Understanding visual behaviour within the urban environment to optimise lighting

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Abstract

A review of the literature suggests that current guidelines for road lighting lack a clear empirical basis. Where there is evidence, this tends to be based on motorists or pedestrians: there is little, if any, consideration given to the needs of cyclists. This thesis presents an investigation of lighting for cycling after dark within an urban environment.

Three empirical investigations were conducted. A field survey was conducted to investigate the influence of the ambient light level on the tendency to cycle. Mobile eye-tracking was used to investigate the gaze behaviour of cyclists in natural settings, using two parallel measurements to reveal the critical of these fixations: performance on an audio dual-task and skin conductance response (SCR), and by that improved the ecological validity of previous similar research. A laboratory experiment was conducted to investigate obstacle detection under variations in the type, location, and level of lighting.

The field study revealed that cycling increases when the ambient light level is higher. This suggests that road lighting might be a tool to encourage more cycling. The eye-tracking study suggested that observing the path ahead is a critical task, reflecting a tendency to search for possible obstacles on the road. Post hoc analysis of the eye-tracking data also suggested an influence of ambient light level on gaze towards aesthetic elements (architectural features) of the environment with such elements are suggested by the literature to be associated with positive cycling experience: this suggests that appropriate road lighting motivates the choice to cycle.

The detection experiment revealed two significant effects: first; that road lighting and bicycle lighting may conflict. In other words, using bicycle lighting on a lit road may impair detection performance, not improve it. Second; that detection is improved when the front bicycle lamp is located on the wheel hub rather than the handlebar.

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Chapter 1. Road lighting for cyclists

1.1 Introduction

Cycling has multifaceted benefits to UK society including; public health, economic, reduction of CO_2 emissions, and reduced energy consumption (Horton et al., 2016). Yet compared to similar developed countries, the proportion of the UK population that regularly cycles remains low (Pucher and Buehler, 2008). This may be due in part to public perceptions of the safety of cycling, with statistics showing high casualties and fatalities on the roads (Lorenc et al., 2008; Willis et al., 2015). Thus improving road safety conditions is vital in promoting more cycling.

Another motivation to cycle is the quality of the experience; one aspect of this is whether cyclists view the surrounding environment as pleasant and enjoyable (Sener et al., 2009a; Xu et al., 2019). In the after dark, road lighting can play a role by enabling such pleasant/attractive elements to be seen while cycling (BSI, 2013).

People cycle for different reasons, e.g. lower travel cost, health benefits, to escape from congestion, and as a life-style choice (Gatersleben and Haddad, 2010). The amount that people cycle is understandably different depending on whether they are a commuter, an everyday cyclist, a leisure cyclist, an occasional cyclist, etc. Regardless of the motivation and amount people cycle, this thesis is focused on improving urban conditions experienced by any person who can use a bicycle effectively.

The safety aspect of cycling could cover a spectrum of subjects ranging from risks emerged from interacting with other motor vehicles (Martínez-Ruiz et al., 2014; Summala et al., 1996); cyclists own risky behaviour e.g. joining the main road from footpath (Krizek and Roland, 2005; Knowles et al., 2009); detecting hazards or obstacles on the road (Schepers and den Brinker, 2011). This spectrum could extend to a subjective dimension such as individuals' perception of how safe is cycling (Heinen et al., 2010; Lawson et al., 2013).

In the context of this study, the term 'safety' is particularly used to refer to the traffic challenges of cycling and here road lighting is proposed to deliver safer cycling, particularly through enhancing cyclists' visual performance during after dark time. For example, improving the ability of cyclists to detect hazards leads to a reduction in accidents on the road, especially ones related to inefficient road light provision.

This chapter first reviews the benefits that increased cycling can bring to UK society along with the safety challenges of this mode of transport, and then explores current road lighting guidelines, outlining lighting specifications to meet the visual needs of cyclists.

1.2 Benefits of cycling

Promoting cycling in the community has gained a considerable amount of attention from the UK government in recent years (DFT, 2017), in keeping with a wider trend in Europe and elsewhere around the world (Pucher and Buehler, 2008).

The benefits of cycling include improved physical health for the cyclist, and less air pollution and less traffic congestion for the general public (DFT, 2017). Public Health England (PHE) have emphasised the wider positive health returns to the public when cycling is adapted by the larger population such as reducing obesity, hypertension, cancer and depression (PHE, 2014). Oja et al. (2011) reviewed the literature of cycling and public health and stated that:" *Cycling has health and functional benefits in young boys and girls and improvements in cardiorespiratory fitness and disease risk factors as well as significant risk reduction for all-cause and cancer mortality and for cardiovascular, cancer, and obesity morbidity in middle-aged and elderly men and women.''* (Oja et al, 2011, p.508)

In their study De Geus et al. (2008) recruited 80 participants (65 intervention group and 15 control group) for one year cycling intervention study to measure risk factors related to coronary heart disease (CHD), this is in addition to assessing the general health and life quality aspects of healthy adults who were untrained and did not cycle to work previously. Health measurements were carried on participants on three consequent events, with 6 months gap in-between. The study found that cycling to work has significantly reduced CHD risk factors and was possibly to develop the general well-being and related aspects in the intervention sample. The risk factors that were improved include density lipoprotein cholesterol (LDL), cholesterol high-density lipoprotein (HDL) and diastolic blood pressure.

The economic benefits of cycling could be separated into two groups: direct (monetary) (DFT, 2015a) and indirect (non-monetary) (Cavill et al., 2008). Grous (2011) reports the 2010 net direct return of cycling to the UK economy to be £2.9 billion, an amount equivalent to two hundred thirty pounds per year per individual cyclist.

Additionally, an estimated 1/3 increase in general retails sales could be anticipated when introducing sustainable transportation projects such as cycling encouraging schemes (Lawlor, 2013). Such projects could also increase the economic worth of nearby land. Increased cycling can also mean greater job opportunities in different business divisions, e.g. cycling hardware retails, industries, training and such (Lawlor, 2013). It has been estimated that a 1/5 increase in cyclist population is equivalent to £207 million savings from reduced traffic jams (DFT, 2015a, 2017), and £71 million savings from reduced CO_2 (Grous, 2011).

Cycling has been found to correlate with good work attendance (Piatkowski et al., 2014). Cycling to work is correlated with lower absenteeism rates, this is especially true for longer commuting distances (Hendriksen et al., 2010). Cycle to work schemes can also have an impact, with one Sheffield (UK)-based case study citing that 75% of participants who did not cycle usually stated they begin to cycle more after 24 months from the intervention start (Uttley and Lovelace, 2016).

Another dimension of cycling to consider are the social benefits. Cycling can promote a better quality of life within a community by making it more vibrant through better social interaction. Cycling itself can be seen as a ‘social practice’ (Spotswood et al., 2015, p. 22).

Generally, the research on cycling took multiple themes, examples are: Gender effect (Aldred et al., 2017; Aldred et al., 2016; Prati, 2018); safety at several dimensions (Aldred et al., 2019; Buehler and Pucher, 2017; Lawson et al., 2013; Schepers et al., 2017; Werneke et al., 2015); the influence of the urban environment on cycling (Meuleners et al., 2019; Nielsen et al., 2013; Saelens et al., 2003); travel behaviour (Fyhri et al., 2017; Heinen and Buehler, 2019; Liu et al., 2017; Meuleners et al., 2019; Plazier et al., 2017).

Examples of recent literature review studies in the following: Stewart et al. (2015) carried a systematic review of 12 studies of which 7 studies of these examined intervention effects on individual and group levels. The remain of studies examined intervention on the environmental level. The review found that environmental intervention encouraged larger population to cycle, in general, despite the authors stated it was difficult to specify which particular segment in the population had shifted to cycling.

Smith et al. (2017) reviewed the literature on the effects of built environment features on the active traveling rates, including cycling, where evidence had been found that intervention on infrastructure level could correlate to an increased cycling level.

Winters et al. (2017) conducted a literature review on cycling research, particularly, on the effect of government policies targeting increasing cyclists' population. The authors extracted the findings of 50 review papers and concluded that increasing the population of cyclists could be achieved by implementing a multi-faceted policy that targets promoting cycling at multi-scales: individual, residential district, municipality, and larger society.

In addition, Fishman (2016) evaluated the literature on the cycling share in the society on a sample of papers published since 2013 and found that the perceived value of cycling is a major motivator to take up cycling as transport choice hence policymakers need to incorporate the value of bicycling when aiming for altering the use of other transport means e.g. car driving. Another finding was that specific demographic groups are more inclined to adopt cycling for travel e.g. white people, above average income, and people living in and near city centres close to cycling promotion schemes influence.

Given the abundance of benefits from increased cycling discussed above, why then are cycling levels lower in the UK than comparable countries?

1.3 Cycling rate in UK

There is a general problem of physical ''inactivity'' in the UK compared to similar developed countries such as the Netherlands, Germany, France, Finland, Australia, and the USA (Hallal et al., 2012), see Figure 1.1 for physical inactivity percentage comparison between the UK and these six countries, which all have a lower inactivity mean than the UK. Evidence has shown that inactivity caused negative costs related to the health of up to £760 million annually (Grous, 2011).

It can be noted that the population of cycling in the UK is less than that of other countries of similar developmental status. Cycling in the UK is also low when considering the average distance cycled per day per individual resident, see Figure 1.2, again comparing to the mean seen in the Netherlands, Denmark, Germany and Finland who all have a larger mean than the UK. The mean of these four countries is also compared with that of the UK with regard to the percentage of trips made by bicycle compared with other transportation means, see Figure 1.3.

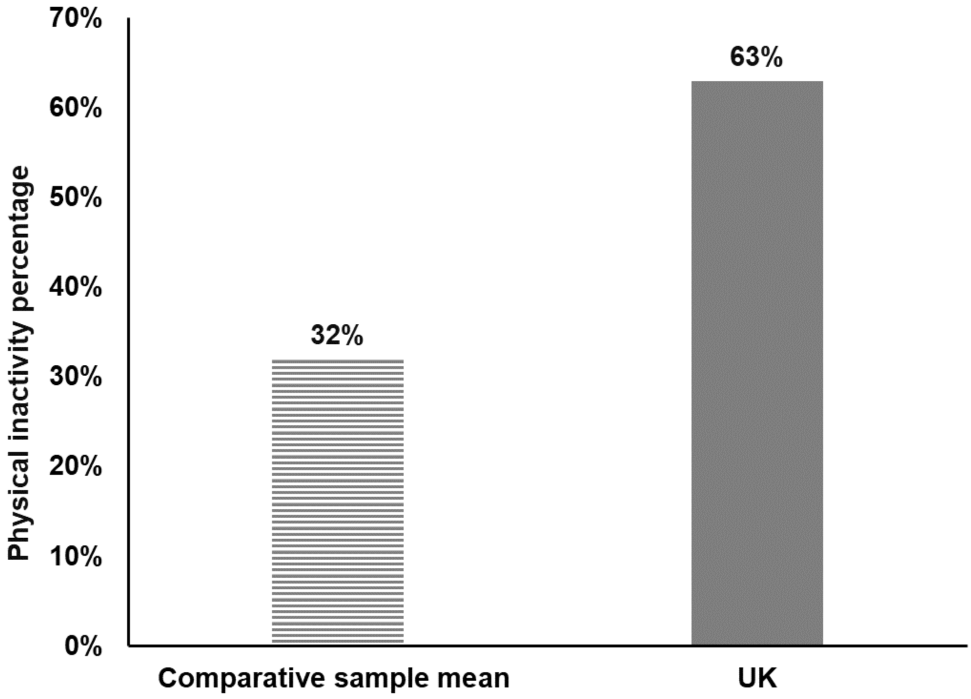

Figure 1.1. Comparable data about physical inactivity level between UK and 6 developed countries: Netherlands, Germany, France, Finland, Australia, and the USA. Based on data from Hallal et al (2012). Note: all countries in the comparative sample had less individual mean than the UK mean.

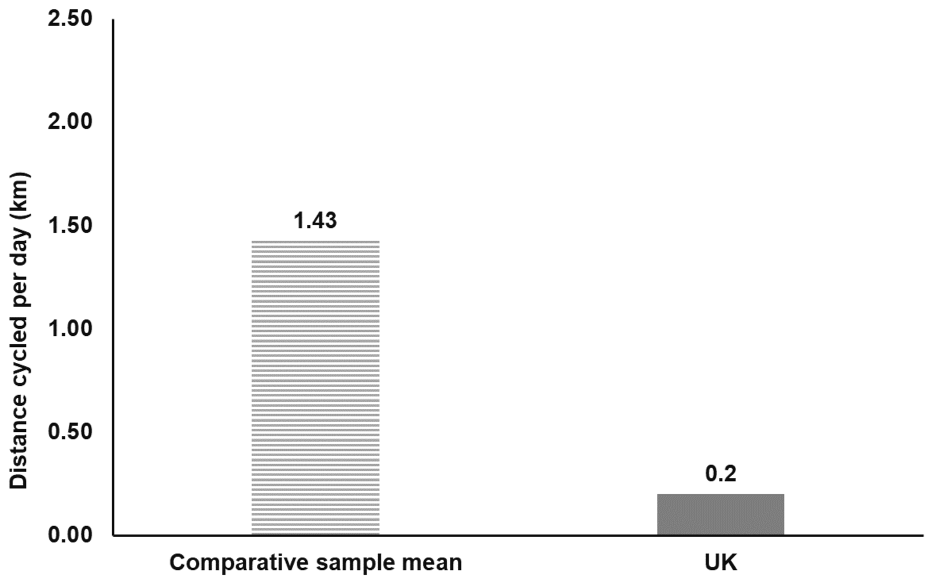

Figure 1. 2 Comparison of distance cycled per person per day between UK and the mean number of Netherlands, Denmark, Germany and Finland. Based on data from Pucher and Buehler (2008). Note: all countries in the comparative sample had larger individual mean than the UK mean.

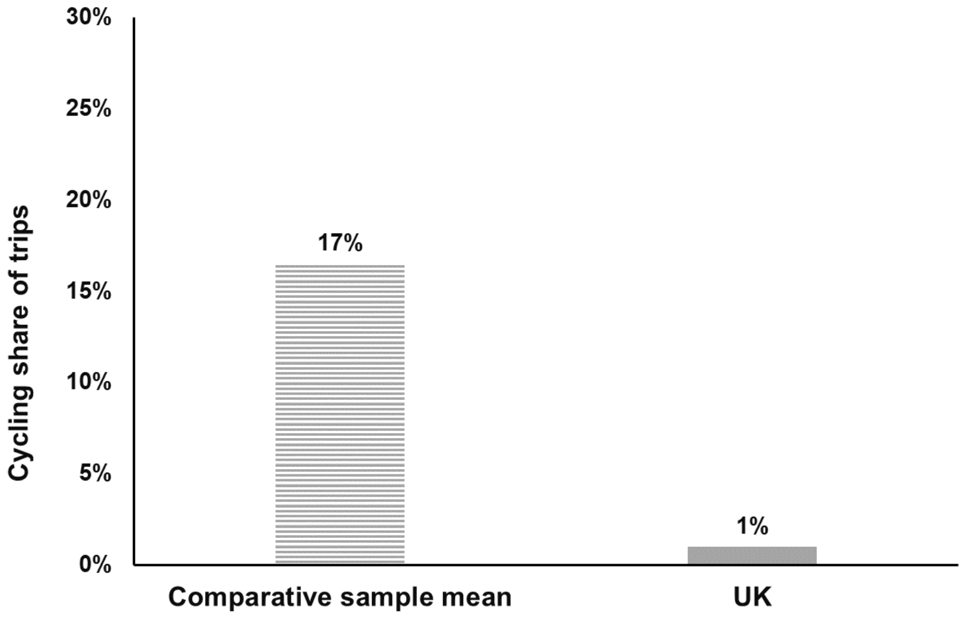

Figure 1.3 Comparison of bicycle share of trips relative to other transportation means between UK and the average of Netherlands, Denmark, Germany and Finland. Based on data from Pucher and Buehler (2008). Note: all countries in the comparative sample had larger individual mean than the UK mean.

Public perceptions toward cycling as a comparably unsafe travel mode of transport is also thought to impact on cycling rates (Gatersleben and Appleton, 2007). In terms of what basis these perceptions have in reality, Figure 1.4 below provides the mean number of fatalities and injuries among cyclists per one hundred million km in three

European countries: Netherlands, Denmark, Germany, as compared to the UK. The graph shows that the probability of risk is much greater in the UK than in the other countries.

Table 1.1 depicts the number of fatalities and serious injury among cyclists in UK in two years, 2014 and 2015, and the average between 2010 - 2014. The number of fatalities slightly decreased in 2015 than in the previous year. This is not necessary an indication of an improved road safety, but could be a matter of exposure i.e. higher cycling rates were seen in 2014 which also happened to be a warm year (DFT, 2015b). However, comparing the figures for 2015 with the 2010 – 2014 average clearly indicates an increase in the number of serious injuries and a small decrease in slight injury category. In this last comparison some may argue this increase in serious injury is an effect of exposure as there was a 3% increase in billion miles cycled in 2015 comparing to the average of years from 2010 to 2014.

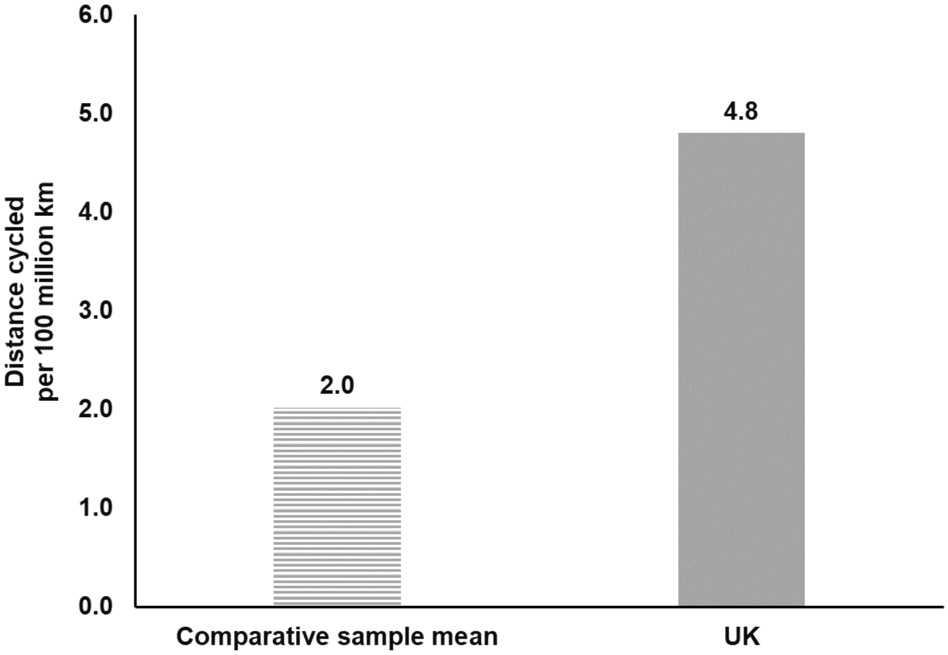

Figure 1.4 Comparison of cycling fatality and injuries per 100 million km cycled distance between UK and the mean of Netherlands, Denmark, Germany. Based on data from Pucher and Buehler (2008). Note: all countries in the comparative sample had less individual mean than the UK mean.

