1.

### 3.3.2 Results

Table 3.2 shows the frequency of correct responses, and these are presented as proportions in Figure 3.9. There was an apparent trend given by the results. The percentage of correct identification given among the four observation durations ranged from 50% to 100%. Accuracy increases when the observation duration becomes longer. The average correct rates for all emotions of both 5.0 s and 10.0 s are equal or over 80% correct identification. Little effect of observation duration can be seen when longer than 5 seconds.

**Table 3.2.** Results of the 2nd pilot study.

| **Luminances (cd/m$^2$)** | **Facial expressions** | **Percentage of correct responses (%)** | | | |
|---|---|---|---|---|---|
| | | **0.5 s** | **1.0 s** | **5.0 s** | **10.0 s** |
| 0.22 | Anger | 70 | 70 | 100 | 100 |
| | Fear | 60 | 60 | 90 | 90 |
| | Happiness | 100 | 100 | 100 | 100 |
| | Sadness | 90 | 80 | 100 | 100 |
| | Neutral | 70 | 70 | 90 | 90 |
| | Overall | 78 | 76 | 96 | 96 |
| 8.3 | Anger | 60 | 90 | 80 | 90 |
| | Fear | 70 | 70 | 80 | 80 |
| | Happiness | 100 | 100 | 100 | 100 |
| | Sadness | 70 | 70 | 90 | 100 |
| | Neutral | 50 | 80 | 90 | 100 |
| | Overall | 70 | 82 | 88 | 94 |

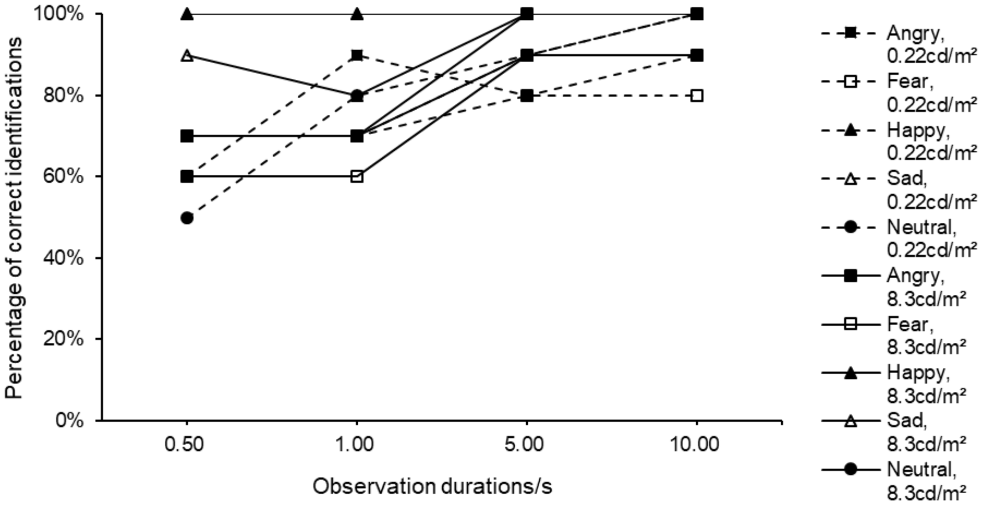


**Figure 3.9.** Results of the 2nd pilot study: identification proportion correctly identifying target faces plotted against the observation duration for two target luminances.

Although two luminances were set on the escarpment and plateau respectively based on the study from Fotios *et al.* (2017), only a slight difference was revealed between the two light conditions. The overall performances of both conditions were over 80% correctly identification rate: 84% in Dim condition, 87% in Bright condition. The maximum difference between the two luminances is 20%. The tendency presented by these data was similar to the results from the pilot study 1. The percentage of correct identification becomes higher when the luminance increased, though the difference between the two light conditions is not obvious.

### 3.3.3 Discussion

One aim of this work was to validate by repetition the results of a previous study. The conditions common to both experiments are a visual distance of 4 m, the LED lamp spectrum, and target luminances of 0.22 cd/m$^2$ and 8.3 cd/m$^2$. Ten participants were recruited for both tests. Figure 3.10 shows the data with correct expression recognition frequencies, compared with the data from Dong *et al.* (2015). A plateau-escarpment relationship between luminance and target durations was indicated in both experiments. With longer durations and high luminances, performance reaches a maximum, and a further increase in either has little effect on performance. The current test found slightly lower performance than that at 1.0 cd/m$^2$ from Dong *et al.* (2015) – even the Bright condition was much higher than 1.0 cd/m$^2$. However, the result from 0.22 cd/m$^2$ was much greater than 0.1 cd/m$^2$ from Dong *et al.* (2015) and performed nearly the same as the Bright condition and close to 1.0 cd/m$^2$ of Dong *et al.* (2015). That might be due to the different task difficulty for the two experiments. The purpose of Dong *et al.* (2015) was to name the celebrity shown in a colour photograph while this pilot study was to judge the emotions from facial expressions. One reason why the previous study exhibited better performance than the current study is that the celebrity used in that test may lead to a potential benefit from familiarity.

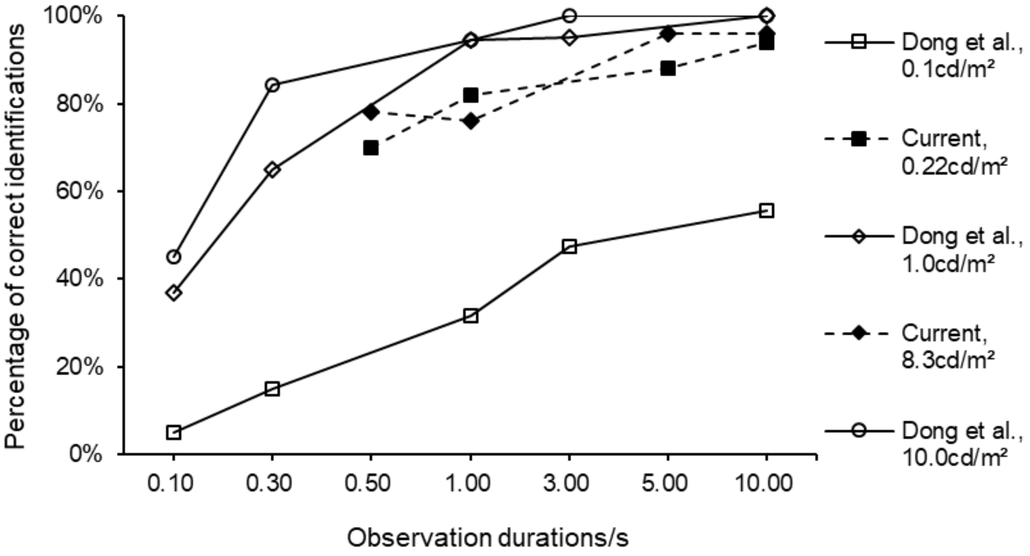
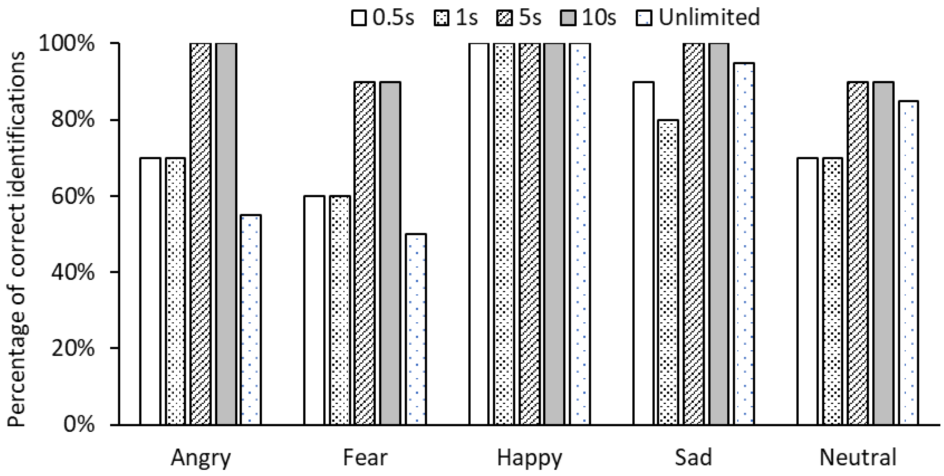
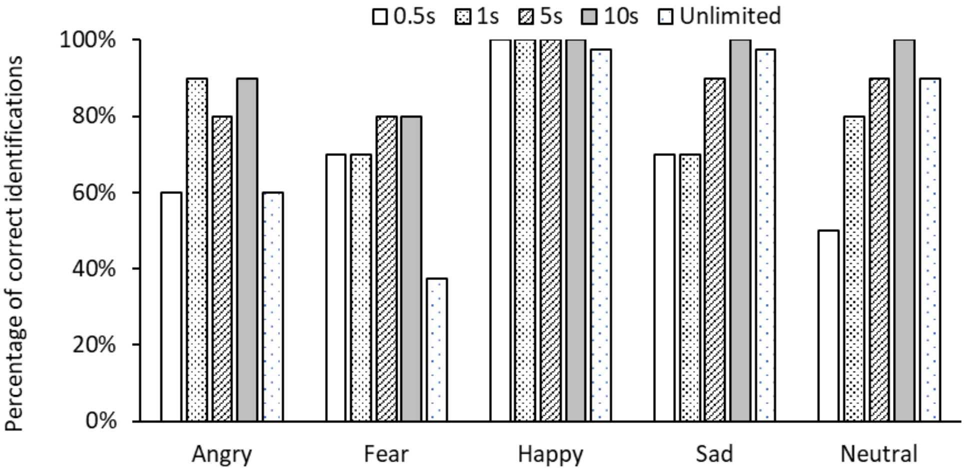


**Figure 3.10.** Identification proportion correctly identifying target faces plotted against the observation duration, for the current study and from previous work (Dong *et al.*, 2015).

Five emotions have been used for participants to discriminate under the same light conditions in pilot studies 1 and 2. The data collected are presented as proportions in Figure 3.11. The data from pilot study 1 used for comparison excluded repeated targets and distractors, and for pilot study 2, the first block and distractors in the second and third blocks were excluded. Although the observation duration of pilot study 1 was unlimited, the performance was worse than seeing that in results from the second pilot study even as the observation duration was limited. It might be due to the two more emotions participants were asked to identify. Happy faces were correctly identified in nearly 100% among all the trials in these two studies. Variation of observation duration and the light condition has no effect on the performance. It matches the finding from Willis *et al.* (2011b), happiness was judged more positively than all other emotions.



Dim condition



Bright condition

**Figure 3.11.** Comparison of the correctly identified proportion of five emotions within five different observation durations.

For the current data, the light conditions influence the performance quite slightly because of the large target size (equivalent to a real face at 4 m distance). Both experiments asked participants to judge the emotions at 4 m distance. Yang and Fotios (2015) suggest that 4 m is an easy condition where an effect of SPD and duration would not be expected while 0.03 cd/m$^2$ was the optimum luminance at such distance for a

50% probability of correct identification. All the results from the second pilot study were equal to or over 50%.

Duration plays an important role in judgments of emotion for those conditions lying on the escarpment, but not in the plateau regions. The data for pilot study 2 exhibits the escarpment-plateau relationship between correct identification proportion and observation duration but not obviously due to the large target size. The performance for 0.5 s and 1.0 s is nearly the same, both in the escarpment region. The frequency of correct responses increased until the duration lasted for 5.0 seconds and reached the plateau. There was no effect of duration if it was longer than 5.0 seconds.

### 3.3.4 Conclusions – Pilot study 2

Pilot study 2 continuously tested the use of 3D printed face models for the facial expression recognition task. The results reveal that the correct identification rates were above 50% for all facial expressions, which shows the same conclusion with pilot study 1: 3D printed face models could replace photograph in future experiments.

## 3.5 Summary

Two pilot studies were carried out to investigate how the identification of emotion from facial expression is affected by lighting, observation duration and the use of 3D printed faces. These factors play a vital role in judging the intent from approaching pedestrians and if they can be seen as a threat.

The results suggested that the 3D printed target faces could be discriminated in a satisfactory accuracy rate under two light conditions, especially for five emotions (happiness, fear, anger, sadness and neutral). Higher luminance and longer duration tended to lead to a higher frequency of correct identification. Although a plateau-escarpment relationship was exhibited between performance and luminance or duration, the effects of higher luminance and longer duration were not significant. If the target probability of correct identification is 50%, all the second pilot study results meet the requirement. With a limited duration of observation at a low light level, it is still possible to discriminate expressions. Therefore, 3D printed faces can be used in future experiments.

However, the 3D printed face models used in this pilot study were not used in the main experiments. Although the correct identification rates were all above a chance level in the pilot studies when observed at a simulated 4 m distance, the surface resolution of the faces is insufficient where smaller faces are needed to represent greater interpersonal distances, i.e. to avoid incorrect identification of the emotion due to the low quality of face models rather than as an effect of lighting.

In subsequent work, these 3D printed face models were replaced by cast models purchased from an external supplier (Figure 3.12).

**Figure 3.12.** Sample of 3D printed face models in happiness used in two pilot studies and cast models used in the next experiments.

# CHAPTER 4. GENERAL METHOD

## 4.1 Introduction

Previous chapters established that observing the near path and other people at a far distance are two critical visual tasks for pedestrians when walking down a street. Looking at the path ahead in the direction of travel could contribute to the detection of trip hazards and judging if approaching people appear threatening might affect the choice of route. While studies have been conducted to explore how lighting changes affect the performance of these two tasks, there were limitations for both obstacle detection and FER experiments. One shared limitation is that obstacle detection and FER have been tested separately. For obstacle detection studies, the target obstacles were always raised relative to the surrounding surface and located directly beneath the luminaire. For FER, the targets tested in previous studies were 2D images of faces.

Three experiments were carried out to further investigate the effect of lighting change on obstacle detection, and FER presented as separate and simultaneous tasks to address these limitations. This chapter describes the apparatus, methods and procedures used in these experiments.

## 4.2 Apparatus – general description

The three experiments were all conducted in a single booth, located in a laboratory located in the Arts Tower in the University of Sheffield with no natural light (covered with black curtains) (Figure 4.1). The lab is located in the upper most floor of the building which people only rarely visit, so noise outside the lab was negligible. The booth was constructed from medium-density fibreboard (MDF). The dimension of the whole booth was 2090 mm depth × 1200 mm width x 1200 mm height, and the visible space inside was 1200 mm depth, 1200 mm width, and 1200 mm height. Visible vertical surfaces, including side and rear walls, were all matt black. The reflectance of the matt black surface was difficult to get a reliable value because it is too low to measure, close to zero. This was designed to simulate a reflectance of outdoor environment after dark. The floor surface, upper and sides of the obstacles and inner surfaces of the tubular housing of each obstacle (which became visible when an obstacle lowered) were matt grey (Munsell N5, reflectance 0.2) because for an unknown surface reflectance, we first assume a diffuse reflectance of 0.2 (CIE 115:2010). The front of the booth was open, allowing participants to see inside. A chin rest was installed at the front of the test booth that held the observation point from participants in the same place in relation to the tasks. Participants were doing the experiments in setting position instead of normal standing position is to prevent fatigue during around 2 hours experiment period, but all experiment settings were converted to simulate when viewing at 1.5 m height (standing position). The detailed are given below.

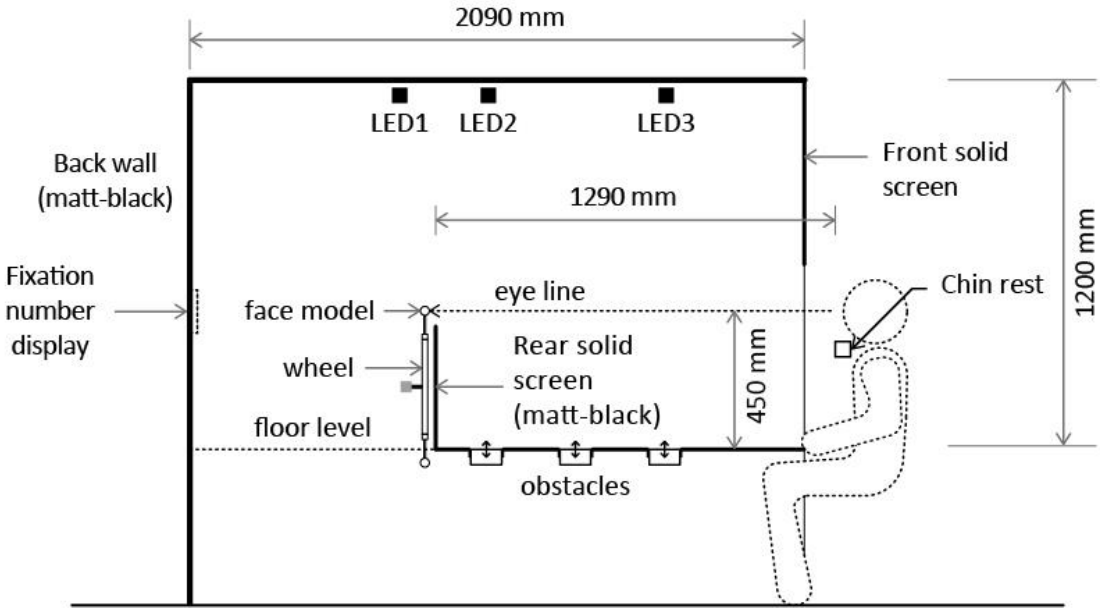


**Figure 4.1.** Side elevation of apparatus.

The floor of the test booth simulated a pavement surface. There are 12 vertical cylinders (100 mm diameter) on the floor, which were normally flush with the floor (Figure 4.2). Four of these (Obstacles 1 - 4) were used and controlled using the servo-driven linear slides. Each of them could raise or lower individually by up to 25 mm in either direction.

Obstacles 1 and 4 were placed on the centre line of the booth, directly ahead of the observation point. The horizontal distances between Obstacle 1/ Obstacle 4 and the observation point were 1220 mm and 640 mm, respectively. Obstacles 2 and 3 were symmetrically placed on the left and right of the centre line. The horizontal distance between the observation point and the two obstacles (Obstacle 2 and 3) was the same at 1010 mm. Table 4.1 shows the visual angles to each obstacle, assuming the participant was looking directly at the fixation target presented at the back.

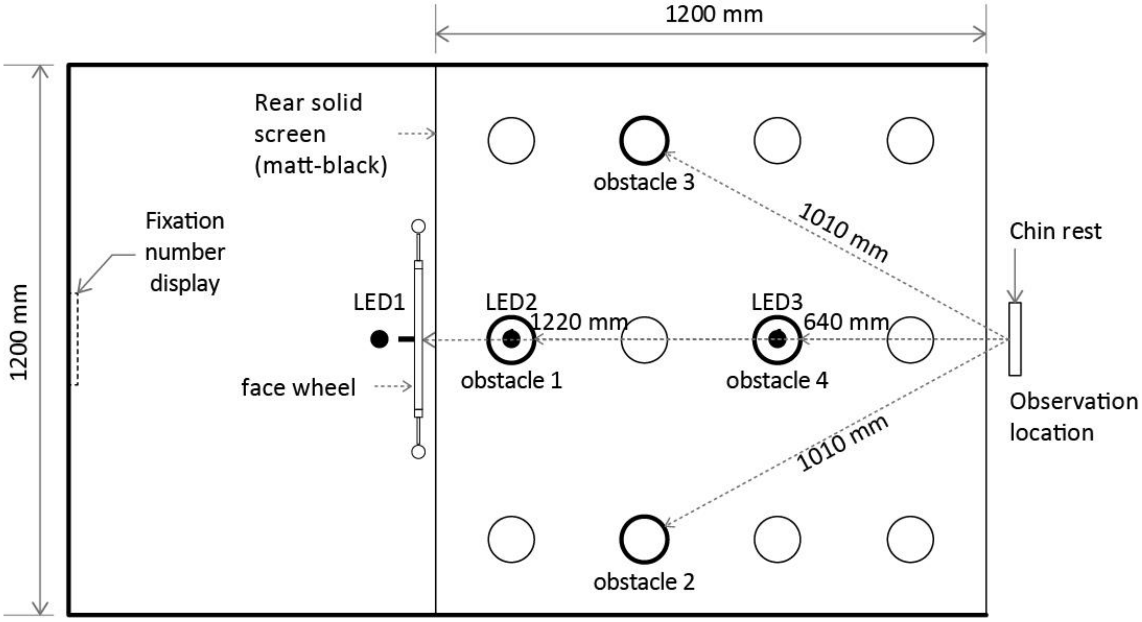


**Figure 4.2.** Plan view of apparatus.

**Table 4.1.** Obstacle locations relative to the fixation point. Note that only Obstacles 1 to 3 were used in Experiment 3.

| **Target** | **Obstacle's angular deviation from the fixation point (degrees)** | | |
|---|---|---|---|
| | Down | Left/Right | Central angle |
| Obstacle 1 | 19.7 | 0 | 19.7 |
| Obstacle 2 & 3 | 23.0 | 24.3 | 33.0 |
| Obstacle 4 | 33.7 | 0 | 33.7 |

Each obstacle was surrounded by a 3 to 4 mm gap, allowing for free vertical movement. A shadow was created by the gap when the obstacle flushing with the floor (Figure 4.3). In order to make the visual pattern of all the obstacles were consistent for the participants, a same gap was designed for the eight inactive obstacles.

A masking noise was generated by an electric motor located underneath the obstacle for two seconds duration between each trial regardless the obstacle was moved or not. The purpose of using this masking noise was to remove audible clues that could help participants judge whether or not an obstacle is presented. A Python program was designed to control the masking noise as for the obstacles, light sources, occlusion spectacles, fixation task and response button logging.

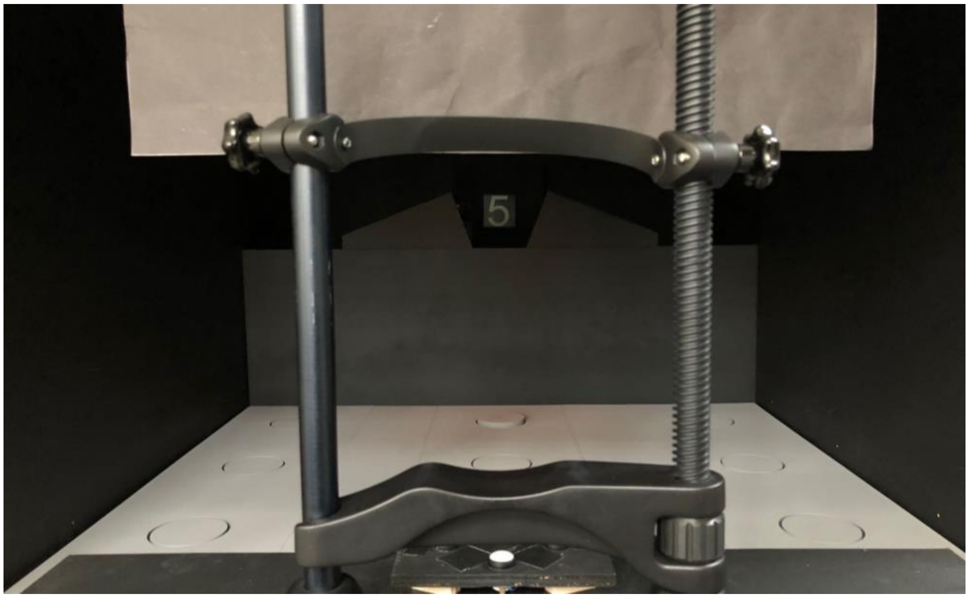


**Figure 4.3.** The scene in Experiment 1 from just behind the observer's position. The photo was taken under daylight from the windows in the laboratory. A button box was positioned in front of the chin rest. Participants pressed the corresponding button when they detect an obstacle. Obstacle 2 is raised in this photo.

There were three identical LED luminaires directly mounted above the same central line as the Obstacle 1 and 4, at three different positions (Figure 4.2). Each housed an array (Osram Ostar Stage) comprising four chromatically different (RGB and White) LEDs, which allowed tuning of luminance and spectral power distribution (SPD) of each luminaire. A 45 mm-diameter colour-mixing lens and a diffuser (3 mm thick opal Perspex) on the front of each array ensured colour uniformity, and a small tubular baffle (40 mm diameter, 35 mm long) constrained the light distribution. A vertical black screen was installed on the front face of the booth above the participants to prevent the participant affected by the glare from direct viewing the LEDs.

The SPD of the light source was not varied in the current three experiments and was set to deliver an S/P ratio of 1.6 (Figure 4.4), Correlated Colour Temperature (CCT) = 2750K and chromaticity coordinates of x = 0.47, y = 0.41. The results from previous studies suggested that the changes of S/P ratio would affect obstacle detection if the horizontal illuminances less than 0.2 lux (Fotios and Cheal, 2009; Fotios and Cheal, 2013; Uttley *et al.*, 2017), but would not affect the performance of FER at any light level (Fotios *et al.*, 2017a; Yang and Fotios, 2015).

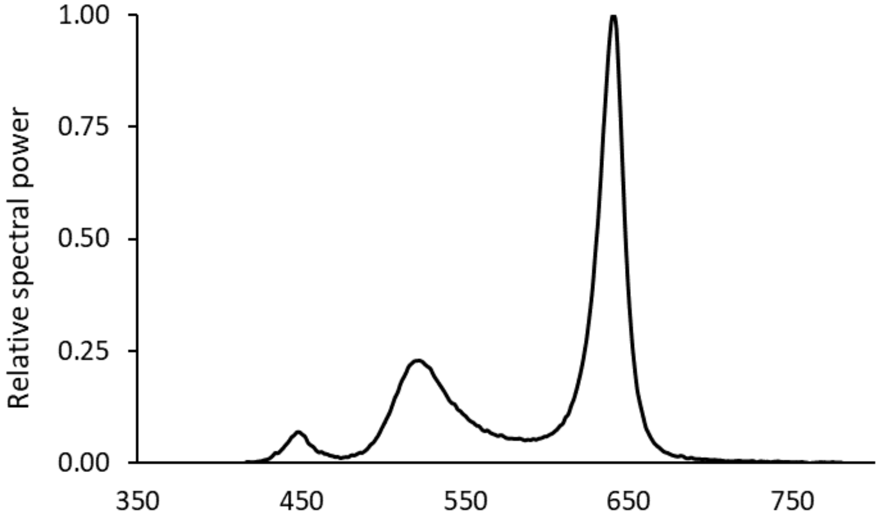


**Figure 4.4.** Spectral power distribution for the LED luminaires.

The observation duration for participants was accurately controlled by a pair of PLATO visual occlusion spectacles (Figure 4.5) (Translucent Technologies Inc, 2018). In the open state ("open shutters"), the spectacles were the same as normal clear lenses that allow participants to obtain visual information. In the closed state ("closed shutters"), details of the observed scene could not be resolved, but the lenses still transmit light as frosted glass, helping maintain visual adaptation in the intervals between trials. Light transmission in the open state and closed state were 90% and 62%, respectively (measured using the test light source). The light spectrum has barely affected the spectacles. When an S/P ratio of 1.60 was measured without spectacles, the S/P ratio decreased to 1.57 in the open state and 1.56 in the closed state with spectacles presented. According to the manufacturer, transitions between the fully open and fully closed states of the liquid crystal shutters take approximately 4 ms. In all three experiments, the observation duration time was set for 500 ms is the typical duration of fixation on other people (Fotios *et al.*, 2018; Fotios and Johansson, 2019). Rather than investigate the impact of changes in observation duration, this single period was chosen to provide a degree of ecological validity, which means the extent to which the finding from laboratory studies can be generalised to real-world settings (Coolican, 2014, p.118). It was also the duration used in some previous FER studies (Table 2.2) and obstacle detection (Table 2.3), which aids comparison with those studies.

**Figure 4.5.** Side-by-side photos of occlusion spectacles in the open state (right) and close state (left).

The apparatus used for all three main experiments was generally the same, but the specific setting was slightly different. The settings for LEDs (LED 1 - 3), obstacles (Obstacle 1 - 4), back display screen and face model wheel were modified based on the design of each experiment (Table 4.2). The detailed settings for each experiment will be described in specific sections.

**Table 4.2.** Apparatus setting for three experiments.

| Experiment number | Items | Usage |
|---|---|---|
| Experiment 1 | LED | LED 1, 2 and 3 |
| | Obstacle | Obstacle 1 - 4 |
| | Back display screen | Used for display digits |
| | Wheel and face models | Not used |
| Experiment 2 | LED | LED 1 and 2 |
| | Obstacle | Obstacle 1 - 4 |
| | Back display screen | Not used |
| | Wheel and face models | Used |
| Experiment 3 | LED | LED 1 and 2 |
| | Obstacle | Obstacle 1 - 3 |
| | Back display screen | Not used |
| | Wheel and face models | Used |

## 4.3 Procedure – general description

For all three experiments, test participants were recruited from the students in the School of Architecture of the University of Sheffield. The number of participants depended on the demand for each experiment. They received a small payment for taking part in this experiment.

Since all the three experiments and along with two pilot studies required data collection from human participants, ethical approval was obtained from the University of Sheffield in May 2017 to cover all the data collection processes (application number: 014272). Data collection followed the University's code of practice and ethical guidelines to recruit participants with the appropriate information to be able to give informed consent. The Participant Information Sheet contains the research objectives, experiment procedure, data protection and complaint contact details. The Consent Form established an agreement with participants to maintain their confidentiality and anonymity throughout the study, without any personal information used in any research publications. All data collected from the experiments were labelled with an identification number and used only for the purposes of this research. As all the experiments shared the same ethics approval, it will not be mentioned again in the following chapters.

Before the main experiment start, each participant was required to confirm normal or corrected-to-normal visual acuity and normal colour vision by using a Landolt-ring chart and Ishihara test book under a simulated daylight source (Verivide D65). After that, the room lighting was then turned off. The LEDs inside the test booth were turned on for participants to adapt to the mesopic conditions of the experiment and start the following procedure of each experiment.

## 4.4 Settings for Experiment 1

No face models were installed in this experiment because its primary purpose was to investigate whether different luminaire position affects the obstacle detection performance of raised and lowered trip hazard. In order to ensure the participants detect the obstacle using their peripheral vision, a concurrent fixation task (number recognition) was added in each trial. During each trial, two random digit numbers in the range of 1 to

9 were displayed randomly within 500 ms duration on a small rectangular LCD screen located in the centre on the back wall at the same height as the observation point (Figure 4.6 and Figure 4.7). These were in a regular Arial font, 100 mm high and white (luminance 0.25 cd/m$^2$) on a black background. When the test participants positioned their head on the chin rest, the horizontal distance between the participant's eyes and the centre of the fixation mark on the screen was 2290 mm, at which the numbers subtended an angle of 2.57°.

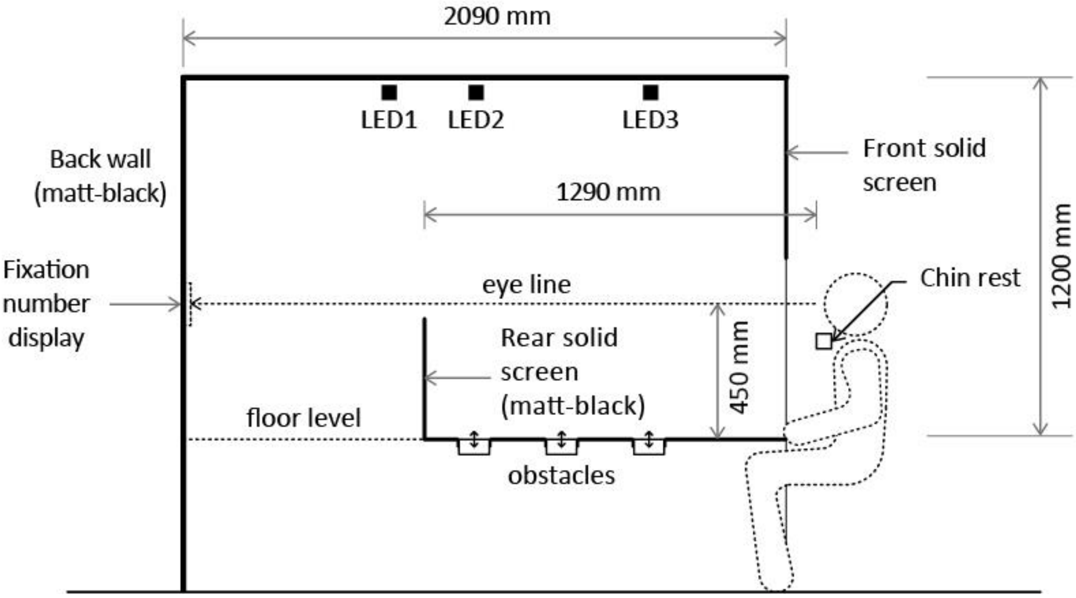


**Figure 4.6.** Side elevation of apparatus used in Experiment 1 (obstacle detection only).

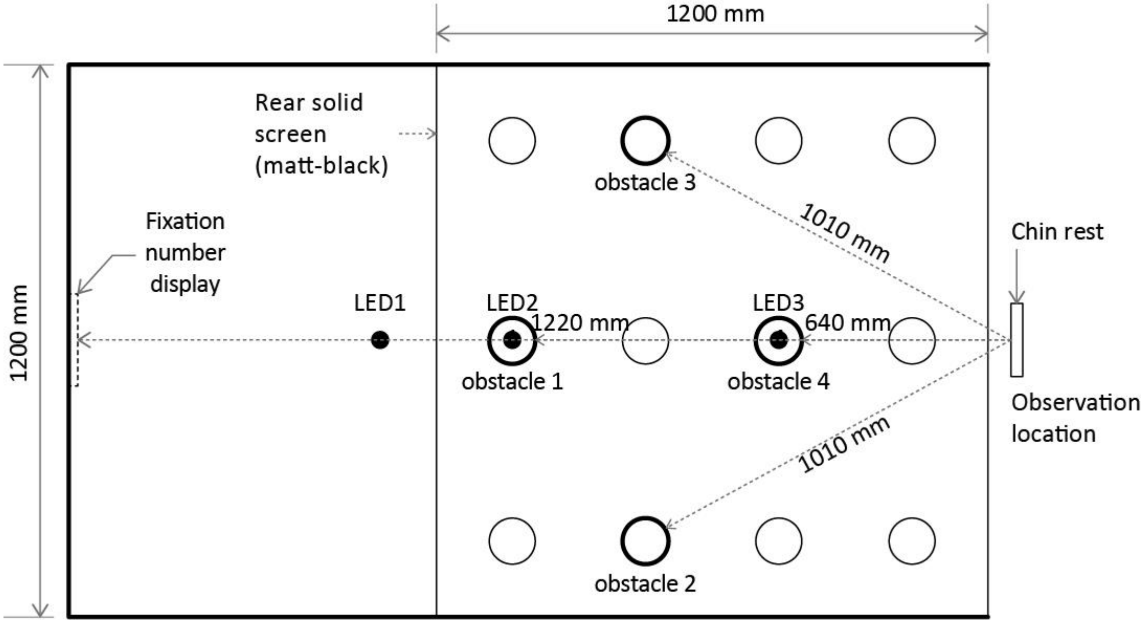


**Figure 4.7.** Top view of apparatus used in Experiment 1 (obstacle detection only).

All three LEDs (LED1 - 3) and four different obstacle locations (Obstacle 1 - 4) were used in Experiment 1. During each trial, only one obstacle was lit by one of the LEDs to create spatial variation.

### 4.4.1 Test variables

Four independent variables were used in Experiment 1: luminaire position, obstacle location, obstacle configuration (above / below surrounding surface) and obstacle size (raised height or lowered depth) (Table 4.3).

**Table 4.3.** Independent variables used in Experiment 1.

| **Variables** | **Level** | **Description** |
|---|---|---|
| LED position | 3 | LED 1, 2 and 3 |
| Obstacle position | 4 | Obstacle 1 – 4 |
| Obstacle size | 5 | Simulating 4.0, 6.3, 10.0, 15.9 and 25.1 mm |
| Obstacle configuration | 2 | Raised and lowered |

Five different obstacle heights were presented in both raised and lowered directions for each participant. The detection performance of Obstacle 1 when it simulated a real height of 10 mm was the primary interest in Experiment 1 because 10 mm was proposed to be the critical obstacle height for pedestrians (Fotios and Uttley, 2018). Two heights greater and lesser than 10 mm were included in trials to enable better characterisation of detection performance. These heights were chosen following a geometric progression ratio of 1.58 (0.2 log unit steps) based on Bailey–Lovie acuity chart (Bailey and Lovie, 1976). The purpose was to bracket detection rates from near zero (unable to detect) to near 100% (easily detectable). Thus, the five different obstacle sizes to simulate in reality were 4.0, 6.3, 10.0, 15.9 and 25.1 mm (Table 4.4).

Previous research suggests that pedestrians tend to detect obstacles at an average distance ahead of 3.4 m (Fotios and Uttley, 2018). The five obstacle sizes used in the experiment were then scaled based on the horizontal distance between the observation point and obstacle location to ensure the subtended visual angles were the same if observing an obstacle at 3.4 m ahead with an eye height of 1.5 m above ground (Table 4.4).

**Table 4.4.** Size (height or depth) of the obstacles used in the experiment.

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

Note: ‘Size’ here only considers the absolute height of the obstacle but ignore the obstacle configurations (raised or lowered).

In each trial, only one of the three LEDs above was switched on to lit the interior of the booth. When the obstacle flush with the floor level, an illuminance of 1.0 lux on the top surface of Obstacle 1 was provided by LED2 which was installed directly above. It could compare the performance with the work from Uttley *et al*. (2017). LED1 and LED3 were included to investigate the impact of light spatial distribution. LED1 was the farthest from the observation position, and LED3 was nearest. All three LEDs were set to provide an illuminance of 1.0 lux on the top surface of Obstacle 1 (in default condition), which means that when Obstacle 1 was moved, the luminance on the front face of Obstacle 1 was varied due to different luminaire positions (Table 4.5). Table 4.6 showed the horizontal illuminances on the top surface of each obstacle when they were in the default setting and the luminance contrast between the target obstacle and its background. The contrast was determined by the luminance on the visible vertical section and adjacent horizontal surface. Different contrast between the target and its background may lead to different obstacle detection performance. For example, the detection rate for Obstacle 1 under LED3 expected to be low because of the low contrast. Setting each luminaire to the same luminous intensity or setting the luminaires to offer the same target luminance are two other ways to investigate spatial distribution.

**Table 4.5.** Summary of lighting metrics.

| Test light condition | Illuminance (lux) * | Chromaticity (x, y) | S/P ratio | Luminance (cd/m$^2$) ** |
|---|---|---|---|---|
| **LED1** | 1.0 | 0.47, 0.41 | 1.6 | 0.007 |
| **LED2** | 1.0 | 0.47, 0.41 | 1.6 | 0.01 |
| **LED3** | 1.0 | 0.47, 0.41 | 1.6 | 0.07 |

Note:
*Horizontal illuminance measured on the top surface of Obstacle 1 when flushing with ground level.
** Luminance of front face of Obstacle 1 when it was raised.

**Table 4.6.** Illuminances on the top surface of each obstacle, when level with the surround, under each lighting condition.

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

### 4.4.2 Test procedure

Twenty young participants aged between 19 and 35 years were recruited for Experiment 1, including 10 males and 10 females. For Experiment 1, only the younger group was included, although previous work suggested age was one factor that might affect obstacle detection (Cheng *et al.*, 2018).

After signed the consent form and switched the light to the apparatus, in the next 20 minutes, the experimenter explained the procedure of the whole experiment, showed the locations of Obstacle 1 – 4 and corresponding response buttons, and described the fixation task to the participants. Then a practice session with 10 test trials was completed by every participant to get familiar with the procedure.

At the start of each trial, the occlusion spectacle shutters were closed for the target obstacle moved (or not maintained at default condition for null conditions) to the setting height, and the first digit number displayed on the screen. An electronic bleep informed the test participant that the spectacles changed from the close state to the open state for 500 ms after a random delay of 1 to 2 seconds. The first digit number lasted for around half of the open state duration on the screen and then being replaced by the second number. Then the spectacles were switched to the close state for 4 seconds. In this period, the participant reported aloud the two random digits they had seen to the experimenter for recording. The target obstacle returned to the ground level, and the second digit number changed to a cross mark. The spectacles reopened for 4 seconds allowing the participant to locate and press the corresponding button of the obstacle if they had detected and to relocate the fixation point currently displaying a cross. The next trial was then started by switched the spectacles to the close state again.

There were 120 combinations of variables (4 obstacle locations x 5 obstacle sizes x 2 obstacle configurations x 3 luminaire positions) presented to each test participant. Besides, in order to ensure the participants indeed paid attention to the tasks and did not press the buttons randomly, 16 null conditions with no obstacle raised or lowered were added for each of the three luminaire positions. For each participant, the order of the 168 trials was randomised allocated.

The experiment for each participant took approximately two hours to complete, including introducing the experiment process, adapting the test light condition, doing the test trials and debriefing. When the participant completed every 42 trials (which was around 15 minutes), a five-minute break was provided to participants to reduce the fatigue.

## 4.5 Settings for Experiment 2 and 3

The test booth was reconfigured (Figure 4.8 and 4.9) for Experiments 2 and 3 in order to test the performance of FER and obstacle detection in parallel task conditions. The light sources were identical to those used in Experiment 1, which were three tuneable arrays of RGBW LEDs installed along the central line. In Experiment 2 and 3, only LED2 and LED3 were used, and they were used simultaneously in all trials (Table 4.2).

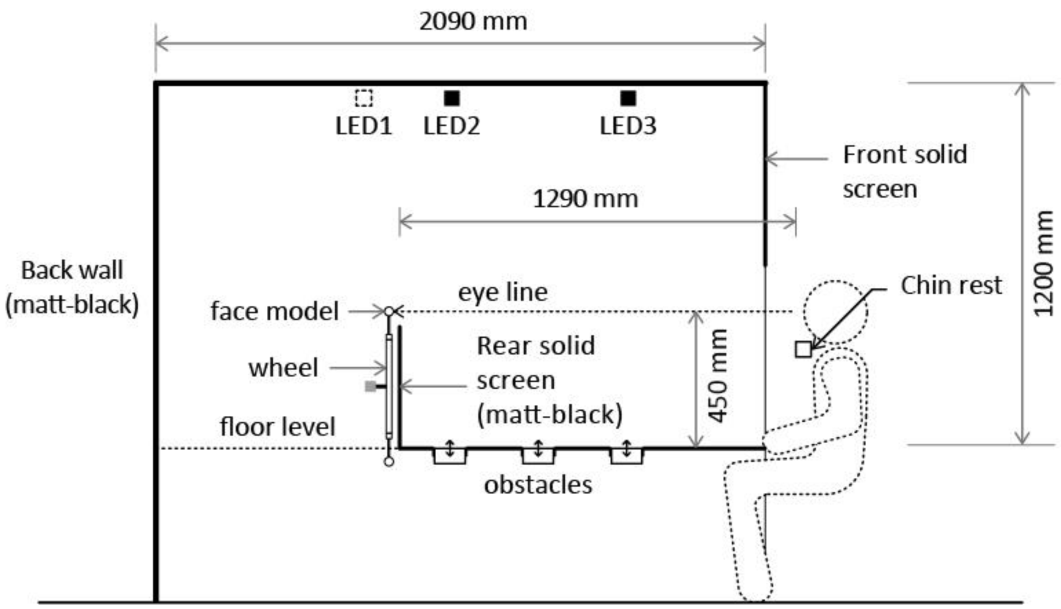


**Figure 4.8.** Side section through the apparatus used in Experiments 2 and 3.
Note, LED1 not used in Experiments 2 and 3.

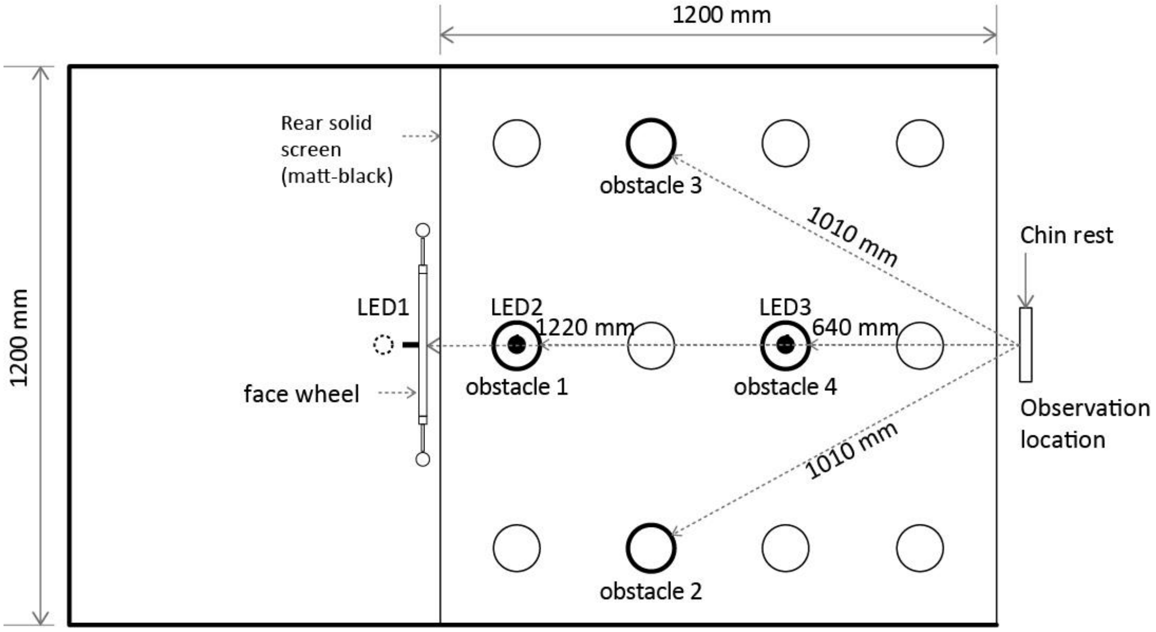


**Figure 4.9.** Plan view of apparatus used in Experiments 2 and 3.
Note: (i) In Experiment 3, Obstacle 4 was not used. (ii) LED1 was not used in the Experiments 2 and 3 but labelled here for consistency with previous work.

The foveal task was changed from number identification to FER. Hence the rectangle LCD screen was abandoned. A robotic wheel (diameter = 800 mm) with 16 turntable posts was installed behind the matt-black solid screen. According to Dr Chris Cheal, who built this apparatus, “this was rotated by a brushless DC motor and 200:1 planetary gearbox, with precise feedback of the angular position via two continuous-rotation potentiometers.” The main Python program controlled the wheel to present a specific (or no) face for a given trial. The rear wall concealed the rest of the target faces and allowing the observer could see only one target face at eye level. The horizontal distance between the presenting target face and the observation point was 1290 mm.

Thirteen representations of 1:6 scale human faces models were fixed around the wheel (Antheads.co.uk). They were cast in light flesh-coloured resin and have a luminance reflectance of 0.78 (see Section 8.5 for discussion of skin tone variation). The mouth, brow, and eye regions are commonly used to characterise the visibility of facial features or facial contrast (Russell, 2009; Porcheron *et al.,* 2017). The Michelson contrast is calculated by the equation of highest luminance - lowest luminance/ highest luminance + lowest luminance (Pelli and Bex, 2013). The current models showed a mouth contrast against the chin of 0.10, which is close to the mean Michelson contrast of 0.12 measured for the 151 Caucasian faces used by Russel (2009). However, note that the luminance contrast in these models was determined by illumination geometry rather than variation in the reflectances of facial features.

Initially, a simulated viewing distance of 10.0 m for the FER task was proposed due to apparatus constraints. Although this distance was shorter than the suggested distance of 15 m (Fotios *et al.*, 2018), it was one of the distances used in previous work (Fotios *et al.*, 2015d). After receiving these 1:6 face models and did a measurement, the vertical height from the chin to the top of the head and from chin to hairline was approximately 36 mm and 34 mm respectively, which is the height of the whole head and face area. These face models were presented at a distance of 1290 mm.

A calculation was then carried out to determine the accurate simulated viewing distance. According to Jayasekara *et al.* (Table 5, 2016), the mean face height of a man was around 242 mm. Thus, an equation can be made based on the visual angel because the visual angle was the same when viewing a face model and looking at other people in reality (Equation 4.1) (Figure 4.10). The result shows that the simulated distance was around 9.2 m. Though it was slightly shorter than 10 m, it still can be compared with the results from the previous study (Fotios *et al.*, 2015d).

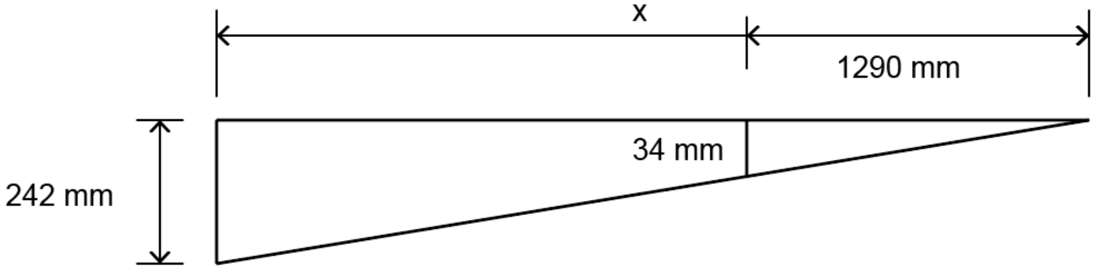


**Figure 4.10.** Diagram of visual angle for Equation 4.1.

**Equation 4.1.** Calculation of simulated viewing distance.

$$\frac{D}{H} = \frac{x}{h}$$

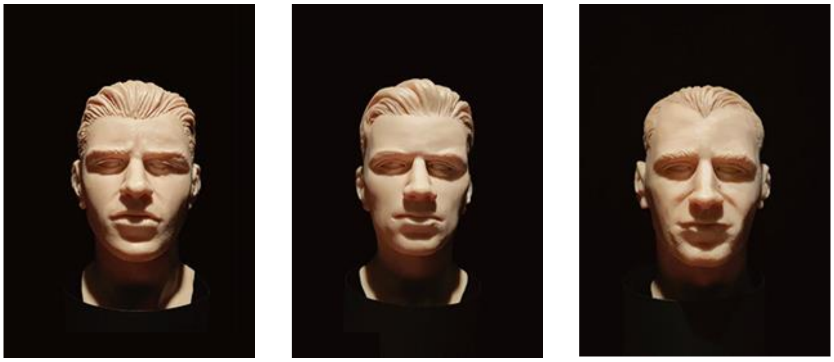
D: The distance between the face model and observation point = 1290 mm;
H: Mean face height in reality = 242 mm;
x: Simulated viewing distance;
h: Actual face height measured from face model = 34 mm

As shown in Figure 4.11, 11 different face models vary by the emotion portrayed by facial emotions, including 4 neutral, 4 happy, 1 sad and 2 angry. Each of the models was mounted on a radial post of the wheel, facing directly towards the observer during trials. The rest five posts of the wheel were left empty and were used for null condition trials.

Four of these (Obstacles 1 - 4) were used in Experiment 2 while only Obstacle 1 – 3 used in Experiment 3 (Table 4.2). For both Experiments 2 and 3, the obstacles were only lowered to simulate potholes because the results from Experiment 1 suggested that the difference in detection rates for raised and lowered objects of the same size were not significant (Fotios *et al.,* 2020).

Anger Anger Sadness Happiness

Happiness Happiness Happiness Neutrality



Neutrality Neutrality Neutrality

**Figure 4.11.** Photographs of the eleven face models. These photographs were taken with the models in the apparatus in the position where they were exposed to observation during trials.

For both Experiments 2 and 3, the main target was Obstacle 1 and Obstacles 2 to 4 were used as distractors. The obstacles were designed to be observed in peripheral vision while maintaining foveal fixation focus on the face targets. The distractor targets were used to avoid participants focusing on one specific obstacle, which might otherwise lead to fixation towards this location.

### 4.5.1 Test variables: Experiment 2

Experiment 2 included four independent variables: the location of the obstacle, depth of a pothole, light level, and emotion portrayed by facial expression (Table 4.7).

**Table 4.7.** Variables used in Experiment 2.

| Variables | Levels | Description |
|---|---|---|
| Obstacle position | 4 | Obstacle 1 – 4 |
| Obstacle size | 5 | Simulating 4.0, 6.3, 10.0, 15.9 and 25.1 mm |
| Light level | 2 | 1.0 and 10.0 lux provided by LED1 and 2 simultaneously |
| Emotion | 4 | 4 happiness, 1 sadness, 2 anger and 4 neutral |

Experiment 2 used four different obstacle locations and five different sizes (Figure 4.9) (Table 4.8). The settings for the obstacles were kept the same as used in Experiment 1 (see Section 4.4.1), simulating real obstacle heights range from 4.0 mm to 25.1 mm in five different levels at an observation distance of 3.4 m. The only difference was the obstacle can only be lowered in the current experiment.

Experiment 2 included all eleven face models. Nine of them were used in a test session, three positive (happy), three neutral and three negatives (angry or sad). For the three positive and three neutral emotions, they were chosen from the four available face models at random.

Photopic measurements are used to describe the conditions, this being the way in which lighting recommendations are given (BSI, 2013; CIE, 2010a). The photopic luminous efficiency function is appropriate for a foveal task which is the FER task in this experiment. Considering the obstacle detection task was performed in low light levels and using peripheral vision, it is more appropriate to define this task by using the mesopic luminous efficiency function (CIE, 2010b). Therefore, for the obstacles, the mesopic luminances were converted from photopic luminances as shown in Table 4.9 (Yao and Fotios, 2019).

**Table 4.8.** Size (height and depth) of the obstacles used in Experiments 2 and 3.

| **Target** | **Depth of simulated pothole (mm)** | **Target size (min. arc)** | **Solid angle (sr)** | **Horizontal distance from eye to the front edge of obstacle (mm)** | **Depth of test pothole (mm)** |
|---|---|---|---|---|---|
| 4 | 4.0 | 3.37 | 0.0002 | 640 | 0.9 |
| 2 & 3 | | | 0.0001 | 1010 | 1.2 |
| 1 | | | 0.0001 | 1220 | 1.3 |
| 4 | 6.3 | 5.34 | 0.0003 | 640 | 1.4 |
| 2 & 3 | | | 0.0002 | 1010 | 1.9 |
| 1 | | | 0.0001 | 1220 | 2.1 |
| 4 | 10.0 | 8.47 | 0.0006 | 640 | 2.3 |
| 2 & 3 | | | 0.0003 | 1010 | 2.9 |
| 1 | | | 0.0002 | 1220 | 3.4 |
| 4 | 15.9 | 13.44 | 0.0009 | 640 | 3.6 |
| 2 & 3 | | | 0.0005 | 1010 | 4.7 |
| 1 | | | 0.0004 | 1220 | 5.4 |
| 4 | 25.1 | 21.32 | 0.0014 | 640 | 5.7 |
| 2 & 3 | | | 0.0007 | 1010 | 7.4 |
| 1 | | | 0.0006 | 1220 | 8.5 |
| Face model | n/a | 72.84 (height) | 0.0006 | 1290 | n/a |

Note: Obstacle 4 has not been used in Experiment 3.

Table 4.9 also shows the scalar and vector illuminances measured at the position where face models were shown, as defined by Cuttle (1997). Vector/scalar ratio has been proposed as a general index of modelling to describe the spatial distribution of illumination about a point (Cuttle, 1997). It has a range of 0 to 4 to represent the perceived directional strength of light flow (Ashdown, 1998). In Experiments 2 and 3, the vector/scalar ratio was around 3.3 in all lighting conditions. The average luminance contrast of the target obstacle against its surrounding area was around 0.82 in Experiment 2. It was calculated by the luminance of the rear vertical surface and its surrounding horizontal area when the obstacle was lowered as described in Section 4.4.1.

**Table 4.9.** Summary of lighting conditions used in Experiments 2 and 3. For all conditions, a same S/P ratio of 1.6 was used (chromaticity coordinates: x, y = 0.47,0.41).

| **Experiment** | **Obstacle characteristics** | | | **Face characteristics** | | | |
|---|---|---|---|---|---|---|---|
| | **Illuminance on the floor (lux) *** | **Photopic luminance on the floor ($cd/m^2$)**** | **Mesopic luminance on the floor ($cd/m^2$)***** | **Photopic luminance on the face ($cd/m^2$) ****** | **Photopic luminance of surround to the face ($cd/m^2$)** | **Scalar illuminance at the face (lux) $E_{(s)}$** | **Vector illuminance at the face (lux) $E_{(v)}$** |
| 2 | 1.0 | 0.07 | 0.07 | 0.16 | 0.002 | 0.30 | 0.98 |
| | 10.0 | 0.73 | 0.85 | 1.65 | 0.014 | 2.94 | 9.79 |
| 3 | 0.33 | 0.02 | 0.03 | 0.05 | 0.001 | 0.10 | 0.34 |
| | 1.0 | 0.07 | 0.07 | 0.16 | 0.002 | 0.30 | 0.98 |
| | 3.3 | 0.25 | 0.29 | 0.53 | 0.006 | 0.95 | 3.15 |
| | 10.0 | 0.73 | 0.85 | 1.65 | 0.014 | 2.94 | 9.79 |
| | 33.3 | 2.51 | 3.00 | 5.63 | 0.043 | 9.60 | 32.53 |

Note:
*Horizontal illuminance measured at the centre of Obstacle 1 when flushing with the floor level.
**Photopic luminance measured at the centre of Obstacle 1 when flushing with the floor level.
***Mesopic luminance calculated according to Yao and Fotios (2019)
**** Luminance was measured on the forehead of a 3D face model.

The light inside the test booth was provided by both LED2 and LED3. Two illuminances were used, 1.0 lux and 10.0 lux, measured at the centre on the top surface of Obstacle 1 when flushing with the floor level (Table 4.9). The current standards recommended average horizontal illuminances for pedestrians in minor roads was in the range of 2.0 and 15 lux (BSI, 2013; CIE, 2010a). The optimal illuminance for detecting obstacles on the pavement was suggested to be 1.0 lux (Boyce, 1985, Fotios and Uttley, 2018), with a negligible increase in detection with higher illuminances (Uttley *et al.,* 2017). A higher illuminance of 10.0 lux was added to improve the detection performance if the previous work had underestimated the optimal illuminance. The luminance on the forehead of the face models was 0.16 and 1.65 cd/m$^2$ correspondingly, which brackets the optimal luminance of 1.0 cd/m$^2$ at a 10 m observation distance for FER proposed by Fotios *et al.* (2015d). For trials at 10 lux, vertical illuminance measured at the eye was 0.23 lux.

### 4.5.2 Test variables: Experiment 3

Experiment 3 was conducted in the same way as Experiment 2, but with a wider range of light levels. To better characterise the relationship between the light level and task performance, three more light levels were added in Experiment 3. To be more specific, the three new light levels were 0.5 log unit steps below, in-between and above 1.0 lux and 10.0 lux (Table 4.9).

Besides, there were three more changes had been made (Table 4.10). In order to keep the whole experiment in a reasonable test duration and balance the trials, the obstacle locations were reduced from four to three (only Obstacle 1 - 3), and the face models used were reduced from nine to six. The categories of facial emotion were kept the same but the number of face models in each category was reduced: two positive (happiness), two negative (one anger and one sadness) and two neutral. The specific face models were picked from those which get the highest recognition rates in Experiment 2. The third change was that besides the face models facing directly to the observer, a small proportion of face models were shown rotated on the vertical axis by 45° to the left or right. The rotated faces were analysed together with other faces and reported in Chapter 7.

The impact of light level changes on task performance can be predicted using Relative Visual Performance (Rea and Ouellette, 1991) (RVP). It is a model which could be used to predict the visual performance change on other tasks, either changing the light condition or the task (Boyce, 2014, p.141). However, the limitation of the RVP model is could only predict the foveal task performance but not for off-axis tasks. In current experiments, the FER task was on-axis, RVP was used to predict the effect of differences between the illuminances used in Experiment 3. Consider observing a face from a young Caucasian female at a distance around 10 m, (Porcheron *et al.,* 2017), with facial contrast averaged across the mouth, eye and brow regions of 0.314 (Weber contrast), subtending a target of 0.0006 steradians to an observer age of 25 years. Here the Weber contrast is calculated by the equation of highest luminance – lowest luminance/background luminance (Pelli and Bex, 2013). The recommended road surface luminance was used to estimate the adaptation luminance (CIE, 2017). Figure 4.12 illustrates the change in RVP for road surface illuminances of 0.33, 1.0, 3.3, 10.0 and 33.3 lux, which were the illuminances used in Experiment 3. The adaptation luminances were 0.02, 0.06, 0.21, 0.64 and 2.12 cd/m$^2$ with an assumed diffuse reflectance of 0.2. When the adaptation luminance is higher than 0.21 cd/m$^2$ (3.3 lux), the improvement of performance is negligible with higher adaptation luminance. If the adaptation luminance is lowered than 0.21 cd/m$^2$, the performance drops dramatically (Figure 4.12). Hence, it was anticipated that the recognition rate would be greater at 10.0 lux compared with 1.0 lux.

**Table 4.10.** Variables used in Experiment 3.

| Variables | Levels | Description |
|---|---|---|
| Obstacle position | 3 | Obstacle 1 – 3 |
| Obstacle size | 5 | Simulating 4.0, 6.3, 10.0, 15.9 and 25.1 mm |
| Light level | 5 | 0.33, 1.0, 3.3, 10.0 and 33.3 lux provided by LED1 and 2 simultaneously |
| Emotion | 4 | 2 happiness, 1 sadness, 1 anger and 2 neutral |

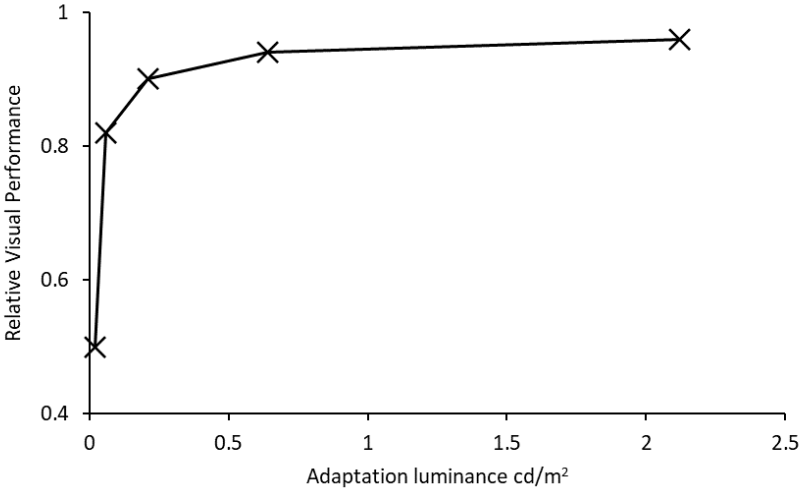


**Figure 4.12.** RVP plotted against adaptation luminance for a facial contrast of 0.314, subtending a solid angle of 0.0006 steradians and an observer of age 25 years.

### 4.5.3 Test procedure: Experiment 2

In both Experiments 2 and 3, thirty test participants of an equal balance of male and female were recruited. After finishing the preparation period described in Section 4.3, the participant was seated facing into the test booth and placed their head upon the chin rest. They put on the occlusion spectacles, which could be worn over their normal lenses.

The photographs of each face were presented to the participant one by one on a laptop screen. The emotion conveyed by each face was also stated at the bottom of the image. Then, these images were presented again randomly but hidden the name of each emotion to ensure the participants were familiar with all facial emotions.

The lighting in the laboratory was then turned off, leaving only the lights in the test booth on. The test participants could adapt to the low lighting condition in the next 20 minutes. Within these 20 minutes, the experimenter explained the procedure of the test and demonstrated the obstacle locations where the obstacle may appear (four in Experiment 2, three in Experiment 3). Besides, the response button box was shown to the participant and ensure they know which button to press when they detect an obstacle.

After the adaptation, a practice session was carried out to confirm the participant was familiar with the facial emotion presented by the real face models. This practise session was conducted under the illuminance of 10.0 lux. There were 22 practice trials in Experiment 2, with all the 11 faces repeated once at random. The observation duration for the first 20 practice trials was unlimited, and the occlusion spectacles were maintained in the open state. For the last two practice trials, the duration was set to 500 ms, which was used in the main experiment.

There were four steps in each trial. (1) With the occlusion spectacles in the closed state, and the obstacle was raised/lowered to setting height (or not move), the chosen face model was moved to the 12 o'clock position on the wheel (empty for no face presented trial). (2) After a beep sound, the occlusion spectacles opened for 500 ms. In this duration, if they detected an obstacle, the participants pressed the corresponding button on the button box. If they saw a face model, stating aloud what the emotion was. If neither a face nor obstacle was seen, the participant did not respond. (3) The occlusion spectacles closed for around 4 seconds. The face model and the face wheel returned to the default position (no obstacle and face model presented). The lighting inside the booth was changed to the one used in the following trail. (4) The occlusion spectacles reopened for 4 seconds to assist the participants in relocating the face model position and adapt to the new lighting condition. The spectacles were then closed again, signalling the start of the next trial.

There were four different types of target events in the experiment (Table 4.11) depending on which target was revealed: an obstacle only, a face only, both a face and an obstacle, or neither (null condition trials).

**Table 4.11.** Summary of target presentations. These trials were repeated for each light level.

| | Target presented | Number of trials | Description |
|---|---|---|---|
| **Experiment 2** | Obstacle-only | 25 | Obstacle 1: five heights, each repeated twice<br>Obstacles 2 to 4: five heights, each once only |
| | Face-only | 27 | 9 faces, each repeated three times |
| | Obstacle and face | 25 | Randomly picked 25 from 27 faces, and paired with 25 obstacle heights |
| | Null | 23 | No obstacle or face appeared |
| **Experiment 3** | Obstacle-only | 20 | Obstacle 1: five heights, each repeated twice<br>Obstacle 2 and 3: five heights, each once only |
| | Face-only | 18 | Facing forward: six faces, each repeated twice.<br>Facing 45°: six faces, once each in left or right directions. |
| | Obstacle and face | 12 | Six faces paired with Obstacle 1: six faces paired with Obstacle 2 or 3; no repeated trials. These dual task conditions always used the forward-facing face. |
| | Null | 12 | No obstacle or face appeared |

As shown in Table 4.11, there were 100 trials under each light level, including all four different types of events which were 200 trials in total for each participant. The four obstacle locations, five different depths and nine face models were used in each experiment. The nine faces used were randomly picked from the 11 face models. The sequential order of these 200 trials was all randomised. The test duration for every 100 trials was around 20 minutes. After 100 trials, a five-minute bread was given to minimise the fatigue for the participants. The whole experiment took approximately 1 hour to complete, from introduction to finish the 200 trials.

### 4.5.4 Test procedure: Experiment 3

In Experiment 3, 30 participants aged 17 to 31 years were recruited. The genders of the participants were balanced.

The procedure of signing the consent form, checking normal acuity and colour vision, familiarisation with emotions used in experiments, dark adaption and introduction of the test were nearly the same as stated in section 4.2 and in Experiment 2 except for difference due to changes in variables.

The practice session was also conducted under 10 lux lighting condition in Experiment 3, including 12 trials, each of the six faces being presented twice. All the remaining settings were kept the same as in Experiment 2.

There were 310 trials in Experiment 3, including combinations of three obstacle locations, five pothole depths, six face models and null conditions. The 62 trials shown in Table 4.11 were each repeated at all five light levels. The presentation order of all the trials was randomised. The whole experiment took around 150 minutes for each participant, including five minutes break after every 100 trials.

## 4.6 Method for data analysis

All test data were checked for normality before the main analysis by visually inspecting distribution plots of the data (histogram and box plot), checking skewness and kurtosis, calculating z-scores of skewness and kurtosis, and applying the Shapiro-Wilk test of normality (sample size < 50). Nearly all data in the three experiments were suggested to be drawn from normally distributed populations. The small proportion of original data which shows a slightly skewed were due to outlying data points (Appendix A). These outliers were isolated from the majority of other trials, and no systematic pattern can be found. A reasonable explanation for this might be caused by participants error, such as suddenly lost attention to the task. These outliers were identified based on visually inspecting the box plot graphs and getting the values of which fall more than 1.5 times interquartile range above or below the extreme values in the interquartile range set (Coolican, 2014). After removing the outliers, all data approximate normally distributed. Therefore, parametric tests have been used throughout. A standard significance level of 0.05 was chosen for all statistical tests.

As the analysis involves comparing differences between more than two conditions, an ANOVA (analysis of variance) test has been used for testing several means and independent variables to avoid Type I errors caused by making multiple comparisons between pairs (*t*-test). In these three experiments, the independent variables are all listed in the above sections. The dependent variables are the obstacle detection rate and facial expression recognition rate. The choice of using between-groups ANOVA or within-group ANOVA (repeated measures ANOVA) is based on whether the variables (factors) are independent or related (Coolican, 2014, p.600).

When performing ANOVA tests, as multiple independent variables were tested simultaneously, the probability of a getting significant result increases. Applying Bonferonni Correction to the *p*-value is commonly used to counteract this problem. However, Bonferonni Correction is a conservative method and still may lead to a high Familywise Error Rate, which is the probability of getting at least one false conclusion (Coolican, 2014, p.597). Therefore, another method named Holm-Bonferroni correction was applied to all the results among the three experiments. It was used to test the data and their associated *p*-value at an alpha level of 0.05 and helps to reduce the Familywise Error Rate caused by making multiple comparisons (Holm, 1979). The original *p*-values were ranked from smallest to greatest and then using H-B alpha = Target α / (n – rank + 1) to calculate the corrected *p*-value thresholds. The actual *p*-value is considered significant only if it is less than the corrected *p*-value threshold. If the two numbers are the same, it is not considered as significant. The testing stops when the first non-rejected hypothesis is reached. All subsequent hypotheses are non-significant. Effect sizes were also added in analysis as a complement value to the *p*-value obtained from ANOVAs. The effect size reported in AVOVAs was Cohen's *f*, which is used in Repeated measures ANOVA; between-subjects ANOVA test. It was calculated by the partial eta-squared ($\eta^2$) which can be generated from SPSS: Cohen's $f = \sqrt{\eta^2/(1-\eta^2)}$. If the 0.1 < Cohen's $f < 0.25$, it is a small effect; if the 0.25 < Cohen's $f < 0.40$, it is a medium effect; if the Cohen's $f > 0.40$, it is a large effect (Cohen, 1988).

## 4.7 Summary

This chapter described the general method adopted in the three main experiments, including apparatus, test variables and test procedure. All three experiments shared the same test booth with slight alterations according to different experiment designs. Experiment 1 was designed to investigate the effect of raised obstacles and potholes on obstacle detection. Four variables have been used: light source position, obstacle position, obstacle size and configuration (raised/lowered) (Table 4.3). The objectives of experiments 2 and 3 were to investigate the influence of dual task conditions requiring obstacle detection and FER to be performed at the same time. Experiments 2 and 3 both used four variables: obstacle position, obstacle size, light level and emotion types (Table 4.7 and 4.10), while Experiment 3 excluded one obstacle position (Obstacle 4) and reduced the number of face models from 11 to 6 but applied three more light levels (0.33, 3.3 and 33.3 lux).