Table 1.1 Fatalities and causalities in the United Kingdom for the period between 2010 to 2015 (after DFT, 2015b).

Status	**2010 - 2014 average***	**2014***	**2015**
Fatalities	111	114	100
Seriously injured	3109	3400	3239
Slightly injured	15983	17830	15505
Total	19203	21344	18844
Billion miles travelled	3.1	3.4	3.2

*For 2014 and average columns, numbers were established from the reported percentages.

Figure 1.5 compares fatality and casualty per billion travelled miles, it shows that cyclists are just under pedestrians and both cyclists and pedestrians are above car drivers in terms of fatality rates. For casualty rates however, cyclists come on the top of all other travel groups by a considerable difference. It could be concluded from these figures that the roads in UK are risky for cyclists, justifying the public perception of this mode of transport as unsafe.

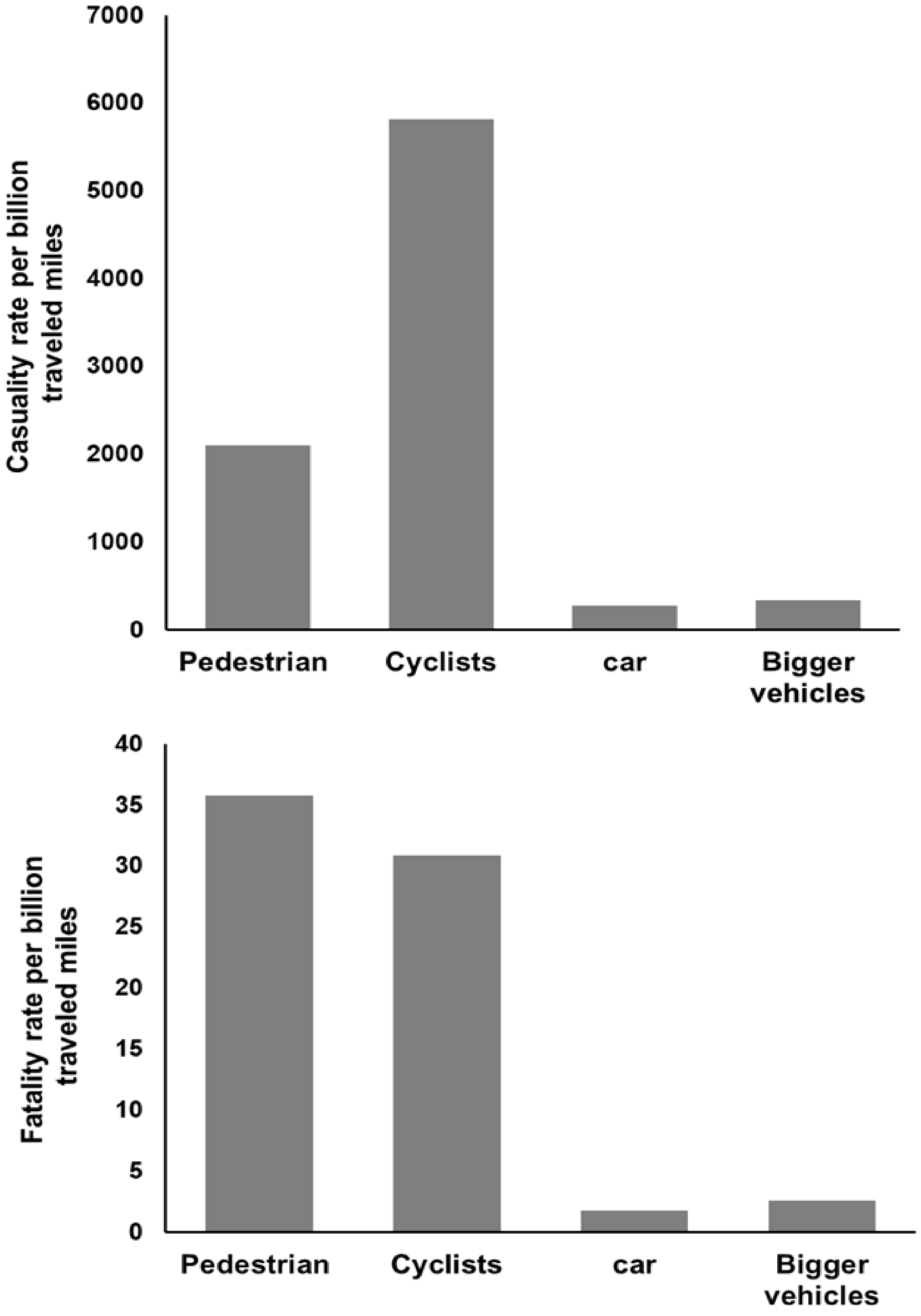

Figure 1.5 Fatality and casualty rate per billion travelled miles of different travel modes. Based on data from DFT (2015b). 'Bigger vehicles' refers to lorries, goods trucks and similar large-sized motor vehicles.

The next section will discuss the proposed role of road lighting in mitigating the safety challenges facing promoting cycling in the UK. Other than road lighting, the literature has suggested several measures that policymakers could take to encourage the uptake of cycling, this includes using independent cycling paths, giving priority for cyclists at intersections, more privileges for cyclists over car drivers in traffic law, the availability of bicycle parks, mixed land use (existence of commercial, residential and service buildings within approachable distance) to reduce the length of cycling trips (Pucher and Buehler, 2008). Besides, factors related to the socio-cultural dimension were also suggested to influence the decision to cycle. For example, Heinen et al. (2013) carried an online questionnaire involving 4000 participants from four districts in the Netherlands where they evaluated the influence of work culture on the tendency to cycle. They found that certain social factors like cycling support culture in the workplace, either by colleagues or the employer, correlate positively with selecting cycling as travel mode. Also, the existence of indoor bicycle storage; availability of changing rooms, and the need to use the bicycle during work time also have been suggested to motivate cycling. On the other hand, long commuting distance; delivering goods tasks and the availability of other transport modes near the workplace have been suggested to demotivate cycling. The authors stated that these findings should be interpreted as indicative giving that they were driven from the overall results pattern rather than a statistical significance value.

Thus, several themes could be followed by research that targets increasing the population of cyclists by improving the conditions on the roads. In the current thesis, the approach will be investigating the influence of light and lighting on cycling promotion, more details in the following section.

1.4 The potential role of lighting

Given the diverse benefits more cycling could potentially bring to society, as discussed earlier, the main aim of this thesis is to provide objective evidence that can contribute to encouraging people to choose cycling more as a travel mode.

The current research pursues this goal by investigating the potential role of road lighting on improving cycling conditions on the roads, first by making cycling safer, and second more enjoyable i.e. improve the cycling experience.

British Standards for road lighting highlight the multidimensional role lighting can play in improving the urban environment for different road users at the after dark (BS 5489-1:2013). When extending beyond the precise definition of safety used in this thesis i.e. traffic safety (see Section 1.1), different lighting approaches to safe cycling could be introduced such as: aiding the identification of hazards on the road, feeling safe about a location (reassurance), and better navigation/movement. Another suggested role of road lighting is aiding the visibility of pleasant scenes e.g. tourist attractions and land marks (Boyce, 2019; BSI, 2013).

The following are several themes where road lighting is suggested to improve the environment for cycling during the after dark:

1) Detecting trip hazards and improve visual performance (Fotios and Cheal, 2013; Uttley et al., 2017).
2) Improvement of quality of life within urban contexts by making journeys more appealing and enjoying thus enhancing cycling experience (Sener et al., 2009b) this could be done by aiding the perception of appealing scenes in the environment (Boyce, 2019).
3) reassurance (Boyce et al., 2000).
4) Being seen by car drivers (Thornley et al., 2008; Twisk and Reurings, 2013).

The work of this thesis extensively covers themes 1 and 2 which will be reviewed in Chapter 2, the literature review, in more detail under Section 2.5 (Visual perception and cycling experience); and Section 2.6 (detecting hazards on the road). The primary focus (detecting hazards) aims to improve the safety conditions on the roads through enabling appropriate lighting for cyclists and will constitute the main body of this thesis, whereas the secondary focus (cycling experience) sought to improve the quality of cycling experience thus increasing the desirability of this travel mode, see Figure 1.6.

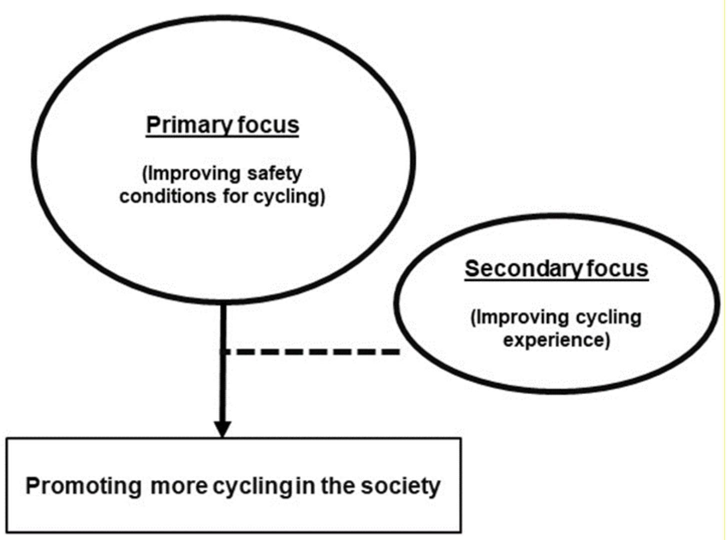

Figure 1. 6. The primary focus and the secondary of the current thesis, each sought to contribute for cycling promotion.

The following section describes current recommendations for road lighting, particularly where related to cyclists in an urban environment.

1.5 Current road lighting guidelines

The requirement to enhance the conditions for cycling routes has received a growing focus in environmental and transport policy (DFT, 2015a). The quality of cycling routes is recognised as being one aspect which affects the decisions of people to cycle (BSI, 2013; Forsyth and Krizek, 2011). After dark lighting enables better visual conditions for cyclists, in order for them to see (significant objects in the environment) and be seen (by other road users such as car drivers). Furthermore, lighting has a role to play in generating an interesting and delightful atmosphere (Boyce, 2019), that is likely to encourage more cycling (BSI, 2013).

Cyclists are supported by two forms of lighting – road lighting and bicycle lighting. In this thesis, ‘road lighting’ refers to the exterior lighting used to illuminate roads and urban areas. This also applies on areas where no motorised movement is present such as footpath, cycle path, parks, etc. Bicycle lighting refers to the lamps fitted to a bicycle, usually a front lamp facing forward enabling the cyclist to see ahead, and a rear lamp facing backwards to enable visibility to road users approaching from behind.

The amount of light provided by a lighting system can be quantified in terms of illuminance or luminance. Illuminance is ‘’the luminous flux falling on a unit area of a surface’’, whereas luminance is ‘’luminous intensity emitted per unit projected area of a source in a given direction’’ (Boyce, 2014, p. 7).

Design guidance for road lighting in subsidiary roads, BS 5489-1:2013 (BSI, 2013), specifies the amount of light in terms of illuminance. Accordingly, in this thesis, illuminance is used when referring to road lighting. To aid understanding, the amount of light from bicycle lighting is characterised instead using luminance. Table 1.2 shows differences between road lighting and bicycle lighting. See Figure 1.7 for road lighting and bicycle lighting illustrations and additional specifications.

Table 1. 2. The terms road lighting and bicycle lighting within the context of current study.

Lighting term	source	Mounting position
Road lighting	Lamp post	Luminaires usually positioned at the top of lamp posts with a mounting height range between 5 -15 m following the street context e.g. subsidiary street or highway (BSI, 2013)
Bicycle lighting	Front lamp on a bicycle	Mounted up to 1500 mm above the ground level (BSI, 1982).

1.5.1 Road lighting for cyclists

The provisions of standardised recommendations are one means of meeting legal obligations for providing adequate lighting settings, with the assumption that recommendations are based on a sound empirical basis. Such recommendations in the UK are supplied by the British Standards documents BS 5489-1:2013 and CEN/TR 13201-1:2014 (BSI, 2013, 2014). CIE 115-2010 (CIE, 2010) is the international equivalent.

The documents outlined above provide criteria for implementing and sustaining road lighting for various situations. CEN/TR 13201-1:2014 which stipulates lighting requirements for a series of lighting classes, the P-classes. The requirements include minimum values of average and minimum illuminance as shown in Table 1.3.

These lighting classes of CEN/TR 13201-1:2014 are implemented to enable the utilisation and progress of services and road-lighting products in nations that are members of the European Union. Consideration has been given to standards of road lighting in these nations through defining the lighting classes and as described in CIE 115:2010 (2nd Edition). The objective is, wherever possible, to harmonise the needs. The purpose of the P-classes, Table 1.3 is for cyclists and pedestrians travelling on footpaths, cycle paths, emergency lanes and other areas of the road which are separate or are adjacent to the carriageway; and also for pedestrian paths, parking areas, schoolyards and residential streets.

Table 1.3. Recommended lighting P-classes for the benefit of cyclists and pedestrians. The table indicates a reproduction of Table 3- P lighting classifications from (BSI,2014).

Class	**Horizontal illuminance for class P**		**Additional requirements if facial recognition is necessary**	
	Average (minimum maintained), lux	**Minimum (maintained), lux**	**lowest illuminance on at a point on vertical plane lx**	**lowest semi-cylindrical illuminance lx**
P1	15	3	5	5
P2	10	2	3	2
P3	7.5	1.5	2.5	1.5
P4	5	1	1.5	1
P5	3	0.6	1	0.6
P6	2	0.4	0.6	0.2
P7	Performance not determined	Performance not determined		

One example of the tables used to determine P-classes is Table 1.4, this choice is prescribed by the traffic flow and the ambient luminance for areas associated with slow-moving vehicles, cycles and pedestrians (subsidiary roads) based on the associated traffic density. It can be observed in the table that ambient luminance i.e. environmental zones E1 to E4, has no effect on the selection of P-classes, however including them in the table is suggested to be informative to light design should the environmental zone of a given context be considered.

Table 1.5 is another table provided in BS 5489-1:2013 document which provides adjustment of lighting classes in response to changes in S/P ratio of the light source.

To explain the S/P ratio, the rods and cones distributed on the eye retina are stimulated differently between photopic vision (daylight or high indoor light levels) compared to scotopic vision (darker environment e.g. Lower ambient light levels) with rods being more active in scotopic environments and likewise cones are in photopic environments. Therefore, the light intensity units could be misleading if the scotopic/photopic ratio which explains a person’s visual responsiveness to the light source is not indicated. In summary, the S/P ratio explains how much of scotopic or photopic vision in response to a light source is stimulated (CIE, 2010).

Table 1.5 illustrates the benefit of higher S/P ratios of a light source in reducing the level of used illuminance for a given P class in three common light conditions as described in the table.

Table 1. 4. Selection of lighting classification on the basis of the context of a subsidiary road with regard to traffic of pedestrians, cyclists and slow-moving vehicles. The table below is a reproduction of table A.6 under selection of lighting classifications (Annex A) from BS 5489-1:2013 (BSI,2013).

Traffic flow	**Lighting class**	
	Ambient luminance: **Very low (E1) [4] or low (E2)**	**Ambient luminance:** **Moderate (E3) or high (E4)**
Busy [1]	P4	P4
Normal [2]	P5	P5
Quiet [3]	P6	P6

[1] Busy road = correlates with high traffic areas and possibly commercial, residential, and public services.

[2] Normal traffic = with a similar traffic flow to residential areas access roads i.e. main entrance/exit of housing district.

[3] Quiet traffic = within roads in residential areas mostly related to immediate properties or could be used to access similar roads and properties.

[4] The ambient luminance descriptions E1 to E4 indicate the environmental zone as described in ILP GN01 [N5].

The Table is initially derived from the Institute of Lighting Professionals (ILP) report: Lighting for Subsidiary Roads (ILP, 2012), where a more detailed table providing more S/P ratios for different light sources could be found.

As the current road light guidelines do not describe the empirical foundations of its recommendations (Fotios and Gibbons, 2018) and that there is a need for more action in producing scientifically-based lighting recommendations, lighting for Subsidiary Roads report (ILP, 2012) is nevertheless a positive step. The current gap is mentioned in ILP report by considering numerous scientific studies on the topic of visual performance and road lighting where a discussion about how the results reveal a long time limitation in some recommended light properties in the guidelines such as the possibility of reducing recommended illuminance level by using higher S/P ratio. Sustrans, an organisation based in the UK which motivates cycling infrastructure, advocates that lighting of a maximum of 5 lux maintained average and 1 lux minimum maintained level should be sustained for cycling activity (Sustrans, 2012).

Table 1. 5. Examples of maintained illuminance with changes in light source S/P ratio. This is a reproduction of Table A.7 under selection of lighting classifications (Annex A) from BS 5489-1:2013 (BSI,2013).

Lighting class	**Benchmark (e.g. Ra* < 60 or unknown S/P ratio)**		**S/P ratio = 1.2 and Ra ≥ 60 (e.g. warm white lamps)**		**S/P ratio = 2 and Ra ≥ 60 (e.g. cool white lamps)**	
	Average (minimum maintained), lux	**Minimum (maintained), lux**	**Average (minimum maintained), lux**	**Minimum (maintained), lux**	**Average (minimum maintained), lux**	**Minimum (maintained), lux**
P1	15	3	13.4	2.7	12.3	2.5
P2	10	2	8.6	1.7	7.7	1.5
P3	7.5	1.5	6.3	1.3	5.5	1.1
P4	5	1	4	0.8	3.4	0.7
P5	3	0.6	2.2	0.4	1.8	0.4
P6	2	0.4	1.4	0.4	1.1	0.4

* Ra = general colour rendering index as defined in CIE 13.3 (CIE, 1995).

However, in areas where potential crime risk is not high, lower levels of lighting are allowed (Sustrans, 2012). Having said that, the Sustrans document refers to light levels on the 2003 version of BS 5489-1 and that report is now out of date, being replaced by the current version in 2013. The main difference between these versions, with regard to the focus of the current study, is replacing the former S-classes by P-classes when addressing road lighting levels for pedestrians and cyclists. In one sense, the information provided in Sustrans' document is outdated.

1.5.2 Bicycle lighting

Within the UK, the required lighting equipment for bicycles which are ridden legally in the hours of darkness is stipulated by the Road Vehicles Lighting Regulations Act 1989 (amended 2009) (DFT, 2009). Bicycles used in of darkness are required to have working lamps and reflectors (BSI, 1992). The lights also need to be visible and clean. On the front of the bicycle, the lamp and reflector must be white, while at the rear they must be red (BSI, 1986). Lamps should be mounted up to 1500 mm maximum above ground level and the rear reflector mounted between 250 and 900mm above ground level (BSI, 1982).