The results of each experiment will be discussed in separate chapters. Before analysing the main effects, the data have been checked for normal distribution. The method of normality check and data analyses were briefly introduced in section 4.5.

# CHAPTER 5. RESULTS OF EXPERIMENT 1: OBSTACLE CONFIGURATION AND LIGHT SOURCE LOCATION

## 5.1 Introduction

According to the eye-tracking experiments reviewed in Section 2.2, a crucial visual task of pedestrians is detecting pavement hazards that may otherwise lead to a tripping accident. There were two limitations from previous obstacle detection experiments: only raised obstacles were used and tended to be located directly underneath the luminaire. In the real situation, besides raised obstacles, trip hazards can also be found as depressed areas, like potholes. If the relative position between luminaire and obstacle were varied to the observer, the luminance of the facing side of the obstacle would be changed. As a result, the contrast and shadow pattern will be changed and may lead to different detection performance. This chapter reports the results from one experiment carried out to explore whether these uncertainties have significant effects.

The apparatus and method used in this experiment were mentioned in Section 4.2 and 4.5. There were four within-subjects variables that have been used in Experiment 1 – obstacle size, obstacle location, luminaire position and obstacle configuration (raised or lowered relative to the floor level) (Table 4.3). The one dependent variable is the obstacle detection rate.

All the data were checked for normality before the main analysis and reported in Chapter 4 and Appendix A.1. All data in the current experiment were suggested normally distributed except for when the obstacles were at the smallest size. The reason might be that the obstacle size was too small for consistent detection. In further analysis, the smallest obstacle size was analysed together with the other four sizes.

## 5.2 Results

The raw results of Experiment 1 are reported in Appendix B.

For the fixation task, two single digit numbers were presented on the LCD screen randomly within the 500 ms observation duration of each trial. The mean correct identification rate for these numbers was 97% (SD = 2%), much higher than a chance level of 11% and slightly better than the previous experiment, which used the same method (91.8%) (Uttley *et al.*, 2017). The chance level performance here means the results to be obtained from random guessing. It is not to be confused with the *p*-value threshold of 0.05, which indicates a 1 in 20 chance/probability of obtaining the result if the independent variable has no effect. As the whole experiment last for 2 hours, participants might lose concentration when the experiment processing. A paired *t*-test was conducted to compare the identification rate of the fixation task between first (mean = 94 %, SD = 4.6%) and last (mean = 97 %, SD = 3.5%) 42 trials (a 15-minute session) of each test participant, it is suggested that there is no reduction in task performance (*p* = 0.103). Thus, in this experiment, it was hence believed that the fixation task was effective in retaining the participant's gaze.

Each test participant viewed 48 null condition trials (16 null condition trials x 3 luminaire positions) in Experiment 1. In total, there were 960 null condition trials for all participants. Null condition trials were those where the obstacle was maintained at default condition flushing with pavement level when the occlusion spectacles opened. The response bias could be assessed by null condition trials, which is the tendency to report yes or no or randomly when uncertain about the presented obstacle. This might be an error in favour of reporting detection in a null condition trial (a false alarm) or not reporting detection in a test trial (a miss). In Experiment 1, there were 238 (24.8%) false alarms that participants pressed the button in null condition trials, which is similar to the false alarms rate (13.7 - 21.2%) found in previous work (Fotios and Cheal, 2009; (Fotios and Cheal, 2013).

Another value to look at is the sensitivity index, *d*', where a higher value of *d*' means that the target was more readily detected. If the *d*' value is near zero, it indicates an inability to tell the difference between a stimulus and background noise, which might indicate that the design of the experiment was not appropriate, or the participants were not completely focused on the task. This bias can have an effect on the apparent detection threshold (Stanislaw and Todorov, 1999). In the current experiment, the *d*' scores for each test participant were in the range of 0.75 to 14.44 (mean = 3.28), which is slightly better than that found in previous work (0.50 – 1.67, mean = 1.06) (Fotios and Cheal, 2013). A *d*' above zero suggests better than chance performance. The participants did not randomly press the button, tended to report only when an obstacle was present and not respond when obstacles were absent.

Results of the fixation target identification task and the null condition trials suggest that test participants conducted this task as required.

### 5.2.1 Obstacle location: Left vs right

Obstacles 2 and 3 were placed on the left and right sides, respectively, at the same peripheral angle from the participant's line of sight. Due to their symmetrical locations, no systematic variation in responses to these two obstacles was anticipated. Figure 5.1 shows the rate at which these obstacles were detected for the three light source locations.

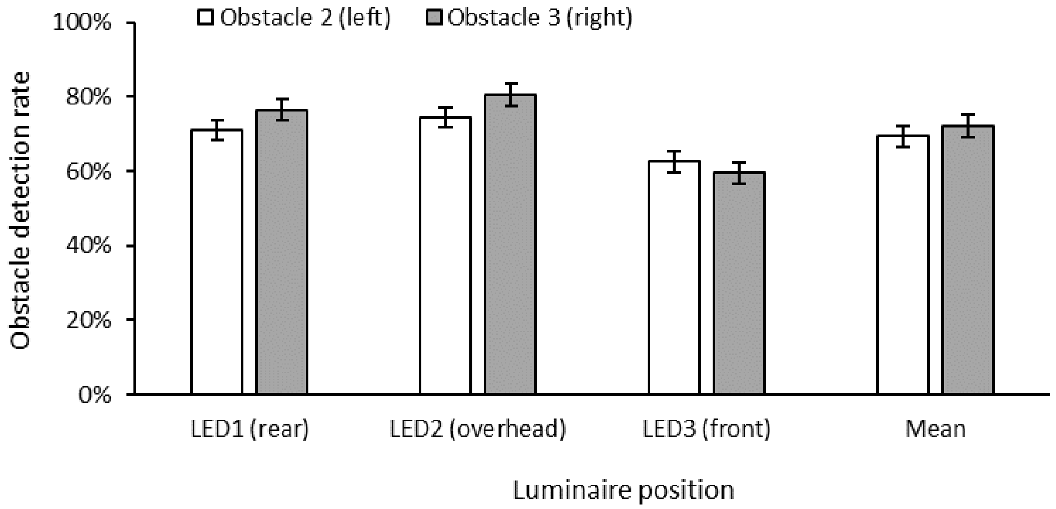


**Figure 5.1.** The detection rate of Obstacle 2 and 3 under LED1, 2 and 3, and the mean detection rate. Error bars show the standard error of the mean.

A 4-way ANOVA was conducted to compare the detection of obstacles 2 and 3. The four dependent variables were luminaire position (LED1, 2 and 3), obstacle location (left/right), obstacle configuration (raised/lowered) and obstacle size. The goal of this first ANOVA was to confirm whether there was a significant difference in detection performance between left and right obstacle positions or any interactions among the four variables. Thus, the main effects of luminaire position, obstacle configuration and obstacle size were ignored. These variables were only used in the ANOVA to examine their interaction with obstacle location.

The results of the ANOVA test are shown in Table 5.1. To account for the multiple measurements of main effect and interactions, the Holm-Bonferroni correction was used to correct the *p*-value threshold.

**Table 5.1.** Results of the first ANOVA test for Obstacle 2 and 3 (with obstacle location and interaction with other factors).

| Main and Interactive Variables(s) | F-statistic (df) | *p*-value | Holm-Bonferroni corrected *p*-value threshold | Significant effect[a] | Effect size (Cohen's *f*) |
|---|---|---|---|---|---|
| Obstacle location | 1.223 (1, 19) | 0.283 | 0.010 | No | 1.03 (large) |
| Obstacle location * Luminaire position | 1.750 (2, 38) | 0.187 | 0.008 | No | 0.30 (medium) |
| Obstacle location * Size | 3.306 (4, 76) | 0.015 | 0.006 | No | 0.42 (large) |
| Obstacle location * Configuration | 3.576 (1, 19) | 0.074 | 0.007 | No | 0.43 (large) |
| Obstacle location * Luminaire position * Size | 1.039 (8, 152) | 0.409 | 0.013 | No | 0.23 (small) |
| Obstacle location * Luminaire position * Configuration | 0.371 (2, 38) | 0.693 | 0.025 | No | 0.14 (small) |
| Obstacle location * Size * Configuration | 0.934 (4, 76) | 0.449 | 0.017 | No | 0.22 (small) |
| Obstacle location * Luminaire position * Size * Configuration | 0.399 (8, 152) | 0.920 | 0.050 | No | 0.15 (small) |

[a] Result suggested to be statistically significant ($p < 0.05$) according to a threshold corrected using Holm-Bonferroni.

First, considering the main effect of obstacle location, these data do not suggest a significant difference in the detection rate for Obstacles 2 and 3 ($p = 0.283$). For the interactions, the original smallest *p*-value was 0.015 (interaction between obstacle location * size). After applying the Holm-Bonferroni correction, the corrected *p*-value threshold was 0.006, smaller than 0.015. Therefore, the interactions between obstacle location and other factors (luminaire position, obstacle configuration and obstacle size) were suggested to be not significant.

Since the first ANOVA suggested the detection performance of Obstacles 2 and 3 did not reveal a significant difference, the response data for these two obstacles were therefore combined as a middle-distance obstacle (Obstacle mid.). The mean detection rate of both obstacles was used in the following analyses.

### 5.2.2 Main effects

Figure 5.2 shows the mean obstacle detection rates under three luminaire positions. It can be seen that the mean obstacle detection rate of LED2 was slightly higher than LED1, but both above 60%, while the performance under LED3 was the lowest. LED2 light tends to provide a higher detection performance compared with front and back lights.

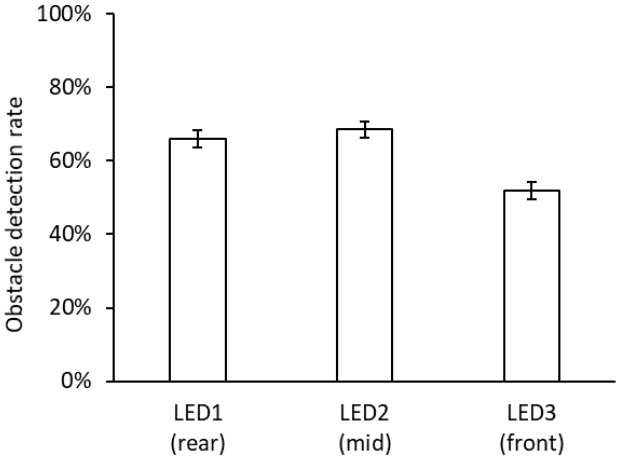


**Figure 5.2.** Mean obstacle detection rate under three luminaire positions. Error bars show the standard error of the mean.

Figure 5.3 shows the mean obstacle detection rates for three different obstacle locations. It can be seen that the detection rate of the middle-distance obstacle was much higher than the other two obstacle locations. Detection rates of both front and rear obstacle locations were below 60%.

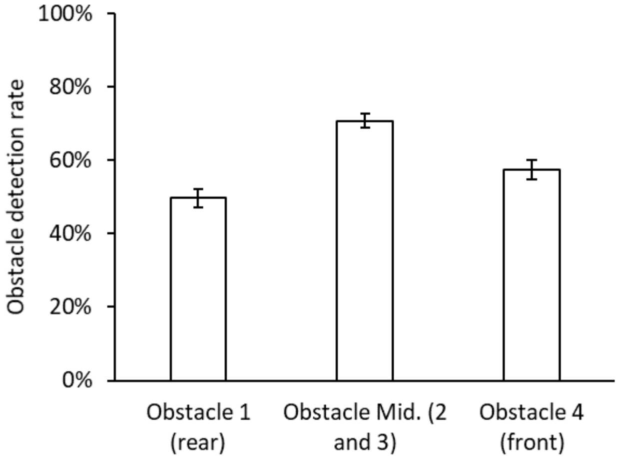


**Figure 5.3.** Mean obstacle detection rate for three different obstacle locations. Error bars show the standard error of the mean.

Figure 5.4 shows the mean detection rates of five different obstacle sizes. It reveals a tendency that the obstacle detection rate increased for larger sizes (heights and depths). The detection rate of the smallest obstacle size was approximately 25% which is near a chance level, while over 90% detection rate when observing the largest obstacle. The increasing rate was nearly the same from the smallest to the largest obstacle size.

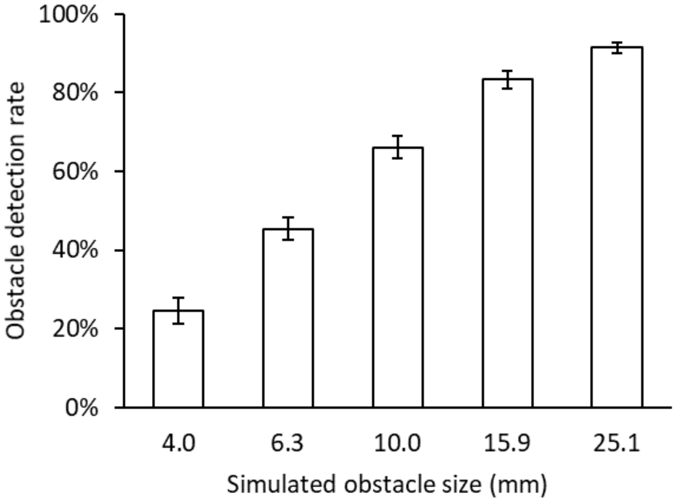


**Figure 5.4.** The mean detection rate for five different obstacle sizes. Error bars show the standard error of the mean.

As shown in Figure 5.5, the detection rates of raised and lowered obstacles were nearly the same, both around 60%.

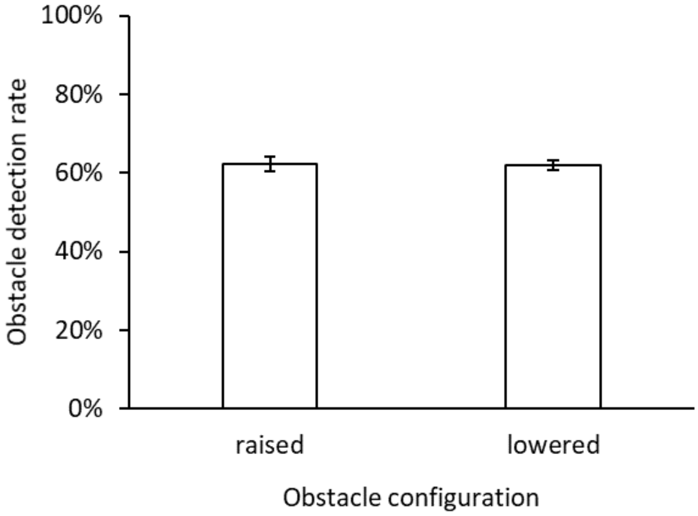


**Figure 5.5.** The mean detection rate for raised and lowered obstacles. Error bars show the standard error of the mean.

A 4-way repeated-measures ANOVA was carried out with the four independent variables, these being luminaire position (LED1, 2 and 3), obstacle location (Obstacle 1, mid. and 4), Obstacle configuration (raised and lowered) and obstacle size (simulating 4.0, 6.3, 10.0, 15.9 and 25.1 mm). The dependent variable was the obstacle detection rate. As described in Section 4.6, Holm-Bonferroni correction was used to determine the corrected *p*-value threshold that accounts for the multiple *p*-values produced by the ANOVA and when performing *t*-tests for *post-hoc* paired-comparisons. The *t*-tests were conducted to assess differences between multiple levels of one variable if a main effect or interaction was significant. Table 5.2 shows the results of this ANOVA test.

The ANOVA test has confirmed that there are significant differences in obstacle detection owing to the effects of luminaire position ($p < 0.001$), obstacle location ($p < 0.001$) and obstacle size ($p < 0.001$), while the effect of obstacle configuration was not significant ($p = 0.410$). As suggested by the tendency shown in Figure 5.2, when the booth was lit by LED3, the detection rates of the obstacles (mean = 52%, SD = 11%, $p < 0.001$) was significantly worse than when lit by LED1 or LED2 (means = 66% and 68%, SD = 10% and 10% respectively). Detection rates for LED1 and LED2 were not statistically different ($p = 0.188$).

As mentioned above, due to there was no significant different between Obstacle 2 and 3 (left and right), the results of them were combined as Obstacle mid. The mean detection rate for the Obstacle mid. was 53% (SD = 8%), which is significantly better than Obstacle 1 (means = 37%, SD = 11%, $p < 0.005$) and Obstacle 4 (means = 43%, SD = 12%, $p < 0.005$) (Figure 5.3). For Obstacle 1 and 4, the *t*-test did not reveal a significant difference on the detection performance ($p = 0.159$).

Table 5.2 suggested there was a significant effect of obstacle size on detection performance ($p < 0.001$). Therefore, several paired *t*-tests were conducted to compare the detection rates for each obstacle size. After corrected the *p*-values with the Holm-Bonferroni method, the results indicated that the detection rate of each obstacle size differed significantly with the other sizes ($p < 0.001$ for all comparisons). It suggested that each level of obstacle size produced a different degree of performance from the participants.

**Table 5.2.** Results of 4-way repeated-measures ANOVA. Independent variables were obstacle location, luminaire position, obstacle size and obstacle configuration. The dependent variable was the detection rate.

| **Main and Interactive Variables(s)** | **F-statistic (df)** | ***p*-value** | **Holm-Bonferroni corrected *p*-value threshold** | **Significant effect[a]** | **Effect size (Cohen's *f*)** |
|---|---|---|---|---|---|
| Luminaire position | 26.422 (2, 38) | <0.001 | 0.003 | Yes | 1.18 (large) |
| Obstacle location | 11.694 (2, 38) | <0.001 | 0.003 | Yes | 0.78 (large) |
| Configuration | 0.710 (1, 19) | 0.410 | 0.017 | No | 0.19 (small) |
| Obstacle size | 154.807 (4, 76) | <0.001 | 0.003 | Yes | 2.86 (large) |
| Obstacle location * Luminaire position | 8.540 (4, 76) | <0.001 | 0.003 | Yes | 0.67 (large) |
| Luminaire position * Configuration | 3.347 (2, 38) | 0.046 | 0.007 | No | 0.42 (large) |
| Obstacle location * Configuration | 3.707 (2, 38) | 0.034 | 0.006 | No | 0.44 (large) |
| Obstacle location * Obstacle size | 2.753 (8, 152) | 0.007 | 0.005 | No | 0.38 (medium) |
| Luminaire position * Obstacle size | 1.167 (8, 152) | 0.323 | 0.010 | No | 0.25 (medium) |
| Configuration * Obstacle size | 1.547 (4, 76) | 0.197 | 0.008 | No | 0.28 (medium) |
| Obstacle location * Luminaire position * Configuration | 0.461 (4, 76) | 0.764 | 0.050 | No | 0.16 (small) |
| Obstacle location * Luminaire position * Obstacle size | 1.827 (16, 304) | 0.027 | 0.006 | No | 0.31 (medium) |
| Luminaire position * Configuration * Obstacle size | 0.620 (8, 152) | 0.760 | 0.025 | No | 0.18 (small) |
| Obstacle location * Configuration * Obstacle size | 1.052 (8, 152) | 0.400 | 0.013 | No | 0.23 (small) |
| Obstacle location * Luminaire position * Configuration * Obstacle size | 1.835 (16, 304) | 0.026 | 0.005 | No | 0.31 (medium) |

[a] Result suggested to be statistically significant ($p < 0.05$) according to a threshold corrected using Holm-Bonferroni.

### 5.2.3 Interactions between factors

Table 5.2 suggests one significant interaction was between obstacle location and luminaire position ($p < 0.001$). As shown in Figure 5.6, for Obstacle 4, the effect of luminaire position on the detection rate was relatively little regardless behind or above the obstacle relative to the observation location (Figure 4.2). For Obstacle 1 and Obstacle mid. (2 and 3), the detection rate decreased as the luminaire position moved from behind or above (LED1, LED2) to in front of (LED3) the obstacle.

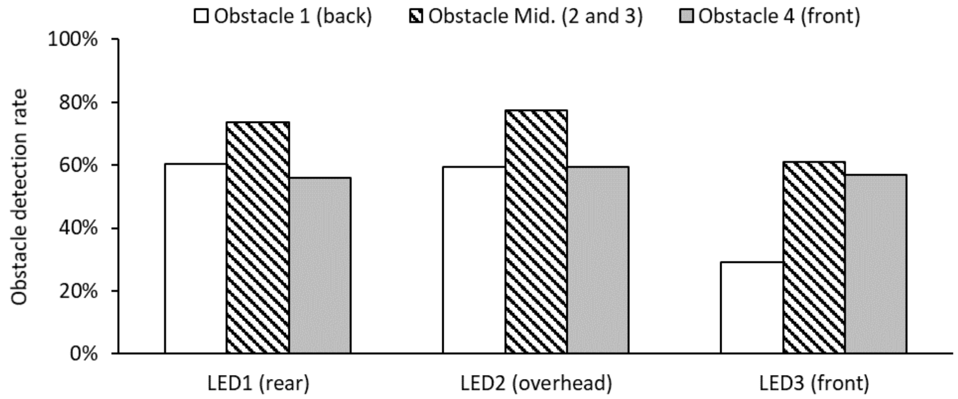


**Figure 5.6.** Mean obstacle detection rates plotted against luminaire position for the three obstacle locations.

Figure 5.6 also shows the mean obstacle detection rates plotted against luminaire position for LED1, 2 and 3. Among the nine cases, the detection rates of six are around 60%. The detection rates for the Obstacle mid. (2 and 3) under LED1 or LED2 are slightly higher, both over 70%. For Obstacle 1 under LED3, the detection rate is dropped below 30%. For each obstacle location, a one-way ANOVA test with Holm-Bonferroni correction was carried out to investigate the effect of luminaire position on detection performance. The results suggested there were significant differences in detection for Obstacle 1 ($p < 0.001$) and Obstacle mid. ($p < 0.001$) but not for Obstacle 4 ($p = 0.781$).

Figure 5.7 shows the obstacle detection rate plotted against target contrast for the nine combinations of obstacle location and luminaire location (target contrast see Table 4.6). This demonstrates that luminance contrast does explain some of the variances in detection rates but also that there is some noise in these data. The detection rate increased when the contrast went higher. The trendline was affected by one anchor point out of the cluster, which was the contrast of Obstacle 1 (contrast = 0.31, detection rate = 29.0%) under LED3. After removing the date of Obstacle 1 under LED3, the new relationship between obstacle detection rate and contrast was shown in Figure 5.8. The trendline was almost flat and nearly not affected by the contrast, which means the performance almost reached a ceiling.

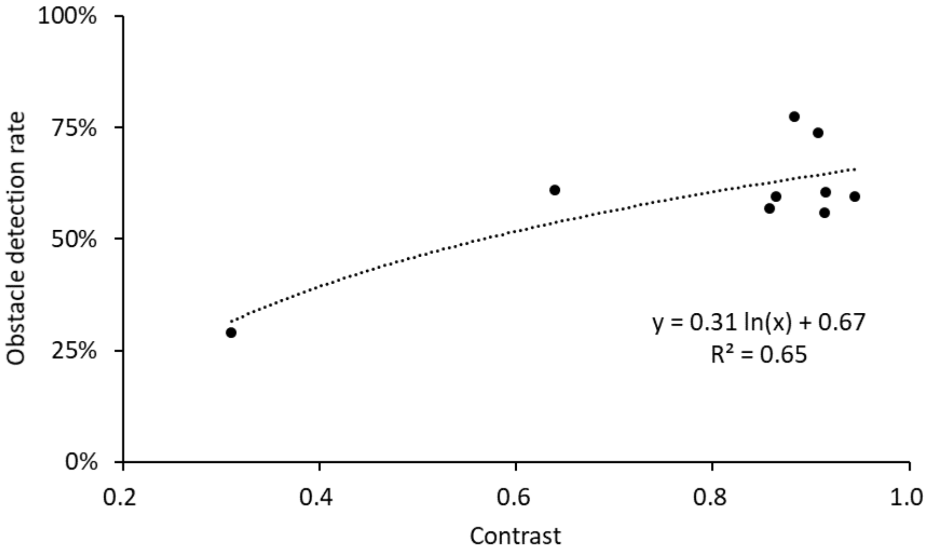


**Figure 5.7.** Obstacle detection rate plotted against target contrast for the nine combinations of obstacle location and light source location. Note that in these data, the two middle obstacles are combined as one item.

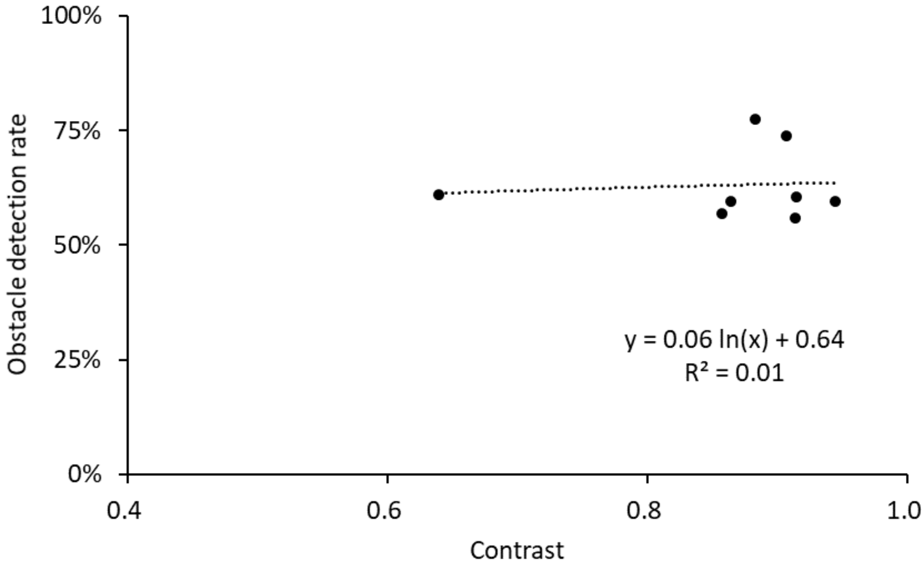


**Figure 5.8.** Obstacle detection rate plotted against target contrast for the eight combinations of obstacle location and light source location (data of Obstacle 1 under LED3 was removed). Note that in these data, the two middle obstacles are combined as one item.

## 5.3 Summary

This chapter reports an experiment developed to investigate the effect of lighting changes on obstacle detection performance based on two uncertainties found in previous works. The two uncertainties were whether the obstacle configurations (raised or lowered relative to the pavement level) and the position of the luminaire relative to the obstacle and observer affect the detection performance.

The results did not reveal a significant detection difference between raised and lowered obstacles when the obstacle size (height or depth) was the same regardless of the configurations. Therefore, it suggests that the findings of previous studies (Fotios and Cheal, 2009; Fotios and Cheal, 2013; Uttley *et al.*, 2017) that used only raised obstacles are applicable to lowered obstacles as well. However, compared with previous studies, three luminaire positions were used in Experiment 1, and the luminaire positions affected the obstacle detection rate significantly. The results indicated that when the luminaire was overhead or behind the obstacle, the detection rate was higher than when the luminaire was in front of the obstacle. In a real street environment, the relative position between the observer, dominant sources of light and obstacle location is variable. It would be impractical to conduct trials for all possible geometries. If the current finding is confirmed, this would suggest that further work to identify appropriate lighting for hazard detection should consider the least favourable spatial geometries that are likely to be encountered.

The obstacle used in Experiment 1 is highly simplified, and it does not accurately reflect all trip hazards and potholes found in a real street environment. The top surface of the obstacle remained flat. When simulating a lowered obstacle, the whole cylinder was lower than the surrounding pavement level, including the entire top surface and the trailing edge viewing from the observation point. However, this did not consider a pothole with only the leading edge being lowered. Both of the scenarios are possible if there is a change in walking direction.

For lowered obstacles, the apparatus resembled a pedestrian's view of a pothole with the whole surface or the trailing edge being lower than ground level but did not present a pothole with only the leading edge being lowered – a change of walking direction means both scenarios are likely. Therefore, the task conducted in the current experiment can be more specifically described as detecting a trip hazard using the leading edge and detecting a pothole using the trailing edge.

Although the results of the current experiment did not indicate the raised or lowered obstacle significantly affect the detection rates for a given height, for the non-detection situation, there might be a difference. An unexpected trip hazard may disrupt a foot swing: the foot is delayed in its movement and may not even make contact with the ground. An unexpected pothole means the leading foot makes contact with the ground at a slightly later and lower than expected moment but still reaches the ground to absorb the transfer of the pedestrian's mass. If the pedestrian step on the edge of an unexpected pothole, an injury may occur, such as a twisted ankle. Data was not identified to support potential variations in the outcomes of incidents involving trip hazards and potholes.

Another limitation of the current experiment and other studies (Fotios and Cheal, 2009; Fotios and Cheal, 2013; Uttley *et al.*, 2017) is that glare source was not considered as it might have an effect on obstacle detection performance. For Experiment 1, only young participants were recruited. The age might be a factor that can affect the detection of raised or lowered obstacles (Table 4.2). Further experiments could compare the detection performance between younger and older age groups.

# CHAPTER 6. RESULTS OF EXPERIMENT 2: DUAL-TASK OF OBSTACLE DETECTION AND FER

## 6.1 Introduction

By reviewing eye-tracking studies, FER has been identified as another important visual task for pedestrians. Route choice might be affected by judging the intent of other pedestrians. Previous studies have investigated the effect on the performance of a FER task of lighting changes, including light level and SPD. The results suggested that a target luminance of 1.0 cd/m$^2$ and 0.33 cd/m$^2$ is optimal for FER at a distance of 10 m and 4 m, respectively. However, there were at least two limitations in previous studies. One is that all the faces used in the FER task were photographs displayed on a 2D screen. The second limitation is that obstacle detection and FER experiments were conducted separately, not in parallel as for real scenarios. Due to the capacity of our attention, impairment in one specific task is expected when conducting multiple tasks simultaneously.

This chapter reports an experiment conducted to explore the impact of dual task performance for two typical visual tasks for pedestrians, obstacle detection and FER. Three-dimensional face models were used to improve ecological validity in the current experiment. However, compared with 2D targets, 3D face models are not expected to have significant advantages because of their static position and the absence of variation in light source position. The use of 3D face models has been pre-tested in two pilot studies (Chapter 3). The results suggest that 3D face models can replace photographs in the following experiments.

The apparatus and method used in this experiment were described in Section 4.5. The dependent variables are the obstacle detection rate and FER rate. As no performance difference has been found between raised and lowered obstacles in Experiment 1, the obstacles were only raised in the current experiment.

All data from Experiment 2 have been checked for normal distribution in advance (Section 4.6, Appendix A.2 and A.3). Only the data for sadness in the FER task do not suggest normal distribution. The reason might be that the face models depicting sadness were less obvious characterisations in comparison with the other emotions. Since the rest of the data were all suggested to be normally distributed, parametric tests were carried out for all data in Experiment 2 to make the statistical tests efficient.

## 6.2 Results

The raw results of Experiment 2 are reported in Appendix C.

Null trials in Experiment 2 were the condition that neither a face model nor a lowered obstacle appeared during the 500 ms observation duration. They were used to assess possible response bias, a tendency toward particular responses, or random responding if the participants were unsure about stimulus detection. A response to an obstacle, a facial emotion or both may be false alarms in null condition trials (but this possibility did not happen in any trial).

In Experiment 2, 27 null condition trials were presented for every participant under each light level, giving 1380 null condition trials in total (27 x 2 light levels x 30 participants). There were 1145 correct reactions (i.e. no response) to the null condition trials, which accounted for 83% (Table 6.1). Face false alarms were, as expected, close to zero because no model head was present (0.003%). An obstacle false alarm was raised in 17% of trials, which is close to the number of false alarms observed in Experiment 1 and previous obstacle detection studies (13.7 - 24.8%) (Fotios and Cheal, 2009, 2013).

As mentioned in Experiment 1, the sensitivity index (*d'*) is used to determine how well the signal can be distinguished (Stanislaw and Todorov, 1999). In Experiment 2, since the false alarm rate of the FER task was extremely low, the *d'* was only calculated for the obstacle detection trials. There were 3000 trials in total for 30 participants that an obstacle was presented as a pothole. They have been detected correctly in 1998 (66.7%) trials. The average *d'* score for all test participants was 1.44, which is within the range of Experiment 1 and previous work (1.06 – 3.28) (Fotios and Cheal, 2013). These findings indicate that participants tended to report detection only when an obstacle appeared and did not react when obstacles were absent.

**Table 6.1.** Responses in null condition trials in Experiment 2.

| **Experiment** | **Total number of null condition trials** | **Correct rejection** | **False alarms** | |
|---|---|---|---|---|
| | | | **Obstacle response** | **Face response** |
| 2 | 1380 | 1145 (83%) | 235 (17.03%) | 4 (0.003%) |

### 6.2.1 Obstacle detection

Figure 6.1 shows how the mean obstacle detection rates under two light levels were both over 60% but the difference between them is not significant.

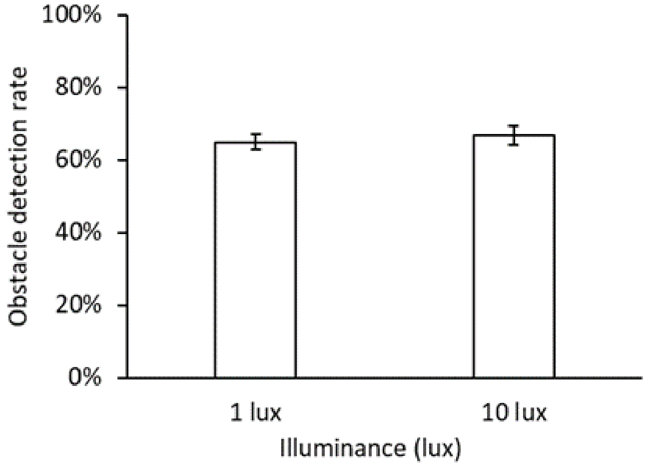


**Figure 6.1.** The effects of illuminance on the pavement obstacle detection rate in Experiment 2. Error bar: 95% confidence interval.

Figure 6.2 shows the mean detection rates for obstacles in single and dual task conditions, with obstacle detection falling from over 70% to less than 60% when participants were also doing the FER task.

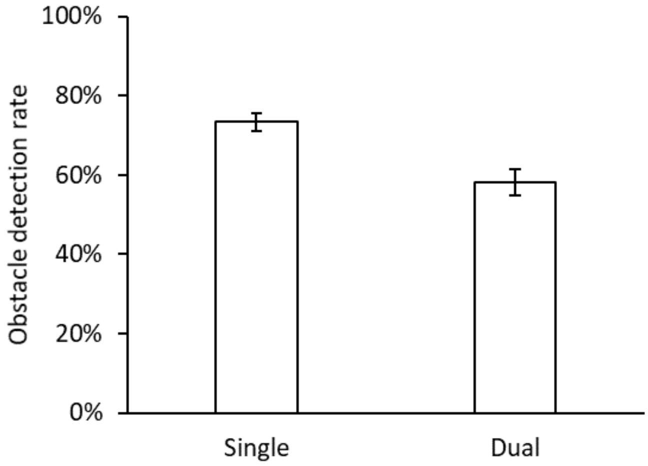


**Figure 6.2.** The effects of task condition on the detection rate in Experiment 2. Error bar: 95% confidence interval.

Mean detection rates for the four different obstacle locations are shown in Figure 6.3. There was a tendency that the detection rate was falling when the distance between the obstacle and observer smaller or the visual angle of the obstacle became larger. The detection rate for Obstacle 1 at almost 70% was the highest among the four obstacle locations, while Obstacle 4 yielded the lowest detection rate at around 60%.