The Road Vehicles Lighting Regulations permit flashing lights to be used on bicycles (front and rear) in the hours of darkness: the flash rate must be between 1 and 4 Hz.

Reflectors are also required to be mounted on the pedals and wheels. Reflectors mounted on the lead and trail edges of pedals are required to be amber (BSI, 1982). Wheel-mounted reflectors should be yellow or white and fitted to both the front and back wheel (DFT, 2010). See Figure 1.7 for illustration about road lighting and bicycle lighting specifications and the related lighting guidelines of each.

A European Union (EU) directive allows equipment evaluated according to the law of different EU nations to be used in the United Kingdom if they have comparable safety specifications. One of the largest bicycle sales markets is in Germany (Fotios and Castleton, 2017a); consequently, the K-mark requirements of Germany are broadly utilised by bicycle lighting equipment manufacturers including those in the UK market.

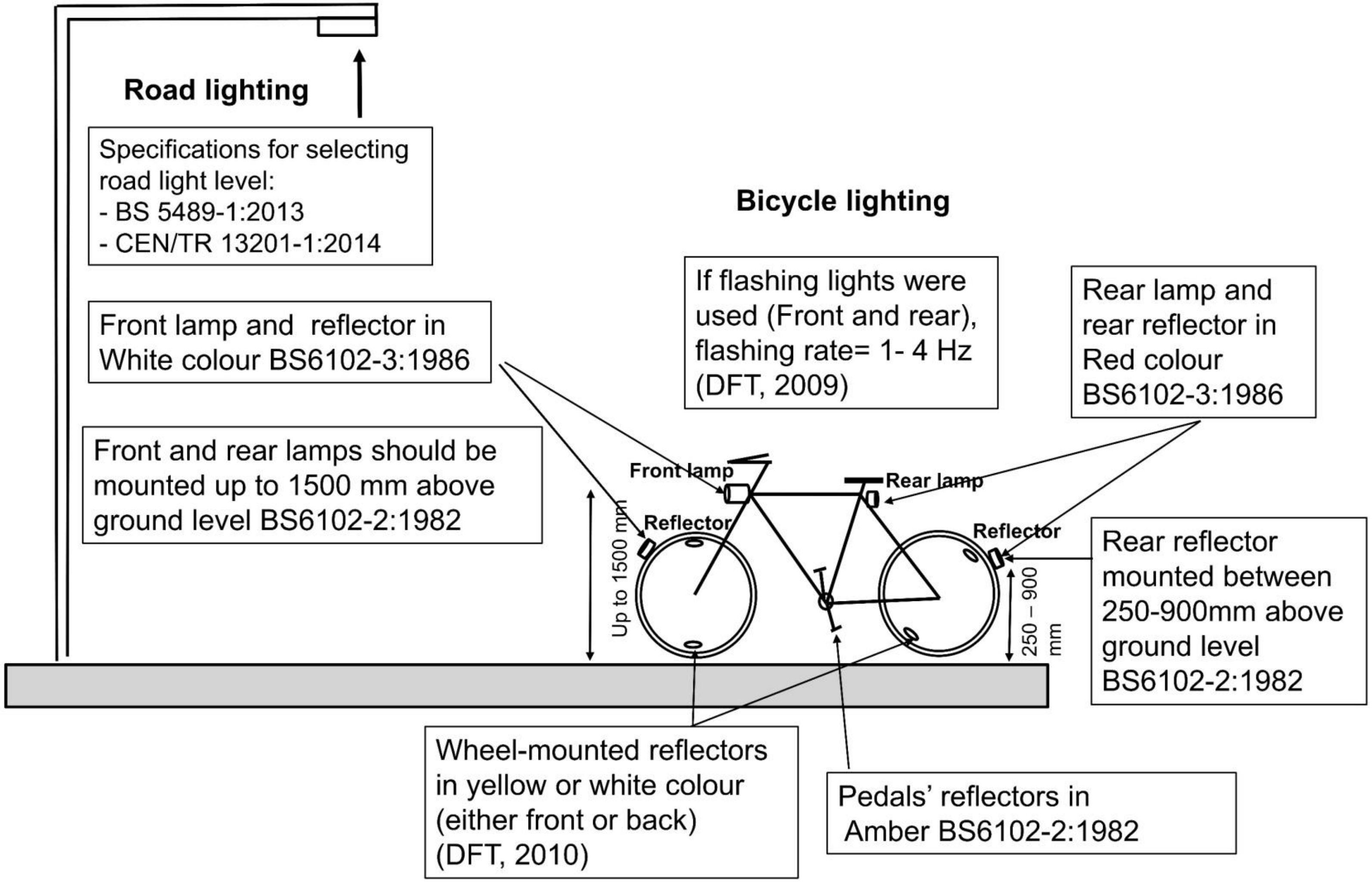

Figure 1. 7. Road lighting and bicycle lighting specifications with the relevant guidelines reference of each.

The K-mark stipulates that the front lamp should satisfy particular illuminance distribution requirements. The necessary illuminance pattern is depicted in Figure 1.8. The HV point is the crossing of a straight line from the lamp in a vertical plane which is 10m from the lamp. At this point, the illuminance ought to be greater than 20 lux. However, the illuminance should be below or equal 2 lux in Zone 1 as it is considered a dark area. The design of this distribution has the intention of supplying sufficient visual clarity forward to the bicycle, while simultaneously restricting possible glare for other road users who are using the road. Furthermore, it has been applied as an objective for bicycle headlamp design (Cai et al., 2014). However, the effectiveness has not yet been assessed with regard to enhanced cyclist vision or safety.

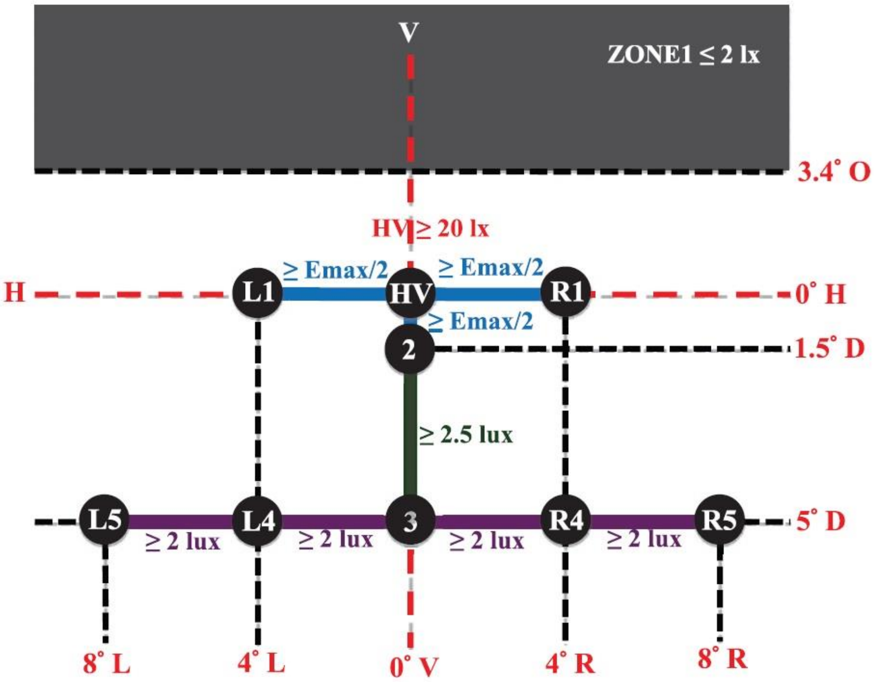

Figure 1. 8. Bicycle lamp lighting specifications as required by the K-mark regulation (after Cai et al., 2014).

1.6 Evidence of lighting for cycling and bicycle lamps

Generally, British road lighting standards do not provide information about whether the grounds used to set a lighting class for a road are empirical or not. This means it is not known if the suggested lighting properties are adequate for cyclists' visual needs or were optimised to its best efficacy. In addition, there is an opportunity to reduce energy consumption should lower light levels than the current used found to be sufficient for the visual performance of different road users. Investigating cyclists' visual needs is proposed to prioritise where and how road lighting would be most beneficial.

A more systematic procedure is therefore needed, placing the empirically evidenced visual needs of road users at the core of lighting-class selection and other light parameters such as road light intensity, bicycle lamp mounting position, bicycle light intensity, S/P, etc.

When comparing British specifications of bicycle lights with other European standards such as the German K-mark regulations, both standards supply a comprehensive illuminance threshold on multiple points on a proposed vertical plane. This is utilised in order to test the suitability of bicycle lamps. Nevertheless, these standards do not inform whether their specifications had considered the various visual tasks performed by cyclists on the road or not, or the best lighting properties to satisfy each.

In the principal British road lighting standard, BS 5489-1:2013 cyclists are not regarded as an independent group of road users like car drivers or pedestrians, and their visual needs are considered to be similar to pedestrians when choosing lighting classifications for a road. This is to say that no particular considerations for cyclists' specific visual requirements are provided.

Standards and recommendations for lighting (and any other item) should be founded in credible empirical data. Such data may be laboratory experiments, designers' experience, and user feedback. The critical requirement is that such data are available to the public so that the basis of standards and recommendations is known, can be challenged, and can be changed with developments in technology, user practice, and scientific understanding. The basis of current guidelines for road lighting is unknown (Fotios and Gibbons, 2018), and will be explored in chapter 2.

1.7 Research aims

The main aims of the current research are:

1- To investigate the influence of ambient light on the public tendency to cycle (chapter 3).
2- To identify the critical visual tasks of cyclists when travelling within urban environment (chapters 4 and 5). This is to establish what visual tasks are important for safe cycling hence to provide appropriate lighting.

3- To investigate the role of ambient light on cyclists' perception towards pleasant/attractive features of urban environment as such perception is proposed to reflect positive cycling experience (chapter 6).
4- To investigate how lighting can support the critical visual needs of cyclists as established in aim 2 (chapters 7 and 8).
5- To provide recommendations and define the area of improvements or confirm existing road lighting guidelines (chapters 9 and 10).

1.8 Thesis structure

This thesis is divided into six parts. The first part comprises Chapter 1, which provides an overall background regarding the benefits of promoting cycling in UK society. It highlights the fact that the cycling population in the UK remains smaller than that of similar developed countries and suggests reasons for this.

Greater attention to the role of lighting is proposed as a means to overcome current challenges facing the promotion of cycling in the UK, particularly with regard to improving road safety conditions for cyclists. The current road lighting guidelines for cyclists are also reviewed, highlighting the need for new empirical evidence to either support current lighting specifications or establish new ones.

Part 1 also explains why targeting and objectively identifying the visual needs of cyclists can help provide new evidence to support or change road lighting guidelines for cyclists.

Part 2 reviews the literature (Chapter 2) on how ambient light can influence the desire to cycle in a community. It explores the utility of eye-tracking methodology and how this approach can be implemented to determine the critical visual tasks undertaken by cyclists. The limitations of previous work are also considered. Followed by how perceptions of aesthetic/attractive scenes in the environment correlate with positive cycling experience and the effect that ambient light and the characteristics of the cycle path have on such perceptions. The review then focuses on studies that have investigated the effect of specific lighting properties on visual performance, particularly visual detection under variations of light properties. This establishes which lighting properties should be investigated to improve current road lighting guidelines for safer cycling.

Part 3 discusses the significance of a study conducted in Sheffield, UK that investigated the effect of ambient light on cycling numbers using a seasonal daylight-saving hours event (Chapter 3). This provided an opportunity to count cyclists at the same hour of the day over two weeks under different ambient light conditions (daylight versus after dark).

Part 4 reports the method and results of the main eye-tracking experiment, which was conducted in a natural setting using two parallel measurements: dual task and skin conductance response. These were used to discriminate critical fixations from the overall number of fixations produced by the eye-tracking apparatus, thus overcoming the limitations of previous research (Chapters 4 and 5). Chapter 6 discusses a pilot study that performed a post hoc analysis on data from the main eye-tracking experiment reported in Chapters 4 and 5. The purpose was to evaluate cyclists' perceptions of attractive/pleasant elements in urban context (architectural features were used as the unit of analyses) where an increased visual engagement, under two ambient light conditions (day and after dark), was utilised as an indication of a positive cycling experience.

Part 5 presents the method and results (Chapters 7 and 8, respectively) of an obstacle detection experiment. This was a critical visual task for cyclists that was based on the results of the main eye-tracking experiment. This laboratory study simulated a real world situation where a cyclist approaches an obstacle on the road. Detection task performance was assessed under different light conditions to evaluate the specific light properties recommended by road lighting guidelines (UK).

Finally, part 6 integrates the findings and results presented in preceding chapters with implications and conclusions to help improve current road lighting specifications for cyclists (Chapters 9 and 10). This part also addresses the limitations of this research and potential areas of research to be carried out in the future.

1.9 Summary

Despite the multiple benefits cycling can bring to society, cycling rates in the UK remain comparatively low. Public concerns over safety, safety in general, are believed to be the main reason behind this, a perception supported by the high number of reported causalities and fatalities of cyclists on the roads. Existing road lighting guidelines state that lighting has a role in making streets safer for cyclists from several aspects. The guidelines recommend parameters of lighting such as the intensity of road light and bicycle light in order to achieve this objective. Despite this, existing road lighting guidelines does not inform about its scientific grounding. Further research is therefore needed to either validate the current guidelines or contribute in establishing a new one. In either case, the potential of road lighting in improving cycling conditions within urban context will be explored.

Other than the safety aspect of cycling the current road lighting guidelines state that it is important to optimise the quality of lighting around pleasant sceneries and attractions, thus to enhance cycling experience by making it more enjoyable. In addition to safety optimisation focus. To enjoy this mode of transport forms a further motivation, and is likely to promote higher cycling levels. It is worth noting that safety and cycling experience objectives are interrelated, for example, a safer cycling path could mean positive cycling experience as safety related challenges on such roads are suggested to be lower than less safe paths. When people feel safe they are, theoretically, more comfortable (Calvey et al., 2015) and more inclined to observe attractive sceneries in the environment around them (Li et al., 2012).

An ideal urban environment for cycling should generally incorporate both safety and an enjoyable experience, both of which are proposed critical to the promotion of cycling in the community.

To determine what further lighting should be provided for cyclists, a key prerequisite is to identify the most important visual tasks carried during the after dark, as such tasks should be satisfied by road lighting for safer cycling.

The following chapter synthesises previous literature on the relation between lighting and cycling including: The influence of ambient light on cyclists' number; approaches used to determine visual tasks of cyclists; indications of positive cycling experience and studies exploring specific lighting properties and visual performance.

Chapter 2. Literature review

2.1 Introduction

Chapter 1 described why promoting cycling in the community is a worthwhile objective, emphasising the benefits to personal health through physical activity and the society well-being by the reduced use of motorised transport reflected in reduced CO2 emissions and traffic jams. In the UK, however, the number of cyclists is far lower than in other countries in Europe (Fotios and Castleton, 2017a; Pucher and Buehler, 2008). One reason for this is that the public does not perceive cycling to be a safe form of travel (Fotios and Castleton, 2017a). Road lighting has the capacity to optimise environmental conditions for cycling during the after dark and by that fewer fatalities and accidents are anticipated (BSI, 2013).

In addition to improving safety conditions on the road for cyclists, another approach to promoting cycling is to improve the cycling experience by making it more enjoyable. A cyclist’s perception of the aesthetic features of an urban environment is believed to reflect positively on the travel experience (Snizek et al., 2013; Titze et al., 2007). Furthermore, the fact that safety concerns are low in a given context, such as cycling on high quality rather than low quality path, promotes more observations of the general environment rather than elements related to cycling tasks or safety such as observing the near path to prevent falling from possible obstacles or other surface irregularities (Vansteenkiste et al., 2014).

Chapter 1 argued that current road lighting guidelines, including those for cycling, are not based on robust scientific foundations (Fotios and Castleton, 2017a; Fotios and Gibbons, 2018). Further research is therefore needed to determine how to optimise road lighting, including the lighting characteristics that are required if the urban environment is to be improved for cyclists.

The current chapter reviews past research on lighting and cycling to determine whether criteria for optimal lighting are known and, if not, to identify what and how further research should be pursuit.

2.2 The influence of ambient light on the decision to cycle

To rise the population of cyclists in the UK and other locations, it needs to be a viable transport mode at all times of the day, including when it is dark. However, there are a number of reasons why darkness may deter people from cycling. For example, it may be harder to see potential hazards. Research involving pedestrians has demonstrated that obstacle detection decreases as illuminance reduces (e.g.Fotios and Cheal, 2009; Uttley et al., 2017) and this is also likely to be true for cyclists. Illuminance is also associated with reassurance (e.g.Boyce et al., 2000; Fotios et al., 2018; Fotios et al., 2015a). For example, when it is dark people may feel less safe and therefore be discouraged from cycling. For prospective cyclists, the fear they will not be seen by vehicle drivers may also demotivate them. This is understandable, as rates of accidents and fatalities among pedestrians and cyclists due to car accidents are higher in poorly lit areas (Eluru et al., 2008). Darkness may therefore increase a prospective cyclist's perceived risk of colliding with a car, dissuading them from using their bicycle when it turns dark.

The effect of light on the decision to cycle was investigated in several studies. For example, in a longitudinal study Heinen et al. (2011) found women to be less inclined to commute by bicycle during the after dark time. Whereas Spencer et al. (2013) who conducted their analysis on interview and focus group transcripts of 24 cyclists found light level factor to be determinate to the decision to cycle or not.

It therefore seems likely that light conditions may influence whether or not someone chooses to cycle. However, confirming this with robust evidence, and quantifying the size of any effect of darkness on cycling rates, is not straightforward. One approach would be to obtain subjective assessments of the impact of darkness on whether someone is likely to choose to cycle, and how safe they might feel when cycling after dark. Such subjective judgements can, however, be prone to bias and produce misleading conclusions (Poulton, 1977, 1982). This is illustrated by research into the effect of light levels on the pedestrians' reassurance (Fotios et al.,2018). A number of past studies have assessed whether illuminance levels influence perceived safety after dark by asking participants to provide a subjective assessment of how safe they feel on roads whose average illuminances vary (e.g.Boomsma and Steg, 2014; Loewen et al., 1993; Rea et al., 2015). For example, Peña-García et al. (2015) asked participants to complete a series of rating scales in five different streets, with each street varying in light intensity and lamp colour. Although Pena-Garcia et al. concluded that higher illuminance of road lighting correlates with people reassurance, this is a trivial finding as it fails to address the impact of stimulus range bias (Fotios, 2016). This is because Pena-Garcia and colleagues collected participants' responses generated by different illuminance levels under varied contexts i.e. different street environments. Had the same street was evaluated and the illuminance levels were the only variable a different set of conclusions would probably have been drawn (Fotios and Castleton, 2017a).