The detection rates of Obstacles 2 and 3 were in the middle and nearly the same with each other.

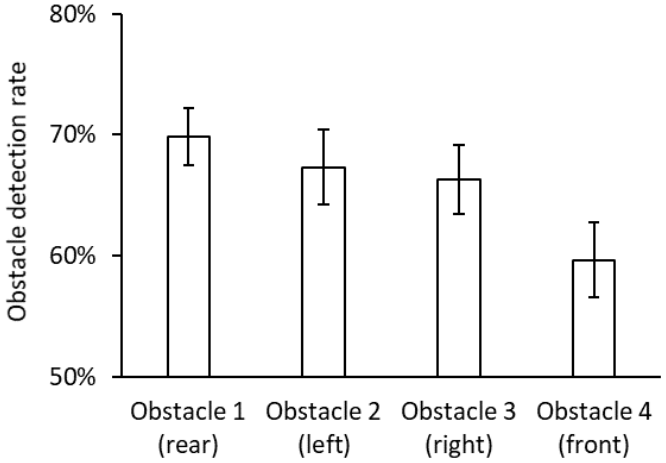


**Figure 6.3.** The effects of obstacle location on detection rate in Experiment 2. Error bar: 95% confidence interval.

Figure 6.4 shows the mean detection rates for five different obstacle sizes. The tendencies of obstacle detection rates under both 1.0 and 10.0 lux were the same. The larger obstacles were detected more frequently, and changes in size above 10 mm had a reduced effect on detection.

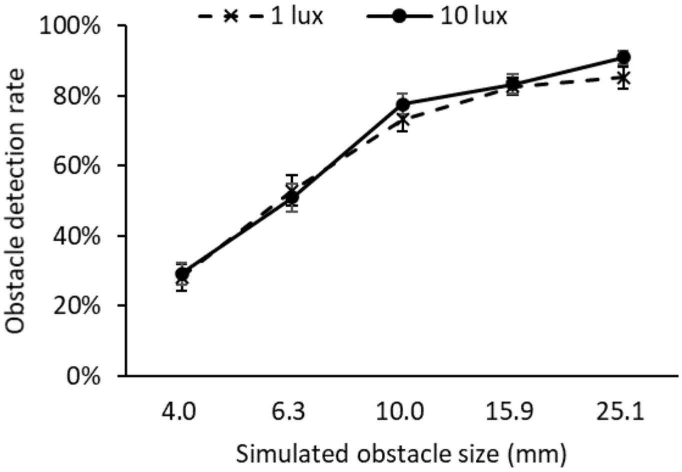


**Figure 6.4.** The effects of obstacle size on detection rate in Experiment 2. Error bar: 95% confidence interval.

A four-way repeated measures ANOVA was carried out with four independent variables: 2 levels of illuminance (1.0 lux and 10.0 lux), 4 levels of obstacle location

(Obstacle 1 - 4), 5 levels of obstacle depths (simulating 4.0, 6.3, 10.0, 15.9 and 25.1 mm) and 2 levels of task condition (single and dual), and with one dependent variable: obstacle detection rate. To account for the error of multiple comparisons, the *p*-value thresholds were adjusted using the Holm-Bonferroni correction method as described in Section 4.6 (Holm, 1979). Table 6.2 shows the results from the ANOVA. For the significant main effects or interactions revealed by the ANOVA test, post hoc paired comparisons *t*-tests with Holm-Bonferroni correction were carried out to measure the differences between levels on each variable.

The results suggest that obstacle location ($p = 0.004$), obstacle size ($p < 0.001$) and task condition ($p < 0.001$) affect the detection performance significantly while the illuminance did not reveal a significant effect ($p = 0.264$). The detection rates for 1.0 lux (mean = 65%, SD = 2.2%) and 10.0 lux were similar (mean = 66%, SD = 2.6%) (Figure 6.1).

As shown in Figure 6.2, the mean correct detection rate for single task condition (mean = 74%, SD = 2.2%) was significantly higher than dual task condition (mean = 58%, SD = 3.2%).

Each test participant observed four different obstacle locations (Figure 6.3). Paired *t*-tests suggested that the detection performance differed significantly between Obstacle 1 and 4 ($p < 0.001$). The detection rate for Obstacle 4 (mean = 60%, SD = 3.1%) was the lowest and the Obstacle 1 was the highest (mean = 70%, SD = 2.3%). For Obstacle 2 and 3, there was no significant effect on detection performance (Obstacle 2: mean = 67%, SD = 3.1%; Obstacle 3: mean = 67%, SD = 2.9%; $p = 0.77$), validating the finding from Experiment 1.

For the five difference obstacle sizes, the mean detection rate increased as the obstacle size became larger (Figure 6.4), ranging from 28% (SD = 3.1%) for the smallest obstacle size under illuminance of 1.0 lux to over 91% (SD = 1.9%) for the largest obstacle under illuminance of 10.0 lux. After doing the paired *t*-tests with Holm-Bonferroni correction, the results suggested a significant effect on detection performance between successive increases in obstacle size ($p < 0.002$ in all cases).

There were two significant interactions were found as shown in Table 6.2. The first was between obstacle location and illuminance ($p = 0.001$). The two illuminances only affected the detection performance significantly for Obstacle 2 ($p = 0.001$) but not for the other three obstacle locations (Obstacle 1, 3 and 4).

**Table 6.2.** Results of 4-way repeated-measures ANOVA for results of Experiment 2, with illuminance, task condition, obstacle location and obstacle size as independent variables and detection rate as the dependent variable.

| **Main and Interactive Variables(s)** | **F-statistic (df)** | ***p*-value** | **Holm-Bonferroni corrected *p*-value threshold** | **Significant effect**[a] | **Effect size (Cohen's *f*)** |
|---|---|---|---|---|---|
| Illuminance | 1.298 (1, 29) | 0.264 | 0.006 | No | 0.21 (small) |
| Task condition | 22.728 (1, 29) | <0.001 | 0.003 | Yes | 0.88 (large) |
| Obstacle location | 4.722 (3, 87) | 0.004 | 0.005 | Yes | 0.40 (large) |
| Obstacle size | 156.039 (4, 116) | <0.001 | 0.003 | Yes | 2.32 (large) |
| Illuminance * Task condition | 0.044 (1, 29) | 0.834 | 0.050 | No | 0.04 (none) |
| Illuminance * Obstacle location | 6.108 (3, 87) | 0.001 | 0.004 | Yes | 0.46 (large) |
| Illuminance * Obstacle size | 0.990 (4, 116) | 0.416 | 0.013 | No | 0.18 (small) |
| Task condition * Obstacle location | 1.238 (3, 87) | 0.301 | 0.007 | No | 0.21 (small) |
| Task condition * Obstacle size | 4.766 (4, 116) | 0.001 | 0.004 | Yes | 0.41 (large) |
| Obstacle location * Obstacle size | 1.602 (12, 348) | 0.089 | 0.006 | No | 0.23 (small) |
| Illuminance * Task condition * Obstacle location | 0.491 (3, 87) | 0.690 | 0.025 | No | 0.13 (small) |
| Illuminance * Task condition * Obstacle size | 0.882 (4, 116) | 0.477 | 0.017 | No | 0.17 (small) |
| Illuminance * Obstacle location * Obstacle size | 1.996 (12, 348) | 0.024 | 0.005 | No | 0.26 (medium) |
| Task condition * Obstacle location * Obstacle size | 1.095 (12, 348) | 0.363 | 0.010 | No | 0.19 (small) |
| Illuminance * Task condition * Obstacle location * Obstacle size | 1.160 (12, 348) | 0.311 | 0.008 | No | 0.20 (small) |

[a] Result suggested to be statistically significant ($p < 0.05$) according to a threshold corrected using Holm-Bonferroni.

The second significant interaction was between task condition and obstacle size (*p* = 0.001) (Table 6.2). When the obstacle size became larger, the detection rates rise from around 25% to over 80% for both single task and dual task conditions (Figure 6.5). The results revealed significant interactions between obstacle size and task condition for the largest four obstacle sizes ($p \leq 0.001$) but not for the smallest (*p* = 0.493). For the largest four obstacle sizes, single task condition has a higher obstacle detection rate compared with dual task condition.

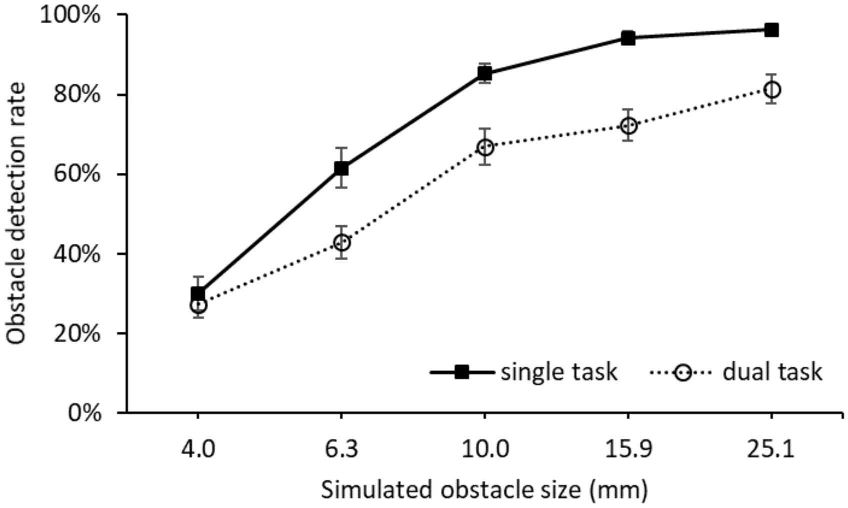


**Figure 6.5.** Mean obstacle detection rates plotted against obstacle size for single-task and dual-task conditions. Error bar: 95% confidence interval.

### 6.2.2 Facial emotion recognition task

Three variables were examined for the FER task in Experiment 2: face luminance (2 levels: 0.16 cd/m$^2$ and 1.65 cd/m$^2$), task condition (2 levels: single and dual) and facial emotion (4 levels: happiness, sadness, anger and neutral).

Figure 6.6 shows the mean FER rate under two light levels in Experiment 2. Although the recognition rates for both light conditions were over 60%, the higher luminance condition provided a better recognition rate than the lower luminance condition.

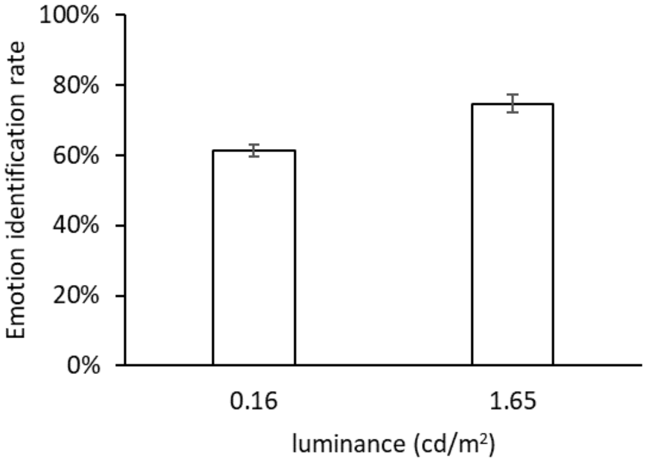


**Figure 6.6.** The effects of luminance on the identification rate in Experiment 2. Error bar: 95% confidence interval.

Figure 6.7 shows the mean recognition rate when performing FER in single and dual task conditions with similar recognition rates, both around 70%.

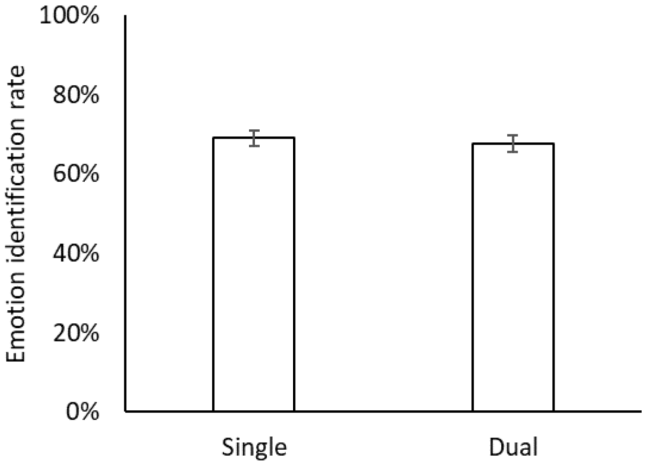


**Figure 6.7.** The effects of task condition on identification rate in Experiment 2. Error bar: 95% confidence interval.

Figure 6.8 shows the mean recognition rates of four different facial emotions. All four emotions were correctly identified in 63 - 71% of occurrences. Though the recognition rate of the neutral expression was slightly better than the other three, the difference between each of them was not obvious.

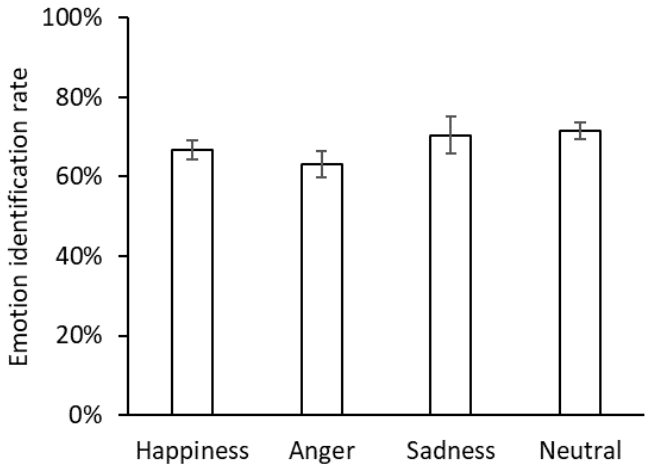


**Figure 6.8.** The effects of facial emotion type on identification rate in Experiment 2. Error bar: 95% confidence interval.

Table 6.3 listed the results from the ANOVA test. The FER was only affected significantly by illuminance (*p* < 0.001). The task condition and facial emotion type were not suggested to have a significant effect on FER performance (*p* = 0.154 and 0.234). As predicted for a typical situation (Section 4.5.1), the FER rate was significantly higher under the luminance of 1.65 cd/m$^2$ (mean = 74.3%, SD = 2.46%) compared with the luminance of 0.16 cd/m$^2$ (mean = 61.2%, SD = 1.71%).

All eleven face models were used (4 happiness, 1 sadness, 2 anger and 4 neutral) in Experiment 2. Figure 6.9 shows the recognition rates for each individual face model. There was some variation in the hairstyles of the face models (Figure 4.9) which possibly could help participants in discriminating the emotions after successive presentations. Therefore, individual difference between face models with the same emotion type has been investigated. The incorrect responses for each emotion were analysed (Table 6.4).

For the individual difference within each emotion type, there was a significant difference among the four happiness faces (*p* = 0.008) and two anger faces (*p* = 0.004) but not among the four neutral faces (*p* = 0.709). By doing the paired *t*-tests with Holm-Bonferroni correction, the performance between Happiness-1 and Happiness-2 (*p* = 0.027), Happiness-2 and Happiness-4 (*p* = 0.021), Anger-1 and Anger-2 (*p* = 0.043) differed significantly.

**Table 6.3.** Results of 3-way repeated-measures ANOVA, with luminance, task condition and facial emotion as independent variables and identification rate as the dependent variable.

| **Main and Interactive Variables(s)** | **F-statistic (df)** | ***p*-value** | **Holm-Bonferroni corrected *p*-value threshold** | **Significant effect**[a] | **Effect size (Cohen's *f*)** |
|---|---|---|---|---|---|
| Illuminance | 47.883 (1, 29) | <0.001 | 0.007 | Yes | 1.29 (large) |
| Task condition | 2.140 (1, 29) | 0.154 | 0.010 | No | 0.27 (medium) |
| Emotion | 1.448 (3, 87) | 0.234 | 0.017 | No | 0.22 (small) |
| Luminance * Task condition | 1.632 (1, 29) | 0.212 | 0.013 | No | 0.24 (small) |
| Luminance * Emotion | 2.016 (3, 87) | 0.118 | 0.008 | No | 0.26 (medium) |
| Task condition * Emotion | 0.381 (3, 87) | 0.767 | 0.050 | No | 0.11 (small) |
| Luminance * Task condition * Emotion | 0.565 (3, 87) | 0.640 | 0.025 | No | 0.14 (small) |

[a] Result suggested to be statistically significant ($p < 0.05$) according to a threshold corrected using Holm-Bonferroni.

## 6.3 Summary

This chapter reports an experiment that investigated the effect of changes in illuminance (1 lux and 10 lux) on the performance of obstacle detection and FER tasks and the impact of making both assessments simultaneously. According to the findings from Experiment 1, there is no significant difference between lowered and raised obstacles. Thus, only lowered obstacles were used in Experiment 2, and the five levels of size were kept the same. For the FER task, 3D face models were used in this experiment rather than photographs used in previous studies (Fotios *et al.*, 2015d; Yang and Fotios, 2015; Fotios *et al.,* 2017a).

The results for obstacle detection suggested that the performance has reached a plateau and the optimal illuminance was not revealed by the data: adding trials at lower illuminance would explore this. For the FER task, the results do not show the optimal luminance has been reached: adding trials at the higher light level would explore this. Hence, the following experiment was carried out with a wider range of light levels (see Table 4.9).

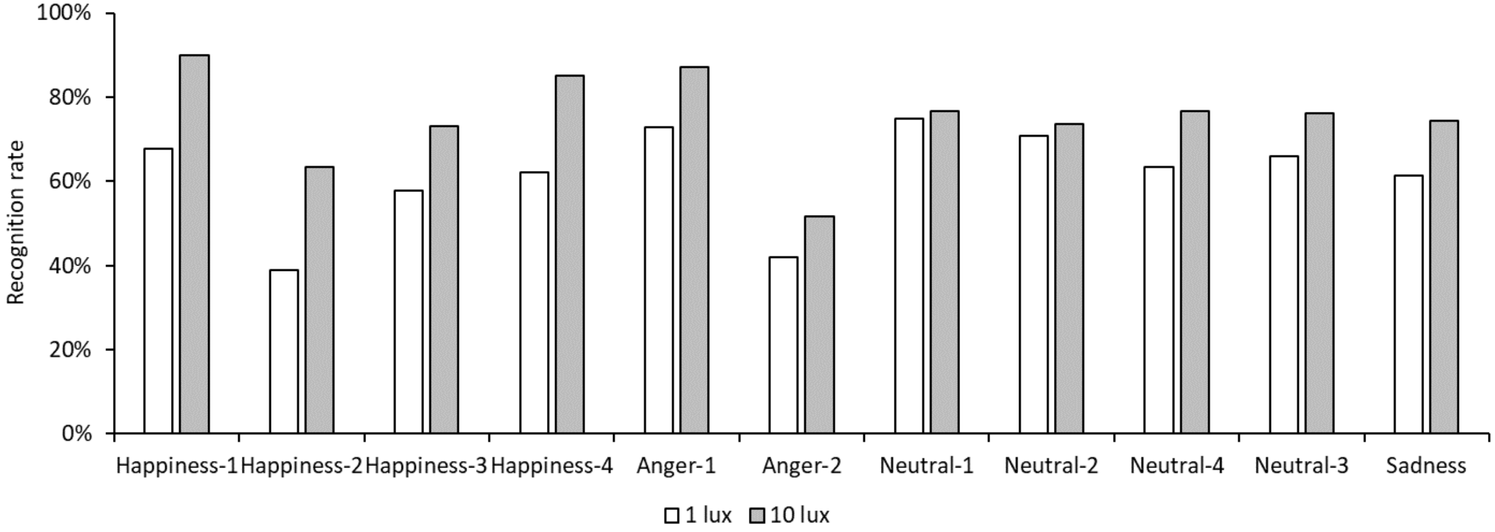


**Figure 6.9.** Correct recognition rates for the face models used in Experiment 2.

**Table 6.4.** Allocation of incorrect responses for four types of emotions in Experiment 2.

| | Happiness-1 | Happiness-2 | Happiness-3 | Happiness-4 | Anger-1 | Anger-2 | Sadness | Neutral-1 | Neutral-2 | Neutral-3 | Neutral-4 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Happiness | - | - | - | - | 9.12% | 4.26% | 3.13% | 5.86% | 5.21% | 3.00% | 2.84% |
| Anger | 8.08% | 16.04% | 7.37% | 10.19% | - | - | 3.13% | 3.91% | 13.89% | 11.33% | 12.50% |
| Sadness | 0.77% | 7.46% | 4.81% | 5.56% | 2.35% | 11.36% | - | 15.63% | 13.89% | 14.67% | 10.80% |
| Neutral | 8.85% | 22.76% | 21.79% | 8.80% | 7.35% | 52.56% | 24.15% | - | - | - | - |

One limitation as in Experiment 1 and other studies (Fotios and Cheal, 2009; Fotios and Cheal, 2013; Uttley *et al.*, 2017) is that the simulated environment did not involve a glare source which might come from vehicle headlamps or road lighting. It could be added as an additional variable to test the effect of glare on obstacle detection and FER. Additionally, no older people were recruited in Experiment 2. Different age groups could be considered as one variable to compare the performance between young and old people.

# CHAPTER 7. RESULTS OF EXPERIMENT 3: DUAL-TASK OF OBSTACLE DETECTION AND FER

## 7.1 Introduction

Chapter 6 reported an experiment conducted primarily to investigate whether the performance of obstacle detection and FER were affected when adding a secondary task. The results suggest that obstacle detection was significantly affected by task condition, obstacle size and obstacle location but not the light level. In Experiment 3, a wider range of illuminances was applied to further explore the effect of lighting change on obstacle detection and FER, and dual task performance of obstacle detection and FER were continuously investigated.

The apparatus and method used in Experiment 3 were nearly the same as in Experiment 2 (Section 4.5).

In Chapter 4.5, Appendix A.4 and A.5, the method and the results for testing normality of data distribution in Experiment 3 are reported. All data were suggested to be normally distributed. Thus, parametric tests have been conducted in the analysis.

## 7.2 Results

The raw results of Experiment 3 are reported in Appendix D.

In Experiment 2, 12 null condition trials were presented to each participant under each light level, giving 1800 null condition trials in total (12 x 5 illuminances x 30 participants).

In all the 1800 null condition trials, correct rejections were 1611 in total. This the right response that the participant did not press a button and not report a face appeared when neither an obstacle nor a face model was presented (Table 7.1). False alarms where the participants incorrectly reported an emotion when none was presented were recorded in only 4 trials (false alarm rate = 0.002%). False alarms where participants incorrectly pressed a button when none was presented were occurred in 189 trials (false alarm rate = 10.5%). The false alarm rate is lower than in both Experiments 1 and 2 (24.8% and 17%) as well as previous studies (13.7 - 21.2%) (Fotios and Cheal, 2009; Fotios and Cheal, 2013).

**Table 7.1.** Responses in null condition trials in Experiments 3.

| Experiment | Total number of null condition trials | Correct rejection | False alarms | |
|---|---|---|---|---|
| | | | Obstacle response | Face response |
| 3 | 1800 | 1611 (89.5 %) | 189 (10.5%) | 4 (0.002%) |

As with experiment 1, sensitivity index *d*' is only calculated for obstacle detection as the false alarm rate for FER was extremely low. Among the 4650 obstacle detection trials, the hit rate was 73.94% and the average *d*' score was 1.82. This is in the range of Experiment 1, Experiment 2 and previous work (1.06 – 3.28) (Fotios and Cheal, 2009; 2013).

### 7.2.1 Obstacle detection

Four independent variables were used in Experiment 3: illuminance, obstacle location, obstacle size and task condition.

As shown in Figure 7.1, the obstacle detection rates were all above 60%. Performance increased slightly when the illuminance became higher until 10.0 lux. However, at an illuminance of 33.3 lux, the detection rate did not continue to grow as expected but dropped a little. A reasonable explanation to this is, in the highest light level, the task was too easy, and participants lost concentration. This could be explained by Yerkes–Dodson law. The performance of one task is related with the arousal. If the task is too simple, the arousal level is low as well, and people may find they are drifting off or even falling asleep before starting the assignment (Diamond *et al*., 2007).

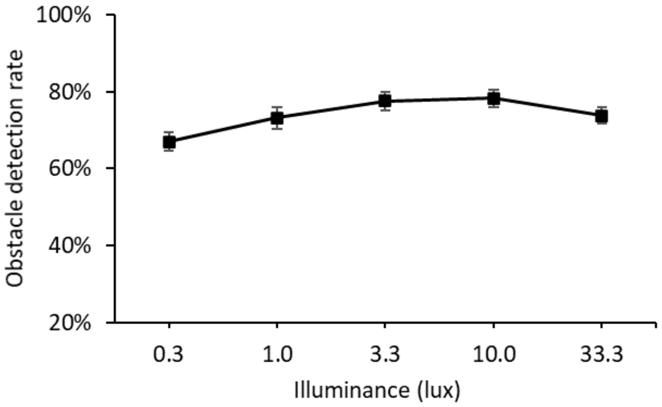


**Figure 7.1.** The effects of illuminance on the detection rate in Experiment 3. Error bar: 95% confidence interval.

Figure 7.2 compares the mean obstacle detection rates between the single-task condition and dual-task condition. When performing obstacle detection only, the detection rate was slightly higher than when doing obstacle detection and FER together.

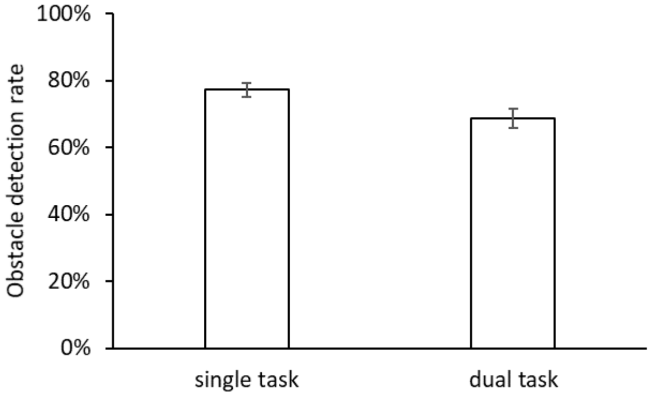


**Figure 7.2.** The effects of task condition on the detection rate in Experiment 3. Error bar: 95% confidence interval.

Figure 7.3 illustrates the tendency of obstacle detection performance when observing different obstacle sizes. Detection increased when the obstacle size being larger. When the simulated obstacle size smaller than 10.0 mm, the detection rate increased rapidly from chance level (around 25%) and reached a plateau at 10.0 mm.

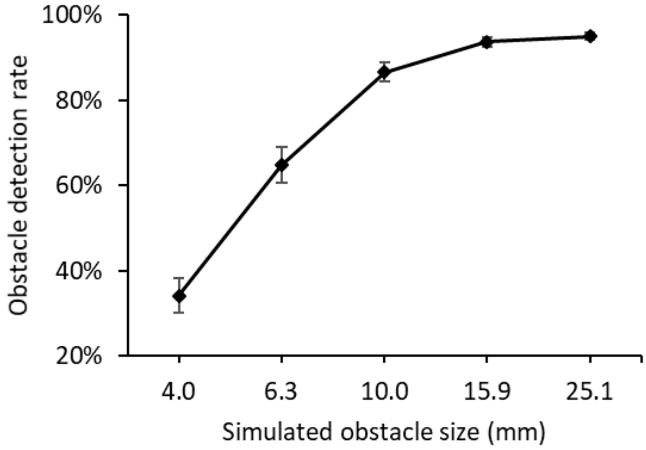


**Figure 7.3.** The effects of simulated obstacle size on detection rate in Experiment 3. Error bar: 95% confidence interval.

Figure 7.4 shows that the mean obstacle detection rates for the three different obstacle locations were nearly the same at approximately 75%.

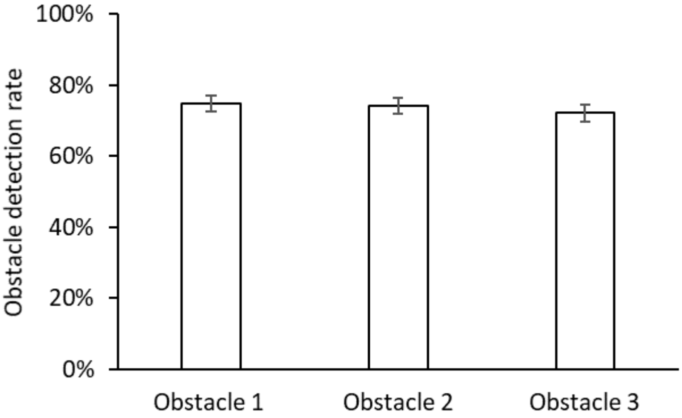


**Figure 7.4.** The effects of obstacle location on detection rate in Experiment 3. Error bar: 95% confidence interval.

**Table 7.2.** Results of 3-way repeated-measures ANOVA in Experiment 3, with illuminance, obstacle location and obstacle size as independent variables and detection rate as the dependent variable.

| **Main and Interactive Variables(s)** | **F-statistic (df)** | ***p*-value** | **Holm-Bonferroni corrected *p*-value threshold** | **Significant effect**[a] | **Effect size (Cohen's *f*)** |
|---|---|---|---|---|---|
| Illuminance | 12.113 (4, 116) | <0.001 | 0.007 | Yes | 0.65 (large) |
| Obstacle location | 0.695 (2, 58) | 0.503 | 0.05 | No | 0.15 (small) |
| Obstacle size | 155.231 (4, 116) | <0.001 | 0.007 | Yes | 2.32 (large) |
| Illuminance * Obstacle location | 3.513 (8, 232) | 0.001 | 0.013 | Yes | 0.35 (medium) |
| Illuminance * Obstacle size | 3.383 (16, 464) | <0.001 | 0.007 | Yes | 0.34 (medium) |
| Obstacle location * Obstacle size | 1.676 (8, 232) | 0.105 | 0.025 | No | 0.24 (small) |
| Illuminance * Obstacle location * Obstacle size | 1.869 (32, 928) | 0.003 | 0.017 | Yes | 0.25 (medium) |

[a] Result suggested to be statistically significant ($p < 0.05$) according to a threshold corrected using Holm-Bonferroni.

In Experiment 3, two three-way repeated-measures ANOVAs were carried out with three independent variables each. This was done instead of a four-way ANOVA because the obstacles and face models were paired randomly in the dual task trials, the combinations presented to participants were different in each experiment. The light level (5 levels: 0.33, 1.0, 3.3, 10.0 and 33.3 lux) and obstacle size (5 levels: simulating

4.0, 6.3, 10.0, 15.9 and 25.1 mm) were the two same variables used in the two ANOVAs. The two different variables were obstacle location (3 levels: Obstacle 1 - 3) and task condition (2 levels: single task and dual task). The results were also corrected by the Holm-Bonferroni method (Table 7.2 and 7.3).

**Table 7.3.** Results of 3-way repeated-measures ANOVA in Experiment 3, with illuminance, task condition and obstacle size as independent variables and detection rate as the dependent variable.

| Main and Interactive Variables(s) | F-statistic (df) | *p*-value | Holm-Bonferroni corrected *p*-value threshold | Significant effect[a] | Effect size (Cohen's *f*) |
|---|---|---|---|---|---|
| Illuminance | 10.303 (4, 116) | <0.001 | 0.007 | Yes | 0.60 (large) |
| Task condition | 8.278 (1, 29) | 0.007 | 0.017 | Yes | 0.53 (large) |
| Obstacle size | 135.685 (4, 116) | <0.001 | 0.007 | Yes | 2.16 (large) |
| Illuminance * Task condition | 5.438 (4, 116) | <0.001 | 0.007 | Yes | 0.43 (large) |
| Illuminance * Obstacle size | 1.707 (16, 464) | 0.042 | 0.025 | No | 0.24 (small) |
| Task condition * Obstacle size | 5.947 (4, 116) | <0.001 | 0.007 | Yes | 0.45 (large) |
| Illuminance * Task condition * Obstacle size | 1.425 (16, 464) | 0.125 | 0.05 | No | 0.22 (small) |

[a] Result suggested to be statistically significant ($p < 0.05$) according to a threshold corrected using Holm-Bonferroni.

As shown in Table 7.2 and 7.3, the results suggested a significant effect of illuminance, obstacle size and task condition on detection performance but not for obstacle location. The mean detection rates of all obstacle locations were nearly the same (Obstacle 1: mean = 75.8%, SD = 2.17%; Obstacle 2: 75.7%, SD = 2.37%; Obstacle 3: 74.0%, SD = 2.40%) (Figure 7.4). The obstacle locations did not reveal a significant difference on detection rates ($p = 0.503$).

*Post-hoc* paired-comparisons were implemented because the light level was suggested to have a significant effect on the obstacle detection rate ($p < 0.001$). As listed in Table 7.4, the performance difference was not significant between 0.33 lux and 1.0 lux ($p = 0.025$) but significant when the illuminance higher than 3.3 lux ($p \leq 0.001$ in all three cases). For illuminances of 1.0 lux and above, the data do not suggest a significant difference, which suggests that the optimal illuminance is in the region of 1.0 lux.

**Table 7.4.** Post hoc paired sample *t*-test with Holm–Bonferroni correction for obstacle detection task under all illuminances in Experiment 3.

| **Horizontal illuminance (lux)** | **Horizontal illuminance (lux)** | | | |
|---|---|---|---|---|
| | **1.0** | **3.3** | **10.0** | **33.0** |
| **0.33** | 0.025 | <0.001[a] | <0.001[a] | 0.001[a] |
| **1.0** | | 0.018 | 0.008 | 0.445 |
| **3.3** | | | 0.581 | 0.01 |
| **10.0** | | | | 0.002[a] |

[a] Result suggested to be statistically significant ($p < 0.05$) according to a threshold corrected using Holm-Bonferroni.

The detection rates increased as the obstacle size became larger under all light levels (Figure 7.5). The mean detection rate continuously increased from 33.6% (SD = 4.01%) at the smallest obstacle size to 95.7% (SD = 0.84%) at the largest obstacle size. A series of paired *t*-tests with Holm–Bonferroni correction suggests that the differences between each obstacle size were significant ($p < 0.001$) except between the largest two obstacle sizes (15.9 mm and 25.1 mm) ($p = 0.377$).

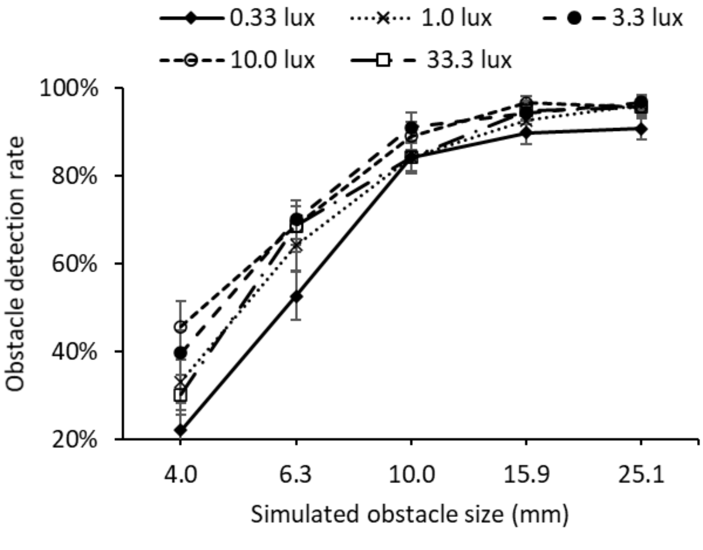


**Figure 7.5.** The effects of illuminance and obstacle size on detection rate in Experiment 3. Error bars show 95% confidence interval.