A further problem with using rating scales is that individuals may be forced to make a judgment about a phenomenon to which they may otherwise pay little or no attention (Fotios et al., 2015a). Flawed responses are also anticipated as a result of the way the assessment questions are structured (Toomingas et al., 1997). Consequently, concerns have been raised that it may not be possible to generalise the findings of subjective assessments about the impact of light and lighting on a behaviour such as the decision to cycle. An alternative, more objective approach is to examine actual behaviour rather than subjective judgements. This involve counting and comparing the number of cyclists during daylight with the number of cyclists when it is dark. However, this observational approach also has its potential drawbacks. For instance, several aspects increase the likelihood of obtaining cycling as a travel mode such as time of day, weather, and purpose of journey (commuting or pleasure), and these may confound any analysis of the effect of light.

What is required is a method that compares cycling rates at the same time of day, whether this is in darkness or daylight. Such a method of analysis has been conducted before, but in a different context – namely the influence of ambient light on road traffic collisions (Sullivan and Flannagan, 2002). For this analysis, the researchers compared the number of accidents involving pedestrians and vehicles at a given time of day in the weeks immediately prior and afterward of daylight saving time. The daylight-saving time (DST) clock change occurs twice a year, usually around the end of March and October. In March, the national clock in the UK is advanced by one hour and then reverts in October. This change is also implemented in other countries, including in Europe and North America. The aim is to ensure that a greater number of daylight hours can be used during the months of March to October. This also affects the times when dawn and dusk occur, meaning that an hour in darkness before daylight saving will be an hour in daylight once the time has changed. This is especially true in the weeks immediately before and after the time change. With regard to the influence on the daily routine, this means that commuting in daylight before the Autumn clock change will become commuting in darkness after the clocks change. The reverse is then true for the Spring clock change. Sullivan and Flannagan (2002) found a significant difference in the number of road traffic accidents prior and afterward the DST clock change, see Figure 2.1.

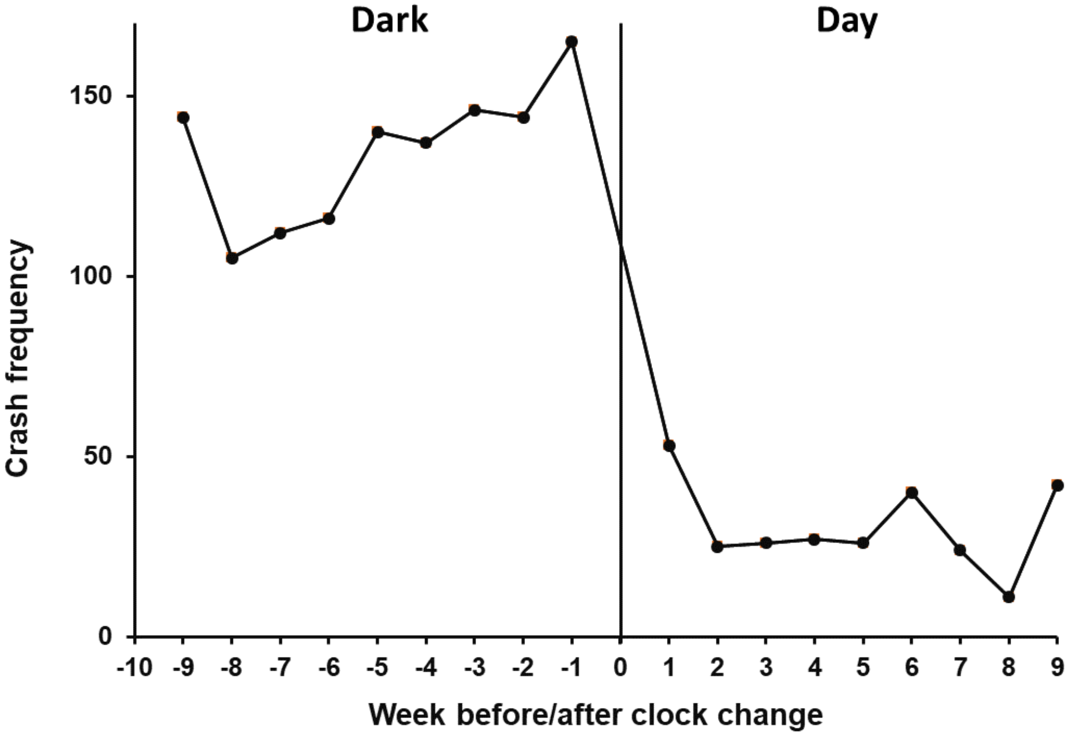

Figure 2. 1. Rate of crashes resulting in pedestrian fatalities in the United States from 1987-1997, prior and afterward the clocks were changed to Daylight Saving Time (DST) (Redrawn from Sullivan and Flannagan, 2002).

The clock-change method has been extended by other researchers to evaluate ambient light effect on the numbers of people walking and cycling, for example, Uttley and Fotios (2017) analysed an established database comprising counts of pedestrians and cyclists over a five-year period from automated counters installed at 31 locations across Arlington, Virginia, USA. The automated counters were located on different types of cycle routes, such as road cycle lanes and cycle tracks. A case hour of 17:00 to 17:59 was chosen for the Autumn clock change, as this time interval fell in daylight prior the clock change and darkness afterward the change. Another case hour of 18:00 to18:59 was selected for the clock change in Spring, where the ambient light was first in darkness and then in daylight after the clock change.

Any observed changes may, however, be attributable to other changes prior and afterward clock change, such as changes in temperature and rainfall. To counter this, four control periods were selected where there was no change in light conditions before and after each clock change: day, early day, dark, late dark. Using the odds ratio (OR) as shown in equation 2.1, they divided the frequencies of the case hour taken two weeks prior and afterward the clock change in both Spring and Autumn DSTs and compared this with the control hours.

$$Odds\ ratio = \frac{A/B}{C/D}$$ **Equation 2. 1.**

Where:

A = frequency of pedestrians or cyclists during the case hour in daylight;

B = frequency of pedestrians or cyclists during the case hour in darkness;

C = frequency of pedestrians or cyclists during control hours when the case hour is in daylight;

D = frequency of pedestrians or cyclist frequency during control hours when the case hour is in darkness.

The A/B ratio denotes daylight/darkness, where a higher ratio indicates a higher tendency to cycle during daylight than after dark. However, this does not account for other influential factors such as the weather. Assuming that the effect of such factors is consistent throughout the day, the C/D ratio thus serves to weight these changes (Szumilas, 2010).

The overall odds ratio of (all control hours were summed) was 1.38 (1.37 – 1.39 95% CI, $p<0.001$) indicating a significant effect of daylight on increasing the desire to cycle (see Equation 3.1 in Chapter 3 for calculations of confidence intervals (CI)).

It was concluded that there is a significant increase in cycling during daylight, which indicated that ambient light played a role in motivating active traveling (Uttley and Fotios, 2017).

However, one limitation of this approach is that only a small portion of time was analysed. This raises a concern about the extent to which the findings could be generalised. Another limitation relates to the possibility that other peripheral events may influence the decision to cycle, such as public events and public holidays. These may generate outliers during the weeks before and after the time change.

To address these limitations, Fotios et al. (2017b) utilised the same odds ratio method used to assess the impact of darkness on cyclist numbers, but this time over the whole year rather than the short periods prior and afterward annual clock changes. An hour was selected that was in daylight during a segment of the year and dark for the remain of the year. Changes in cyclist frequencies during this hour were again evaluated with changes in control hours, where the light condition was constant over the same period. The overall odds ratio was 1.67 (1.66 – 1.68 95% CI, $p<0.001$), which again confirmed the negative impact darkness has on the public tendency to cycle.

Both studies (Fotios et al., 2017b; Uttley and Fotios, 2017) used cyclist count data from a single city in the USA. Different countries, and different cities within any given country, may have different tendencies with regard to cycling due to differences in terrain, cycling infrastructure, public activeness, and the correlation between residential, leisure, and industrial areas. For example, Pucher and Buehler (2008) found that the share of cycling trips relative to other means of transportation in the UK is much lower than the mean percentage of Netherlands, Denmark, Germany, and Finland, 1% and 17% respectively, see Figure 1.3. It is therefore not known whether the findings established from one city in the USA are generalisable to other cities within the USA or to locations in other countries. It is, however, reasonable to predict differences in cycling trends between distant countries such as the UK and US given variations in traffic, land use, culture, mean income, and transportation networks (Hallal et al., 2012; Pucher and Buehler, 2008). Further work is therefore needed to determine whether ambient light level influence the decision to cycle in other locations.

2.3 Potential impact of lighting on cycling

As described previously, people may be discouraged from cycling when it turns dark – although further studies (in a range of locations) are needed to confirm this – which limits any attempts to increase cycling uptake. Road lighting and lighting on off-road cycle paths can potentially counteract the negative impact of darkness on cycling rates given that the cycling rate was significantly lower on unlit off-road paths compared with lit on-road paths (Fotios et al., 2017b).

As discussed in Section 1.4, road lighting also has the potential to improve reassurance among pedestrians and other road users (Boyce et al., 2000; Fotios et al., 2018; Fotios et al., 2015a). This is important because areas perceived as safe are associated with increased activeness (Foster et al., 2016). Section 2.2 highlighted the fact that research on lighting and pedestrians' reassurance that employs subjective evaluations may be inaccurate due to not considering the effect of stimulus range bias. Other studies have therefore attempted to provide more robust evidence by comparing ratings of reassurance during daylight and darkness, and then using any differences as a measure of the impact of lighting factor.

For instance, Boyce et al. (2000) used this approach to investigate the association between illuminance and reassurance level during after dark. They collected responses from participants using rating scale questionnaires, once during daylight and again during dark. This enabled a comparison to be drawn between daylight and road lighting (after dark) within a given area. The objectivity of what is an essentially subjective method, the rating scale, was increased by using the same fundamental items in the questionnaires, the same location, and altering only the light environment. This approach aimed to isolate the light variable from other potential sources that may influence reassurance level. Boyce et al. concluded that illuminance level was significant for participants' reassurance, but its effect diminishes once illuminance reaches a certain level of intensity (i.e., a performance plateau).

Lighting may therefore have similar effects on cyclists' reassurance. This is likely to include how fearful cyclists are of not being seen by vehicle drivers, and this could demotivate them from cycling after dark when visual conditions are worse.

Lighting could therefore play a positive role in facilitating safe movement after dark. Previous studies have shown that properties such as light intensity and S/P ratio can facilitate the detection of road obstacles, which are a hazard when travelling after dark (Fotios and Cheal, 2013; Uttley et al., 2017). Further details regarding light and detection performance are discussed in Section 2.6.1.

Light and lighting may also influence another factor related to a person's motivation to cycle, one that is often overlooked or not discussed in the cycling literature – the aesthetic appeal of the surrounding environment. Although safety-related aspects of an environment, particularly traffic safety, are major determinants of whether someone chooses to cycle (the primary focus in this thesis), research has shown that the visual appeal or aesthetics of the environment may also have a substantial influence (the secondary focus, see Figure 1.6). For instance, Titze et al. (2007) administered a cycling questionnaire to evaluate environmental factors associated with cycling behaviour and found that attractiveness of the environment along the cycle path positively influenced the cycling experience. Snizek et al. (2013) employed an on-line survey to investigate the correlation between cyclists' positive and negative experiences and different features of the urban environment in the city of Copenhagen, Denmark. They found that aesthetic features of the urban environment contributed to a positive cycling experience. However, concerns may be raised regarding whether participants were biased by the questionnaire/survey design (Poulton, 1982), as discussed earlier in Section 2.2.

Being able to appreciate our environment whilst cycling relies on being able to adequately see it. This suggests that ambient light, and lighting when it is dark, may play a role in enabling potential cyclists to appreciate the aesthetic qualities of the environment during their journey. Further details on the perception of aesthetic features of the environment and its influence on the desire to cycle and the experience of cycling are discussed in Section 2.5.

As discussed previously, light and lighting influence reassurance level toward a location. It also affects how safely people can move through a location, for example by avoiding hazards and obstacles. These aspects may also influence the ability to appreciate the aesthetics of that environment. For example, if greater cognitive capacity is required to assess the reassurance level of an area or to look out for hazards, people may be less able to look up and around at the wider setting for aesthetic reasons.

2.4 Where do cyclists look?

Light and lighting are likely to influence a range of factors that contribute to a cyclist's initial decision to cycle, in this thesis their safety when they are cycling, and their experience during that journey. This influence is linked to how cyclists perceive their environment. Developing a deeper understanding of how cyclists visually sample the environment, both during daylight and after dark, will help identify key features of the environment cyclists need or want to see. Such information can be used to inform future urban design planning and promote cycling, particularly in terms of how lighting can be designed and implemented to enable cyclists to see what they need to see when it is dark. However, research on the visual behaviour of cyclists within urban environment is lacking, particularly in the context of lighting and light conditions. One particular gap is an understanding of what the key visual tasks are for cyclists.

British standards for road lighting BS5489-1:2013 (BSI, 2013) describe key visual tasks for motorists and pedestrians. For motorists, these are manoeuvring/negotiating other traffic and avoiding obstacles/hazards on road surfaces. For pedestrians, the key visual tasks are detecting pavement irregularity, e.g., obstacles, and recognising the identity/intentions of others on the road in order to take safety measures if needed. By contrast, although the benefits of road lighting for cyclists are mentioned, there is no description of the visual tasks they have to accomplish.

British standard guidelines CEN/TR 13201-1:2014 (BSI, 2014) also differentiate between the visual tasks undertaken by pedestrians and vehicle drivers, stating that the difference in speed makes it more critical for pedestrians to observe near objects and this should be reflected in the light values used. However, in this document, cyclists were grouped with pedestrians without any further consideration as to their own particular visual tasks. Cycling, however, can be considered a mode of transport that is distinct from driving and walking, one reason is that it operates at a different speed (Parkin and Rotheram, 2010).

Furthermore, it is not enough to specify cyclists' visual tasks in general, research needs to identify which of these tasks are critical. This is important for understanding which features of the environment are essential for safe cycling. Identification of such features is useful from a lighting design perspective – it is not possible or desirable to illuminate all areas of an environment a cyclist passes through after dark; however, identifying the critical visual tasks of cyclists will help prioritise which features of the environment should be better lit than others.

Observation of these safety-essential objects are referred to in this thesis as critical visual tasks. Identifying the critical visual tasks of cyclists is a prerequisite for providing appropriate road lighting for cycling. An awareness of non-critical visual behaviour may also be useful when considering how a cyclist experiences the aesthetics of their surroundings during their journey. This can help address how a cyclist looks at their environment when not engaged in safety-critical visual tasks.

One approach to establishing the critical visual tasks of cyclists would be to ask people directly, either by questionnaire or through interviews. Asking people to report their behaviour and the thoughts they have while carrying out this behaviour is a common form of social research (Fernández-Heredia et al., 2014; Gatersleben and Uzzell, 2007). However, as described previously, self-report instruments such as questionnaires can be prone to bias (Poulton, 1977, 1982) and, in the context of understanding visual behaviour, may be inappropriate method to employ. This is because participants may be unaware of where they are looking or how frequently they look at features in the environment (Clarke et al., 2017).

By contrast, eye-tracking can objectively measure and record an individual's eye movements. Since its early use in the late 1800s (Huey, 1898), the technology involved has undergone considerable advancement in recent years to make it a reliable and convenient method. The most widely used method at the present time is 'video-based pupil/corneal reflection'. This requires the use of two cameras, one recording the visual scene and one recording eye movement, both embedded into the eye-tracking apparatus worn by the participant. Computer vision algorithms are then used to identify and record the position of the pupil and corneal reflection. Through calibration, the point at which the person is gazing can then be superimposed onto the scene recorded by the field-of-view camera. The image recorded by this camera depicts the scene observed by the participant, with a cursor indicating the locus of gaze. This technology can also be implemented in mobile apparatus worn by the participant. This enables the participant to move freely around their environment, making the method especially useful for naturalistic studies, see Figure 2.2.

Eye-tracking therefore provides a reliable approach for assessing where cyclists look. Several studies have thus implemented eye-tracking to investigate the visual behaviour of cyclists (e.g. Boya et al., 2017; Mantuano et al., 2017; Vansteenkiste et al., 2014a; Vansteenkiste et al., 2017).

Figure 2. 2. SMI eye-tracking glasses and mobile recording device used in the studies reported in Chapters 4,5, and 6.

Eye-tracking was also used by (Fotios et al., 2015b) to identify the critical visual tasks undertaken by pedestrians. A review of relevant eye-tracking research on cycling is given in Section 2.4.3 and Table 2.1. First, some background is provided on eye movements and why it is useful to study them.

In summary, although the benefits of road lighting for cyclists are mentioned in the current road lighting guidelines, there is limited information available regarding the visual tasks undertaken by cyclists. Further research using eye-tracking in natural settings is proposed as an objective instrument able to evaluate cyclists' visual behaviour under different ambient light conditions.

2.4.1 Studying eye movements

Human vision utilises more than a third of brain resources (Findlay et al., 2003). This means that sight is much more than simply an image reflected on the retina of the eye. Studying eye movements could therefore potentially provide an objective means of understanding the cognitive processes associated with visual performance, such as the important visual tasks undertaken by cyclists in a given situation.

Two types of photoreceptor are distributed over the retina, cones and rods, with the former providing higher spatial resolution than the latter. Cones are concentrated within a 2° visual angle within the centre of the retina (the fovea) and provide high spatial resolution and the ability to retrieve small details. The rest of the visual field is dominated by rods, which have a lower degree of spatial vision than cones but are able to operate at much lower levels of light. Figure 2.3 shows the distribution of rods and cones over the retina. Foveal vision is therefore used for retrieving high visual detail; however, because it occupies a marginal portion of the retina, it is only used to observe objects that capture attention. This is a fundamental reason why people move their eyes, as it enables them to obtain greater visual detail from an important object first detected using peripheral rod-based vision (Hooge and Erkelens, 1999). The movement that occurs when the eye shifts from one location to another is called a saccade; however, during saccades the eye does not capture any visual information. The details are obtained when the eyes settle on an item in between saccades; such instances are called fixations (Holmqvist et al., 2011).

In the context of lighting, it is important to recognise that changes in ambient light and the presence of artificial light generate three types of light environment: photopic (daylight or indoor with high light levels); mesopic (semi dark light condition e.g. dusk or after dark conditions with artificial lighting); and scotopic (after dark with no or marginal artificial lighting, known as night vision) (Boyce, 2014). A mesopic environment ranging between about 0.005 and 5 cd/m^2 (Boyce, 2014) is associated with conditions when the road lighting is on (after dark) and provides the context for current research. Rod and cone photoreceptors are both active in this condition and the dominance of one over the other is determined by several light properties; for example, light intensity. Generally, at lower light levels, such as in mesopic conditions, rods are more sensitive than cones and therefore more responsive (Boyce, 2014).

Indeed, because they are more sensitive to certain wavelengths of light than others, rods are especially sensitive to spectral power distribution (SPD) aspect. The SPD is a light metric that describes the power of variation of wavelengths on a graph (ranging from 380 – 780 nm) each wavelength representing a colour within the spectrum provided by of a light source (Boyce, 2014).

The SPD of light, and S/P ratio, in an environment is therefore likely to influence peripheral detection in particular, as peripheral vision is dominated by the spectrally sensitive rods rather than cones. Moreover, light intensity (illuminance/luminance level) is also likely to influence detection ability in such conditions.

Eye movement or gaze behaviour in a given context can reveal how people analyse and then interact with their surrounding environment. One of the principles underlying this proposition is that once something is being attended to, it is difficult to look elsewhere (Hoffman and Subramaniam, 1995).

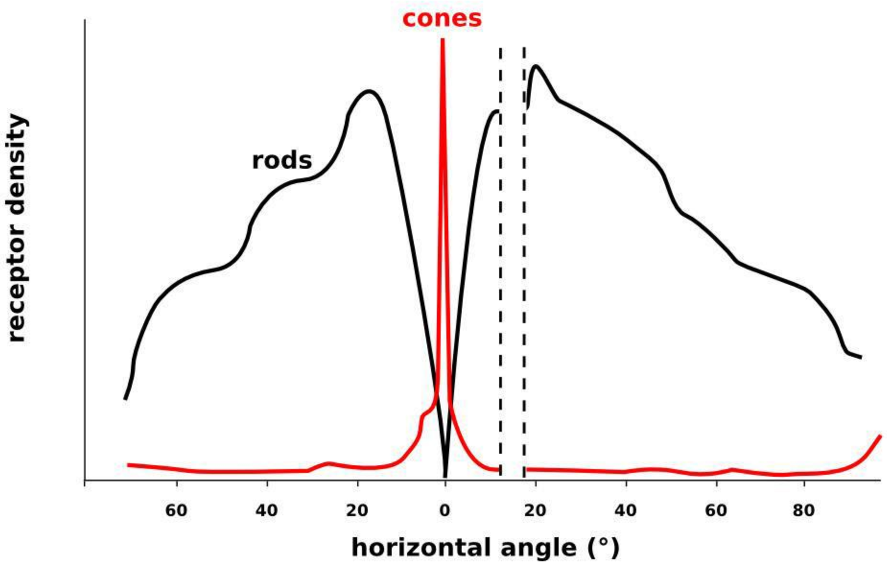

Figure 2. 3. Concentrations of rods and cones from the centre point of the fovea. Image created by Jonas Tallus, reproduced under Creative Commons license. From Osterberg (1935).

Therefore, it is often assumed that fixating on an object means it has secured an individual's cognitive attention. Hayhoe et al. (2003) also identified an association between the directions in which people look and the actions they subsequently take. For example, an individual's eyes will directly fixate on a tool such as a smart phone before grasping it and picking it up.

Eye-tracking apparatus is able to record the saccades, fixations, blinks, pupil size, and gaze direction of the wearer. Rothkopf et al. (2007) found that these metrics can reveal the patterns of cognition exhibited in a specific situation and show why people visually behave in a certain way. Although eye movements and visual behaviour clearly reveal important characteristics of cognition and perception, some eye movements may be less significant than others. For example, it is possible to look directly at something without attending to it. This is illustrated by instances of mindless reading, where our eyes move over the words on a page whilst our minds are elsewhere. Known as attentional blindness (Foulsham et al., 2013), such instances correlate with failing to process something we are looking at directly.

Further discussion of significant versus non-significant visual behaviour is provided in Section 2.4.4.2. A further potential limitation of eye-tracking is the potentially unrepresentative or unrealistic gaze behaviour that is produced in laboratory settings to study eye movements. This is a particular issue when trying to understand the interaction between a cyclists' visual behaviour and their surrounding environment. A discussion of the limitations of eye-tracking research in laboratory settings is provided in the following section.

2.4.2 Eye-tracking: laboratory vs real world studies

Most eye-tracking research to date has been conducted in laboratories. This enables researchers to control experimental variables with precision along with any confounds that may otherwise affect the experimental outcomes. It also enables researchers to minimise the disadvantages of utilising eye-tracking methodology. For instance, some eye-tracking models often need to be fixed in position, which restricts the scope of research in terms of the contexts that can be investigated. Furthermore, despite technological advances, eye-trackers may be overly sensitive and do not yield effective outcomes unless the recording conditions are optimal (Holmqvist et al., 2011). Such conditions are easier to ensure in a laboratory setting.

Nevertheless, the precision afforded in such settings can also be a drawback as it may limit the generalisability of the findings to a real world environment. Consequently, even ostensibly similar studies may yield divergent and inconsistent findings because, in a highly controlled laboratory environment, even a minor change in experimental settings could yield a considerable difference in results. Patla and Vickers (2003), for example, conducted a laboratory study to determine people's direction of gaze whilst walking. They found that 60% of gazes were focused directly onto the path ahead (termed 'travel gaze') and participants proceeded at a steady pace. However, in an almost identical study, Marigold and Patla (2007) found that fewer than 1% of fixations were classifiable as travel gaze. Such a divergent outcome may be the result of variations in the setup of the experiments as the studies involved different tasks and the ground surface used also differed. Thus, even minimal differences in environmental conditions can amplify differences in gaze. This is especially true when there is little else in the immediate environment to capture people's attention, which is a common feature of laboratory experiments.

External aspects of the environment, such as sound, can be a strong determinant of the direction and nature of our gaze. For example, Frens et al. (1995) found that the simultaneous presentation of auditory stimuli and visual stimuli reduces the time spent gazing at the visual stimuli. This suggests that, in natural contexts, we are more probably to orient to the direction of the sounds (Quigley et al., 2008). Results such as these show how holistic environments influence gaze behaviour differently and highlight the role cross-modality processing plays in eye movements. Such everyday environments are not easy to simulate in a laboratory setting.

Jovancevic-Misic and Hayhoe (2009) monitored participants' gaze whilst walking along a circular path within the confines of a large laboratory. Four sets of 12 laps were completed by each participant. At the same time, several confederate pedestrians walked the same path but were asked to behave in a certain way when they approached the participant (e.g. walk towards the participant with the intention to collide or to move away). The results showed that participants learnt the behaviour of the confederates and thus determined the likelihood and duration of fixations directed towards them. Jovancevic-Misic and Hayhoe concluded that the direction of gaze is learnt by people through their experience interacting within an environment. If they are repeatedly exposed to the same environment, their subsequent gaze behaviour will adapt accordingly as they learn. However, this experiment lacks authenticity as such conditions do not reflect the dynamism of the natural environment.

Caution is therefore required when extrapolating findings to everyday, real world situations. Furthermore, the clear theoretical implication that emerges is that, to develop a full understanding of gaze behaviour, laboratory research on eye-movements should be supplemented by research conducted in everyday, natural environments. In so doing, researchers will be able to investigate eye-movements in a range of natural environments. This will help them understand the features that cause such movements to differ in varying conditions. The authentic nature of such research also means that participants are exposed to a more active spectrum of visual (and non-visual) influencers. Consequently, they are able to choose for themselves what to look at and how long to spend looking at it. They are freed from the restrictions of laboratory environments such as limited physical movement and social interactions. The utilisation of eye-tracking research in naturalistic contexts may therefore address several of the inherent limitations of laboratory-based research while providing insights into gaze behaviour. Advances in eye-tracking technology such as the use of glasses with in-built cameras, wireless technology, and smartphones means that such technology is becoming increasingly commonplace and more mobile, facilitating opportunities for use in real world, outdoor environments. However, real world eye-tracking is itself beset by several limitations, often arising as a result of sacrificing the control and precision provided in laboratory settings. In practical and logistical terms, this has implications for the reliability of the data. An obvious example is that of varying weather conditions, especially sunlight. Most eye-tracking devices illuminate the eye using infrared light so that they can determine the direction and position of the pupil. Too much sunlight will flood the eye and render the infrared image unclear. This means the eye-tracking results may be inaccurate, or the signal may be lost altogether (Holmqvist et al., 2011).

A second limitation that arises from the use of real world eye-tracking is that it is no longer possible to maintain rigid control of the features in the environment experienced by participants, or indeed the environment itself. Thus, although environmental unpredictability is a core methodological strength in terms of providing an ecologically valid and authentic context, ensuring that all participants are exposed to identical conditions, or the requisite stimuli within those conditions, becomes extremely problematic.

2.4.3 Previous eye-tracking research on cycling

Eye-tracking studies on cycling have largely been conducted inside the simulated environment of laboratories (Hollands et al., 2002; Vansteenkiste et al., 2014b). Real world studies on cycling have only recently begun to emerge (e.g.Boya et al., 2017; Vansteenkiste et al., 2014a; Vansteenkiste et al., 2017) and remain limited in number. Naturalistic eye-tracking studies on cycling are therefore regarded as pioneering.

For example, Vansteenkiste et al. (2013) carried an experiment in an internal environment where cyclists were requested to cycle along three lanes, each of a different width, using three speed levels. They found that as the cycling became more challenging, involving less space and higher velocity, the rate of safety-related fixations such as looking towards the near path increased and there were correspondingly fewer fixations on the general environment. However, in the real world, arbitrary sounds could impact where people look (Quigley et al., 2008). Different aspects such as features of the surround context, road users, and vehicles could also influence the gaze behaviour of a cyclist, none of which were present in Vansteenkiste et al. (2013) study. This underlines the difference between visual behaviour in natural settings compared to the lab environment.

Boya et al. (2017) used eye-tracking to investigate information acquisition among experienced and novice cyclists in a study of athletic performance and exertion. They asked participants to cycle at a convenient pace for approximately 10 miles on a stationary bicycle. The results showed that experienced cyclists fixated primary on the speed information, motivated by higher performance level, and secondary on distance information (e.g. distance to target information) and were also selective regarding which sources to read. By contrast, beginners tended to focus mainly on distance information, which indicated a higher level of exertion.

Vansteenkiste et al. (2014a) also employed eye-tracking to compare the gaze behaviour of cyclists on a low-quality path (surface comprised of large tiles, some of which had been moved or were missing) to those on a high-quality path (recently re-laid path with a brick surface). Although 10 participants (aged 22 to 24) were recruited, poor quality recordings and traffic conditions meant that data from five participants only were included in the analysis. Participants were asked to cycle a 4 km route around the city that included two straight cycling tracks, high quality and low quality tracks (120 m and 134 m, respectively = approximately each with 25 seconds of video time). Participants did not know which section of the route would be chosen for analysis.

The researchers found that cycling on the low-quality path led to more fixations on the near-road region than on the region further away. This suggests that low road surface quality results in a reduced awareness of distant environmental elements and increased awareness of the area just ahead of the bicycle. This is explained by the higher cognitive load required when cycling on a low-quality track possibly due to greater difficulty in maintaining balance and control of the bicycle or simply because they needed to observe the path surface most of the time to prevent stepping into an obstacle for example. Cycling on a higher quality path with fewer surface irregularities and reduced demand for safety-critical fixations also led to gaze distribution being evenly spread between different regions of the environment. This confirmed previous findings (e.g. Land, 1998; Wilkie et al., 2008) that showed a sustained observation of the road surface is not essential all the time, particularly on good quality, safe routes, and that visual attention could be distributed between various regions of interest. Vansteenkiste et al. (2017) repeated the study with children learning to cycle and found identical patterns of gaze behaviour for low- and high-quality paths.

Mantuano et al. (2017) recruited 16 participants to cycle a defined route in Bologna city centre (Italy) while wearing eye-tracking equipment. They aimed to identify elements in the urban context that could be a risk alarming to cyclists. The researchers found that in ideal cycling conditions, where there are minimal or no safety concerns such as nearby pedestrians or traffic, there is an equilibrium in the distribution of fixations between the centre of visual scene (including the path) and distanced segments of the scene. However, when safety concerns are present this proposed equilibrium is disturbed. They found road discontinuities such as road joints and the existence of nearby pedestrians to be the main source of visual equilibrium disturbance.

Table 2. 1. Summary of previous eye-tracking studies on cycling.

Study	Fixation duration (Milliseconds) ¹	Percentage of data omitted ²	Tracking ratio ³	Findings/implications
Indoor cycling eye-tracking studies				
1) Vansteenkiste et al. (2013)	120 Ms	37%	85 %	The higher speed is correlated with cycling on a wider lane. When cycling on a narrow lane, more fixations are observed on the path. This may be because the steering task is challenging whereas on a wider lane more fixations classified under the general environment are observed, which may indicate a lower cognitive load.
2) Vansteenkiste et al. (2015)	120 Ms	59%	85%	On wider lanes, children looked more at the surrounding environment whereas on narrow lanes they shifted their gaze to near regions. Children are slower than adults when using narrow lanes. The implications are similar to Vansteenkiste et al. (2013).
Real world cycling eye-tracking studies				
3) Mantuano et al. (2017)	Just mentioned the use of fixation detection algorithm	19%	80%	On a shared path, cyclists pay a lot of attention to pedestrians, possibly to avoid accidents. This is likely to reduce the amount of attention paid to other possible hazards.
4) Vansteenkiste et al. (2014a)	Used x, y coordinates of gaze cursor to calculate eye movement distribution. No mention of fixation duration.	50%	80%	On low-quality path, attention was shifted to the nearby visual region ahead of the bicycle and gaze was directed to the path surface, with less attention being paid to the general environment. This possibly indicates reduced alertness to other hazards such as pedestrians, cars, and so on.

Table 2.1 (Cont.)

The effect of experience on gaze behaviour					
5)	**Boya et al. (2017)**	100 Ms	Not mentioned	Not mentioned	Experienced cyclists looked at primary information e.g., speed other than distance, for longer than novice cyclists. They looked less frequently at road information during the last quarter of the trial. This suggests that cycling experience influences gaze behaviour.
6)	**Vansteenkiste et al. (2017)**	SMI fixation detection algorithm and no fixation duration reported	Adults 17% Children 25%	Trials with less than 50% of data were omitted	Children showed visual-motion planning different from adult cyclists but did not reduce speed on the low-quality path than on the high-quality path. Different groups of cyclists have different visual strategies.

[1] Fixation duration, measured in milliseconds, is the minimum duration (threshold) used to consider moments where the gaze rests on an object as a fixation. Any fixation with a duration below this threshold was omitted from fixation data.

[2] Percentage of data omitted denotes data not included in the analysis for quality reasons.

[3] Tracking ratio is the percentage of frames in which the eye tracker can determine the direction of gaze. For example, when eye-tracking at 60 Hz and the apparatus is able to measure the direction of the eye at 50 frames per second, the tracking ratio would be 50/60 = 83.33% i.e. The percentage of time gaze direction could be determined in respect to the trial duration.

Table 2. 2. Sample size and method implemented in eye-tracking studies reported in Table 2.1.

	Study	Method	Sample size [1]
1)	**Vansteenkiste et al. (2013)**	On a gymnasium floor, three straight lanes (all 15 m) were drawn to investigate gaze behaviour while varying the lane width.	19 recruited, 12 used (21-28 years old)
2)	**Vansteenkiste et al. (2015)**	Same method as Vansteenkiste et al (2013) but instead used children participants to investigate whether their visual strategy differed from adult observers.	17 recruited, 7 used (8-year-old children)
3)	**Mantuano et al. (2017)**	Seven different urban locations were used, each with different characteristics (total length 3 km) to determine how different urban items e.g., path continuity, intersections, and presence of pedestrians, can influence visual behaviour.	16 recruited, 13 used (age mean = 25 ± 7 years)
4)	**Vansteenkiste et al. (2014a)**	High-quality and low-quality paths were chosen from a longer 4 km route to investigate gaze behaviour patterns for each. Participants were naive as to which segment of the longer route would be analysed.	10 recruited, 5 used (22-24 years old)
5)	**Boya et al. (2017)**	An indoor study compared the visual behaviour of experienced vs novice cyclists using an information acquisition task. While cycling on a fixed cycle, the screen showed a simulation of a cycling situation that was slightly offset from the centre of the participant's visual field. The participant therefore needed to turn his/her neck to be able to see. This was to avoid accidental fixations and ensure only genuine fixations toward the information presented on the screen were produced.	20 participants (10 experienced and 10 novice) (age mean = 37 years)
6)	**Vansteenkiste et al. (2017)**	A replication of Vansteenkiste et al.'s (2014a) study but with children to compare each type of visual behaviour.	Adults: 18 recruited, 15 used (age mean = 26.5 years) Children: 16 recruited, 12 used (age mean = 9 years)

[1] Recruited= The initial sample participated in the study. Used= The actual sample used after excluding low quality trials.

Eye-tracking is therefore an objective method for establishing gaze behaviour. This thesis is primarily concerned with the gaze behaviour of cyclists: establishing where they look will inform considerations as to what needs to be lit after dark to ensure safe travel then potentially encourage more people to cycle in such conditions. However, only few studies on cyclists' gaze behaviour using eye-tracking could be found. Moreover, no studies have examined cyclists' gaze after dark, which is desirable information regarding the provision of lighting for cyclists.

A key finding that emerges consistently from eye-tracking studies carried out with cyclists is that task difficulty can affect where a cyclist looks. For example, narrowing of the path (Vansteenkiste et al., 2013) and a reduction in surface quality (Vansteenkiste et al., 2014a) can increase fixations towards the near path. When travelling around a bend, cyclists' dominant area of fixation will change depending on their speed due to changes in task demands (Vansteenkiste et al., 2014b).

Previous eye-tracking research with cyclists also has implications for the visual behaviour of cyclists after dark. It is reasonable to assume that the task demands associated with cycling, and the level of safety concerns, may increase when it is dark due to reduced amounts of visual information. In addition, people may be less likely to cycle when it is dark, probably similar to pedestrians (Fotios et al., 2017b), which means they have less experience of cycling under lower light levels. Variations in the level of experience can result in differences in how information in the environment is visually sampled (Boya et al., 2017; Vansteenkiste et al., 2017).

Based on the above, variations in task demands and experience imply that the gaze patterns of cyclists are likely to differ between conditions of daylight and darkness. This requires confirmation, along with the nature of any differences caused by the ambient light conditions. The implications of previous cycling eye-tracking research can be summarised as follows:

- Cyclists fixate more on the near path when in challenging situations, such as cycling on a narrow cycle lane (Vansteenkiste et al., 2013; Vansteenkiste al., 2014b) or on a low-quality path where there are obstacles and irregularity on the road surface.

- More fixations on the general environment or far regions can be anticipated once on a high-quality road or in less hazardous situations (Mantuano et al., 2017; Vansteenkiste et al., 2014a).
- The experience of cycling influences visual behaviour (Boya et al., 2017).

2.4.4 Limitations of previous eye-tracking research

As discussed in Section 2.4.3, a small number of studies have utilised eye-tracking to record cyclists' gaze behaviour in real world environments. These have explored the increase in safety-related fixations in challenging environments, differences in information acquisition based on experience, differences in gaze behaviour as a result of path quality, and gaze behaviour indicative of optimal conditions. However, despite their value, these studies have several inherent limitations as will be discussed in the following.

2.4.4.1 A lack of naturalistic studies

Although some cycling eye-tracking studies have been conducted outdoors, they cannot be considered fully naturalistic. For example, Vansteenkiste et al. (2014a) only included short sections of the route cycled, namely high quality (120 m) and low quality (136 m) paths. Each section consisted of a straight cycling track adjacent to greenery and water canal on one side and trees some distance from the main road on the other. Consequently, the findings do not reflect the visual behaviour of a cyclist when traveling through several parts of the city as there would be variations in urban features and traffic conditions, including time spent cycling on the main road or in separate cycling lanes i.e. cycling on different types of cycle path.