The ANOVA also suggested there was a significant effect of task condition on detection performance in the current experiment as shown in Experiment 2 ($p = 0.007$). The obstacle detection rate in single task trials was higher (mean = 77.1%, SD = 1.98%) than in dual task trials (mean = 70.5%, SD = 2.99%).

There is one apparent anomaly in these data: performance at 33.3 lux is significantly lower (*p* = 0.002) than at 10.0 lux. The decline in performance was consistent for all three obstacle locations (Figure 7.6).

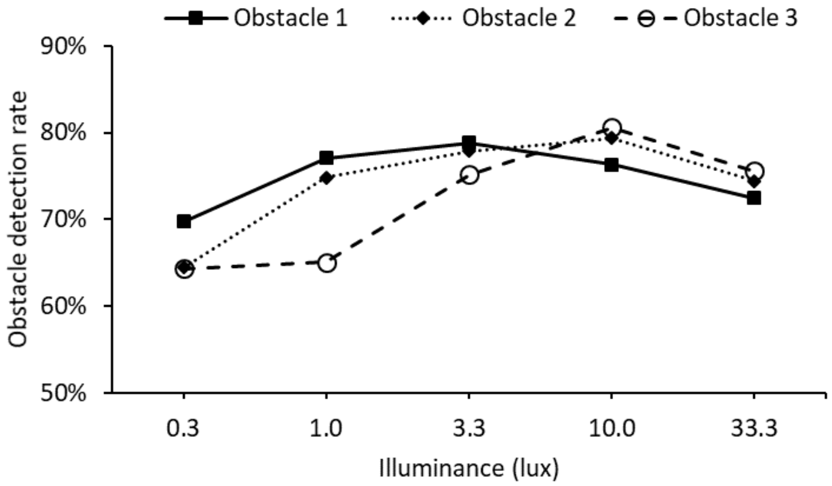


**Figure 7.6.** Mean obstacle detection rates plotted against illuminance for the three obstacle locations.

Figure 7.7 shows performance on the single task and dual task conditions separately and shows that the decline in performance at 33.3 lux occurred with single task trials but not with dual task trials. One possible reason is the participants paid more attention to seeking an expected target at the expense of obstacle detection. If single task obstacle detection used the number recognition fixation task as in Experiment 1, this reduction in performance might be changed.

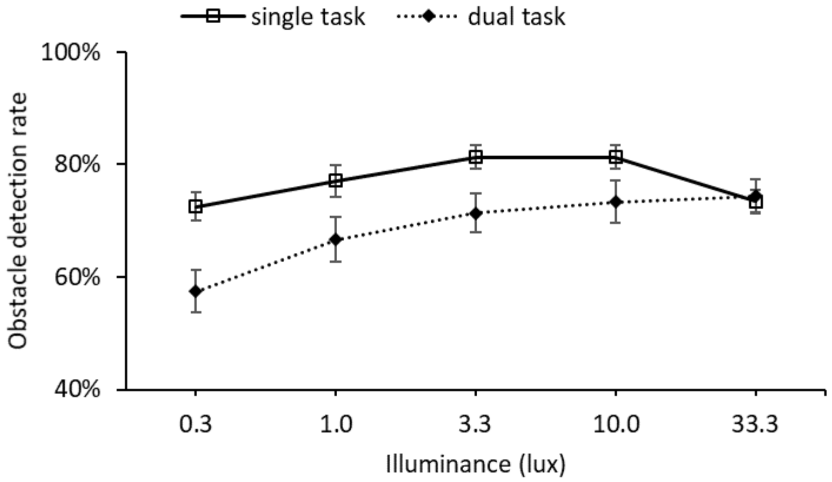


**Figure 7.7.** Mean obstacle detection rates plotted against illuminance for single task and dual task conditions.

### 7.2.2 Facial emotion recognition task

Figure 7.8 shows the mean FER rate of all emotion types under five different luminances. The recognition rate increased when luminance was higher while the growth rate became slower when the luminance went above 0.53 cd/m$^2$.

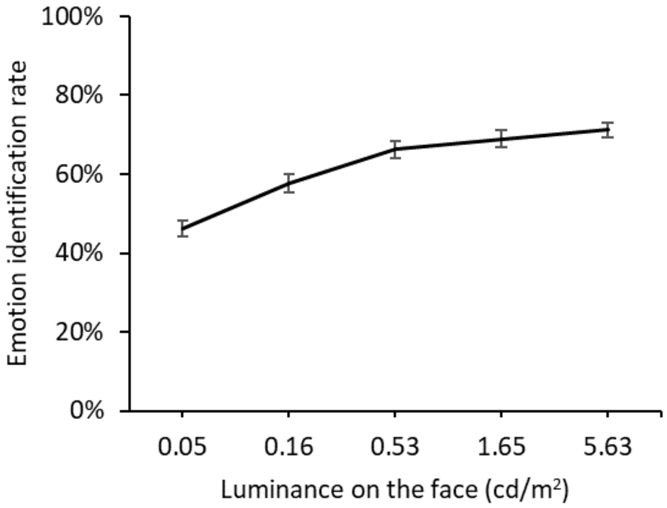


**Figure 7.8.** The effects of luminance on the identification rate in Experiment 3. Error bar: 95% confidence interval.

Figure 7.9 compares the mean recognition rates under single task and dual task conditions. The recognition rate when doing two tasks simultaneously was higher than when doing only the FER task by nearly 10%.

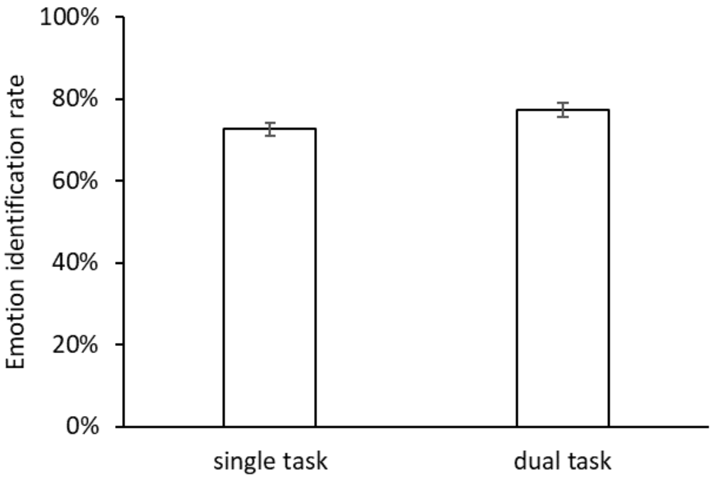


**Figure 7.9.** The effects of task condition on identification rate in Experiment 3. Error bar: 95% confidence interval.

Figure 7.10 shows the mean recognition rates of four different emotion types. The recognition rates of all emotions were above 60%, except sadness which has not reached 50%.

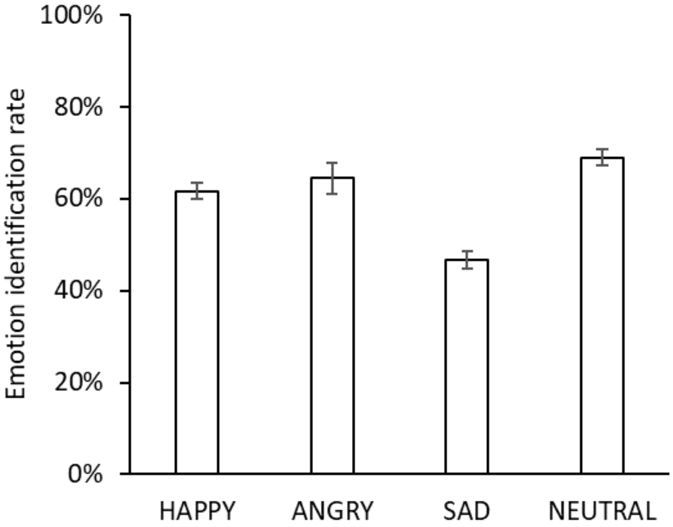


**Figure 7.10.** The effects of facial emotion type on identification rate in Experiment 3. Error bar: 95% confidence interval.

**Table 7.5.** Results of 3-way repeated-measures ANOVA, with luminance, task condition and facial emotion type as independent variables and identification rate as the dependent variable.

| **Main and Interactive Variables(s)** | **F-statistic (df)** | ***p*-value** | **Holm-Bonferroni corrected *p*-value threshold** | **Significant effect**[a] | **Effect size (Cohen's *f*)** |
|---|---|---|---|---|---|
| Luminance | 56.655 (4, 116) | <0.001 | 0.007 | Yes | 1.40 (large) |
| Task condition | 20.662 (1, 29) | <0.001 | 0.007 | Yes | 0.84 (large) |
| Emotion | 37.968 (3, 87) | <0.001 | 0.007 | Yes | 1.14 (large) |
| Luminance * Task condition | 1.510 (4, 116) | 0.204 | 0.017 | No | 0.22 (small) |
| Luminance * Emotion | 4.737 (12, 348) | <0.001 | 0.007 | Yes | 0.40 (large) |
| Task condition * Emotion | 0.292 (3, 87) | 0.831 | 0.050 | No | 0.10 (small) |
| Luminance * Task condition * Emotion | 0.739 (12, 348) | 0.713 | 0.025 | No | 0.16 (small) |

[a] Result suggested to be statistically significant ($p < 0.05$) according to a threshold corrected using Holm-Bonferroni.

A three-way ANOVA was carried out for the FER task with three independent variables: luminance (5 levels: 0.05, 0.16, 0.53, 1.65 and 5.63 cd/m$^2$), task condition (2 levels: single task and dual task) and facial emotion type (4 levels: happiness, anger, sadness and neutral) in Experiment 3. The dependent variable was the recognition rate. As above, the *p*-value threshold was corrected by Holm-Bonferroni correction. The results are shown in Table 7.5.

As shown in Table 7.5, all the three variables affected the recognition performance significantly ($p < 0.001$). The correct recognition rate increased with increasing luminance, from 55.4% (SD = 2.15%) at 0.33 lux to 85.4% (SD = 1.93%) at 33.3 lux (Figure 7.8).

The results from the paired comparisons *t*-tests were suggested that the recognition performance at 0.05 cd/m$^2$ was significantly lower than at higher luminance ($p < 0.001$) (Table 7.6). Also, performance at 0.16 cd/m$^2$ was significantly lower than at higher luminance ($p < 0.001$). The performance difference was not suggested to be significant between 0.53 cd/m$^2$ and higher luminances. The significant difference of detection rates between 0.16 cd/m$^2$ and 1.65 cd/m$^2$ in this experiment validates the findings from Experiment 2.

**Table 7.6.** Post hoc paired sample *t*-test with Holm–Bonferroni correction for FER under all luminance in Experiment 3.

| **Luminance on the face (cd/m$^2$)** | **Luminance on the face(cd/m$^2$)** | | | |
|---|---|---|---|---|
| | **0.16** | **0.53** | **1.65** | **5.63** |
| **0.05** | <0.001[a] | <0.001[a] | <0.001[a] | <0.001[a] |
| **0.16** | | <0.001[a] | <0.001[a] | <0.001[a] |
| **0.53** | | | 0.188 | 0.026 |
| **1.65** | | | | 0.135 |

[a] Result suggested to be statistically significant ($p < 0.05$) according to a threshold corrected using Holm-Bonferroni.

The recognition performance differed significantly between single task and dual task condition ($p < 0.001$) (Table 7.5). The correct recognition rate in dual task condition (mean = 77.3%, SD = 1.64%) was significantly higher than in single task condition (mean = 72.6%, SD = 1.67%) (Figure 7.9). This suggests that the participants tended to pay more attention to the FER task at the cost of peripheral detection performance in dual task condition.

The recognition rates for all types of facial expressions were over 50%, which was higher than the chance level. The expression of sadness was correctly recognised in 56.0% (SD = 1.85%) which was slightly lower than the other three expressions (happiness: mean = 74.0%, SD = 1.79%; anger: mean = 77.3%, SD = 3.36%; neutral: mean = 82.7%, SD = 1.67%). Paired-sample *t*-tests suggested that the difference between each type of emotion was significant ($p \leq 0.01$) but not between happiness and anger ($p = 0.153$).

## 7.3 Summary

This chapter described an experiment developed based on Experiment 2, carried out to further investigate the performance of obstacle detection and FER tasks under different light levels, and compared the performance when doing obstacle detection only and along with a FER task. Three more illuminances were added in the current experiment to better understand the relationship between illuminance and the performance of the two key visual tasks for pedestrians.

The results suggest that illuminance, obstacle size and task condition had significant effects on obstacle detection performance, while obstacle location did not. Detection performance increased as illuminance became higher and reached the plateau at 1.0 lux (Figure 7.1 and Table 7.4). For the FER task, luminance, task condition and emotion type are all suggest affecting the recognition rate significantly. The recognition rate in Experiment 3 increased when luminance was increasing and reached a ceiling at 0.53 cd/m$^2$. This tendency was the same as predicted by the RVP model used in Section 4.5.2. Thus, 0.53 cd/m$^2$ is suggested to be the optimal luminance for the FER task (Figure 7.8 and Table 7.6). For obstacle detection, performance was better when only an obstacle was presented, but FER performance was better in those trials where a face and an obstacle were presented simultaneously.

Two shared limitations with both Experiment 1, 2 and previous studies are that no glare source was included, and only young people were recruited. Future experiments can add glare sources to simulate a more real street environment after dark and investigate the age effect on these two tasks. Additionally, although rotated face models were presented in Experiment 3, the sample size was too small for analysis. More rotated face models could be included in experiments to simulate when observing other pedestrians from different angles.

# CHAPTER 8. DISCUSSION

## 8.1 Introduction

The purpose of this thesis was to explore how road lighting changes affect the ability of pedestrians to detect pavement obstacles and recognise the facial expressions of other people after dark. Compared with previous studies, the main improvements in the experiment design for an obstacle detection task are consideration of the possible effects of obstacle configuration, spatial variation and task condition. For a more realistic FER task, the experiment used 3D face models instead of photographs and added obstacle detection as a parallel secondary task. This chapter firstly compares the main effects between the three experiments and previous studies to check if the results are consistent and could be replicated. Although the three experiments were developed from previous studies, they were still laboratory-based, which in comparison with field experiments, involve a less realistic setting but have the advantage of making the control of independent (and extraneous) variables easier and more consistent. Therefore, these limitations are discussed to point out the direction of future research.

## 8.2 Repeatability of the Experiments

Experiment 1 mainly explored the effect of obstacle configuration (raised or lowered) and light source location on obstacle detection performance. Performance between raised and lowered obstacles did not differ significantly. Therefore, compared with previous studies using only a single luminaire position (Fotios and Cheal, 2009; Fotios and Cheal, 2013; Uttley *et al.*, 2017), the results in Experiment 1 suggest that the results from previous studies are valid indicators for the detection of lowered obstacles. However, there was a significant difference in detection performance due to different luminaire positions. An overhead light source allowed a higher performance compared with a source behind or in front of the obstacle. As the following two experiments did not involve different luminaire positions, this finding may need further work to confirm.

Experiment 2 and 3 were carried out to investigate the detection of obstacle on the pavements and recognition of facial emotion under different lighting conditions. Compared with previous work, dual task condition was considered as a variable: the next trial may be obstacle detection, FER, both or none of the above. The aim was to test the hypothesis that the performance of individual task would be impaired when performing multi-tasks and thus the extent to which this would influence the optimal light level concluded from the data.

Two light levels were used in Experiment 2, photopic illuminances of 1.0 and 10.0 lux measured at the centre on the top surface of Obstacle 1 (see Table 4.9). This did not significantly affect the obstacle detection performance, but the FER rate increases as the illuminance became higher as expected by using the RVP model. For the obstacle detection task, the detection rate was significantly higher in the trials where only an obstacle was presented compared with the trials that required the participant to respond to both tasks. For FER, the task condition did not reveal a significant difference which might because the FER task was the foveal task.

Five light levels were used in Experiment 3, photopic illuminances of 0.33, 1.0, 3.3, 10.0 and 33.3 lux measured on Obstacle 1 (see Table 4.9). There was a significant effect of illuminance on obstacle detection performance. The detection rate at 0.33 lux was significantly lower than at higher illuminances. When the illuminance was between 1.0 lux and 10.0 lux, the performance difference was not suggested to be significant, which validates the finding from Experiment 2. These findings, along with those of Fotios and Uttley (2018) and Boyce (1985), an illuminance of 1.0 lux is sufficient for pedestrians to avoid trip hazards.

There was also a significant effect of light level changes on FER performance. The correct recognition rate increased progressively as the light level became higher. The results of Experiment 3 were as predicted by the RVP model: the FER performance was suggested to differed significantly when the luminance was in the range of 0.05 cd/m$^2$ to 0.53 cd/m$^2$, but not significantly if the luminance was higher than 0.53 cd/m$^2$. Compared with the optimal luminance for the FER task proposed by Fotios *et al.* (2015d), 1.0 cd/m$^2$ at 10 m distance, the optimal luminance (0.53 cd/m$^2$) suggested in Experiment 3 was slightly lower. This might be due to the selection of stimulus. In Experiment 3, the luminance of 1.0 cd/m$^2$ was not included but stepped from 0.53 to 1.65 cd/m$^2$ while Fotios *et al.* (2015d) used only three luminances (0.01, 0.1 and 1.0 cd/m$^2$) and thus led to a less precise estimation of the optimum.

Both the obstacle detection and FER tasks suggested task condition influenced the performance significantly. For the obstacle detection task, the detection rate was higher when only an obstacle appeared. However, for the FER task, the recognition rate was higher when the participants were required to perform both tasks simultaneously.

## 8.3 Comparison with previous studies

Previous studies were conducted in a laboratory environment (including those studies in Tables 2.2 and 2.3), the participant is only required to perform one task, such as obstacle detection or FER, but not both at the same time. In the natural environment, a pedestrian is required to attend multiple tasks, either simultaneously or by rapidly switching between tasks intuitively. Therefore, Experiment 2 and 3 were developed from previous studies to better resemble the natural situation by requiring responses to one, both, or neither of two tasks randomly. By comparing the results between current experiments (the randomly occurring single-task trials) and previous work (which were single task by default), the effect of multi-tasking on the individual task performance was determined. More importantly, synthesise the results of the current work and previous studies to provide evidence or suggestions to current standards for road lighting of pedestrians.

Figure 8.1 demonstrates the comparison of obstacle detection task between Experiments 2 and 3 and three previous studies (Fotios and Cheal, 2009; Fotios and Cheal, 2013; Uttley *et al.*, 2017). The result from Experiment 1 is not included because only one illuminance (1.0 lux) was used, which cannot reveal the relationship between illuminance and detection rate. Since these experiments used different apparatus and settings, the results have been converted into a visual angle (arcmin) subtended at the observation point. One degree equals to 60 arcmins (a minute of arc). To make the data from these experiments were comparable, data used from previous studies were for the obstacles in a similar location to Obstacle 1 in the current work, and for the current work, only the results from obstacle-only trials are used (Table 8.1).

Data from all five experiments reveal a similar and consistent tendency except the result of Experiment 3 under the highest illuminance. It means the methods used in all of these experiments and the results obtained are repeatable and reliable. The experiment design, methodology and theoretical framework could be adopted in future experiments.

Different with previous studies, Experiment 2 and 3 involved dual task conditions, the test participant did not know which of the two tasks (if not both) they would be required to complete before the occlusion spectacles were opened. As expected, there was an impairment on both obstacle detection and FER tasks under single task condition due to lack of anticipation compared with previous studies where the task was known (Figure 8.1).

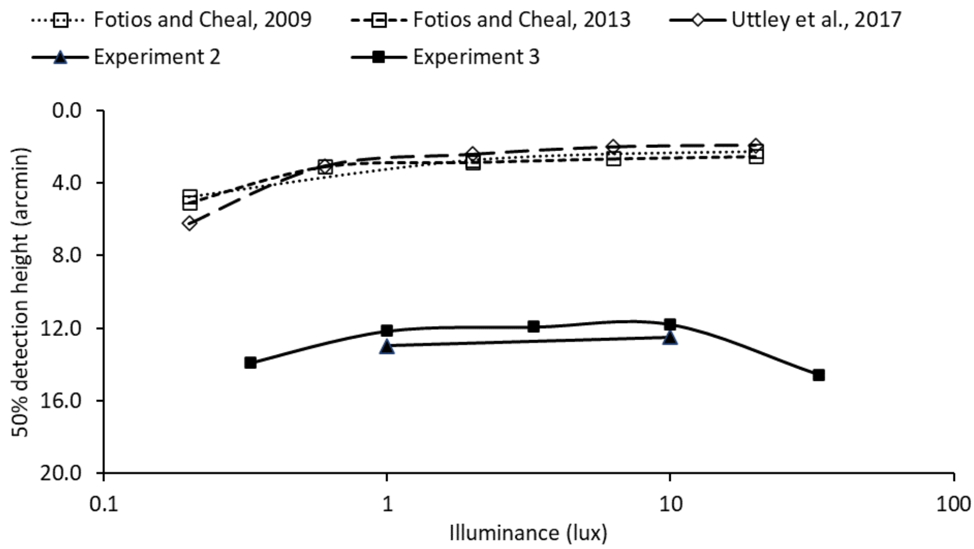


**Figure 8.1.** Obstacle height for 50% detection rate (in visual angle subtended at the eye) plotted against illuminance for three previous studies and the two current experiments (single task condition only). The conditions used for this comparison are shown in Table 8.1.

**Table 8.1.** Conditions compared for five experiments of obstacle detection.

| **Study** | **Light condition** | **Observation time (ms)** | **Detection target** | **Fixation target** | **Obstacle configuration** |
|---|---|---|---|---|---|
| Fotios and Cheal, 2009 | 0.2, 2.0 and 20.0 lux (S/P = 1.8) | 300 | Obstacle 1 (10.5° off-axis at the centre line) | Static mark | Raised |
| Fotios and Cheal, 2013 | 0.20, 0.63, 2.0, 6.32 and 20 lux (S/P = 0.6) | 300 | Obstacle 1 (10.5° off-axis at the centre line) | Static mark | Raised |
| Uttley *et al.*, 2017 | 0.2, 0.6, 2.0, 6.3, 20.0 lux (S/P = 1.6) | Continuous | 1 (only 1 obstacle used) | Dynamic fixation target | Raised |
| Experiment 2 | 1 and 10 lux (S/P = 1.6) | 500 | Obstacle 1 (19.7° off-axis at the centre line) | 3D face model | Lowered |
| Experiment 3 | 0.33, 1.0, 3.3, 10.0 and 33.3 lux (S/P = 1.6) | 500 | Obstacle 1 (19.7° off-axis at the centre line) | 3D face model | Lowered |

Note: participants were all in young age (between 16-35 years old).

In the previous studies (Fotios and Cheal, 2009; Fotios and Cheal, 2013; Uttley *et al.*, 2017), the performance of obstacle detection was improved when the illuminance on the target became higher and eventually plateauing at around 0.63 lux. Although there was a reduction of detection rate at all illuminances in Experiments 2 and 3 and a larger obstacle size was required for a 50% detection rate, it still suggests a performance plateau is reached at about 1.0 lux.

According to CIE 236:2019 (CIE, 2019), it was concluded from the then-available data that horizontal illuminances of 1.0 lux (minimum) and 4 lux (mean) are sufficient for obstacle detection and reassurance respectively. This research confirms the findings from Boyce (1985) and Fotios and Uttley (2018), 1.0 lux is sufficient for pedestrians at all age groups to detect obstacle safely under all lamp type. In this case, P4 class (mean illuminance 5.0 lux, minimum illuminance 1.0 lux) could meet the requirements.

For FER, the results from Experiments 2 and 3 were compared with a previous study (Fotios *et al.*, 2015d) which has a similar condition (S/P ratio and target distance) (Figure 8.2). The comparison only used the data from face-only trials in the current work (Table 8.2). The performance difference between the current work and Fotios *et al.* (2015d) was not significant for the targets under a similar light condition. It suggested that the FER performance was not influenced by the potential need to conduct an alternative or additional task.

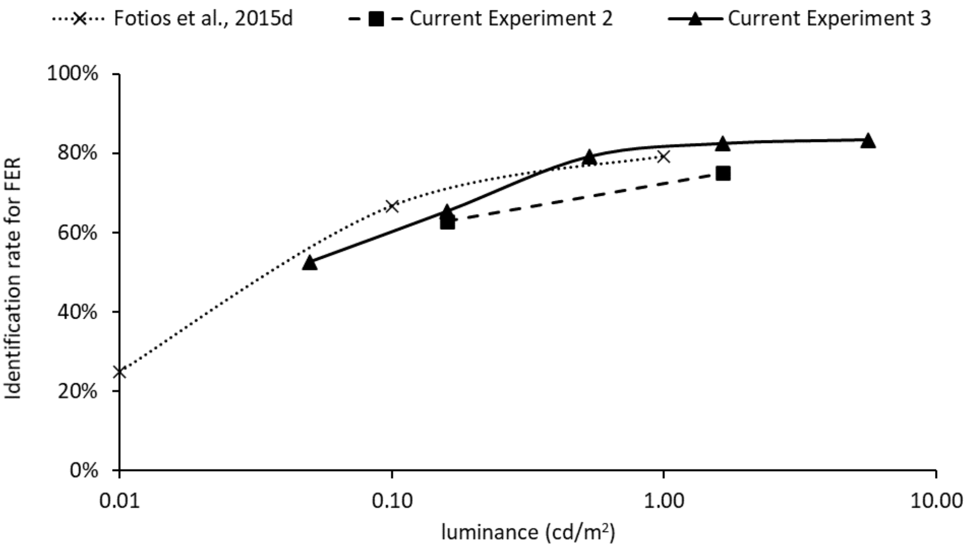


**Figure 8.2.** FER rate plotted against target luminance for two previous studies and Experiment 2 and 3 (only used single task condition data). The condition used to compare are listed in Table 8.2.

**Table 8.2.** Conditions compared in Figure 8.2 for three FER experiments. All three experiments simulated an approximately 10 m interpersonal distance.

| Study | Light condition | Fixation target |
|---|---|---|
| Fotios *et al.*, 2015d | 0.01, 0.1 and 1.0 cd/m$^2$ (S/P = 1.8) | 2D photographs |
| Experiment 2 | 0.16 and 1.65 cd/m$^2$ (S/P = 1.6) | 3D model |
| Experiment 3 | 0.05, 0.16, 0.53, 1.65 and 5.63 cd/m$^2$ (S/P = 1.6) | 3D model |

Note: Observation durations were 1000 ms in Fotios *et al.* (2015d) and 500 ms in the two current experiments.

For the optimal luminance of FER task, Fotios *et al.* (2015d) suggested the minimum luminance was in the range of 0.1 – 1.0 cd/m$^2$ when observing at 4 m distance. In the following experiment (Yang and Fotios, 2015), the data indicated the optimum luminance for FER at same distance was 0.33 cd/m$^2$ which was in the range suggested by the first experiment. The results from Experiment 2 and 3 suggested the optimum luminance was 0.53 cd/m$^2$. It was lower than that reported previously. As mentioned in Section 8.2, this might be due to the selection of light levels. Both Experiment 2 and 3 did not include 1.0 cd/m$^2$ but stepped from 0.53 cd/m$^2$ to 1.65 cd/m$^2$. Further experiments with more light levels may be required to better determine the relationship between luminance and FER performance. My colleague conducted a field survey to investigate the effect of lighting changes on pedestrian reassurance when walking after dark in an urban location (Fotios *et al.*, 2018). Reassurance is also an important part contributing to walking safety after dark. This research was carried out in daytime and after dark to employ the day–dark approach to analysis of optimal lighting. The results suggested a minimum horizontal illuminance was around 2.0 lux. It was slightly higher than the optimal illuminance proposed in current work for obstacle detection.

## 8.4 Multi-tasking and task performance

By comparing the performance on a task when only that task was conducted to the performance on that task when a second task was also attended, the results suggest an impairment on performance of peripheral detection task but not for FER task (foveal task). This conclusion is similar to the findings from comparing the performance of single task and dual task condition using the data of the current study only. The performance on a specific single task is the datum for both approaches while the difference is the comparator. In the former approach, the task condition was the same, but the participant was uncertain as to which target event would be presented in the upcoming trial. In the latter, it was the performance of that task in the same observation duration as a second task.

Multi-tasking appears to have affected one task but not the other due to a decrease in attention available to perform each task. This may be due to the priority of a task. In experimental trials, the priority can be advised by the experimenter but there is a possibility that participants may not obey such instructions (Ranney *et al.,* 2001). In a natural situation, a self-selected priority could be determined by the consequences of the impaired performance on each task. Attention is allocated in priority to the stimuli that are associated with threats of fear (Maratos and Pessoa, 2019). As seen in the results, if a greater threat or fear comes from the unknown intentions of other people, the attention is prioritised to FER rather than detection task. In this circumstance, the impairment on the detection task was greater than the FER task.

An alternative explanation to the multi-tasking impaired one specific task type is this impairment was caused by the target location. Compared with the foveal task, the performance was impaired by performing multiple tasks if the target is in the peripheral vision. If the task locations had been swapped, then the feature of the task impairment may have changed, leading instead to impairment of FER rather than obstacle detection. The approach used in the current work was intended to follow the typical experimental design of previous studies (using the peripheral vision to detect the obstacle and using foveal vision to recognise the facial emotion) and is suggested by eye-tracking to be ecologically valid: there is a natural inclination to look at another person if he/she appears in our vision field (Fotios *et al.,* 2015a; Fotios *et al.,* 2015b).

## 8.5 Tripping risk

The results from eye-tracking experiments suggested the fixation duration on one people is normally around 500 ms. Within this duration, there is a possibility that the pedestrian may fall or trip due to an unseen obstacle on the pavement if he/she focuses on people. Seeing an obstacle at least two steps (about 800 to 1000 ms) ahead is required to modify gait pattern successfully and avoid a hazard safely (Patla and Vickers, 2003). A pedestrian’s average walking speed varies with age, dropping from 1.25 m/s for a 14 to 64 years old person to 0.97 m/s for people aged 65 and older (Knoblauch *et al.*, 1996). The typical distance for detecting an obstacle is 3.4 ahead (Fotios and Uttley, 2018). If a pedestrian spends the next 500 ms fixating another person and the obstacle has not been detected, the walking distances are 0.62 m (younger) or 0.48 m (older) based on the average walking speed. It would take another

2.2 s (younger) or 3.0 s (older) to waling the remaining 2.78 m (younger) or 2.92 m (older) which means the remaining time is longer than required to modify gait.

## 8.6 Limitations

One limitation in the current work is only male Caucasian faces were used (Figure 4.9). This was not a purposeful choice but a consequence of availability. The 3D printed face models used in the previous pilot studies were from a validated database while the final products did not provide sufficient resolution. The face models used in Experiments 2 and 3 have a much higher resolution but not represent non-Caucasian faces or female faces.

This raises the question of whether ethnicity and gender play a role in FER. Since to a higher contrast resulting in faster recognition, it is possible that skin tones may affect the ability to recognise facial expressions if the facial contrast varies caused by different skin tones. For the current work, the optimal luminance was estimated by using one facial contrast. It may be suboptimal for other faces if the facial contrast varies due to different skin tones. Rea and Ouelletter (1991) have investigated this by comparing the RVP for contrasts associated with different skin tones.

Facial contrast is characterised by the contrast of the lips, eyebrows and eyes against the skin immediately surrounding these features separately (Russell, 2009; Porcheron *et al.,* 2017). For the current analysis, we used the mean average of those individual contrasts. It worth noting that, for facial contrast, Weber contrast is calculated here as is required to determine RVP. The young female faces were used from Porcheron *et al.* (2017). Facial contrast varies with skin type and hence we used the Caucasian and South African faces, which correspond approximately to types II and VI of the Fitzpatrick Scale (ARPNSA, 2021). The facial contrasts of these faces are 0.314 (Caucasian face) and 0.138 (South African face).

The adaptation luminance was taken as the average from the lit surface (CIE, 2017): an adaptation luminance of 0.6 cd/m$^2$ represents a road lit to an average illuminance of approximately 10 lux. RVP was calculated using a 25-year-old observer and a target subtended 0.0006 steradians, simulating a 10-meter interpersonal distance. The results indicated that RVP for the Caucasian face (0.94) was higher than the South African face (0.87). In other words, the light level required to recognise a facial emotion on a South African face is higher than on a Caucasian face.

Since females have higher facial contrast than males, gender is expected to affect FER (Russell, 2009). Previous FER studies (Fotios *et al.*, 2015; Fotios *et al.*, 2017a; Yang and Fotios, 2015) used a balanced number of male and female target faces but there were no comments on the performance differences caused by the target gender.

Facial recognition accuracy is maintained over a wide range of lighting directions, but lighting from extreme directions can impair it (Liu *et al.,* 1999). In Experiments 2 and 3, the light direction inside the apparatus was fixed, provided by LED2 and 3 simultaneously (Figure 4.6). Therefore, the vector/scalar ratio was maintained at about 3.3 for all cases (Table 4.9). In order to get an idea of the typical vector/scalar ratio range, field measurements were carried out on a minor road. The vector/scalar ratio (3.5) was the highest when measured directly under a lamp post and decreased to around 1.0 when measured in the middle of two successive lamp posts. Thus, the lighting condition used in the current work was simulating a situation when observing a target people standing nearby a lamp post.

There is one limitation of the face models. The hairstyle of all the anger, sadness and neutral faces were swept-back but not for all happiness faces. Among the four happiness faces, only Happiness-4 had swept-back hair while the hair of the other three were combed to the side (Figure 4.9). As a result, it is possible that discriminations were influenced by hairstyle to some extent, not on facial expression in isolation. If that were the case, the error rate for Happiness-4 would be higher than the other three happiness faces because of the confusion with the other facial expressions. However, the results of Experiment 2 did not reflect this: the error rates for happiness faces 1 – 4 were 32%, 61%, 42% and 38% under 1.0 lux, and 10%, 37%, 27% and 15% under 10.0 lux. Figure 6.9 illustrates the correct recognition rates for all the faces used in Experiment 2. As previously mentioned in Section 6.2.2, the results from the statistical analysis did not suggest a consistent performance difference between Happiness 4 and the other three happiness faces.

In a natural situation, some pedestrians may choose to wear a hat against bad weather or due to the reason of fashion. All the face models used in the current work were without a head covering. A hat would impair facial recognition by affecting the perception of facial configuration, especially in the forehead area (Freire and Lee, 2001) which is why the current work focused on FER rather than identity recognition. If the hat has a brim, the ability to recognise facial expressions could be reduced under road lighting. The overall luminance of the face and the luminance contrast of facial features may be both decreased. If the pedestrian wears a pair of glasses or put the hands in front of the face, facial details may be obscured as well (Gros and Straub, 2019; Drira *et al.,* 3013). Further studies are needed to address these limitations and thus to consider the effect of lighting changes on FER.

As mentioned above, the face models used in the current work were not designed or validated for the intention of being used in research which raises two questions. First, were the results obtained from the current work valid and repeatable? Table 8.3 listed the recognition performance from different studies. Ebner *et al.* (2010) established the FACES database, which contains photos of actors portraying various expressions. The correct recognition rate was in the range of 0.68 to 0.96 in their experiments, which were conducted under "good" lighting condition and with unlimited observation duration. Yang and Fotios (2015) then used a sample of the FACES photographs to carry out an experiment to investigate the effect of changes in luminance and S/P ratio on FER performance. Table 8.3 demonstrates the proportion of correct recognition for the trials with a luminance of 0.33 cd/m$^2$ on the face and averaged across the types of light sources used. Comparing the results with Ebner *et al.* (2010) (0.68 to 0.96), the recognition rate was nearly the same for trials simulating a distance of 4 m (0.65 to 0.96) but dropped dramatically in the trials simulating a 15 m distance (0.12 to 0.60). A viewing distance of about 10 m was simulated in the current work. The recognition rate was in the range of 0.63 to 0.83, which is between the rates found in previous work for evaluations simulating 4 m and 15 m.

**Table 8.3.** Proportion of correct identification of unique facial expressions as reported by Ebner *et al.* (2010) and Yang and Fotios (2015).

| **Expression** | **Proportion of correct recognition** | | | | |
|---|---|---|---|---|---|
| | Ebner *et al.*, 2010 | Yang and Fotios, 2015 4 m | Yang and Fotios, 2015 15 m | Current work Exp 2 10 m | Current work Exp 3 10 m |
| Happiness | 0.96 | 0.96 | 0.58 | 0.68 | 0.74 |
| Neutral | 0.87 | 0.96 | 0.60 | 0.70 | 0.83 |
| Anger | 0.81 | 0.81 | 0.29 | 0.63 | 0.77 |
| Fear | 0.81 | 0.65 | 0.21 | - | - |
| Sadness | 0.73 | 0.77 | 0.12 | 0.68 | 0.56 |
| Disgust | 0.68 | 0.71 | 0.17 | - | - |

Note: For Yang and Fotios (2015), these are data for face luminance of 0.33 cd/m$^2$, averaged across with targets scaled to represent interpersonal distances of 4 m and 15 m. For Experiments 2 and 3, the data are averaged across all combinations of illuminance and task condition. The expressions are listed in descending order as defined by the results of Ebner *et al*. (2010).

The second question concerning the validity of the face models is the degree to which they were confused with other facial expressions. As shown in Table 8.4, the correct recognition rates of all the facial expressions presented in Experiments 2 and 3 were higher than incorrect responses. The data also suggest a response bias among the incorrect responses, the proportion of neutral expression was higher than the others. An explanation for this might because the participants tended to say "neutral" if they were unsure about what were the facial expressions presented. In further experiments, this could be possibly controlled by choice of visual targets.

**Table 8.4.** Proportions of responses given for each type of expression.

| **Response** | **Proportions of responses given** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Experiment 2** | | | | **Experiment 3** | | | |
| | Happy | Angry | Sad | Neutral | Happy | Angry | Sad | Neutral |
| Happy | 0.68 | 0.07 | 0.03 | 0.04 | 0.74 | 0.06 | 0.01 | 0.02 |
| Angry | 0.11 | 0.63 | 0.03 | 0.10 | 0.09 | 0.77 | 0.03 | 0.02 |
| Sad | 0.05 | 0.04 | 0.68 | 0.13 | 0.04 | 0.04 | 0.56 | 0.11 |
| Neutral | 0.17 | 0.24 | 0.24 | 0.70 | 0.12 | 0.11 | 0.37 | 0.83 |

Note: columns do not add to 100% due to misses – no response given after the onset of the target

Some facial expressions might lead to misunderstandings such as anger, fear and surprise in the pilot study, and anger, sad and neutral in Experiment 2 and 3. A question may be raised, is the ability to identify the more subtle differences between facial expressions related to understanding the intent of others? Previous work (Willis *et al.*, 2011a; 2010b) stated that the facial emotional expressions are related to the approachability. Therefore, it is important for pedestrians to see the facial expression changes and may influence their decisions. However, there are no evidence shows more-subtle differences might also affect interpretation of intent. If it did, this would mean a need to see smaller details of the face. In order to maintain the visual performance, small target requires higher illuminance which might influence the conclusions about optimal lighting (Attwood *et al.*, 2004).

Four obstacle locations were used in the current work. Although the sequence of where the obstacle appeared was randomised in each experiment, the participants would get a familiarity with the locations after a few trials. The effect of location familiarity can be seen in the study from Boyce and Rea (1990) about intruder detection (Boyce and Rea, 1990). In their experiment 1, the intruders were asked to walk towards the observers along the centre line in the test site, where was an open area with fences to use as barriers for hiding behind. In their experiment 2, intruders were allowed to move around freely in the test site to avoid being found by the guard. The results (their table 18) show that the detection distances were longer if known the route of the intruder beforehand (e.g.: 86.8 m, HPS flood lighting) than unknown (60.4 m, HPS flood lighting). This suggests that it may be more easily for the participant to detect an obstacle if it appears in a known or expected location. More research is needed to see if this has an effect on determining the optimal lighting for pedestrians.

Only one lighting geometry was used in Experiments 2 and 3. Different lighting systems (lamp posts, catenary lighting, and bollards) lead to different geometries between the lighting and lit surfaces and therefore to different shadowing, which would influence task performance. An experiment compared the obstacle detection performance between lighting from overhead road lighting and a cycle-mounted lamp, the results suggested that the cycle lamp makes detection worse due to a reduction in obstacle-surround contrast except at low illuminance condition (0.2 lux) but the performance between different cycle lamp locations were similar (Fotios *et al.*, 2017b). Experiment 1 revealed a significant effect of relative location changes on obstacle detection rate. When the light source was directly over the obstacles, it had a higher detection rate, and when the light source was in front of the obstacle, the detection rate was lower. The differences were averaged in Experiments 2 and 3 by using light sources at both locations (LED 2 and 3) (Figure 4.7). The results gained in this research were suitable for lighting overhead the target but in future experiments, different lighting geometries could be considered as a new variable.

Eye movements are proactive, seeking out the information needed for a task in the moments before that task is carried out (Land, 2006). In Experiments 2 and 3, the participants were asked to fixate at the location where a face model may appear. It is possible that they preferred to fixate towards the obstacle field rather than the location of the face model, particularly in the trials where no face model was presented. One question might be raised: one of the independent variables was face expression. Thus, the null condition should have removed only the expression on the face while not the whole head which was the fixation target, such as present a plain cylinder in the same colour and size as the heads. A reason to explain this is the laboratory setting aims to simulate a real street environment, and a “no face” model does not exist in a real situation. However, the effect of using a plain cylinder or empty post to represent the null condition could be investigated in further work.

The current work did not take gaze behaviour into account. Fotios *et al.* (2016) used an eye-tracking device to investigate gaze behaviour during peripheral obstacle detection.

The results suggested that the participants were followed the instruction from the experimenter indeed if they were told to fixate towards a fixation mark. However, this experiment (Fotios *et al.,* 2016) only involved one single task and the target used to maintain the gaze direction was a fixation mark. In further experiments, the tendency to maintain fixation as instructed will be needed to investigate in a condition, which involves multiple tasks at two locations or when the fixation mark (here, the face model) is absent. The observation duration is another factor that may affect the gaze behaviour. Mean fixation durations are approximately between 200 ms and 500 ms (Hooge and Erkelens, 1998) but may vary based on task characteristics (Salthouse and Ellis, 1980). The observation duration increases as the difficulty of a task grow and can be as short as 120 ms (Land, 2006). The observation duration (500 ms) was fixed in the current work. Gaze behaviour may be changed if the observation durations become shorter or longer. The results of one study using a search task (Hooge and Erkelens, 1998) suggest that the fixation duration was not affected by the reductions in observation duration (from 3.0s, to 2.25 or 1.5s). Test participants are capable of very brief fixation durations but may not do so if continuous maximum performance leads to stress (Salthouse and Ellis, 1980).

In all of my experiments, only young participants were recruited. I have identified the target user as pedestrians, a vulnerable road user group, but have not considered individual variations which would influence the degree of vulnerability. The reason was due to the difficulty of performing dual tasks, hoping to gain experience and seek feedback from young participants who have better visual function. Visual function deteriorates as people getting older, including a reduction on absolute sensitivity to light, visual acuity, contrast sensitivity, colour discriminating, smaller visual fields and greater sensitivity to glare (Boyce, 2014). For obstacle detection task, Uttley *et al.* (2017) compared the obstacle detection performance between younger and older groups before. The results only suggested older participants had a poorer performance than younger participants at the lowest illuminance. However, it is still worth exploring the effect of age on performance under multi tasks condition in future experiments.

Participants were seated in all experiments. While pedestrians are, of course, standing, this does not change their vision but the geometry between their eyes and the targets. The apparatus was therefore designed to present the targets at correct relative positions and all experiment settings were converted to when viewing in 1.5 height. In future work, it would be interested to ask participants to walk because the act of walking increases cognitive load and then may reduce task performance. One disadvantage of walking however is that it is not possible to maintain a fixed viewing position. Despite the fact that the terms of multi-tasking were mentioned in the current work, only two tasks were considered. The need to attend to, or expect to attend to, more than two tasks would further reduce the attention for anyone task and the expectation of the next task in a series, and in doing so, may further impair individual task performance.

Finally, my experiments and previous studies (Fotios and Cheal, 2009; Fotios and Cheal, 2013; Uttley *et al.*, 2017; Fotios *et al.*, 2015d; Yang and Fotios, 2015) were conducted in laboratory environment. The advantages of investigating an effect by doing quantitative research in a laboratory environment is the variables could be controlled precisely. The results were interpreted from statistical analysis which could define which variable has a significant effect on the results. In comparison, the disadvantages are, first, cannot include many variables in one experiment. Secondly, it cannot represent the real condition in reality although the aim to simulate a real environment. As mentioned in Chapter 1, my colleague evaluated the impact of road lighting on reassurance after dark by asking the participants to answer questionnaires (Fotios *et al.*, 2019b). Participants were walking down several real minor roads in this research. Compared with laboratory-based experiments, participants were doing the experiment in real environment. However, it cannot exclude the variables not related with the study and the results might be affected by them. For example, when investigating how the road lighting affect the reassurance of pedestrians, the results might be influenced by other factors such as weather and constructions near the road.

The research on obstacle detection and FER still need to consider many different conditions, such as in extreme weather. Current experiments only test the road surface with 0.2 reflectance. If the road surface was covered by snow, ice or leaves, the visual task performance might be affected. These conditions could be considered as potential research area.

## 8.7 Summary

This chapter compared the results of the three main experiments as well as with previous studies concerning obstacle detection and FER. Experiment 1 involved raised and lowered obstacles; detection performance did not reveal a difference between different obstacle configurations. It means the results from previous studies which only used raised obstacles are still valid. The primary purpose of Experiment 2 and 3 was to investigate whether multi-tasking affects the performance of obstacle detection and FER when they are done simultaneously. Comparing the results of these two experiments with past studies employing isolated tasks suggests that performance on the peripheral detection task has been impaired but performance on the foveal FER task has not. Although there was an impairment in obstacle detection, the optimal illuminance is still suggested to be 1.0 lux as shown in previous studies. For FER, 0.53 cd/m$^2$ was suggested to be the optimal luminance when observing at approximately 10 m distance which is a slightly lower luminance than reported previously. It might be due to light level selection in the experiment design phase. Though the SPD was not the same as used in previous studies, it was suggested not affected the FER significantly.

Although these experiments were an advance on previous studies, by the use of different obstacle configurations, luminaire positions and 3D face models, there were some limitations that need to be considered and could be addressed in future experiments. For instance, although Experiment 1 used different luminaire positions to create spatial variation, Experiment 2 and 3 only used a fixed lighting direction. Future studies could consider the effect of spatial variation on the performance of the two tasks. Secondly, participants may become too familiar with the obstacle locations after several trials. Whether this familiarity affects the results is required to determine. Also, 3D face models used in Experiment 2 and 3 were all Caucasian male faces. Future experiments may consider using different ethnicities and balance the gender. Additionally, current results might be influenced if the models wear hats or other head coverings. Although Experiment 3 included some target heads not facing directly toward the observer, but the sample size was too small to analyse. Current experiments only involved two tasks, but a pedestrian in a real setting may expect to perform more tasks simultaneously. Finally, the effect of a glare source on task performance could also be investigated.

# CHAPTER 9. CONCLUSION

Road lighting should improve walking safety for pedestrians at the same time as minimising negative impacts such as unnecessary energy consumption, glare and light pollution. While intending to deliver this optimum, current lighting standards make little use of empirical evidence from studies with pedestrians (Fotios and Gibbons, 2018; Fotios, 2020). A review of eye-tracking studies (Fotios *et al.*, 2015a; Fotios *et al.*, 2015b) indicates that obstacle detection and evaluation of the intentions of approaching people are two key visual tasks for pedestrians. Facial emotion recognition (FER) is one of the methods for conducting this evaluation. This work investigated how lighting changes affect the ability of pedestrians to perform obstacle detection and FER tasks after dark.

The first aim was to test can three-dimensional face models replace photographs in FER experiments. The second aim was to compare the obstacle detection performance between raised obstacle and lowered obstacle. The third aim is to investigate if there is an effect when performing obstacle detection and FER at the same time, thus validating previous studies which have considered each task in isolation. This chapter begins with a summary of the experiments carried out in my research and defining optimal illuminance and luminance for obstacle detection and FER by comparing the results with previous studies. At last, the limitations of my research are discussed, and I propose some advice for future research on road lighting for pedestrians.

In Chapter 2, a review of previous studies concerning obstacle detection and FER pointed out some limitations for these studies. One shared limitation is either obstacle detection or FER experiments was done separately. When performing multi-tasking, the performance for both tasks or for one task might be impaired. Besides, for FER, previous studies used photographs displayed on a screen rather than realistic 3D faces. Compared with photographs, 3D models can display patterns of luminance contrast and shadow when the lighting condition or the relative position between luminaire and target is changed. For obstacle detection, two further uncertainties not included in earlier experiments were obstacle configuration and the location relative to the luminaire. Therefore, this thesis addresses these limitations, which are listed in Section 2.6.

Two pilot studies were carried out to test whether 3D face models could replace photographs for FER experiments. Comparing the results with previous works (Dong *et al.*, 2015; Yang and Fotios, 2015; Ebner *et al.*, 2010), it is suggested that the 3D printed models could be used in future FER experiments. However, since the 3D printed models had relatively poor resolution (Figure 3.12), they were replaced by cast reproductions of hand-carved models in three main experiments.

Experiment 1 was conducted to further investigate the effect of lighting changes on obstacle detection performance. This experiment mainly explored the difference between detecting raised obstacles and lowered obstacles and when the relative position of luminaire and obstacle was changed. Four independent variables were used: LED position (3 levels), obstacle position (4 levels), obstacle size (5 levels) and obstacle configuration (2 levels). The dependent variable was the detection rate. The results did not suggest that the detection performance differed significantly, which means the conclusions from previous studies only using raised obstacles are still valid. Experiment 1 used three luminaire positions and four obstacle locations to create spatial variation. The results suggested that there was a significant effect of luminaire position and obstacle location on the detection rate. The overhead lamp provided the best detection rate while the worst performance resulted from the light source in front of the obstacle.

Experiment 2 used 3D cast face models to investigate whether obstacle detection and FER were affected by lighting changes or dual tasking. Five independent variables were used: illuminance (2 levels), obstacle location (4 levels), obstacle size (5 levels), task condition (2 levels) and emotion type (4 levels). Two dependent variables were obstacle detection rate and FER rate. The results suggested that for obstacle detection, task condition, obstacle location and obstacle size influenced the detection rate significantly. For FER, the only significant effect was found to be illuminance. However, there were only two illuminances used in Experiment 2: 1.0 and 10.0 lux. Performance for obstacle detection already reached the plateau at 1.0 lux while FER still did not appear to reach a ceiling at 10.0 lux. Therefore, a wider range of illuminances was added in Experiment 3 to further explore the relationship between light level and performance.

Experiment 3 was developed from Experiment 2 that continued to investigate the effect of lighting changes and task condition on obstacle detection and FER. Five independent variables were used: illuminance (5 levels), obstacle location (3 levels), obstacle size (5 levels), task condition (2 levels) and emotion type (4 levels). Two dependent variables were obstacle detection rate and FER rate. The main difference with Experiment 2 was the addition of three light levels to better characterise the relationship between the amount of light and the performance of the two tasks. Also, the number of obstacle locations and face models were both reduced. The results suggest that illuminance, obstacle size and task condition have a significant effect on obstacle detection performance, while luminance, task condition and emotion types affect FER significantly. Comparing the performance under each light level suggested that the obstacle detection and FER performance both increased as illuminance became higher and reached the plateau at 1.0 lux and 0.53 cd/m$^{2,}$ respectively. When performing two tasks at the same time, there was a reduction in the performance of both tasks.

From the results of the current work and previous studies, a horizontal illuminance of 1.0 lux is still suggested to be the optimal illuminance for obstacle detection after dark, even when performing FER at the same time. For FER, a luminance of 0.53 cd/m$^2$ measured on the face is proposed to be the optimal luminance when observing at a distance of 9.2 m. This slightly lower than the luminance of 1.0 cd/m$^2$ suggested by previous work. The reason might be because the light levels used in Experiment 3 were different and did not include 1.0 cd/m$^2$.

However, there are some limitations in the current work that could be considered in future research. The results from Experiment 1 suggested that the relative position between luminaire and obstacle has a significant effect on obstacle detection performance: this was not included as a variable in Experiments 2 and 3 following a need to reduce the number of test conditions examined. In real road situation, the relative position between lamp and pedestrians were always changed with their movement. This leads to a variation of a shadow from an obstacle or approaching people and results in contrast change which might affect obstacle detection and FER performance. Experiment 1 investigated the spatial variation for obstacle detection and the results have not been validated. Therefore, future experiments could consider the effect of spatial variation on obstacle detection and FER by using multiple obstacles and luminaire positions.

In this research, multi-tasking condition only involved two tasks: obstacle detection and FER. In a real street environment, pedestrians are possibly required to conduct multiple tasks simultaneously, not just two tasks. Attention might be diverted to other activities and impair obstacle detection and FER, such as using a mobile phone, chatting with friends and listening to music. More distractors could be added in the future study to further investigate the effect when performing multi tasks.

Pedestrians may be exposed to glare from road lighting, vehicle lighting, illuminated signs, security lighting and building lighting. Previous studies suggested that peripheral vision after dark might be impaired due to glare (Aksahi and Rea, 2001; Theeuwe *et* *al.*, 2002) though they were mainly focused on drivers. In future experiments, glare source could be added as a new variable to test if there is an impairment on both off-axis and on-axis tasks for pedestrians and a reduction on the optimal illuminance and luminance proposed for obstacle detection and FER.

Additionally, for obstacle detection, although four different obstacle locations were randomised to appear during the experiment, participants may get familiar after some trials. Further study could explore if this has an effect on performance. For FER, the face models used in Experiment 2 and 3 were all male Caucasian faces. Further work may consider improving the diversity of face models, such as using various ethnicities, genders and ages. Besides, rotated faces could be involved in experiments not only looking straight forward toward the observer and under different luminaire positions.

There are two main theoretical contributions and three methodological contributions in this research. For the theoretical contributions, firstly, the obstacle detection performance is not affected by obstacle configurations (raised or lowered). Secondly, there is an impairment when performing multi tasks compared with single task. For the methodological contributions, firstly, the occlusion glasses were tested and could be used in future experiments to control the observation duration. Secondly, 3D face models were validated and can replace photographs in future FER studies. Thirdly, the results in current research did not suggest a significant difference between raised and lowered obstacle. In the future experiments, this variable could be excluded and use only one configuration.

The design methodology was also tested in the current work and could be continuously used in the future. This research was developed from previous studies. Some variables like S/P ratios and participants ages were excluded in current research. One reason is they do not have effect or only has effect under very low light level. Another is due to test duration and the consideration of variable control. In my research, the results suggested that the obstacle configurations do not have significant effect on detection performance. Thus, in the future experiments, this could be excluded to add more variables such as glare and different age groups.

As mentioned before, sustainable development is the concept promoted by the UN and many countries over the world. By comparing the results of current research and previous studies, the illuminance of 1.0 lux and luminance of 0.53 cd/m$^2$ was proposed as optimal light level for obstacle detection and FER tasks. CIE 236:2019 (CIE, 2019) concluded from the then-available data that horizontal illuminances of 1.0 lux (minimum) and 4 lux (mean) are sufficient for obstacle detection and reassurance respectively. In this case, P4 (mean illuminance 5.0 lux, minimum illuminance 1.0 lux) would therefore be sufficient for the suggested needs of obstacle detection and reassurance, and the needs of interpersonal evaluation (CIE 115:2010). This could provide guidelines to the urban planner and lighting designers when designing minor roads or planning cities, meeting the requirements of road users, reduce energy consumption and minimising the impact on nature. However, this is suggested by current research and previous studies, tested in an ideal and laboratory environment. In reality, the condition would be more complex and have to consider more factors, different road users and even the impact on natural environment.

# APPENDIX A. NORMALITY CHECK

**Table A.1.** Normality profile for Experiment 1.

| | | Fixation target identification | Left vs right obstacle location | | LED position | | | Raised vs lowered | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Obstacle 2 | Obstacle 3 | 1 | 2 | 3 | Raised | Lowered |
| **Central Tendency** | Mean | 0.978 | 0.679 | 0.713 | 0.660 | 0.685 | 0.520 | 0.616 | 0.602 |
| | 95% CI of mean* | 0.972-0.984 | 0.622-0.736 | 0.658-0.768 | 0.614-0.706 | 0.640-0.730 | 0.470-0.570 | 0.568-0.664 | 0.565-0.639 |
| | Median | 0.980 | 0.680 | 0.750 | 0.675 | 0.675 | 0.500 | 0.600 | 0.620 |
| Normality? | Yes if median is in 95% CI of mean | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Graphical** (Symmetric? Yes/ No) | Histogram | Yes | No | No | Yes | Yes | No | Yes | Yes |
| | Box Plot | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| | Normal Q-Q Plot | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Normality? | | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Measures of dispersion** | Z-score of skewness** | -1.535 | -0.027 | -0.553 | -0.568 | -1.953 | 0.076 | 0.189 | -0.277 |
| | Z-score of kurtosis *** | -0.215 | -1.545 | -1.250 | -0.856 | -0.525 | -0.847 | -1.129 | -1.381 |
| Normality? | (within ±2) | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Statistical tests** | Sample size | 20 | | | | | | | |
| Shappiro-Wilks | Level of significance | 0.062 | 0.092 | 0.137 | 0.339 | 0.894 | 0.733 | 0.412 | 0.079 |
| Normality? | (not normal if p<0.05) | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Overall assessment of normality** | | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |

Note: *CI=Confidence Interval

** Z-score of skewness = Statistic/ standard error, both values provided by SPSS

*** Z-score of kurtosis = Statistic/ standard error, both values provided by SPSS

| | | Obstacle position | | | Obstacle size (mm) | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Obstacle 1 (back) | Obstacle 2&3 (mid) | Obstacle 4 (front) | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| **Central Tendency** | Mean | 0.373 | 0.531 | 0.431 | 0.246 | 0.454 | 0.660 | 0.833 | 0.915 |
| | 95% CI of mean* | 0.321-0.424 | 0.491-0.570 | 0.375-0.488 | 0.177-0.315 | 0.393-0.515 | 0.601-0.720 | 0.788-0.879 | 0.887-0.943 |
| | Median | 0.375 | 0.531 | 0.450 | 0.167 | 0.458 | 0.667 | 0.833 | 0.917 |
| Normality? | Yes if median is in 95% CI of mean | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |
| **Graphical** (Symmetric? Yes/ No) | Histogram | Yes | Yes | Yes | No | Yes | Yes | Yes | No |
| | Box Plot | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |
| | Normal Q-Q Plot | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Normality? | | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |
| **Measures of dispersion** | Z-score of skewness** | 0.229 | -0.408 | -1.602 | 1.416 | 1.854 | -0.224 | -1.018 | -1.445 |
| | Z-score of kurtosis*** | -0.806 | -0.496 | 0.799 | -0.988 | 2.627 | 0.116 | 0.739 | 0.089 |
| Normality? | (within ±2) | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes |
| **Statistical tests** | Sample size | 20 | | | | | | | |
| Shappiro-Wilks | Level of significance | 0.662 | 0.831 | 0.419 | 0.007 | 0.068 | 0.402 | 0.078 | 0.051 |
| Normality? | (not normal if p<0.05) | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |
| **Overall assessment of normality** | | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |

Note: *CI=Confidence Interval
** Z-score of skewness = Statistic/ standard error, both values provided by SPSS
*** Z-score of kurtosis = Statistic/ standard error, both values provided by SPSS

**Table A.2.** Normality profile for Experiment 2: obstacle detection analysis only.

| | | Illuminance | | Obstacle location | | | |
|---|---|---|---|---|---|---|---|
| | | 1.0 lux | 10.0 lux | 1 | 2 | 3 | 4 |
| **Central Tendency** | Mean | 0.570 | 0.592 | 0.698 | 0.673 | 0.655 | 0.595 |
| | 95% CI of mean* | 0.495-0.645 | 0.524-0.659 | 0.651-0.746 | 0.610-0.736 | 0.607-0.723 | 0.532-0.658 |
| | Median | 0.550 | 0.575 | 0.700 | 0.675 | 0.675 | 0.600 |
| Normality? | Yes if median is in 95% CI of mean | Yes | Yes | Yes | Yes | Yes | Yes |
| **Graphical** (Symmetric? Yes/ No) | Histogram | No | Yes | No | Yes | Yes | Yes |
| | Box Plot | Yes | Yes | Yes | Yes | Yes | Yes |
| | Normal Q-Q Plot | Yes | Yes | Yes | Yes | Yes | Yes |
| Normality? | | Yes | Yes | Yes | Yes | Yes | Yes |
| **Measures of dispersion** | Z-score of skewness** | -0.370 | -0.230 | 0.609 | 1.040 | -1.679 | -0.614 |
| | Z-score of kurtosis*** | -1.130 | -0.439 | -1.051 | -0.786 | 1.020 | -0.641 |
| Normality? | (within ±2) | Yes | Yes | Yes | Yes | Yes | Yes |
| **Statistical tests** | Sample size | 30 | | | | | |
| Shappiro-Wilks | Level of significance | 0.172 | 0.569 | 0.133 | 0.128 | 0.237 | 0.503 |
| Normality? | (not normal if p<0.05) | Yes | Yes | Yes | Yes | Yes | Yes |
| **Overall assessment of normality** | | Yes | Yes | Yes | Yes | Yes | Yes |

Note: *CI=Confidence Interval

** Z-score of skewness = Statistic/ standard error, both values provided by SPSS

*** Z-score of kurtosis = Statistic/ standard error, both values provided by SPSS

| | | Task condition | | Obstacle size (mm) | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Single | Dual | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| **Central Tendency** | Mean | 0.735 | 0.581 | 0.288 | 0.522 | 0.758 | 0.839 | 0.896 |
| | 95% CI of mean* | 0.689-0.781 | 0.515-0.647 | 0.224-0.351 | 0.446-0.598 | 0.699-0.817 | 0.797-0.880 | 0.858-0.934 |
| | Median | 0.769 | 0.588 | 0.250 | 0.547 | 0.766 | 0.844 | 0.922 |
| Normality? | Yes if median is in 95% CI of mean | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Graphical** (Symmetric? Yes/ No) | Histogram | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| | Box Plot | Yes | Yes | Yes | Yes | Yes | Yes | No |
| | Normal Q-Q Plot | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Normality? | | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Measures of dispersion** | Z-score of skewness** | -1.073 | -0.211 | 0.623 | -0.368 | -0.843 | -0.415 | -1.133 |
| | Z-score of kurtosis*** | -0.984 | -0.834 | -1.269 | -0.885 | -0.627 | -1.430 | -1.565 |
| Normality? | (within ±2) | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Statistical tests** | Sample size | 30 | | | | | | |
| Shappiro-Wilks | Level of significance | 0.082 | 0.423 | 0.178 | 0.295 | 0.567 | 0.089 | 0.002 |
| Normality? | (not normal if p<0.05) | Yes | Yes | Yes | Yes | Yes | Yes | No |
| **Overall assessment of normality** | | Yes | Yes | Yes | Yes | Yes | Yes | Yes |

Note: *CI=Confidence Interval
** Z-score of skewness = Statistic/ standard error, both values provided by SPSS
*** Z-score of kurtosis = Statistic/ standard error, both values provided by SPSS

**Table A.3.** Normality profile for Experiment 2: FER analysis only.

| | | Emotion | | | |
|---|---|---|---|---|---|
| | | Happiness | Anger | Sadness | Neutral |
| **Central Tendency** | Mean | 0.667 | 0.631 | 0.696 | 0.717 |
| | 95% CI of mean* | 0.619-0.716 | 0.562-0.700 | 0.601-0.790 | 0.673-0.761 |
| | Median | 0.667 | 0.625 | 0.750 | 0.686 |
| Normality? | Yes if median is in 95% CI of mean | Yes | Yes | Yes | Yes |
| **Graphical** (Symmetric? Yes/ No) | Histogram | Yes | Yes | No | Yes |
| | Box Plot | Yes | Yes | Yes | Yes |
| | Normal Q-Q Plot | Yes | Yes | Yes | Yes |
| Normality? | | Yes | Yes | Yes | Yes |
| **Measures of dispersion** | Z-score of skewness** | -1.429 | -0.775 | -2.889 | -0.180 |
| | Z-score of kurtosis*** | 1.098 | -0.413 | 1.307 | -1.269 |
| Normality? | (within ±2) | Yes | Yes | No | Yes |
| **Statistical tests** | Sample size | 30 | | | |
| Shappiro-Wilks | Level of significance | 0.446 | 0.713 | 0.002 | 0.079 |
| Normality? | (not normal if p<0.05) | Yes | Yes | No | Yes |
| **Overall assessment of normality** | | Yes | Yes | No | Yes |

Note: *CI=Confidence Interval
** Z-score of skewness = Statistic/ standard error, both values provided by SPSS
*** Z-score of kurtosis = Statistic/ standard error, both values provided by SPSS

| | | Task condition | | Illuminance | |
|---|---|---|---|---|---|
| | | Single | Dual | 1.0 lux | 10.0 lux |
| **Central Tendency** | Mean | 0.690 | 0.667 | 0.612 | 0.743 |
| | 95% CI of mean* | 0.649-0.730 | 0.622-0.710 | 0.578-0.647 | 0.693-0.794 |
| | Median | 0.698 | 0.694 | 0.611 | 0.768 |
| Normality? | Yes if median is in 95% CI of mean | Yes | Yes | Yes | Yes |
| **Graphical** | Histogram | Yes | Yes | Yes | Yes |
| (Symmetric? | Box Plot | Yes | Yes | Yes | Yes |
| Yes/ No) | Normal Q-Q Plot | Yes | Yes | Yes | Yes |
| Normality? | | Yes | Yes | Yes | Yes |
| **Measures of** | Z-score of skewness** | -0.459 | -2.035 | -1.145 | -1.459 |
| **dispersion** | Z-score of kurtosis*** | 0.118 | 0.611 | 0.026 | -0.241 |
| Normality? | (within ±2) | Yes | No | Yes | Yes |
| **Statistical tests** | Sample size | 30 | | | |
| Shappiro-Wilks | Level of significance | 0.696 | 0.079 | 0.239 | 0.262 |
| Normality? | (not normal if p<0.05) | Yes | Yes | Yes | Yes |
| **Overall assessment of normality** | | Yes | Yes | Yes | Yes |

Note: *CI=Confidence Interval
** Z-score of skewness = Statistic/ standard error, both values provided by SPSS
*** Z-score of kurtosis = Statistic/ standard error, both values provided by SPSS

**Table A.4.** Normality profile for Experiment 3: obstacle detection analysis only.

| | | Illuminance (lux) | | | | | Obstacle position | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 0.3 | 1.0 | 3.3 | 10.0 | 33.3 | 1 | 2 | 3 |
| **Central Tendency** | Mean | 0.664 | 0.730 | 0.766 | 0.784 | 0.746 | 0.758 | 0.757 | 0.740 |
| | 95% CI of mean* | 0.611-0.718 | 0.670-0.790 | 0.713-0.819 | 0.731-0.836 | 0.699-0.794 | 0.714-0.802 | 0.708-0.805 | 0.690-0.789 |
| | Median | 0.696 | 0.771 | 0.800 | 0.813 | 0.779 | 0.782 | 0.780 | 0.740 |
| Normality? | Yes if median is in 95% CI of mean | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Graphical** (Symmetric? Yes/ No) | Histogram | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| | Box Plot | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| | Normal Q-Q Plot | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Normality? | | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Measures of dispersion** | Z-score of skewness** | 0.108 | -1.150 | -1.834 | -0.752 | -0.625 | -0.899 | -0.740 | -0.546 |
| | Z-score of kurtosis*** | -1.433 | -0.516 | 0.154 | -1.260 | -0.972 | 0.011 | -1.270 | -0.492 |
| Normality? | (within ±2) | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Statistical tests** | Sample size | | | | | | | | |
| Shappiro-Wilks | Level of significance | 0.109 | 0.224 | 0.044 | 0.079 | 0.277 | 0.700 | 0.175 | 0.901 |
| Normality? | (not normal if p<0.05) | Yes | Yes | No | Yes | Yes | Yes | Yes | Yes |
| **Overall assessment of normality** | | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |

Note: *CI=Confidence Interval

** Z-score of skewness = Statistic/ standard error, both values provided by SPSS

*** Z-score of kurtosis = Statistic/ standard error, both values provided by SPSS

|  |  | Task condition |  | Obstacle size (mm) |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
|  |  | Single | Dual | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| **Central Tendency** | Mean | 0.771 | 0.705 | 0.336 | 0.649 | 0.870 | 0.946 | 0.957 |
|  | 95% CI of mean* | 0.730-0.811 | 0.644-0.766 | 0.254-0.418 | 0.565-0.732 | 0.824-0.915 | 0.924-0.968 | 0.940-0.0.974 |
|  | Median | 0.790 | 0.727 | 0.328 | 0.706 | 0.906 | 0.967 | 0.967 |
| Normality? | Yes if median is in 95% CI of mean | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Graphical** (Symmetric? Yes/ No) | Histogram | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
|  | Box Plot | Yes | Yes | Yes | Yes | Yes | No | No |
|  | Normal Q-Q Plot | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Normality? |  | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Measures of dispersion** | Z-score of skewness** | -1.459 | -1.965 | 0.869 | -0.670 | -2.768 | -1.998 | -3.622 |
|  | Z-score of kurtosis*** | 0.300 | 0.832 | -0.758 | -1.447 | 0.996 | -0.520 | 3.341 |
| Normality? | (within ±2) | Yes | Yes | Yes | Yes | No | Yes | No |
| **Statistical tests** | Sample size | 30 |  |  |  |  |  |  |
| Shappiro-Wilks | Level of significance | 0.288 | 0.138 | 0.305 | 0.059 | 0.003 | 0.001 | 0.001 |
| Normality? | (not normal if p<0.05) | Yes | Yes | Yes | Yes | No | No | No |
| **Overall assessment of normality** |  | Yes | Yes | Yes | Yes | Yes | Yes | Yes |