By contrast, Mantuano et al. (2017) asked cyclists to travel around different areas of Bologna, Italy. This meant that the route involved a variety of cycling contexts, including different types of cycling path such as mixed use with pedestrians, on the road, and cycling-only tracks. However, Mantuano and colleagues only reported the results for one segment of the cycled route thus not reflecting cyclists' visual behaviour within variety of urban contexts.

Boya et al. (2017) focused on one particular visual behaviour, the acquisition of road information. They also used an indoor cycle and video screen rather than conducting the study outdoors on real roads or paths.

There has therefore been a limited focus in the literature on the critical visual tasks undertaken by cyclists in naturalistic settings (see Table 2.1 for details of the contexts of previous eye-tracking studies). The second limitation of previous eye-tracking studies on cycling, the critical fixations aspect, will now be considered in more detail.

2.4.4.2 Critical fixations (visual attention)

Naturalistic research involves exposure of a broader array of dynamic visual stimuli than is the case in artificial environments such as those in laboratory studies. Consequently, it becomes very difficult to ascertain whether cognitive attention is actually being oriented to the location of the item being fixated or is being directed elsewhere. Furthermore, in natural environments, non-visual processes may also capture attention; for example, when negotiating the immediate environment, walking, or planning what to do next (Hausdorff et al., 2005). In contrary, in a laboratory environment, it is more likely that participants will specifically focus their attention on the objects they are observing as they will be less distracted by external distractions and thus their cognitive resources will be fully engaged. The link between attention and gaze is therefore a more problematic issue in eye-tracking research conducted in the real world. The relationship between attention and gaze behaviour is assumed to be close, which makes eye-tracking a valid method for assessing cognition (Rothkopf et al., 2007). However, the dynamic of this association is not entirely clear. Eye-tracking studies utilising reading tasks have shown there is a gap between attention and visual patterns among participants. For instance, Foulsham et al. (2013) found that although the number of fixations on a text may be high, this did not correlate with a greater understanding of the material being read.

To build on this research, a parallel form of measurement when using eye-tracking is needed to differentiate between critical fixations (correlates with genuine attention) and normal fixations (genuine attention is unknown). This will help clarify the cognitive status of the participant and whether they are mentally engaged with the item on which they are visually fixating.

Critical fixations are instances when a person is evidently paying cognitive attention to a specific item. This can be determined by implementing a secondary task such as an audio dual task, involving a reaction to a sound stimulus, where a reduced efficiency in the subordinate task indicates the presence of a significant visual item. (See Chapter 4: Sections 4.2 and 4.3 for a literature review of the audio dual task and skin conductance response (SCR) methods proposed in this thesis to enable the discrimination of critical fixations from the broader set of normal fixations).

The dual task approach has previously been used in pedestrian eye-tracking context to distinguish critical fixations (Fotios et al., 2015b; Fotios et al., 2015c). However, an aspect that previous eye-tracking research on cycling has failed to address is the ability to distinguish critical fixations from the remaining set of fixations. The literature on eye-tracking and cycling was therefore reviewed to assess the suitability of eye-tracking as a tool for identifying the critical visual tasks undertaken by cyclists. It is only by addressing these gaps can objective evidence be provided with respect to the critical visual tasks undertaken by cyclists.

As mentioned earlier, the perception of non-safety elements of the environment, especially the aesthetic features, was suggested to be a motivation for cycling as it enthuses a positive cycling experience, this will be discussed in more details in the following section.

2.5 Visual perception and cycling experience

In the context of efforts to promote cycling as a travel means that is sustainable, it is pertinent to ask whether and in what way the built environment exerts its influence. For several environmental features this influence will be more direct; for example, secure parking for cycles, measures to calm motorised traffic, and the use of separate cycle lanes (Pucher and Buehler, 2008). For other environmental features, the influence is likely to be more indirect, as is the case for landscape, water surfaces, and architecture (Ball et al., 2001; Forsyth and Krizek, 2011; Snizek et al., 2013). Such features can be characterised as relating to the aesthetics of the environment.

Snizek et al. (2013) conducted an on-line survey to investigate the correlation between cyclists' positive and negative experiences and different features of the urban environment. Respondents were asked to identify up to six locations in municipalities in Copenhagen and Frederiksberg, Denmark through which they had cycled: three locations where their experiences were positive and three locations where they were negative. Overall, 398 cyclists responded and 890 locations were extracted for analysis. The results indicated that aesthetic features of the urban environment such as water surfaces and green edges contribute to a positive cycling experience. These findings highlight the crucial role such aspects play in promoting an invigorating and valuable cycling experience.

Titze et al. (2007) recruited 538 students to carry a cycling questionnaire to assess the environmental, social and personal factors associated with cycling behaviour. Two categories of cyclists were evaluated, regular and irregular. The tendency to cycle for the latter group was found to be influenced by attractiveness of the environment along the cycle path. The appearance of the environment has been shown to influence other forms of active travel besides cycling, such as walking. For example, Borst et al. (2008) investigated the relationship between the attractiveness of streets and the desire to walk in three areas in Schiedam, Netherlands. Subjects were required to record which streets they preferred or not walking along, resulting in each street having a perceived attractiveness for walking value. This was compared against a range of physical characteristics related to the street in order to assess which characteristics were most associated with streets considered more walkable.

The results indicated that the visual attractiveness of a street encourages people to walk. This supports a possible correlation between certain features of the urban environment and the desire to engage in active travel. The researchers concluded that the existence of business buildings e.g. shops and restaurants in the street influence how attractive a street is for walking along compared with other types of building such as high rise or vacant buildings.

The results of all these studies indicate that viewing certain attractive features of the urban environment can encourage physical activity (Borst et al., 2008; Larco et al., 2012) and enhance people’s travel experience, notable examples of such features being landscapes (Velarde et al., 2007), bodies of water (Snizek et al., 2013), and attractive architectural features (Sussman and Hollander, 2014). Furthermore, cycling for leisure or pleasure, even when commuting, is suggested to be a strong motive for engaging in cycling (Sener et al., 2009b).

Therefore, providing an attractive and stimulating visual environment for cycling can provide physiological benefits (Section 1.2) as well as psychological benefits such as overcoming stress and fatigue, and enhancing overall health. Velarde et al. (2007) confirmed these psychological benefits in a review of the literature on visual perceptions of urban or natural landscapes and their effect on well-being.

Previous research and development concerning design practice have, however, placed only limited emphasis on the quality and aesthetic experience of cycling (Forsyth and Krizek, 2011). Although cyclists' perception of the urban environment is a neglected factor, it is an important one to consider if cycling promotion influencers to be fully understood.

The safety focus of previous cycling studies is evident in the literature on eye-tracking, where most research on cyclists’ visual performance has primarily been concerned with issues of safety. For example, investigating visual behaviour when traveling on a low quality path compared to a high quality path (Vansteenkiste et al., 2014a) or comparing cycling on a path shared with pedestrians with paths for cyclists only (Mantuano et al., 2017).

With most research focused on safe cycling and related facilities, only a limited amount of research has been conducted on the quality aspects of cycling. Further research is therefore required to understand the perceived features of the environment that are linked more closely to cyclists’ experience of the environment i.e. enjoyment. The following section, therefore, reviews the role of light in facilitating the perception of aesthetic features of the urban environment.

2.5.1 Light and the perception of aesthetic features

As noted previously, Section 2.2, cycling during daylight occurs more frequently than cycling after dark, even when taking place at the same hour of the day (Fotios et al., 2017b; Uttley and Fotios, 2017). One reason for this may be that people feel less safe when cycling in darkness. However, little is known about the way light might influence the perception of aesthetic urban features, yet this may be another factor that influences whether people choose to cycle at night.

For example, in their investigation of the visual tasks of pedestrians, Fotios et al. (2015b) found differences in visual behaviour between daytime and after dark conditions. In particular, pedestrians tended to fixate more on the path during the night than during the day, thus reducing the instances of observing the surrounding environment. This suggests light properties influence the way people visually experience their surroundings and are likely to encourage more active travelling.

To explore this further, Painter and Farrington (1997) evaluated the influence of optimised road lighting on the number of pedestrians observed on predefined streets. Their method involved counting the number of pedestrians in three areas: an intervention area (where lighting was improved for the assessment), nearby zone and control zone (the latter two with no lighting intervention). The results show a definite increase in the number of walkers following the improvement of road lighting.

It was suggested earlier that the cycling experience could be improved by the inclusion of aesthetic elements near to the cycling path (Snizek et al., 2013). This was also suggested to increase active travelling (Borst et al., 2008). In this respect lighting plays a role in enabling the perception of such features, particularly during after dark (Boyce, 2019).

Lighting also has the potential to improve public well-being as observing aesthetic features can reduce anxiety and stress levels (Kaplan and Kaplan, 1989; Korpela et al., 2008; Ulrich, 1979). Aside from the positive health benefits derived from visual engagement with natural scenes, it is clear that people receive pleasure from such visual engagement (Kaplan and Kaplan, 1989) and appropriate lighting after dark is decisive in facilitating this pleasure as it enables seeing such elements.

The Attention restoration theory (ART) developed by Kaplan and Kaplan (1989) suggests observing pleasant scenes of the environment enhances people restoration from fatigue and stress hence benefits the well-being. Nikunen et al. (2014) studied the influence of several light attributes (e.g. Brightness, evenness, colour quality) on the different components of ART, including the 'fascination' produced from perceiving pleasant scenes, being an essential component of ART. A total of 55 participants carried a rating scale questionnaire while walking through five locations, on the outskirts of Helsinki, Finland. The first three locations were pathways between residential areas where greenery and trees are dominant in the surround. The other two locations were walking paths near housing units. The findings of the study, although explorative, hinted at a potential role of lighting in promoting pleasant environments by enabling better perception of aesthetic aspects thus contributing positively to pedestrians’ experience and well-being. In their study Karmanov and Hamel (2008) stressed that attractive feature of built environment have the same capacity of producing restoration as appealing natural sceneries.

To study the influence of light after dark on the desirability of public squares to the public, Nasar and Bokharaei (2017) recruited 62 participants and asked them to rate their impressions of 24 simulated images representing three public plazas where the light modes in 3D constructed images were varied. The light variables that were used to create 8 mixes of light modes were bright vs dim, uniform vs non-uniform, and overhead vs peripheral.

Nasar and Bokharaei found that a combination of bright, uniform and overhead illuminance had contributed to making the plazas more aesthetically appealing, interesting, and places which participants wanted to walk to and around. Among the lighting variables, brightness was reported to have the most significant effect on making a place desirable. However, the use of simulated images of public squares raises a concern as to whether the findings can be extrapolated to a real-life situation where the control of different variables is more challenging.

Nevertheless, lighting appears to render aesthetic elements within the urban context more conspicuous, thus providing a positive experience for observers (Boyce, 2019). Road lighting can achieve this through three suggested pathways:

- Guiding the observers attention to specific places (Boyce, 2019; Edensor, 2015).
- Promoting a sense of safety (reassurance), thus making people feel less reluctant to cycle near these areas (Boyce et al., 2000; Fotios et al., 2015a).
- Aiding vision to capture precise details of different elements that the human eye, understandably, cannot otherwise do at lower levels of light (Gregory, 1973).

Nevertheless, regardless of which of these pathways is taken, real world studies that empirically investigate the influence of ambient light on cyclists’ perception of aesthetic elements remains scarce.

2.5.2 The influence of cycle paths

Research does, however suggest, that cyclists' perception of the built environment is influenced by the paths on which they travel. For instance, Vansteenkiste et al. (2014a) found that when cycling on a low quality road surface eye-tracking fixations shifted from more distant to closer areas. The researchers argued that the quality of the path surface influenced cyclists' observation of the general environment due to an ingrained high awareness of safety when cycling on a road with poor surface conditions.

Thus, cyclists may be less able to experience their visual environment on low quality or less safe cycle routes due to an increased need to observe the near path. This reduces any potential benefits of a pleasing and stimulating urban environment and potentially may limit the quality of the cycling experience.

However, this is not likely to be the only feature that determines safety-related visual attention. For example, proximity to and interactions with other forms of traffic are also likely to be a salient factor (Jacobsen et al., 2009).

For example, cycling routes that are integrated into main roads are cognitively demanding as the attention of cyclists is directed towards safety and steering issues (Pucher and Buehler, 2008). If cyclists have to focus more on interactions with other forms of traffic, they will be less able to experience and enjoy their visual surroundings.

This is why Forsyth and Krizek (2011) argued that a separate cycle path could increase cyclists' visual engagement with their urban surroundings. Such paths are considered safe even when a potential increase in collisions between pedestrians and cyclists is accounted for (Krizek et al., 2009). Snizek et al. (2013), for instance, found that using a designated cycle path engendered positive cycling experiences, whereas cycling on main roads was associated with negative cycling experiences.

Moreover, these paths may provide an increased opportunity for cyclists to view enjoyable aspects of their environment such as architecture, social activities, and greenery, all of which enhance the overall cycling experience. Previously, it was found that a significant source of cycling motivation is the presence of routes with beautiful scenery (Winters et al., 2011).

Fotios et al. (2017b) identified a difference in the tendency to cycle after dark between two types of cycle path. Specifically, people tend to cycle more on lit on-road cycle paths than unlit footpaths or off-road cycle paths. The obvious variable that differs between these paths is road lighting, although other characteristics of the cycle path may also contribute, such as proximity to motorised vehicles. However, the way in which cyclists experience aesthetic aspects of the urban environment, and the influence of light levels and cycle paths on this experience, have yet to be addressed.

The current section has discussed factors proposed to influence cyclists' perception of environment aesthetic features giving that these are suggested to evoke good cycling experience once present within the visual field; this is covering the literature of the secondary focus for promoting cycling followed in the current study. The following section will review the literature about the primary focus, the safety aspect of cycling, specifically detecting hazards on the roads and the role of road lighting and bicycle lighting properties in detection performance as assessed by previous studies. Detecting hazards was selected for further literature over other safety aspects of cycling, e.g. cyclists' conspicuity to nearby car drivers, for several reasons. First, it enables assessing light properties' influence on cyclists' visual performance. Second, the existence of previous studies in this particular area that focused on other groups of road users such as pedestrians and car drivers hence providing an opportunity to extend the research to cyclists.

2.6 Detecting hazards on the road

Vansteenkiste et al. (2014a) and Mantuano et al. (2017) state that observing the path is a critical visual task for cyclists. This is most probably because it enables cyclists to detect obstacles in the road or surface irregularities and thus avoid potential accidents such as swerving on the road or tripping into a pothole, so the visibility of road obstacles is critical for safe cycling (Fabriek et al., 2012).

Previous research on pedestrians has shown also that this is a critical visual task (Caminada and Van Bommel, 1984; Fotios et al., 2015c). Road lighting must therefore provide adequate road surface visibility as a preventive measure against cycling accidents in addition to improving cyclists' conspicuity to other road users (Fotios et al., 2017a). Unfortunately, current road lighting guidelines do not provide any empirical evidence as to how light should be provided to improve cyclists' capacity to spot possible hazards on the route (Fotios and Goodman, 2012) (see Chapter 1: Section 1.6). To acquire such evidence, further information is needed on how light can influence the visual tasks undertaken by cyclists, particularly those that are critical for their safety.

The following sections will therefore start with a review of previous studies on hazard detection performance, including the effect of specific lighting properties such as intensity (illuminance/luminance level), S/P ratio.

Potential hazards are surface irregularities such as a raised tile or broken pavement edge, and any unexpected object on the cycle path that could initiate an accident. These hazards may result in the falling of cyclists or cause an unexpected swerve to avoid surface irregularities if not given enough time to take evasive action (Fotios and Cheal, 2013). Swerving on a road shared with motorised vehicles is clearly a high risk for a cyclist.

In after dark conditions, detection of potential hazards on the cycle path is more difficult as vision is impaired due to reduced levels of light. However, appropriate road lighting can help mitigate against this. Uttley et al. (2017) investigated the effect of road lighting on obstacle detection by pedestrians. They found that specific light intensities and S/P ratios enhanced pedestrians' ability to detect obstacles. Further investigation is required to establish whether these findings are replicable in the context of cycling given differences in posture, travel speed, and the ability to negotiate hazards. If not, different forms of road lighting maybe needed.

For instance, a cyclist may fixate on the path for reasons other than searching for possible hazards, such as navigating the bicycle or maintaining it at a specific position within the cycling lane. Thus, looking at the path may be more critical to a cyclist than a pedestrian. If this visual difference can be confirmed empirically, it will suggest that enhancing the visibility of the road surface for cyclists is a priority for road lighting.

2.6.1 Road lighting and detection

Properties of light such as intensity and S/P ratio are believed to affect the detection of objects using peripheral vision. However, there is a point beyond which there is no further improvement in performance, otherwise known as a plateau (Rea and Ouellette, 1991). More details in the following.

When it is dark, rods outperform cones in respect to sensitivity to light, with the former dominant over most of the retinal area (peripheral vision) except for 2° dominated by cones (foveal vision). The latter are more responsive in photopic conditions and are used to retrieve precise details. Given the larger size of the peripheral area and the fact it is dominated by rods, hazard detection during the after dark is a function of peripheral vision (Boyce, 2014; Uttley et al., 2017). At low levels of light, such as when cycling after dark, peripheral detection is expected to be enhanced by higher levels of luminance and S/P ratio.

To the best of the author’s knowledge, no previous laboratory studies have investigated the effect of lighting properties on the visual detection of obstacles in the context of cycling. However, several studies exploring this interaction have been conducted in relation to driving cars and pedestrians. For example, Bullough and Rea (2000) explored hazard detection among drivers under mesopic conditions using a driving simulation apparatus. To assess foveal vision, they evaluated light intensity (luminance) and S/P ratio. Participants were asked to drive along a predefined route where light efficiency was quantified in terms of the rate of accidents that occurred. Luminances of 0.1 to 3.0 cd/m² and four S/P ratios (ranging from 0.64 to 3.77) were tested. The results showed that luminance level was significant in terms of safe driving whereas S/P was not. This can be explained by the fact that S/P only exerts an effect on peripheral vision, whereas the study only tested performance of foveal vision

The experiment was then repeated using a peripheral detection task. For this task, a target shifted 18° from the central visual axis appeared at random intervals. Participants were asked to respond out loud once they had detected it. The researchers found that the detection rate was affected by an increase in both luminance and S/P ratio.

Crabb et al. (2006) then conducted an outdoor detection study in which participants were asked to sit inside a stationary car located on the road and detect a target that appeared within their peripheral vision. The target was a flip-dot panel that changed from black to grey. Participants needed to respond every time this change occurred. Road lighting was used to illuminate the panel so that two different lamps (high pressured sodium and metal halide) could be compared. The results showed that neither light intensity nor S/P had any effect. This may be because luminance from the car headlamps, which also fell on the peripheral target, was not accounted for, which raises concerns about the accuracy of the reported light levels.

In another outdoor study, Akashi et al. (2007) asked participants to drive a car along a road where a combination of car headlamps and variations of road lighting were tested to assess peripheral detection. A peripheral target simulating a pedestrian was positioned 8.3° away from a centrally located fixation target. Participants were asked to use braking and accelerating as responses to the detection of the peripheral target, depending on whether the target was moving into the road or away from the road. Three different lamps were assessed (including the headlamps at the fixation target): high pressure sodium HPS (0.115 cd/m² and S/P = 0.91), high luminance metal halide HLMH (0.115 cd/m² and S/P = 1.28), and low luminance metal halide LLMH (0.0.089 cd/m² and S/P = 1.32).

The results showed that detection performance was greater under HLMH than HPS, although both had an identical luminance value. This suggests that S/P ratio may influence detection performance. The performance under LLMH, however, did not significantly differ from that under HPS although the luminance value of LLMH was lower. It may therefore be the case that the higher S/P ratio of LLMH compensates for its lower luminance relative to the HPS lamp.

Research on peripheral detection has also been conducted in contexts other than car driving. For example, He et al. (1997) measured reaction times to assess detection performance under a range of different light values produced inside a chamber. The target was situated 15° away from the central axis. Participants were asked to press a button each time they saw the target. They were also told to continually fixate on a point in the centre of the apparatus to ensure only their peripheral vision was used.

Two common light lamps were compared in this study; metal halide and high-pressure sodium with S/P ratios of 1.67 and 0.61, respectively. Eight luminance values ranging from 0.003 to 10 cd/m² were tested. Participants responded faster under a metal halide lamp than under a high-pressure sodium lamp. The authors concluded that metal halide lamp light properties were better at facilitating detection, supposedly due to higher S/P ratio

Similarly, Eloholma et al. (2006) employed a reaction time task to assess detection performance in relation to light metrics. They used a peripheral target of 0.29° visual size positioned 10° off-axis. The target was presented in five colours: red, amber, green, cyan, and blue, each of which varied in terms of S/P values and peak wavelengths. Three different levels of background luminance were assessed: 1, 0.1, and 0.01 cd/m^2 with two contrast variations: 0.2-low and 3.0-high. The researchers found that lower luminance correlated with lower detection performance and that a low contrast had a negative effect on performance. At the highest level of luminance, the effect of colour was exhibited in low contrast conditions. The colour effect was present at lower luminance values but only in higher contrast conditions. This suggests that the contrast levels, high or low, act in opposite ways with respect to the level of light intensity.

In all these studies, participants were required to fixate on a point or a target located at the central axis as the detection target was placed off-axis at a distance determined by the experimenter to ensure foveal vision was not being used. However, such an approach does not entirely prevent participants from fixating on the peripheral target. Akashi et al. (2014) attempted to address this by asking participants to affix a random moving needle to a point on the central axis using a control scroll. Either a low- or high-level contrast was used as the background to the needle. The needle task thus ensured that peripheral vision only was utilised for detection.

A second detection task (the main test on peripheral detection) was then performed. For this task, a 0.75° visual size peripheral target was placed on four off-axis locations (at different distances). When participants detected a target, they had to release a button they were holding. The performance was measured in terms of reaction times.

Overall, three variations of light were tested: HPS (S/P 0.44, 0.1 cd/m^2); Fluorescent lamp (S/P 1.97, 0.1 cd/m^2); and a second fluorescent lamp (S/P 1.97, 0.03 cd/m^2). The results showed that the low contrast foveal task only affected performance under the 0.03 cd/m^2 florescent lamp. In the high contrast foveal task, performance under the 0.03 cd/m^2 florescent lamp was the same as performance under HPS in both low and high contrast conditions. This indicates that, although luminance was low, both contrast and S/P ratio may improve detection performance. The 0.1 cd/m^2 florescent lamp achieved the highest overall performance.

The obstacle detection studies that are most relevant to cyclists are those that investigated obstacle detection among pedestrians. Although cyclists and pedestrians should be considered two separate modal groups, they are perhaps more closely aligned than cyclists and drivers due to greater similarities in speeds and task requirements.

In experimental research involving pedestrians, Uttley et al. (2017) tested the ability to detect obstacles under various levels of road lighting: 0.2, 0.6, 2, 6.3, and 20 lux, and three S/P ratios (1.2, 1.6, 2.0), resulting in 15 light combinations. To simulate walking in the real world, an obstacle was located in the centre of a 1-1 scale apparatus. This obstacle consisted of a cylinder situated flush with the floor of the apparatus and raised to seven different heights ranging from 0.5 to 28.4 mm, which were presented randomly. The obstacle progressed to the designated height at two different speeds, 1mm/s and 2mm/s. These were designed to simulate the way real world obstacles increase in size when pedestrians approach them. Participants were then asked to perform a secondary foveal task while walking on a treadmill. This task involved following the path of a moving crosshair projected onto the far side of the apparatus. The foveal task prevented participants from fixating on the obstacle directly and thus ensured peripheral vision was used.

The researchers found that increasing illuminance correlated with better detection performance but this plateaued at approximately 2 lux. There was therefore no benefit in increasing illuminance beyond this value, although it may be beneficial in situations where obstacle detection is not the only purpose of the lighting. They also found that the S/P ratio only influences visual capacity at the smallest value of light (0.2 lux).

Based on the above, luminance level alone is not sufficient to predict detection performance, other light attributes should also be considered such as SPD values (e.g. S/P ratio), contrast levels, and colour properties. Task difficulty (e.g., detecting a low contrast target versus a high contrast target) may also influence the effect of S/P ratio on detection performance. Table 2.3 provides a summary of previous studies on lighting properties and detection performance.

Table 2. 3. Summary of previous research on detection performance under different light properties.

Study	Method	Lighting factors tested		Detection target	Findings/Conclusions
		Lamp type Luminance/illuminance	S/P ratio		
Akashi et al. (2007)	Driving apparatus outdoor	High pressure sodium (HPS), high luminance metal halide (HLMH), and low luminance metal halide (LLMH): 0.115, 0.115, and 0.089 cd/m², respectively	HPS = 0.91 HLMH = 1.28 LLMH = 1.32	Detection target positioned 8.3° away from foveal target	Although HLMH had a luminance level similar to HPS, it achieved better detection performance. This indicates the effect of the higher S/P ratio of the HLMH lamp. LLMH achieved similar performance to HPS although the former has lower luminance value; again, this was due to the higher S/P ratio.
Akashi et al. (2014)	Customised apparatus	HPS and MH lamps 0.1 and 0.03 cd/m²	Not reported	Target was shown off axis at eccentricities ranging between 5° - 30°	MH lamp outperformed HPS when both were at a higher luminance level. When MH was at a lower luminance level, its performance was equal to that of HPS when the latter was at higher luminance, however, this was the case when high contrast task was performed.
Bullough and Rea (2000)	Driving simulation	0.1 to 3.0 cd/m²	Four levels 0.64 to 3.77	Distance of 18° from axis	Increased luminance and S/P improved detection performance.
Crabb et al. (2006)	Outdoor Stationary car	Two types of lamps (HPS and MH) Light levels: 0.08 – 0.67 cd/m² at 15° eccentricities, 0.05 – 0.32 cd/m² at 25° eccentricity	Not reported	Flip-dot panel changed from black to grey: positioned at 15° and 25°	No effect of light intensity or S/P on detection was found.

Table 2.3 (Cont.)

Eloholma et al. (2006)	Driving simulation	0.01, 0.1, and 1.9 cd/m²	5 colours used for targets, resulting in S/P ratios of 0.43, 0.59, 1.98, 3.44, and 11.4 (high contrast target). 2 colours with S/P ratios of 1.35 and 5.22 (low contrast target)	Target shown 10° from axis	The lower performance was exhibited at lower luminance levels, especially at a lower S/P ratio. Low contrast influenced detection when combined with a high S/P ratio (for all luminance levels). High contrast only influenced detection at lower levels of luminance.
Fotios and Cheal (2009)	Customised apparatus	One HPS and two MH 0.2, 2.0, and 20 lux	S/P ratio = 0,57, 1.22, and 1.77	Targets raised from floor at several eccentricities ranging from 10° - 42°	Detection improved with increased illuminance, suggesting a plateau was reached at around 2 lux. Increasing the S/P ratio was beneficial to detection, however, this is only at the smallest illuminance value (0.2 lux).
He et al. (1997)	Customised apparatus Reaction time task used to measure performance	Comparing two lamps: MH, HPS. 8 luminance levels from 0.003 - 10 cd/m²	MH = 1.67 HPS = 0.61	Target located 15° from axis	Detection was better as the luminance level was higher, reaching a plateau after 1 cd/m². Participants reacted faster under the MH lamp than the HPS lamp. This suggests that higher S/P improved detection performance.
Uttley et al. (2017)	Laboratory pedestrians study.	0.2, 0.6, 2, 6.3, and 20 lux	Three levels: 1.2, 1.6, 2.0	Foveal fixation task used to test peripheral detection	Detection performance plateau was reached at 2 lux (similar to some previous studies). S/P ratio enhanced performance but exclusively at the smallest road light value of 0.02 lux.

The results of the studies reviewed in this section may not be linked directly to cycling. For example, cycling is slower than driving, therefore the distance at which an object needs to be detected will be much greater when driving. The task demands of cycling and driving may also be very different and these are likely to influence detection performance (Eloholma et al, 2006).

In summary, research that focuses on improving visual performance among cyclists is scarce and existing studies do not usually address the effect of road lighting properties on visual performance of cyclists, particularly. Further empirical investigation is thus required to establish objective evidence that could be used to inform or confirm the current road lighting guidelines for cycling.

2.6.2 Bicycle lighting and hazard detection

Unlike pedestrians, cyclists' vision after dark is also influenced by bicycle light, which serves as an additional light source alongside road lighting. As discussed in Section 1.5.2 of Chapter 1, little information is given in the British standards (BS 5489-1:2013; CEN/TR 13201-1:2014; BS 6102/2:1982) on optimal bicycle light intensity or mounting positions for the different visual tasks performed by cyclists on roads, including detecting hazards on road surface. In addition, an understanding of how road light and bicycle light interact with each other and their combined influence on detection tasks is yet to be addressed.

When cycling after dark, the bicycle light projects light onto objects from a vertical or semi vertical angle, unlike the horizontal projection of road light. Moreover, when light properties differ between the two sources, a contrast is likely to occur either between the side of the object and the area ahead of it (surrounding area), or between the side and top of the object. The contrast effect has been investigated in earlier detection studies (Akashi et al., 2007; Eloholma et al., 2006). Another factor that may enhance the perceptual clarity of an object is the pattern of the shadow it casts (Boyce, 2014). The length or clarity of the shadow is determined by the intensity of the light, angle of projection of the light source, and the height of the object.

In terms of where to mount the bicycle light (front lamp) on a bicycle, for optimum visual performance, no specific mounting location is given in the British standards and K mark guidelines (see Chapter 1, section 1.5.2). The guidelines only state that the front bicycle lamp can be mounted up to 1500 mm above ground level (BSI, 1982) and that it should be white (BSI, 1986), although no empirical evidence is provided to support these guidelines. Possible mounting positions for the bicycle lamp, such as the bicycle hub or cyclist helmet, are not mentioned. From a lighting perspective, the position at which the bicycle lamp is mounted is proposed to have an influence on several light properties such as the target contrast level (Park et al., 2017) hence a proposed effect on visual performance.

In summary, detecting hazards is an important visual task for both pedestrians and car drivers, although whether this is the same for cyclists is yet to be confirmed. However, it is likely that observation of the path and the detection of hazards such as obstacles on the road will also be important. Studies have found that light properties such as S/P ratio, contrast level and light intensity (luminance/illuminance) have an effect on visual performance, although this has not been verified specifically in relation to cycling. Further empirical research is therefore required to ascertain whether this is indeed the case. In addition, no specific reference is given regarding the ideal mounting position of a cycle lamp for visual performance. Similarly, there is no empirical justification provided in the road lighting guidelines regarding the intensity of bicycle lighting needed for a visual performance. Finally, little is known about the interaction of bicycle lights and road lights or their combined visual impact on cyclists' performance which represents a clear gap in the literature. The key to addressing this is to first identify the critical visual tasks undertaken by cyclists (as discussed at Section 2.4.4.2). This is a prerequisite for knowing how and where to provide suitable road lighting.

Observation of the path and detection performance are both considered important when examining the visual behaviour of cyclists and are relevant to their safety (the main focus followed in this thesis to promote more cycling). However, another aspect of a cyclist's visual behaviour is their ability to see and appreciate the aesthetic/attractive environment (the secondary approach, see Figure 1.6). Being able to appreciate the visual characteristics of the surrounding environment can enhance the experience of cycling, although there has been limited objective analysis of this topic in relation to how cyclists distribute their gaze in relation to their surroundings, as was discussed under Section 2.5.

The limitations identified earlier in this chapter and their relation to the research aims, approach to the problem, primary goal, and the propositions are presented in Figure 2.4.

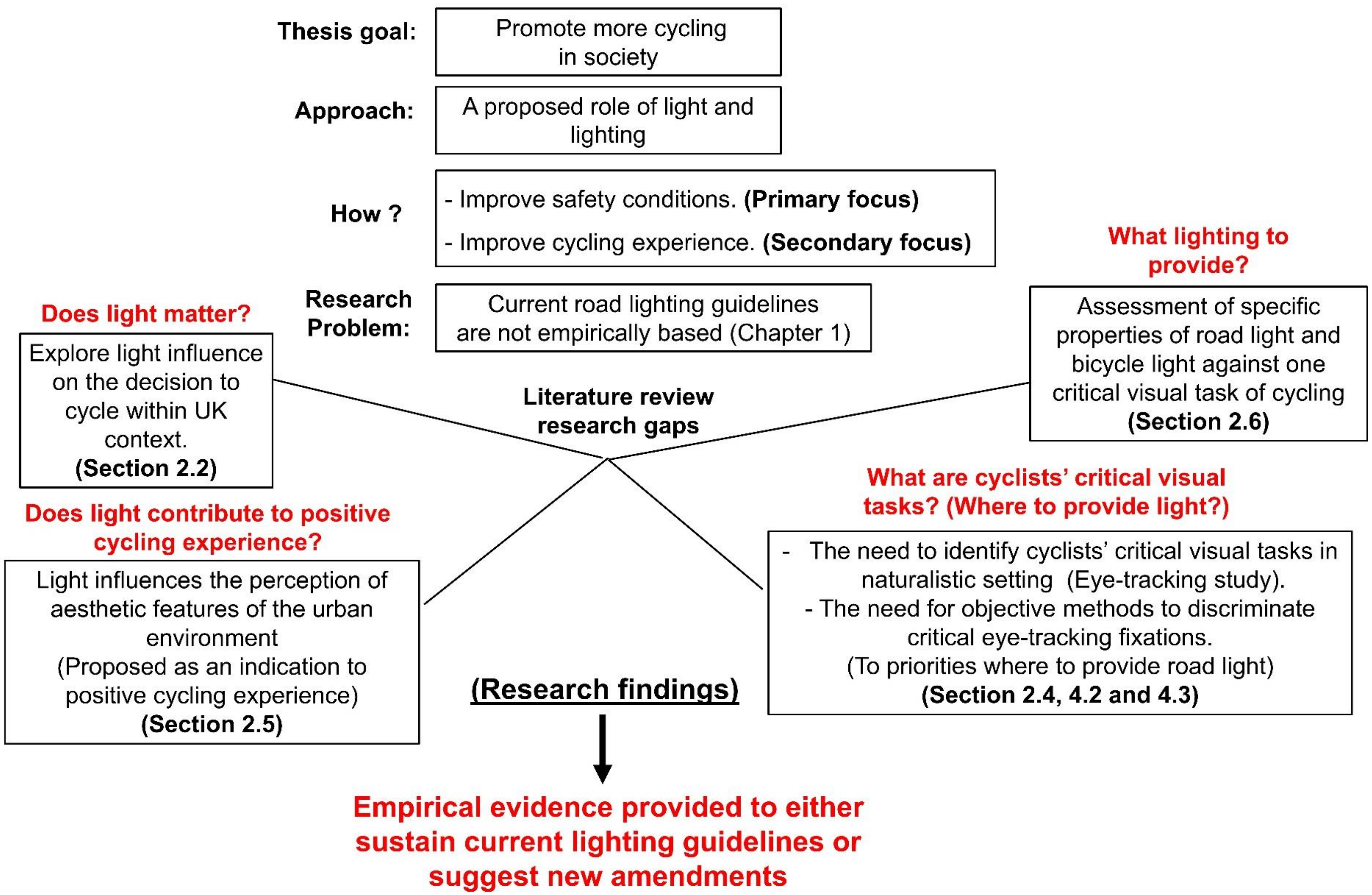

Figure 2. 4. Research limitations identified in the literature review and their links to the research goal, approach, main problem, and the propositions.

2.7 Research questions

The aim of this research is to investigate the visual behaviour of cyclists within an urban environment. The principal goal is to identify the critical visual tasks undertaken by cyclists. This is a prerequisite for providing appropriate road lighting that will enable safe cycling. In particular, the identified critical visual task(s) should be assessed under variations of road light and bicycle light properties. In addition, the study sought to provide empirical evidence to explain the effect of ambient light levels on the numbers of cyclists in a given location; and the perception of aesthetic/attractive features of the urban environment. The latter was suggested to improve the cycling experience and hence is another motivation for cycling besides improving road safety.

The research questions shown in Table 2.4 reflect the aims of the research discussed previously, in Chapter 1 under Section 1.7.

Table 2. 4. Research questions and the related literature sections.

Question no.	Research question	Literature Section
1	Does ambient light affect numbers of cyclists?	2.2
2	What objective methods can be implemented to discriminate important visual tasks of cyclists?	2.4.4.2 4.2 and 4.3
3	What are the critical visual tasks of cyclists in urban environment?	2.4.4.2 2.6
4	How do ambient light and the characteristics of cycle paths influence cyclists' perception of aesthetic features of the urban environment with such perception proposed to be an indication of positive cycling experience?	2.5 6.2
5	What levels of road light illuminance improve visual performance of cyclists?	2.6.1
6	What level of bicycle light aids cyclists' visual performance? Does the mounting position of the bicycle lamp matter?	2.6.2

Figure 2.5 presents the four studies conducted in the current thesis to answer the research questions: two main studies and two pilot studies. It shows that the main eye-tracking study and obstacle detection task constitute the main focus followed to

promote cycling and thus the main body of this thesis. Both studies address the safety aspects of cycling (see Chapter 1 Section 1.4, Figure 1.6). Also related to safety, the aim of the first pilot study was to establish the relationship between lighting and cycling by measuring the influence of ambient light on the number of cyclists observed. The second pilot study investigated the effect of ambient light on cyclists' perception of aesthetic features of the urban environment. This related to the secondary focus followed in the thesis to promote cycling, see Figure 1.6.