Note: *CI=Confidence Interval

** Z-score of skewness = Statistic/ standard error, both values provided by SPSS

*** Z-score of kurtosis = Statistic/ standard error, both values provided by SPSS

**Table A.5.** Normality profile for Experiment 3: FER analysis only.

| | | Emotion | | | |
|---|---|---|---|---|---|
| | | Happiness | Anger | Sadness | Neutral |
| **Central Tendency** | Mean | 0.746 | 0.778 | 0.563 | 0.831 |
| | 95% CI of mean* | 0.710-0.783 | 0.740-0.816 | 0.494-0.631 | 0.797-0.866 |
| | Median | 0.763 | 0.783 | 0.575 | 0.833 |
| Normality? | Yes if median is in 95% CI of mean | Yes | Yes | Yes | Yes |
| **Graphical** (Symmetric? Yes/ No) | Histogram | Yes | Yes | No | Yes |
| | Box Plot | Yes | Yes | Yes | Yes |
| | Normal Q-Q Plot | Yes | Yes | Yes | Yes |
| Normality? | | Yes | Yes | Yes | Yes |
| **Measures of dispersion** | Z-score of skewness** | -1.988 | -0.698 | -0.595 | -1.058 |
| | Z-score of kurtosis*** | 0.583 | -0.187 | -0.570 | -0.564 |
| Normality? | (within ±2) | Yes | Yes | No | Yes |
| **Statistical tests** Shappiro-Wilks | Sample size | 30 | | | |
| | Level of significance | 0.051 | 0.319 | 0.531 | 0.166 |
| Normality? | (not normal if p<0.05) | Yes | Yes | No | Yes |
| **Overall assessment of normality** | | Yes | Yes | Yes | Yes |

Note: *CI=Confidence Interval

** Z-score of skewness = Statistic/ standard error, both values provided by SPSS

*** Z-score of kurtosis = Statistic/ standard error, both values provided by SPSS

|  |  | Task condition |  | Illuminance (lux) |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
|  |  | Single | Dual | 0.3 | 1.0 | 3.3 | 10.0 | 33.3 |
| **Central Tendency** | Mean | 0.706 | 0.753 | 0.543 | 0.686 | 0.781 | 0.806 | 0.833 |
|  | 95% CI of mean* | 0.672-0.740 | 0.719-0.787 | 0.498-0.586 | 0.641-0.731 | 0.737-0.824 | 0.762-0.851 | 0.793-0.872 |
|  | Median | 0.692 | 0.738 | 0.536 | 0.688 | 0.766 | 0.807 | 0.844 |
| Normality? | Yes if median is in 95% CI of mean | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Graphical** (Symmetric? Yes/ No) | Histogram | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
|  | Box Plot | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
|  | Normal Q-Q Plot | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Normality? |  | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Measures of dispersion** | Z-score of skewness** | 0.286 | 1.007 | 0.726 | -0.276 | -1.101 | -0.169 | -0.796 |
|  | Z-score of kurtosis*** | -0.968 | -0.495 | 0.239 | -1.390 | 0.625 | -1.260 | -1.323 |
| Normality? | (within ±2) | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Statistical tests** | Sample size | 30 |  |  |  |  |  |  |
| Shappiro-Wilks | Level of significance | 0.538 | 0.421 | 0.981 | 0.143 | 0.238 | 0.205 | 0.053 |
| Normality? | (not normal if p<0.05) | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Overall assessment of normality** |  | Yes | Yes | Yes | Yes | Yes | Yes | Yes |

Note: *CI=Confidence Interval

** Z-score of skewness = Statistic/ standard error, both values provided by SPSS

*** Z-score of kurtosis = Statistic/ standard error, both values provided by SPSS

# APPENDIX B. EXPERIMENT 1 RAW DATA

LED position: LED1, LED2 and LED3

Obstacle position: Obstacle 1, 2, 3 and 4

Obstacle size: 4.0, 6.3, 10.0, 15.9 and 25.1 mm

Obstacle configuration: Raised and lowered

For the number listed in below Tables, as each combination appeared once in the test for each participant, 1 = right response; 0 = wrong response

**Table B.1.** Obstacle detection raw results of Obstacle 1 under LED1 in Experiment 1.

| Participant number | Obstacle 1 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Raised | | | | | Lowered | | | | |
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 2 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 1 |
| 3 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 4 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 5 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 |
| 6 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 7 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 8 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| 9 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 |
| 10 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| 11 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 12 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 13 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 1 |
| 14 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 15 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| 16 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 17 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 18 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 19 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 20 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 1 |

**Table B.2.** Obstacle detection raw results of Obstacle 2 under LED1 in Experiment 1.

| Participant number | Obstacle 2 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Raised | | | | | Lowered | | | | |
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 2 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 3 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 |
| 4 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 |
| 5 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 6 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 7 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 8 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 9 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |
| 10 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 11 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 12 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 13 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 14 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 15 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 |
| 16 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 17 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 |
| 18 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 |
| 19 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 20 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |

**Table B.3.** Obstacle detection raw results of Obstacle 3 under LED1 in Experiment 1.

| Participant number | Obstacle 3 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Raised | | | | | Lowered | | | | |
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 3 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 |
| 4 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 |
| 5 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 6 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |
| 7 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 8 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 9 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 10 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 11 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 12 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 13 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 |
| 14 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 15 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 |
| 16 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 |
| 17 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 18 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 1 |
| 19 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 20 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |

**Table B.4.** Obstacle detection raw results of Obstacle 4 under LED1 in Experiment 1.

| Participant number | Obstacle 4 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Raised | | | | | Lowered | | | | |
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 2 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 3 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 4 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 |
| 5 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 6 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 7 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 8 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 9 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 |
| 10 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 |
| 11 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 12 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| 13 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 |
| 14 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 15 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 16 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 17 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| 18 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 19 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 |
| 20 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 |

**Table B.5.** Obstacle detection raw results of Obstacle 1 under LED2 in Experiment 1.

| Participant number | Obstacle 1 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Raised | | | | | Lowered | | | | |
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 2 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 3 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 4 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 5 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 |
| 6 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 |
| 7 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 9 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 10 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| 11 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 12 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 |
| 13 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 14 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 15 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 |
| 16 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 17 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 |
| 18 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 19 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 |
| 20 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |

**Table B.6.** Obstacle detection raw results of Obstacle 2 under LED2 in Experiment 1.

| Participant number | Obstacle 2 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Raised | | | | | Lowered | | | | |
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 3 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 4 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 |
| 5 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 6 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 7 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 8 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 9 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 10 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 11 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 12 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 13 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 14 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 15 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 16 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 17 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 18 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 1 |
| 19 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 20 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |

**Table B.7.** Obstacle detection raw results of Obstacle 3 under LED2 in Experiment 1.

| Participant number | Obstacle 3 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Raised | | | | | Lowered | | | | |
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 3 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 4 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 6 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 7 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 8 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 9 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 |
| 10 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 11 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 12 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 13 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 |
| 14 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 15 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 16 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 17 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 18 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 0 |
| 19 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 |
| 20 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |

**Table B.8.** Obstacle detection raw results of Obstacle 4 under LED2 in Experiment 1.

| Participant number | Obstacle 4 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Raised | | | | | Lowered | | | | |
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 2 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 |
| 3 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 |
| 4 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 5 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 6 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 7 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 8 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 9 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 10 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 11 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 |
| 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 13 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 |
| 14 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 17 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 |
| 18 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 |
| 19 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 20 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

**Table B.9.** Obstacle detection raw results of Obstacle 1 under LED3 in Experiment 1.

| Participant number | Obstacle 1 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Raised | | | | | Lowered | | | | |
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 3 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |
| 4 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| 6 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 |
| 11 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 12 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 |
| 13 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| 14 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 |
| 15 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 |
| 16 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 17 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 18 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| 19 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

**Table B.10.** Obstacle detection raw results of Obstacle 2 under LED3 in Experiment 1.

| Participant number | Obstacle 2 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Raised | | | | | Lowered | | | | |
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 |
| 3 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 |
| 4 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 5 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 6 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 7 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 |
| 8 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 9 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 10 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 11 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 12 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 13 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 14 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 15 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 |
| 16 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 17 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 18 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 |
| 19 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 |
| 20 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 |

**Table B.11.** Obstacle detection raw results of Obstacle 3 under LED3 in Experiment 1.

| Participant number | Obstacle 3 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Raised | | | | | Lowered | | | | |
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 2 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 3 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 4 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 1 |
| 5 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 7 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 |
| 8 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 9 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 10 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 11 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 |
| 12 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 13 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 14 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 |
| 15 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 16 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 17 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 18 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 |
| 19 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |
| 20 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 |

**Table B.12.** Obstacle detection raw results of Obstacle 4 under LED3 in Experiment 1.

| Participant number | Obstacle 4 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Raised | | | | | Lowered | | | | |
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 2 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 3 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 4 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 5 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 6 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 7 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 8 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 9 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 10 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 11 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 1 |
| 12 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 14 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 15 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 16 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 17 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 18 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| 19 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 |
| 20 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |

# APPENDIX C. EXPERIMENT 2 RAW DATA

Illuminance: 1 lux and 10 lux

Obstacle position: Obstacle 1, 2, 3 and 4

Obstacle size: 4.0, 6.3, 10.0, 15.9 and 25.1 mm

Task condition: single and dual

Emotion: happiness, sadness, anger and neutral

Numbers from 0 to 1 listed in the Tables represent the percentage of correct responses.

**Table C.1.** Raw results of obstacle detection task of Obstacle 1 under 1 lux condition in Experiment 2.

| Participant number | Obstacle 1 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Single | | | | | Dual | | | | |
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0 | 0.5 | 1 | 1 | 1 | 0.5 | 0.5 | 1 | 1 | 1 |
| 2 | 0 | 1 | 1 | 0.5 | 1 | 1 | 1 | 1 | 0.5 | 1 |
| 3 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0.5 | 0.5 | 1 |
| 4 | 0 | 0.5 | 1 | 1 | 1 | 0.5 | 0.5 | 1 | 1 | 1 |
| 5 | 0 | 1 | 1 | 1 | 1 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| 6 | 1 | 0.5 | 1 | 0.5 | 1 | 1 | 1 | 1 | 1 | 1 |
| 7 | 0 | 0.5 | 1 | 0.5 | 1 | 0 | 0.5 | 0.5 | 1 | 1 |
| 8 | 0 | 0.5 | 1 | 1 | 1 | 0.5 | 0 | 1 | 1 | 1 |
| 9 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 10 | 0 | 0.5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0.5 |
| 11 | 0.5 | 0.5 | 0.5 | 0.5 | 1 | 0 | 0 | 0.5 | 1 | 1 |
| 12 | 0.5 | 0.5 | 1 | 1 | 1 | 0.5 | 0.5 | 0.5 | 1 | 1 |
| 13 | 0 | 1 | 1 | 1 | 1 | 0.5 | 0.5 | 0 | 1 | 1 |
| 14 | 1 | 0.5 | 0.5 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 15 | 1 | 1 | 1 | 1 | 1 | 0 | 0.5 | 0.5 | 0 | 0.5 |
| 16 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 17 | 0 | 0.5 | 1 | 1 | 1 | 0.5 | 0 | 1 | 0.5 | 1 |
| 18 | 1 | 0.5 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0.5 |
| 19 | 1 | 0.5 | 1 | 1 | 1 | 0 | 0 | 0 | 0.5 | 1 |
| 20 | 0 | 1 | 1 | 1 | 1 | 0.5 | 1 | 1 | 1 | 1 |
| 21 | 0.5 | 1 | 1 | 1 | 1 | 0 | 0 | 0.5 | 0.5 | 0.5 |
| 22 | 0 | 1 | 1 | 1 | 1 | 0.5 | 0.5 | 0 | 1 | 1 |
| 23 | 0.5 | 1 | 1 | 1 | 1 | 0 | 0.5 | 0 | 1 | 1 |
| 24 | 0 | 0 | 1 | 1 | 1 | 0 | 0.5 | 0.5 | 1 | 0.5 |
| 25 | 0.5 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0.5 | 0.5 |
| 26 | 0 | 0 | 0.5 | 0.5 | 1 | 0 | 0.5 | 1 | 1 | 1 |
| 27 | 0 | 0 | 0.5 | 0.5 | 0.5 | 0 | 0.5 | 0.5 | 0.5 | 1 |
| 28 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 29 | 0.5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 30 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0.5 | 1 |

**Table C.2.** Raw results of obstacle detection task of Obstacle 2 under 1 lux condition in Experiment 2.

| Participant number | Obstacle 2 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Single | | | | | Dual | | | | |
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| 3 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 |
| 4 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 |
| 5 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 |
| 6 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 7 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 8 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| 9 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 10 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |
| 11 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 12 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 13 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 14 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |
| 15 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 |
| 16 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 17 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 |
| 18 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 |
| 19 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 |
| 20 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 21 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| 22 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 23 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 |
| 24 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 1 |
| 25 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 26 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 27 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| 28 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 29 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| 30 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 |

**Table C.3.** Raw results of obstacle detection task of Obstacle 3 under 1 lux condition in Experiment 2.

| Participant number | Obstacle 3 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Single | | | | | Dual | | | | |
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 3 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 |
| 4 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 5 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 6 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 7 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 8 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 9 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 10 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 |
| 11 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| 12 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 |
| 13 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 14 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 |
| 15 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 |
| 16 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 17 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 18 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |
| 19 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 20 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 21 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |
| 22 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 |
| 23 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 |
| 24 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 |
| 25 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| 26 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 27 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 |
| 28 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 29 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 30 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |

**Table C.4.** Raw results of obstacle detection task of Obstacle 4 under 1 lux condition in Experiment 2.

| Participant number | Obstacle 4 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Single | | | | | Dual | | | | |
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 2 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 3 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 |
| 4 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| 6 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 7 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| 8 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 9 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 10 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 11 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| 12 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 |
| 13 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 14 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| 15 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| 16 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| 17 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 18 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| 19 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 20 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 |
| 21 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 22 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 23 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 |
| 24 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| 25 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 26 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 27 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 |
| 28 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |
| 29 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 30 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |

**Table C.5.** Raw results of obstacle detection task of Obstacle 1 under 10 lux condition in Experiment 2.

| Participant number | Obstacle 1 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Single | | | | | Dual | | | | |
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0 | 0 | 1 | 1 | 1 | 0 | 0.5 | 0.5 | 1 | 1 |
| 2 | 0 | 1 | 1 | 0.5 | 1 | 1 | 1 | 0.5 | 1 | 0.5 |
| 3 | 0 | 0 | 0.5 | 1 | 1 | 0.5 | 0.5 | 0.5 | 0.5 | 1 |
| 4 | 0.5 | 1 | 1 | 1 | 1 | 0.5 | 1 | 1 | 1 | 1 |
| 5 | 1 | 1 | 1 | 1 | 1 | 0.5 | 0 | 1 | 1 | 1 |
| 6 | 0.5 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 7 | 0 | 0 | 1 | 1 | 1 | 0.5 | 0 | 0.5 | 1 | 1 |
| 8 | 0 | 1 | 1 | 1 | 1 | 0.5 | 1 | 1 | 0.5 | 1 |
| 9 | 0 | 1 | 1 | 1 | 0.5 | 0 | 0 | 1 | 0.5 | 1 |
| 10 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0.5 | 1 | 1 |
| 11 | 0 | 1 | 1 | 1 | 1 | 0 | 0.5 | 1 | 0.5 | 0.5 |
| 12 | 0 | 0.5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 13 | 0.5 | 0.5 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0.5 |
| 14 | 0.5 | 1 | 1 | 1 | 1 | 0.5 | 0.5 | 0.5 | 1 | 1 |
| 15 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0.5 | 0.5 | 0.5 |
| 16 | 0.5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 17 | 0 | 0 | 1 | 1 | 1 | 0.5 | 0 | 1 | 0.5 | 1 |
| 18 | 0.5 | 0.5 | 1 | 1 | 1 | 0 | 0.5 | 0.5 | 0.5 | 0.5 |
| 19 | 0.5 | 0.5 | 1 | 1 | 1 | 0 | 0 | 0.5 | 0.5 | 0.5 |
| 20 | 0.5 | 1 | 1 | 1 | 1 | 1 | 0.5 | 1 | 1 | 1 |
| 21 | 0 | 0.5 | 1 | 1 | 1 | 0.5 | 0.5 | 1 | 0.5 | 0 |
| 22 | 1 | 1 | 1 | 1 | 1 | 0 | 0.5 | 1 | 1 | 1 |
| 23 | 1 | 1 | 1 | 1 | 1 | 0 | 0.5 | 0.5 | 0.5 | 1 |
| 24 | 0.5 | 0.5 | 1 | 1 | 1 | 0 | 0 | 0 | 0.5 | 1 |
| 25 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0.5 | 1 | 1 |
| 26 | 0 | 0 | 1 | 1 | 1 | 0 | 0.5 | 1 | 1 | 1 |
| 27 | 0 | 0 | 1 | 1 | 1 | 1 | 0.5 | 0.5 | 1 | 1 |
| 28 | 0 | 0.5 | 1 | 1 | 1 | 0 | 0 | 0.5 | 0.5 | 0.5 |
| 29 | 0.5 | 1 | 1 | 1 | 1 | 0 | 0.5 | 0.5 | 1 | 1 |
| 30 | 0 | 1 | 1 | 0.5 | 1 | 0.5 | 1 | 1 | 1 | 1 |

**Table C.6.** Raw results of obstacle detection task of Obstacle 2 under 10 lux condition in Experiment 2.

| Participant number | Obstacle 2 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Single | | | | | Dual | | | | |
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 3 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 4 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 5 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 6 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 7 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |
| 8 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 9 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 |
| 10 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 11 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |
| 12 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 13 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 14 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 |
| 15 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 |
| 16 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 17 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 18 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |
| 19 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| 20 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 21 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 |
| 22 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 23 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |
| 24 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 0 |
| 25 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 26 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 27 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 |
| 28 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 29 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 30 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |

**Table C.7.** Raw results of obstacle detection task of Obstacle 3 under 10 lux condition in Experiment 2.

| Participant number | Obstacle 3 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Single | | | | | Dual | | | | |
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 2 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |
| 3 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 4 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 5 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 6 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 7 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| 8 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 9 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 10 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 |
| 11 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 12 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 13 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 |
| 14 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| 15 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |
| 16 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 17 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 |
| 18 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 |
| 19 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 20 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 21 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 |
| 22 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| 23 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 |
| 24 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 25 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 |
| 26 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 27 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| 28 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 29 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 30 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |

**Table C.8.** Raw results of obstacle detection task of Obstacle 4 under 10 lux condition in Experiment 2.

| Participant number | Obstacle 4 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Single | | | | | Dual | | | | |
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| 2 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 |
| 3 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| 4 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 5 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 6 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 7 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 1 |
| 8 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 9 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 10 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 11 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| 12 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 13 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 14 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 15 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| 16 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 17 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 18 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 0 |
| 19 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 20 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 21 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| 22 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |
| 23 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 0 |
| 24 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 |
| 25 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 26 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 27 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 |
| 28 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |
| 29 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| 30 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 |

**Table C.9.** Raw results of FER task under 1 lux condition in Experiment 2.

| Participant number | Happiness | | Anger | | Sadness | | Neutral | |
|---|---|---|---|---|---|---|---|---|
| | Single | Dual | Single | Dual | Single | Dual | Single | Dual |
| 1 | 0.33 | 0.50 | 0.17 | 0.33 | 1.00 | 0.67 | 0.22 | 0.75 |
| 2 | 0.67 | 0.38 | 0.50 | 0.33 | 1.00 | 0.67 | 0.44 | 0.50 |
| 3 | 0.56 | 0.50 | 0.00 | 0.33 | 0.33 | 0.00 | 0.89 | 0.50 |
| 4 | 0.56 | 0.22 | 0.50 | 0.83 | 0.00 | 0.00 | 1.00 | 0.75 |
| 5 | 0.33 | 0.50 | 0.67 | 0.67 | 0.33 | 0.00 | 0.56 | 0.38 |
| 6 | 0.78 | 0.38 | 0.67 | 0.60 | 0.33 | 1.00 | 0.22 | 0.67 |
| 7 | 0.56 | 0.44 | 1.00 | 0.60 | 0.33 | 0.50 | 0.89 | 1.00 |
| 8 | 0.44 | 0.75 | 0.83 | 0.60 | 1.00 | 1.00 | 0.78 | 0.44 |
| 9 | 0.89 | 0.67 | 0.50 | 0.83 | 1.00 | 0.67 | 0.78 | 0.71 |
| 10 | 0.56 | 0.89 | 0.17 | 0.40 | 0.67 | 0.33 | 0.78 | 0.75 |
| 11 | 0.33 | 0.44 | 0.67 | 1.00 | 0.67 | 0.00 | 0.89 | 0.88 |
| 12 | 0.67 | 0.33 | 0.50 | 0.60 | 1.00 | 0.67 | 0.44 | 0.50 |
| 13 | 0.33 | 0.44 | 0.50 | 0.33 | 1.00 | 1.00 | 0.89 | 1.00 |
| 14 | 0.44 | 0.44 | 0.83 | 0.50 | 1.00 | 1.00 | 0.56 | 0.50 |
| 15 | 0.56 | 0.56 | 0.50 | 0.40 | 1.00 | 0.67 | 0.89 | 0.50 |
| 16 | 0.00 | 0.25 | 0.50 | 0.83 | 1.00 | 1.00 | 0.56 | 0.75 |
| 17 | 0.44 | 0.75 | 1.00 | 0.83 | 0.00 | 0.33 | 0.89 | 0.63 |
| 18 | 0.78 | 0.88 | 0.50 | 0.50 | 1.00 | 1.00 | 0.67 | 0.63 |
| 19 | 0.67 | 0.78 | 0.67 | 0.67 | 0.67 | 0.33 | 0.78 | 0.86 |
| 20 | 0.89 | 0.63 | 1.00 | 0.50 | 0.67 | 0.67 | 1.00 | 0.63 |
| 21 | 0.44 | 0.38 | 0.67 | 0.60 | 0.33 | 1.00 | 0.78 | 0.89 |
| 22 | 0.56 | 0.44 | 0.67 | 0.60 | 0.67 | 0.50 | 0.56 | 0.67 |
| 23 | 0.56 | 0.50 | 1.00 | 1.00 | 0.67 | 0.33 | 0.44 | 0.44 |
| 24 | 0.78 | 0.67 | 0.17 | 0.33 | 0.67 | 1.00 | 0.44 | 0.57 |
| 25 | 1.00 | 0.67 | 0.00 | 0.20 | 0.00 | 0.33 | 0.89 | 0.75 |
| 26 | 0.56 | 0.67 | 0.50 | 0.60 | 1.00 | 0.67 | 0.89 | 0.88 |
| 27 | 0.89 | 0.89 | 1.00 | 0.20 | 1.00 | 0.67 | 0.44 | 0.75 |
| 28 | 0.67 | 0.56 | 0.50 | 0.67 | 0.67 | 0.33 | 0.78 | 0.71 |
| 29 | 0.67 | 0.44 | 0.50 | 0.33 | 1.00 | 0.50 | 0.44 | 0.63 |
| 30 | 0.33 | 0.56 | 0.83 | 0.60 | 0.67 | 0.67 | 0.78 | 0.63 |

**Table C.10.** Raw results of FER task under 10 lux condition in Experiment 2.

| Participant number | Happiness | | Anger | | Sadness | | Neutral | |
|---|---|---|---|---|---|---|---|---|
| | Single | Dual | Single | Dual | Single | Dual | Single | Dual |
| 1 | 0.78 | 0.63 | 0.67 | 0.50 | 1.00 | 1.00 | 0.78 | 0.75 |
| 2 | 1.00 | 0.63 | 0.50 | 0.67 | 0.67 | 0.33 | 0.89 | 0.63 |
| 3 | 0.67 | 0.63 | 0.83 | 0.50 | 0.33 | 0.00 | 0.22 | 0.25 |
| 4 | 0.56 | 0.67 | 0.33 | 0.50 | 0.00 | 0.00 | 1.00 | 0.86 |
| 5 | 0.89 | 0.88 | 1.00 | 0.83 | 1.00 | 0.67 | 1.00 | 0.75 |
| 6 | 1.00 | 0.75 | 0.50 | 0.60 | 0.67 | 1.00 | 0.89 | 0.78 |
| 7 | 1.00 | 1.00 | 1.00 | 0.80 | 1.00 | 1.00 | 0.78 | 0.67 |
| 8 | 0.89 | 0.88 | 0.67 | 0.80 | 1.00 | 1.00 | 0.67 | 0.89 |
| 9 | 0.78 | 0.89 | 1.00 | 0.67 | 1.00 | 1.00 | 0.89 | 0.86 |
| 10 | 0.56 | 0.89 | 0.67 | 0.20 | 0.33 | 0.67 | 1.00 | 0.75 |
| 11 | 0.78 | 0.67 | 0.67 | 1.00 | 0.33 | 0.00 | 0.78 | 0.75 |
| 12 | 0.89 | 0.56 | 0.67 | 0.00 | 0.67 | 0.67 | 0.67 | 0.75 |
| 13 | 0.89 | 0.89 | 0.33 | 0.67 | 1.00 | 1.00 | 1.00 | 0.71 |
| 14 | 0.67 | 0.67 | 0.50 | 0.50 | 0.67 | 1.00 | 0.33 | 0.88 |
| 15 | 0.78 | 0.78 | 0.67 | 0.60 | 1.00 | 0.33 | 0.56 | 0.63 |
| 16 | 0.44 | 0.50 | 1.00 | 0.67 | 1.00 | 1.00 | 0.67 | 0.63 |
| 17 | 0.67 | 0.88 | 1.00 | 0.67 | 0.67 | 1.00 | 0.78 | 0.88 |
| 18 | 0.78 | 1.00 | 0.67 | 0.67 | 0.67 | 1.00 | 0.89 | 1.00 |
| 19 | 1.00 | 0.78 | 0.50 | 0.67 | 1.00 | 1.00 | 0.89 | 0.71 |
| 20 | 0.89 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.88 |
| 21 | 0.78 | 0.88 | 0.67 | 1.00 | 1.00 | 0.67 | 0.67 | 0.67 |
| 22 | 0.78 | 0.89 | 0.67 | 0.40 | 0.67 | 1.00 | 0.56 | 0.89 |
| 23 | 0.89 | 1.00 | 0.83 | 1.00 | 1.00 | 1.00 | 0.78 | 0.78 |
| 24 | 1.00 | 0.78 | 0.17 | 0.83 | 0.33 | 0.33 | 0.89 | 0.43 |
| 25 | 0.56 | 0.67 | 0.33 | 0.20 | 0.33 | 0.33 | 0.67 | 0.88 |
| 26 | 0.78 | 1.00 | 0.83 | 1.00 | 0.67 | 1.00 | 0.89 | 0.75 |
| 27 | 0.89 | 0.89 | 0.67 | 0.80 | 1.00 | 0.67 | 0.56 | 0.63 |
| 28 | 0.56 | 0.56 | 0.83 | 0.83 | 1.00 | 1.00 | 0.89 | 1.00 |
| 29 | 0.33 | 0.44 | 0.83 | 0.83 | 0.67 | 1.00 | 0.67 | 0.75 |
| 30 | 0.67 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 0.56 | 0.75 |

# APPENDIX D. EXPERIMENT 3 RAW DATA

Illuminance: 0.33, 1.0, 3.3, 10.0 and 33.3 lux

Obstacle position: Obstacle 1, 2 and 3

Obstacle size: 4.0, 6.3, 10.0, 15.9 and 25.1 mm

Task condition: single and dual

Emotion: happiness, sadness, anger and neutral

Values from 0.00 to 1.00 in the Tables below represent percentages of correct responses.

**Table D.1.** Raw results of obstacle detection task under 0.33 lux condition in Experiment 3.

| Participant number | Obstacle 1 | | | | | Obstacle 2 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0.00 | 0.33 | 0.67 | 0.67 | 1.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 |
| 2 | 0.33 | 0.33 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 1.00 | 0.67 | 1.00 |
| 3 | 0.00 | 0.33 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 4 | 0.00 | 0.33 | 1.00 | 1.00 | 0.67 | 0.00 | 0.50 | 0.00 | 1.00 | 0.50 |
| 5 | 0.33 | 0.33 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 0.00 | 0.00 | 1.00 |
| 6 | 0.00 | 0.33 | 0.50 | 1.00 | 0.67 | 0.00 | 0.50 | 0.50 | 1.00 | 1.00 |
| 7 | 0.67 | 0.67 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 8 | 0.67 | 0.67 | 1.00 | 1.00 | 1.00 | 0.50 | 0.50 | 0.50 | 1.00 | 1.00 |
| 9 | 0.67 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 10 | 0.00 | 0.33 | 0.67 | 0.67 | 1.00 | 0.00 | 0.50 | 0.50 | 1.00 | 0.67 |
| 11 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 0.67 |
| 12 | 0.00 | 0.33 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 |
| 13 | 0.33 | 0.67 | 1.00 | 0.67 | 0.33 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 14 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 15 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 16 | 0.00 | 0.33 | 0.67 | 0.75 | 1.00 | 0.50 | 0.50 | 0.50 | 1.00 | 1.00 |
| 17 | 1.00 | 0.67 | 1.00 | 0.67 | 1.00 | 0.50 | 0.50 | 0.50 | 1.00 | 1.00 |
| 18 | 0.00 | 0.67 | 1.00 | 0.67 | 1.00 | 0.50 | 0.50 | 1.00 | 0.50 | 1.00 |
| 19 | 0.00 | 0.00 | 0.67 | 1.00 | 1.00 | 0.00 | 0.00 | 0.50 | 1.00 | 1.00 |
| 20 | 0.33 | 0.33 | 0.67 | 1.00 | 0.67 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 |
| 21 | 0.00 | 0.67 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 0.50 | 1.00 |
| 22 | 0.00 | 0.33 | 0.67 | 1.00 | 0.67 | 0.00 | 0.00 | 0.50 | 0.00 | 1.00 |
| 23 | 0.00 | 0.00 | 0.67 | 1.00 | 1.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 |
| 24 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 1.00 | 0.50 | 0.00 |
| 25 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 26 | 0.33 | 1.00 | 1.00 | 1.00 | 0.67 | 0.50 | 0.50 | 0.50 | 1.00 | 1.00 |
| 27 | 0.00 | 0.00 | 0.67 | 1.00 | 1.00 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 28 | 1.00 | 0.67 | 1.00 | 1.00 | 1.00 | 0.50 | 0.50 | 1.00 | 1.00 | 1.00 |
| 29 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 0.50 | 1.00 | 1.00 |
| 30 | 0.00 | 0.33 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.50 | 1.00 | 1.00 |

| Participant number | Obstacle 3 | | | | |
|---|---|---|---|---|---|
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0.00 | 0.00 | 0.50 | 0.50 | 1.00 |
| 2 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 3 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 4 | 0.00 | 0.00 | 0.33 | 1.00 | 1.00 |
| 5 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 6 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 7 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 8 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 9 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 10 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 11 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 12 | 0.00 | 1.00 | 1.00 | 0.50 | 1.00 |
| 13 | 0.00 | 0.00 | 0.50 | 1.00 | 1.00 |
| 14 | 0.00 | 1.00 | 1.00 | 0.50 | 1.00 |
| 15 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 |
| 16 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 |
| 17 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 |
| 18 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 19 | 0.00 | 0.00 | 1.00 | 0.50 | 1.00 |
| 20 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 |
| 21 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 22 | 0.00 | 0.00 | 1.00 | 1.00 | 0.50 |
| 23 | 0.00 | 0.00 | 1.00 | 0.50 | 1.00 |
| 24 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 25 | 0.50 | 1.00 | 1.00 | 1.00 | 0.50 |
| 26 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 27 | 0.00 | 1.00 | 1.00 | 1.00 | 0.50 |
| 28 | 0.00 | 0.00 | 1.00 | 1.00 | 0.50 |
| 29 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 30 | 0.00 | 0.00 | 0.00 | 1.00 | 0.50 |

**Table D.2.** Raw results of obstacle detection task under 1.0 lux condition in Experiment 3.

| Participant number | Obstacle 1 | | | | | Obstacle 2 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0.25 | 0.33 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 2 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 0.50 | 1.00 | 1.00 |
| 3 | 0.00 | 0.33 | 0.67 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 4 | 0.33 | 0.67 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 |
| 5 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 6 | 0.00 | 0.00 | 0.25 | 1.00 | 1.00 | 0.00 | 0.00 | 0.50 | 1.00 | 1.00 |
| 7 | 0.00 | 0.67 | 0.75 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 8 | 0.67 | 0.67 | 1.00 | 1.00 | 1.00 | 0.50 | 0.50 | 1.00 | 1.00 | 0.50 |
| 9 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 10 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 11 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 12 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.50 | 1.00 | 0.50 |
| 13 | 0.67 | 0.67 | 1.00 | 0.67 | 0.67 | 0.50 | 0.50 | 0.00 | 1.00 | 1.00 |
| 14 | 0.33 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 15 | 0.33 | 1.00 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 16 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.50 | 1.00 | 1.00 |
| 17 | 0.67 | 1.00 | 0.67 | 0.75 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 18 | 0.33 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 19 | 0.33 | 0.67 | 1.00 | 1.00 | 1.00 | 0.50 | 0.50 | 1.00 | 0.50 | 1.00 |
| 20 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 21 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 |
| 22 | 0.00 | 0.67 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.50 | 0.50 | 1.00 |
| 23 | 0.00 | 0.00 | 0.33 | 0.67 | 1.00 | 0.00 | 0.00 | 0.50 | 0.50 | 1.00 |
| 24 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 0.50 | 1.00 | 0.00 |
| 25 | 1.00 | 1.00 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 26 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 0.50 | 0.50 | 1.00 | 1.00 |
| 27 | 0.00 | 0.33 | 1.00 | 1.00 | 0.67 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 28 | 0.33 | 0.67 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 29 | 0.33 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 30 | 0.33 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.50 | 1.00 | 1.00 |

| Participant number | Obstacle 3 | | | | |
|---|---|---|---|---|---|
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0.00 | 0.00 | 0.50 | 0.50 | 1.00 |
| 2 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 |
| 3 | 0.00 | 0.50 | 0.67 | 1.00 | 0.50 |
| 4 | 0.00 | 0.00 | 0.50 | 1.00 | 1.00 |
| 5 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 6 | 0.00 | 0.00 | 0.50 | 0.00 | 1.00 |
| 7 | 0.00 | 0.50 | 1.00 | 0.50 | 1.00 |
| 8 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 |
| 9 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 10 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 11 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 12 | 0.00 | 0.50 | 0.50 | 1.00 | 1.00 |
| 13 | 0.00 | 0.50 | 0.50 | 0.50 | 0.50 |
| 14 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 15 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 16 | 0.50 | 0.00 | 1.00 | 0.50 | 1.00 |
| 17 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 18 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 19 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 |
| 20 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 21 | 0.50 | 0.50 | 1.00 | 0.50 | 1.00 |
| 22 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 23 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 |
| 24 | 0.00 | 0.50 | 0.00 | 1.00 | 1.00 |
| 25 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 26 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 27 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 28 | 0.50 | 0.50 | 1.00 | 1.00 | 1.00 |
| 29 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 30 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 |

**Table D.3.** Raw results of obstacle detection task under 3.3 lux condition in Experiment 3.

| Participant number | Obstacle 1 | | | | | Obstacle 2 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0.50 | 0.33 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 |
| 2 | 1.00 | 0.33 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 3 | 0.33 | 0.33 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 4 | 0.00 | 0.33 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.50 | 1.00 | 0.67 |
| 5 | 0.33 | 0.67 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 6 | 0.00 | 0.00 | 0.75 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 0.67 |
| 7 | 0.33 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 8 | 0.67 | 0.67 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 9 | 0.67 | 0.33 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 10 | 0.00 | 0.67 | 1.00 | 1.00 | 1.00 | 0.00 | 0.50 | 1.00 | 0.50 | 1.00 |
| 11 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 12 | 0.33 | 0.67 | 1.00 | 1.00 | 1.00 | 0.50 | 0.50 | 1.00 | 1.00 | 1.00 |
| 13 | 0.00 | 0.33 | 1.00 | 0.67 | 1.00 | 0.50 | 0.50 | 0.50 | 1.00 | 0.50 |
| 14 | 0.33 | 0.33 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 |
| 15 | 0.67 | 0.67 | 1.00 | 1.00 | 1.00 | 0.50 | 0.50 | 1.00 | 1.00 | 1.00 |
| 16 | 0.00 | 1.00 | 1.00 | 0.67 | 1.00 | 0.00 | 1.00 | 0.50 | 0.50 | 1.00 |
| 17 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 0.50 | 1.00 |
| 18 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 19 | 0.00 | 0.67 | 1.00 | 0.75 | 1.00 | 0.00 | 0.50 | 0.50 | 1.00 | 1.00 |
| 20 | 0.33 | 0.67 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 21 | 0.67 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 22 | 0.67 | 1.00 | 1.00 | 0.75 | 1.00 | 1.00 | 0.50 | 0.50 | 1.00 | 1.00 |
| 23 | 0.00 | 0.00 | 0.00 | 0.75 | 1.00 | 0.00 | 0.50 | 0.50 | 1.00 | 1.00 |
| 24 | 0.67 | 0.67 | 1.00 | 1.00 | 0.67 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 25 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 26 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 0.50 | 1.00 | 1.00 | 1.00 |
| 27 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 28 | 0.67 | 0.67 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 29 | 0.33 | 0.33 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 30 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 0.50 | 0.50 | 1.00 | 1.00 |

| Participant number | Obstacle 3 | | | | |
|---|---|---|---|---|---|
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0.00 | 0.50 | 0.50 | 1.00 | 1.00 |
| 2 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 3 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 4 | 0.00 | 0.00 | 0.75 | 1.00 | 1.00 |
| 5 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 6 | 0.00 | 1.00 | 0.50 | 1.00 | 1.00 |
| 7 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 8 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 9 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 10 | 0.00 | 0.00 | 1.00 | 1.00 | 0.50 |
| 11 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 12 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 13 | 0.00 | 0.00 | 0.50 | 0.50 | 1.00 |
| 14 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 15 | 0.50 | 1.00 | 0.00 | 1.00 | 1.00 |
| 16 | 0.00 | 0.50 | 1.00 | 1.00 | 0.50 |
| 17 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 18 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 19 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 |
| 20 | 0.50 | 0.50 | 1.00 | 1.00 | 1.00 |
| 21 | 0.50 | 1.00 | 1.00 | 0.67 | 1.00 |
| 22 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 23 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 |
| 24 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 25 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 26 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 27 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 28 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 29 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 30 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |

**Table D.4.** Raw results of obstacle detection task under 10.0 lux condition in Experiment 3.

| Participant number | Obstacle 1 | | | | | Obstacle 2 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0.00 | 0.67 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 0.50 |
| 2 | 0.33 | 0.33 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 |
| 3 | 0.67 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 4 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 |
| 5 | 0.67 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 |
| 6 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.50 | 0.50 | 1.00 |
| 7 | 0.33 | 1.00 | 1.00 | 1.00 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 8 | 0.33 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 9 | 0.33 | 0.67 | 1.00 | 1.00 | 1.00 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 10 | 0.00 | 0.33 | 0.67 | 1.00 | 1.00 | 0.50 | 0.00 | 1.00 | 1.00 | 1.00 |
| 11 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 12 | 0.33 | 0.33 | 0.67 | 1.00 | 1.00 | 0.50 | 0.50 | 1.00 | 1.00 | 1.00 |
| 13 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.50 | 0.50 | 0.50 | 1.00 | 1.00 |
| 14 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 15 | 1.00 | 1.00 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 16 | 0.00 | 0.67 | 1.00 | 0.75 | 1.00 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 17 | 0.33 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 18 | 0.33 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 19 | 0.00 | 0.33 | 0.67 | 0.75 | 1.00 | 0.00 | 0.50 | 0.50 | 1.00 | 1.00 |
| 20 | 0.67 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 21 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 22 | 0.33 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 |
| 23 | 0.00 | 0.00 | 0.33 | 1.00 | 1.00 | 0.00 | 0.50 | 1.00 | 0.50 | 1.00 |
| 24 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 25 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 26 | 0.67 | 0.67 | 0.67 | 1.00 | 1.00 | 0.50 | 0.50 | 1.00 | 1.00 | 1.00 |
| 27 | 0.00 | 0.67 | 0.67 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 28 | 0.33 | 0.33 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 29 | 0.00 | 0.33 | 1.00 | 1.00 | 1.00 | 0.50 | 0.50 | 1.00 | 1.00 | 1.00 |
| 30 | 0.33 | 0.00 | 0.67 | 1.00 | 1.00 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |

| Participant number | Obstacle 3 | | | | |
|---|---|---|---|---|---|
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 2 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 |
| 3 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 4 | 0.00 | 0.50 | 0.75 | 1.00 | 1.00 |
| 5 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 6 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 7 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 8 | 0.50 | 0.50 | 1.00 | 1.00 | 1.00 |
| 9 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 10 | 0.50 | 0.50 | 0.00 | 1.00 | 1.00 |
| 11 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 12 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 13 | 0.50 | 0.50 | 0.00 | 1.00 | 0.50 |
| 14 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 15 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 |
| 16 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 17 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 18 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 19 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 20 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 21 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 22 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 23 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 24 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 25 | 1.00 | 0.50 | 1.00 | 1.00 | 0.50 |
| 26 | 0.50 | 0.50 | 1.00 | 1.00 | 1.00 |
| 27 | 0.50 | 1.00 | 1.00 | 1.00 | 0.50 |
| 28 | 0.00 | 1.00 | 1.00 | 1.00 | 0.50 |
| 29 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 30 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |

**Table D.5.** Raw results of obstacle detection task under 33.3 lux condition in Experiment 3.

| Participant number | Obstacle 1 | | | | | Obstacle 2 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0.00 | 0.33 | 0.67 | 1.00 | 0.67 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 2 | 0.00 | 0.67 | 0.67 | 1.00 | 1.00 | 0.50 | 1.00 | 0.50 | 1.00 | 1.00 |
| 3 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 4 | 0.00 | 0.67 | 0.50 | 0.50 | 1.00 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 5 | 1.00 | 1.00 | 0.75 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 6 | 0.00 | 0.00 | 0.75 | 0.67 | 1.00 | 0.00 | 0.50 | 0.00 | 1.00 | 1.00 |
| 7 | 0.33 | 1.00 | 0.67 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 0.75 |
| 8 | 0.33 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 0.67 |
| 9 | 0.33 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 10 | 0.33 | 0.67 | 0.00 | 1.00 | 1.00 | 0.00 | 0.00 | 1.00 | 1.00 | 0.67 |
| 11 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 12 | 0.33 | 0.33 | 1.00 | 1.00 | 1.00 | 0.50 | 0.50 | 1.00 | 1.00 | 1.00 |
| 13 | 0.00 | 0.33 | 0.00 | 1.00 | 1.00 | 0.50 | 0.50 | 0.50 | 0.50 | 1.00 |
| 14 | 0.67 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 15 | 0.33 | 0.67 | 0.50 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 16 | 0.00 | 0.33 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.50 | 1.00 | 1.00 |
| 17 | 0.00 | 0.67 | 0.67 | 0.67 | 1.00 | 0.00 | 1.00 | 1.00 | 0.50 | 1.00 |
| 18 | 0.33 | 1.00 | 0.67 | 1.00 | 1.00 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 19 | 0.00 | 0.33 | 0.67 | 0.75 | 0.67 | 0.50 | 0.00 | 1.00 | 1.00 | 1.00 |
| 20 | 0.00 | 0.33 | 0.67 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 21 | 0.33 | 0.67 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 22 | 0.33 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 |
| 23 | 0.00 | 0.67 | 0.67 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 24 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 25 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 26 | 0.67 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 27 | 0.00 | 0.67 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 28 | 0.00 | 0.67 | 1.00 | 0.67 | 1.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 |
| 29 | 0.00 | 0.67 | 0.67 | 1.00 | 1.00 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 30 | 0.00 | 0.67 | 0.67 | 1.00 | 1.00 | 0.00 | 0.50 | 0.50 | 1.00 | 1.00 |

| Participant number | Obstacle 3 | | | | |
|---|---|---|---|---|---|
| | 4.0 | 6.3 | 10.0 | 15.9 | 25.1 |
| 1 | 0.00 | 0.50 | 0.50 | 1.00 | 1.00 |
| 2 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 3 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 4 | 0.00 | 1.00 | 0.00 | 1.00 | 1.00 |
| 5 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 |
| 6 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 7 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 8 | 0.00 | 1.00 | 0.50 | 1.00 | 1.00 |
| 9 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 10 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 11 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 12 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 13 | 0.00 | 0.00 | 0.50 | 1.00 | 1.00 |
| 14 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 15 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 16 | 0.50 | 0.50 | 1.00 | 1.00 | 1.00 |
| 17 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 18 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 19 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 20 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 21 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 22 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 23 | 0.00 | 0.00 | 0.00 | 0.50 | 1.00 |
| 24 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| 25 | 0.50 | 0.00 | 1.00 | 0.50 | 1.00 |
| 26 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |
| 27 | 0.50 | 0.50 | 1.00 | 1.00 | 1.00 |
| 28 | 0.50 | 0.00 | 1.00 | 1.00 | 0.50 |
| 29 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 30 | 0.50 | 0.00 | 1.00 | 1.00 | 1.00 |

**Table D.6.** Raw results of FER task under 0.33 lux condition in Experiment 3.

| Participant number | Happiness | | Anger | | Sadness | | Neutral | |
|---|---|---|---|---|---|---|---|---|
| | Single | Dual | Single | Dual | Single | Dual | Single | Dual |
| 1 | 0.5 | 0.3 | 0.7 | 0.0 | 0.3 | 0.0 | 0.7 | 1.0 |
| 2 | 0.7 | 0.8 | 0.7 | 0.5 | 0.3 | 0.5 | 1.0 | 0.8 |
| 3 | 0.3 | 0.5 | 1.0 | 0.5 | 0.3 | 1.0 | 0.5 | 0.3 |
| 4 | 0.5 | 0.3 | 0.7 | 0.0 | 0.3 | 0.5 | 0.5 | 1.0 |
| 5 | 0.5 | 0.5 | 0.3 | 0.0 | 0.7 | 1.0 | 0.5 | 0.3 |
| 6 | 0.5 | 0.3 | 0.7 | 0.5 | 0.0 | 0.5 | 0.5 | 1.0 |
| 7 | 0.5 | 0.8 | 0.7 | 1.0 | 1.0 | 0.0 | 0.8 | 1.0 |
| 8 | 0.3 | 0.8 | 0.7 | 0.5 | 1.0 | 1.0 | 0.7 | 1.0 |
| 9 | 0.7 | 0.5 | 0.3 | 1.0 | 0.3 | 0.5 | 0.8 | 0.8 |
| 10 | 0.3 | 0.5 | 1.0 | 0.5 | 0.0 | 1.0 | 0.7 | 1.0 |
| 11 | 0.5 | 1.0 | 1.0 | 1.0 | 0.7 | 0.5 | 1.0 | 1.0 |
| 12 | 0.7 | 0.5 | 0.7 | 0.5 | 0.3 | 1.0 | 1.0 | 0.8 |
| 13 | 0.3 | 0.5 | 0.3 | 1.0 | 0.7 | 0.5 | 1.0 | 0.8 |
| 14 | 0.2 | 0.3 | 0.0 | 0.5 | 1.0 | 0.5 | 0.8 | 0.8 |
| 15 | 0.2 | 0.0 | 0.7 | 1.0 | 0.7 | 0.5 | 0.5 | 1.0 |
| 16 | 0.5 | 0.5 | 0.0 | 1.0 | 0.0 | 0.0 | 0.7 | 0.8 |
| 17 | 0.3 | 0.3 | 0.7 | 0.5 | 0.3 | 0.5 | 0.8 | 1.0 |
| 18 | 0.7 | 1.0 | 0.7 | 0.0 | 0.3 | 0.0 | 0.5 | 1.0 |
| 19 | 0.2 | 0.0 | 0.3 | 0.0 | 0.0 | 1.0 | 0.5 | 0.5 |
| 20 | 0.3 | 0.5 | 0.0 | 0.0 | 0.7 | 0.0 | 0.5 | 0.8 |
| 21 | 0.3 | 1.0 | 0.3 | 0.0 | 0.3 | 0.0 | 0.8 | 0.3 |
| 22 | 0.3 | 0.5 | 0.3 | 0.5 | 1.0 | 0.0 | 0.2 | 0.5 |
| 23 | 0.7 | 0.8 | 0.3 | 0.0 | 0.7 | 0.5 | 0.5 | 0.8 |
| 24 | 0.2 | 0.5 | 0.3 | 1.0 | 0.3 | 1.0 | 1.0 | 0.8 |
| 25 | 0.3 | 0.5 | 0.7 | 0.5 | 0.3 | 0.5 | 0.8 | 1.0 |
| 26 | 0.2 | 0.3 | 1.0 | 1.0 | 0.7 | 0.0 | 0.5 | 0.3 |
| 27 | 0.5 | 0.5 | 0.3 | 0.0 | 0.7 | 0.5 | 0.7 | 0.8 |
| 28 | 0.2 | 1.0 | 0.3 | 0.5 | 0.3 | 0.0 | 0.7 | 1.0 |
| 29 | 0.3 | 0.5 | 0.7 | 0.5 | 0.0 | 1.0 | 0.7 | 1.0 |
| 30 | 0.2 | 0.5 | 0.3 | 1.0 | 0.7 | 0.0 | 0.8 | 1.0 |

**Table D.7.** Raw results of FER task under 1.0 lux condition in Experiment 3.

| Participant number | Happiness | | Anger | | Sadness | | Neutral | |
|---|---|---|---|---|---|---|---|---|
| | Single | Dual | Single | Dual | Single | Dual | Single | Dual |
| 1 | 0.7 | 0.8 | 1.0 | 1.0 | 1.0 | 0.5 | 1.0 | 1.0 |
| 2 | 1.0 | 0.8 | 0.7 | 1.0 | 1.0 | 0.5 | 0.8 | 1.0 |
| 3 | 0.8 | 0.8 | 0.7 | 1.0 | 0.3 | 1.0 | 1.0 | 1.0 |
| 4 | 0.7 | 0.8 | 1.0 | 1.0 | 0.0 | 0.5 | 0.3 | 1.0 |
| 5 | 0.5 | 1.0 | 0.0 | 1.0 | 0.3 | 1.0 | 0.8 | 0.8 |
| 6 | 0.8 | 1.0 | 0.0 | 0.5 | 0.7 | 0.5 | 0.7 | 0.5 |
| 7 | 0.7 | 0.8 | 1.0 | 1.0 | 0.7 | 0.0 | 1.0 | 1.0 |
| 8 | 0.7 | 1.0 | 0.3 | 1.0 | 0.7 | 1.0 | 0.7 | 1.0 |
| 9 | 0.8 | 0.8 | 1.0 | 0.5 | 1.0 | 1.0 | 0.3 | 0.5 |
| 10 | 0.7 | 0.8 | 0.7 | 0.5 | 0.3 | 0.0 | 0.7 | 0.8 |
| 11 | 0.7 | 1.0 | 1.0 | 1.0 | 0.7 | 0.5 | 1.0 | 1.0 |
| 12 | 0.7 | 0.8 | 1.0 | 1.0 | 1.0 | 0.5 | 0.8 | 1.0 |
| 13 | 0.7 | 0.3 | 1.0 | 1.0 | 0.3 | 0.0 | 1.0 | 1.0 |
| 14 | 0.3 | 0.8 | 0.3 | 1.0 | 0.3 | 0.0 | 1.0 | 0.8 |
| 15 | 0.7 | 1.0 | 1.0 | 1.0 | 0.3 | 1.0 | 1.0 | 0.8 |
| 16 | 0.5 | 0.8 | 0.7 | 1.0 | 0.7 | 0.0 | 0.7 | 0.8 |
| 17 | 0.7 | 0.8 | 0.7 | 1.0 | 0.0 | 1.0 | 0.8 | 1.0 |
| 18 | 0.7 | 0.8 | 1.0 | 0.5 | 0.0 | 0.0 | 0.8 | 0.8 |
| 19 | 0.3 | 0.5 | 0.7 | 1.0 | 0.7 | 0.5 | 0.5 | 0.8 |
| 20 | 0.7 | 0.3 | 0.3 | 0.5 | 0.3 | 1.0 | 1.0 | 0.5 |
| 21 | 0.5 | 0.8 | 1.0 | 0.5 | 0.7 | 0.5 | 0.7 | 1.0 |
| 22 | 0.5 | 0.5 | 0.0 | 1.0 | 0.3 | 0.5 | 0.5 | 0.5 |
| 23 | 0.5 | 1.0 | 0.7 | 0.5 | 0.3 | 0.5 | 0.5 | 0.8 |
| 24 | 0.7 | 0.8 | 1.0 | 1.0 | 0.3 | 1.0 | 0.8 | 0.8 |
| 25 | 0.5 | 0.8 | 0.7 | 0.5 | 1.0 | 0.5 | 0.5 | 0.8 |
| 26 | 0.3 | 0.8 | 0.7 | 1.0 | 0.3 | 1.0 | 0.8 | 0.8 |
| 27 | 0.5 | 0.5 | 0.7 | 1.0 | 0.3 | 1.0 | 0.8 | 1.0 |
| 28 | 0.5 | 0.8 | 0.7 | 0.0 | 0.0 | 0.5 | 0.7 | 0.8 |
| 29 | 0.5 | 1.0 | 0.3 | 1.0 | 1.0 | 0.5 | 1.0 | 1.0 |
| 30 | 0.5 | 0.8 | 0.3 | 0.5 | 0.3 | 0.0 | 0.8 | 0.8 |

**Table D.8.** Raw results of FER task under 3.3 lux condition in Experiment 3.

| Participant number | Happiness | | Anger | | Sadness | | Neutral | |
|---|---|---|---|---|---|---|---|---|
| | Single | Dual | Single | Dual | Single | Dual | Single | Dual |
| 1 | 0.7 | 1.0 | 0.7 | 1.0 | 0.7 | 0.5 | 1.0 | 1.0 |
| 2 | 1.0 | 0.5 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| 3 | 1.0 | 0.8 | 0.3 | 1.0 | 1.0 | 1.0 | 0.8 | 0.8 |
| 4 | 0.7 | 0.8 | 0.7 | 1.0 | 1.0 | 0.5 | 1.0 | 1.0 |
| 5 | 1.0 | 1.0 | 0.7 | 0.5 | 0.7 | 0.0 | 0.8 | 1.0 |
| 6 | 0.8 | 1.0 | 1.0 | 1.0 | 0.3 | 0.5 | 0.8 | 0.5 |
| 7 | 0.8 | 0.8 | 1.0 | 1.0 | 0.3 | 0.0 | 0.8 | 0.8 |
| 8 | 1.0 | 0.8 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.8 |
| 9 | 0.7 | 0.3 | 1.0 | 1.0 | 0.7 | 0.5 | 0.7 | 0.8 |
| 10 | 0.5 | 0.8 | 1.0 | 0.5 | 0.3 | 1.0 | 0.8 | 0.8 |
| 11 | 0.5 | 1.0 | 1.0 | 1.0 | 0.7 | 1.0 | 0.8 | 0.8 |
| 12 | 0.7 | 0.8 | 1.0 | 1.0 | 0.7 | 0.5 | 1.0 | 0.8 |
| 13 | 1.0 | 0.8 | 0.7 | 1.0 | 0.7 | 1.0 | 1.0 | 1.0 |
| 14 | 0.7 | 0.3 | 1.0 | 1.0 | 0.3 | 0.0 | 0.5 | 0.3 |
| 15 | 1.0 | 0.8 | 0.7 | 1.0 | 0.7 | 1.0 | 0.5 | 0.5 |
| 16 | 0.7 | 0.8 | 1.0 | 1.0 | 0.3 | 0.5 | 0.7 | 1.0 |
| 17 | 1.0 | 1.0 | 0.7 | 1.0 | 0.7 | 0.5 | 1.0 | 1.0 |
| 18 | 1.0 | 1.0 | 0.7 | 1.0 | 0.3 | 1.0 | 1.0 | 1.0 |
| 19 | 0.5 | 0.5 | 0.3 | 0.5 | 0.3 | 0.5 | 0.7 | 0.8 |
| 20 | 0.8 | 0.8 | 0.7 | 1.0 | 0.3 | 0.5 | 1.0 | 0.8 |
| 21 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.8 | 1.0 |
| 22 | 0.8 | 1.0 | 1.0 | 0.5 | 1.0 | 0.0 | 0.5 | 0.8 |
| 23 | 0.8 | 1.0 | 0.7 | 1.0 | 0.3 | 0.5 | 0.8 | 1.0 |
| 24 | 1.0 | 1.0 | 1.0 | 1.0 | 0.7 | 1.0 | 1.0 | 1.0 |
| 25 | 0.7 | 1.0 | 1.0 | 1.0 | 0.3 | 1.0 | 0.5 | 0.8 |
| 26 | 0.8 | 1.0 | 0.7 | 0.5 | 0.7 | 0.5 | 0.7 | 0.8 |
| 27 | 0.7 | 0.8 | 1.0 | 1.0 | 0.7 | 0.5 | 1.0 | 0.8 |
| 28 | 1.0 | 1.0 | 1.0 | 1.0 | 0.3 | 0.0 | 0.8 | 1.0 |
| 29 | 1.0 | 1.0 | 1.0 | 1.0 | 0.7 | 1.0 | 1.0 | 0.8 |
| 30 | 0.7 | 1.0 | 1.0 | 0.5 | 0.7 | 0.0 | 0.5 | 1.0 |

**Table D.9.** Raw results of FER task under 10.0 lux condition in Experiment 3.

| Participant number | Happiness | | Anger | | Sadness | | Neutral | |
|---|---|---|---|---|---|---|---|---|
| | Single | Dual | Single | Dual | Single | Dual | Single | Dual |
| 1 | 1.0 | 0.8 | 1.0 | 1.0 | 0.3 | 0.5 | 1.0 | 0.8 |
| 2 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| 3 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.8 |
| 4 | 1.0 | 1.0 | 1.0 | 1.0 | 0.0 | 1.0 | 0.8 | 1.0 |
| 5 | 0.7 | 0.8 | 1.0 | 1.0 | 0.0 | 0.5 | 1.0 | 1.0 |
| 6 | 0.8 | 1.0 | 0.7 | 1.0 | 0.7 | 0.0 | 1.0 | 0.8 |
| 7 | 0.8 | 0.8 | 0.3 | 0.5 | 0.7 | 0.5 | 1.0 | 1.0 |
| 8 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.0 | 1.0 | 1.0 |
| 9 | 0.7 | 0.8 | 0.7 | 1.0 | 0.7 | 1.0 | 0.8 | 1.0 |
| 10 | 0.8 | 0.8 | 1.0 | 1.0 | 0.7 | 1.0 | 0.8 | 1.0 |
| 11 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.8 | 1.0 |
| 12 | 1.0 | 1.0 | 1.0 | 1.0 | 0.7 | 1.0 | 1.0 | 1.0 |
| 13 | 0.7 | 0.8 | 0.7 | 0.5 | 0.0 | 0.5 | 1.0 | 0.8 |
| 14 | 0.7 | 0.8 | 0.3 | 0.5 | 0.3 | 1.0 | 0.8 | 0.5 |
| 15 | 0.7 | 1.0 | 1.0 | 1.0 | 0.3 | 1.0 | 1.0 | 0.5 |
| 16 | 1.0 | 1.0 | 0.7 | 1.0 | 0.7 | 0.5 | 0.8 | 0.8 |
| 17 | 1.0 | 1.0 | 0.7 | 1.0 | 1.0 | 0.5 | 1.0 | 0.5 |
| 18 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 | 0.0 | 0.8 | 1.0 |
| 19 | 0.5 | 0.8 | 0.7 | 0.5 | 0.7 | 0.5 | 1.0 | 1.0 |
| 20 | 0.8 | 1.0 | 1.0 | 1.0 | 1.0 | 0.5 | 1.0 | 0.8 |
| 21 | 1.0 | 1.0 | 1.0 | 1.0 | 0.7 | 1.0 | 1.0 | 1.0 |
| 22 | 0.8 | 1.0 | 0.7 | 1.0 | 0.3 | 0.0 | 0.8 | 1.0 |
| 23 | 1.0 | 1.0 | 1.0 | 1.0 | 0.3 | 0.0 | 0.7 | 0.5 |
| 24 | 1.0 | 1.0 | 0.7 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| 25 | 0.8 | 0.5 | 0.7 | 0.5 | 0.3 | 0.5 | 0.8 | 0.8 |
| 26 | 0.8 | 0.8 | 1.0 | 1.0 | 0.3 | 0.5 | 0.7 | 1.0 |
| 27 | 0.8 | 0.8 | 0.7 | 1.0 | 1.0 | 1.0 | 0.8 | 1.0 |
| 28 | 1.0 | 0.8 | 0.7 | 1.0 | 0.0 | 0.0 | 1.0 | 1.0 |
| 29 | 0.8 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.8 | 1.0 |
| 30 | 0.8 | 0.5 | 1.0 | 1.0 | 0.0 | 0.5 | 0.5 | 1.0 |

**Table D.10.** Raw results of FER task under 33.3 lux condition in Experiment 3.

| Participant number | Happiness | | Anger | | Sadness | | Neutral | |
|---|---|---|---|---|---|---|---|---|
| | Single | Dual | Single | Dual | Single | Dual | Single | Dual |
| 1 | 1.0 | 1.0 | 1.0 | 1.0 | 0.7 | 0.5 | 0.8 | 1.0 |
| 2 | 1.0 | 1.0 | 1.0 | 1.0 | 0.7 | 1.0 | 1.0 | 1.0 |
| 3 | 0.8 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| 4 | 1.0 | 1.0 | 1.0 | 0.5 | 0.3 | 0.5 | 0.8 | 1.0 |
| 5 | 1.0 | 1.0 | 0.0 | 1.0 | 0.7 | 0.0 | 0.7 | 1.0 |
| 6 | 0.8 | 1.0 | 0.7 | 0.5 | 1.0 | 0.5 | 0.5 | 0.8 |
| 7 | 0.8 | 1.0 | 1.0 | 1.0 | 0.3 | 0.5 | 1.0 | 1.0 |
| 8 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 | 0.5 | 1.0 | 1.0 |
| 9 | 0.5 | 0.5 | 1.0 | 1.0 | 0.7 | 0.5 | 1.0 | 1.0 |
| 10 | 0.7 | 0.8 | 1.0 | 1.0 | 0.7 | 1.0 | 0.7 | 1.0 |
| 11 | 1.0 | 1.0 | 1.0 | 1.0 | 0.7 | 1.0 | 1.0 | 1.0 |
| 12 | 1.0 | 1.0 | 0.7 | 1.0 | 0.7 | 0.5 | 1.0 | 1.0 |
| 13 | 0.8 | 0.8 | 0.7 | 1.0 | 0.0 | 0.5 | 1.0 | 1.0 |
| 14 | 0.5 | 0.8 | 1.0 | 1.0 | 0.7 | 0.5 | 0.5 | 1.0 |
| 15 | 1.0 | 1.0 | 0.7 | 0.5 | 0.3 | 0.5 | 1.0 | 1.0 |
| 16 | 1.0 | 1.0 | 1.0 | 1.0 | 0.7 | 1.0 | 1.0 | 0.8 |
| 17 | 1.0 | 1.0 | 1.0 | 0.5 | 0.0 | 0.5 | 1.0 | 1.0 |
| 18 | 1.0 | 1.0 | 1.0 | 0.5 | 0.7 | 0.5 | 1.0 | 1.0 |
| 19 | 0.8 | 1.0 | 1.0 | 1.0 | 0.7 | 1.0 | 0.8 | 1.0 |
| 20 | 0.8 | 1.0 | 1.0 | 1.0 | 0.7 | 1.0 | 0.8 | 1.0 |
| 21 | 1.0 | 1.0 | 1.0 | 1.0 | 0.7 | 1.0 | 1.0 | 1.0 |
| 22 | 0.8 | 1.0 | 0.7 | 1.0 | 0.3 | 0.5 | 0.8 | 0.5 |
| 23 | 1.0 | 1.0 | 1.0 | 0.5 | 0.0 | 0.0 | 0.7 | 1.0 |
| 24 | 1.0 | 1.0 | 1.0 | 1.0 | 0.7 | 1.0 | 1.0 | 1.0 |
| 25 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.8 |
| 26 | 0.8 | 0.8 | 0.7 | 1.0 | 0.7 | 1.0 | 0.8 | 1.0 |
| 27 | 1.0 | 1.0 | 1.0 | 1.0 | 0.7 | 1.0 | 0.8 | 1.0 |
| 28 | 1.0 | 1.0 | 1.0 | 1.0 | 0.3 | 0.0 | 0.8 | 1.0 |
| 29 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.8 | 0.8 |
| 30 | 1.0 | 1.0 | 0.3 | 1.0 | 0.0 | 0.0 | 0.7 | 1.0 |

# APPENDIX E. EXAMPLE OF PARTICIPANT INFORMATION SHEET AND CONSENT FORM (EXPERIMENT 3)

## Participant Information Sheet

### Effect of lighting on obstacle detection and recognition of facial expression

You are invited to take part in a research project being carried out by researchers at the University of Sheffield. Before deciding whether to take part it is important you understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you like more information – contact details are below. Take time to decide whether or not your wish to take part. Thanks for reading this.

### 1. What is the project's purpose?

The aim of the project is to understand how lighting affects our ability to detect obstacles on the path in front of us, and judge the intentions of others by recognising their emotional expression. Road lighting has an important role in helping pedestrians achieve these two tasks. The evidence collected during this project will help inform new national and international guidelines that outline the lighting requirements for pedestrian areas.

### 2. What will happen to me if I take part?

The project involves an experiment carried out in the lighting laboratory on the 19th floor of the Arts Tower. The experiment will involve looking in to a test chamber through one open side. The chamber will be lit from above, under different lighting conditions to simulate the types of light conditions you would typically find under road lighting at night. Within the chamber, small obstacles may appear from the floor surface, or a 3D printed face displaying a particular emotional expression may appear at the centre of the chamber. You will be asked to wear a pair of customised glasses that will normally be opaque to prevent you seeing the test chamber, but periodically will become transparent to reveal the chamber for a brief period (approximately half a second) before becoming opaque again. Your task will be to indicate if you see one of the obstacles present in the chamber, and to indicate what emotion the face is expressing, if it is present, based on what you can see of the chamber for the brief period the glasses become transparent.

The experiment should take about 2.5 hours to complete, with regular breaks during this time. As the experiment will take place at several different lighting conditions, you will not need to carry out the test session and respond to what you see in the chamber for the first 20 minutes, as your eyes adapt. During this time you will be given further details about the experiment and asked to sign a consent form. You will also have an opportunity to become familiar with the test procedure and the apparatus. The experiment testing will only begin after this first 20-minute period, and should take the next 130 minutes to complete, including regular breaks to rest your eyes. As compensation for giving up your time, and to cover any expenses incurred as a result of taking part in the experiment, you will be given £25 at the end of the session.

### 3. What are the possible disadvantages and risks of taking part?

Taking part in this research is entirely voluntary. If you decide to take part you will be asked to sign a consent form. You can still withdraw at any time without giving a reason. The lighting conditions used for this research are similar to those found under normal road lighting. This means the light levels will be relatively low, but you will be sat in a chair during the testing and therefore there will be no risk of you being unable to see where you are walking. The light levels also simulate real road lighting conditions, and therefore will not be dissimilar to what you might encounter if walking a street at night. There will be no flashing lights.

Although this experiment is scheduled to take 2.5 hour to complete, you will have the opportunity for regular breaks during this time, and you will be able to sit down throughout.

### 4. What are the possible benefits of taking part?

You will receive £25 after completing the test session. You will also be contributing to an important piece of scientific research that will influence how future street environments are designed and maintained.

### 5. What happens if the research study stops earlier than expected?

It is possible we may complete a session earlier than anticipated. In this situation you will be free to go, and will still be paid the full £25 payment.

### 6. What if something goes wrong?

If something goes wrong in the experiment and you are unhappy with how you have been treated you can raise a complaint with the research project lead or the University. For this research project, Professor Steve Fotios is the overall lead for the whole project (steve.fotios@sheffield.ac.uk). If you feel your complaint was not handled satisfactorily you can also contact the University’s Registrar and Secretary at registrar@sheffield.ac.uk.

### 7. Will taking part in this project be kept confidential?

For this research we would like to record your age, gender, and your responses to the test questions. We will use these data in our analyses and will retain the data for future use. Future uses include our further analyses of the data and sharing the results with other researchers. We will ask you to add your name and sign the Consent to Participate form: this is to enable the researcher to confirm that we did seek informed consent to participate. Your name will not be included in our records of results: in other words, all data that you provide will be anonymised and it will not be possible to identify you from the data collected.

### 8. What will happen to the results of the research project?

The results will be published in academic journals and in professional body magazines. The results will also be presented at academic conferences, and will be used as evidence during review and revisions of standards, guidelines and design criteria related to the street environment.

### 9. Who is organising and the research?

The project is organised and run by members of the Lighting Research Group in the School of Architecture, University of Sheffield. The project is being undertaken by Yichang Mao, a PhD student in the School of Architecture, and is led by Professor Steve Fotios.

### 10. Who has ethically reviewed the project?

The project has been approved by the School of Architecture’s Ethics Review Committee at the University of Sheffield.

### 11. Contact for further information

Please contact Yichong Mao, ymao14@sheffield.ac.uk, or Professor Steve Fotios, project lead, at steve.fotios@sheffield.ac.uk.

**Thank you for reading this. We hope you would like to take part in this research project. To do so please contact Yichong Mao at** ymao14@sheffield.ac.uk**.**

# Participant Consent and Record Form

**(Personal information will be kept strictly confidential)**

**Title of Research Project:** Effect of lighting on obstacle detection and recognition of facial expression

**Name of Researcher:** Yichong Mao

**Participant Identification Number for this project:**

1. I confirm that I have read and understand the information sheet explaining the above research project and I have had the opportunity to ask questions about the project. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason and without there being any negative consequences. ☐

3. I understand that my responses during the experiment will be kept strictly confidential. I understand that my name will not be linked with the research materials, and I will not be identifiable in the report or reports that result from the research. ☐

4. I agree for the data collected from me to be used in future research ☐

5. I agree to take part in the above research project ☐

6. I confirm that I am physically fit and healthy enough to take part in this project, based on the information I have been given about what will be required ☐

7. Please indicate if you wear glasses or contact lenses for:

a) near-sighted tasks, e.g. reading? ☐ (Tick if applicable)
b) far-sighted tasks, e.g. driving? ☐ (Tick if applicable)

**Please turn over**

8. Please give your age (in years)

9. Please indicate your gender

☐ Male

☐ Female

Please sign below to confirm that you have voluntarily decided to participate in this study. Thank you.

| | | |
|---|---|---|
| ______________________________ | ________________ | ______________________ |
| Name of Participant | Date | Signature |

| | | |
|---|---|---|
| ______________________________ | ________________ | _______________________ |
| Name of Researcher | Date | Signature |

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