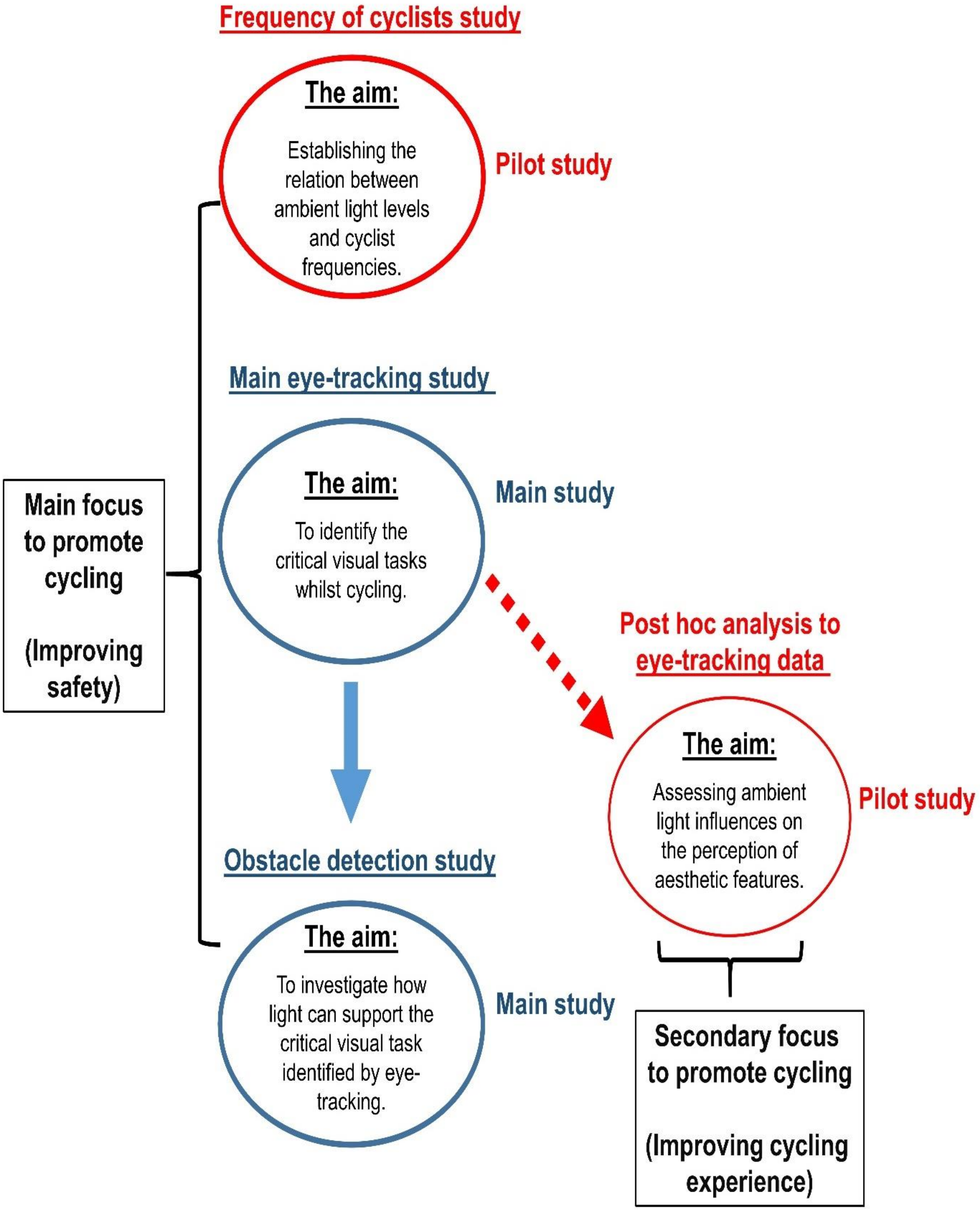

Figure 2. 5. The four studies conducted in the current thesis: two main and two pilot studies. The obstacle detection study was a consequence of the main eye-tracking study, and both constituted the main body of the research. The two pilot studies sought to empirically explore the influence of ambient light on the decision to cycle and the perception of aesthetic features of the environment.

2.8 Summary

Previous studies have established that ambient light can influence the decision to cycle or not; however, this is yet to be confirmed in the context of the UK. Knowing that light matters for cyclists makes it important to determine where and how it should be provided. This means the critical visual tasks undertaken by cyclists need to be identified, for which eye-tracking was proposed as a suitably objective method. However, previous work on cycling/eye-tracking has lacked the intensity of naturalistic studies. Furthermore, the discrimination of critical eye fixations from overall fixations was not carried out in previous studies, which meant that no information was provided as to whether participants paid genuine attention to what they observed.

Previous studies investigating the effect of specific lighting properties on visual performance were therefore reviewed to ascertain the lighting properties that need to be investigated to improve or confirm current road lighting guidelines.

In addition to improving safety aspects, a secondary focus to promoting cycling also identified in the literature review was to improve the cycling experience. Specifically, such research focused on how perceptions of aesthetic features of the environment may correlate with a positive cycling experience.

Chapter 3. Ambient light influences cyclist frequencies

3.1 Introduction

As discussed in Chapter 2, there is some evidence that the level of ambient light influences the propensity to cycle (Fotios et al., 2017b; Uttley and Fotios, 2017); specifically, for a given time of day, there are more cyclists when it is daylight than when it is dark. The data of Fotios et al. (2017b) and Uttley and Fotios (2017) were collected in one city in the USA. It is not yet known whether the conclusion is generalizable to other locations where the weather, cycling infrastructure and cycling culture may be different. This chapter reports a brief field study conducted in Sheffield, UK, to test whether the influence of ambient light on cycling persists.

3.2 Method

The numbers of passing cyclists were counted in two urban locations in Sheffield, a city in the UK. The counting was done by on-location observation rather than using automated counters. These counts were made between 18:30 and 19:30 for five days before and five days following the springtime clock change in 2016. For the first period the test hour approached darkness; for the second period the test hour approached daylight. With the assumption that variations in climate between these periods other than daylight were minimal, then a comparison of cycle counts between the two periods isolates an effect of ambient light from other influences.

In 2016, the springtime clock change occurred in the UK on 27 March. On this day, the clocks were moved forward one hour and the time of sunset occurred approximately one hour later. Cycle counts were conducted for five consecutive days (Monday to Friday) for a period of two weeks before and after the clock change, i.e. 14-18 March (before changeover, after dark light condition) and 4-8 April (after changeover, daylight light condition). The weeks immediately before and after the clock change were avoided because the clock changeover date fell within the school Easter holiday period in the area in which the data was collected. This is because people were not undergoing their usual routines which would have unfairly influenced the results. This timescale is illustrated in Figure 3.1.

Figure 3. 1. Observation schedule for the cycle count field study. Cyclists were counted for a one-hour period over five days before clock change (darkness) and five days after clock change (daylight).

The latest sunset time during the after dark week was 18:16, while the earliest sunset time during the daylight week was 19:47 (TimeAndDate, 2018). Therefore, to count the frequency of cyclists, a one-hour recording period from 18:30 – 19:30 was chosen, this is referred to as case hour (the experimental period). This ensured it was dark during the after dark week (before the clock changeover) and light during the daylight week (after the clock changeover). In addition to these case hour periods, cyclists were also counted during a control hour period where the light condition was the same in both weeks: this control hour period was 17:30 – 18:00 and was a period of daylight during both the before- and after-changeover weeks.

Counts were recorded in two locations, location 1 referred to as *City* was approximately 1.2 km from the city centre and contained a high number of shops and commercial properties. In this location, which is an intersection of two roads: London Road and Boston street, two observers recorded data of the two streets with each observer counting frequency for one direction, to ensure optimum counting. Location 2, defined here as the *Suburban* area was situated approximately 4.2 km from the city centre in a residential neighbourhood, with housing the dominant type of building in the immediate area, one observer counted at this location. All observers remained constant at same positions throughout both weeks Images of the two locations are shown in Figure 3.2. The authors knowledge of these two areas suggested that cyclist numbers would be higher in location 1 than in location 2.

Figure 3. 2. Images of the two locations where cyclist numbers were counted, City (left) and Suburban (right).

The frequency of cyclists was recorded during the control hour (17:30-18:00) and case hour (18:30-19:30) periods. This included any cyclist passing in either direction who was visible on the street from the observer's location.

This was carried out for five days of each week at the City location (Monday to Friday), but only four days of each week at the Suburban location. This was due to an enforced change of location on the first day of recording (the initially selected location was found to have too few cyclists to provide meaningful data), and a public event (football match) occurring nearby on one day in the second week which would have provided unrepresentative data.

3.3 Odds ratio

Calculations of odds ratio (Equation 2.1 in Chapter 2) and confidence intervals (CI) (Equation 3.1 below) are adopted in the current study, where cycling frequency under two different light conditions, daylight and darkness, is evaluated by isolating light condition from other pressing factors which may have an influence such as: weather, season, traffic, etc.

In definition, odds ratio is a calculation used to test the causation between certain factors or conditions and a result assumed related to them (Johansson et al., 2009). The idea stands on finding the chances a specific result will occur when particular conditions exist, in comparison with the chances that the result will still exist when these particular conditions are gone.

The confidence interval is an estimation of the uncertainty embedded in the outcome of a given analysis (Carpenter and Bithell, 2000), where the true value may exist in between the interval (95 % confidence level).

In their study Johansson et al. (2009) used odd ratios to assess the rates of traffic accidents when light condition is altered from darkness to daylight. By doing this they isolated the effect of light condition from other factors which might have an influence over traffic accident rates.

In the current study, frequencies of cycling passing by observation locations, for case hour, were summed up separately, one time for dark condition and another for daylight (week before and after clock change, respectively). Then the ratio between the two totals is calculated. The outcome ratio then is compared with the control hour ratio which is the frequency of cyclists also taken in the same two weeks, but here always in daylight (17:30 to 18:00).

The calculation and explanation of odds ratio is presented in equation 2.1.[1], in Section 2.2. When the odds ratio is > 1 this will be an insinuation for a positive effect of daylight on the increasing frequency of cycling. As in this case the number of cyclists during daylight week is larger than the darkness week, to account to other confound circumstances, which may have an effect over cycling frequencies, other than light condition, the control hours of the two weeks where light condition is always daylight is integrated in the calculation.

An odds ratio equal to 1 will mean cycling frequency is not significantly different between light conditions, a null value, whereas an odds ratio of greater than 1.0 indicates an increase in cycling in the daylight period than the after dark period. The Odds Ratio was considered to be 'significantly' greater than 1.0 if the lower limit of the 95% CI was greater than 1.0. Equation 3.1 presents calculation of the 95% CI conducted for each odds ratio (Szumilas, 2010).

$$95\%\ CI = exp\left(ln\ (odds\ ratio) \pm 1.96\ \sqrt{\frac{1}{A}+\frac{1}{B}+\frac{1}{C}+\frac{1}{D}} \right) \qquad \textbf{Equation 3. 1}$$

---

[1] Odds ratio=(A/B)/(C/D) Equation 2.1

3.4 Results

The frequencies of cyclists before and after the clock change, and the significance of these differences, for the two locations and the control and case hours including odds ratio and 95% CI determined from these data are shown in Table 3.1 and Figure 3.3.

At the city location, Table 3.1 shows there was an increase (25%) in cycling frequency for the case hour in the second week after the clock change (daylight) compared with the first week (after dark), with the number of cyclists increasing from 360 to 451; and for the control hour the difference in cyclist numbers before and after clock was not high, 411 and 406 for the two weeks, respectively. At the suburban location cycling frequency increased from 36 to 59 (63 %) during the case hour, and increased also from 30 to 46 in the control hour.

Table 3. 1. Cycling frequencies before and after springtime clock change with odds ratio and 95% CI calculations.

Location	**Recording period**	**Observed cyclist frequencies**			**Odds ratio (95% CI)**
		Before (Case hour in darkness)[1]	**After** (Case hour in daylight)	**Increase (%)**	
City	Case hour	360	451	25%	1.27 (1.04-1.54)
	Control hour	411	406	-1%	
Suburban	Case hour	36	59	63%	1.06 (0.57-1.98)
	control hour	30	46	53%	
Both	Case hour	396	510	29%	1.25 (1.04-1.51)
	Control hour	441	452	2%	

[1] The control hours for the two weeks were always in daylight.

Consider next the data for both locations combined. The cycling frequency increased from 396 to 510 during the case hour (29%) increase, and from 441 to 452 during control hour.

According to the confidence intervals shown in Table 3.1 there was a significant effect of daylight on cyclist numbers at the city location but not the suburban location, because the lower limit of CI was below 1 for the suburban location. The significant effect was retained when the two locations were merged, which may be because the city location had a much greater sample than the suburban location.

Figure 3.3. depicts the values presented in Table 3.1 where there was a significant effect suggested at the city location and all data combined.

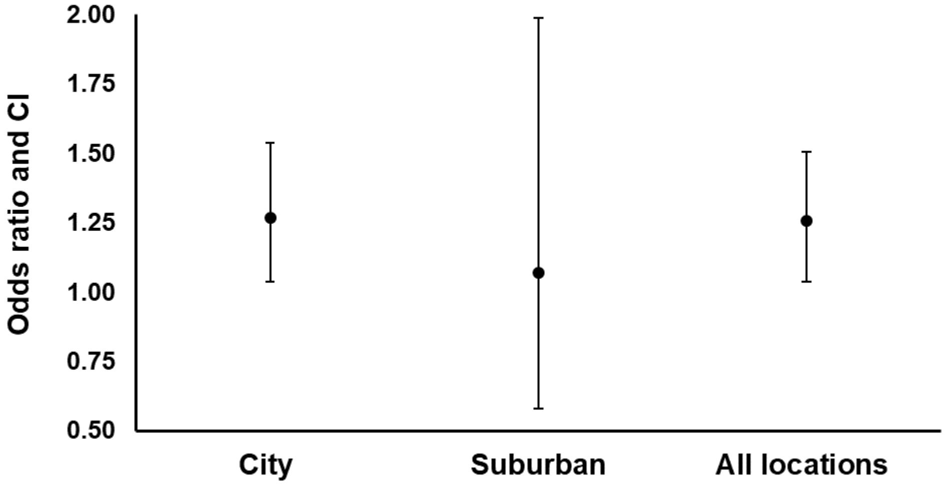

Figure 3. 3. Odds ratios (in dots) of cycling frequencies before and after springtime clock change event for city, suburban, and both locations. The error bars represent the upper and lower limits of 95% CI.

3.5 Discussion

A daylight-saving approach investigated whether the ambient light condition (daylight vs after dark) influences the number of cyclists present on two locations in Sheffield city centre. This question is important as it establishes the role lighting may play in encouraging cycling after dark. The springtime clock change was used as an event to compare ambient light conditions (daylight versus after dark) whilst keeping periodic and precise time of the day aspects continuous. This approach has previously been adopted in analyses of vehicle accidents (Sood and Ghosh, 2007; Sullivan and Flannagan, 2002) and studies of pedestrian and cyclist frequencies (Fotios et al., 2017b; Uttley and Fotios, 2017). Cyclist numbers were observed at two locations: the effect of daylight was found to be significant at one location but not at the other.

This may be an indication that other factors may outweigh any influence of daylight at this location (Suburban), or more precise, at the point at which the cyclists made their decisions as to whether or not to cycle.

In their studies (Fotios et al., 2017b; Uttley and Fotios, 2017) have only reported the mean frequency across all counters in the analysis. It may be possible that if some locations were assessed rather individually, an inconsistence between locations, similar to the one revealed in this study at suburban location may have been revealed.

However, the odds ratio, CI and p-value calculated in the current study for the total count of cyclists (all locations) fell in similar ranges of previous studies. This provides a degree of confidence that an increased level of ambient light (daylight) aids the decision for cycling, see Table 3.2.

Table 3. 2. The odds ratio and CI of the current (all locations) and comparative studies.

Measurement	The current study	(Uttley and Fotios, 2017)	(Fotios et al., 2017b)
Odds ratio	1.26	1.38	1.67
95% (CI)[1]	1.04 – 1.51	1.37 – 1.39	1.66 – 1.68
Pearson's Chi-Square (P<0.05) [2]	0.016	0.001	0.001

[1] 95% confidence interval should be used as a proxy to indicate significant odds ratio, by that it is not a statistical significance value (Szumilas, 2010).

[2] Pearson's Chi-Square (p<0.05) indicates whether the odds ratio is significantly larger than 1 i.e. more cycling during daylight comparing to after dark.

Climatic conditions are an important consideration regarding whether someone chooses to walk or cycle to a location (de Montigny et al., 2012; Miranda-Moreno and Nosal, 2011) and it is possible the weather was a factor influencing the presence of cyclists in this study. However, field notes taken by observers at both locations indicated little difference in the weather conditions between the before and after weeks during the data collection periods, with only a brief rain shower recorded on one day, the 8th April 2016, and all other days providing sunny or slightly overcast conditions. Recorded meteorological data from local weather stations (TimeAndDate, 2018) indicated similar conditions across both data collection weeks, with mean rainfall during data collection periods recorded as 0.0 mm in both weeks and mean temperatures changing by only 3 °C (6° during the week before the clock change, 9°C during the week after the clock change). The weather is therefore unlikely to have been a major cause of any changes in the frequencies of cyclists.

3.6 Summary

A field study was conducted in which cyclists were counted as they passed two locations in Sheffield city. A comparison of cycle counts using an odds ratio and confidence interval approach demonstrated that there were more cyclists in daytime than after dark, for the same time of day. This confirms the findings of previous studies that light has effect on the rate of cycling at a particular location (Fotios et al., 2017b; Uttley and Fotios, 2017). The next chapter describes the method used to investigate the visual behaviour of cyclists in real world.

Chapter 4. Eye-tracking: Method

4.1 Introduction

People are suggested to be inclined to cycle when there is more ambient light (Chapter 3). At those times of day when the amount of natural light varies significantly throughout the year, the number of cyclists drops when it becomes darker. This suggests that cycling activity should also be influenced by the amount of road lighting which, in the UK, is specified in BS5489-1:2013. However, the validity of the data behind this standard has since been questioned (Fotios and Gibbons, 2018).

This means that current road lighting guidance is not sufficiently grounded in empirical data to be confident that lighting design to encourage cycling is optimal, see Chapter 1, Section 1.6. If lighting is to be optimised to meet cyclists' requirements, then it would be useful to know what objects or items cyclists need to observe, particularly those objects or items which contribute to their safety, as public concerns about the safety of cycling may reduce the tendency to cycle, see Chapter 1, Section 1.3. One way to investigate this is to use eye-tracking when cycling in a natural environment. While past studies have used eye-tracking to explore cyclist gaze behaviour, few have investigated gaze in natural settings and few, if any, have sought to identify the significance of fixated objects, examples of studies that did not implement a method to discriminate critical fixations from the whole fixations data are: (Boya et al., 2017; Mantuano et al., 2017; Schmidt and von Stülpnagel, 2018; Vansteenkiste et al., 2014a).

People fixate on different objects in the environment. Some of these fixations invite cognitive engagement such as fixations which may relate to personal safety. Other fixations might not stimulate such cognitive engagement, thus allowing the mind to wander or invite marginal cognitive engagement. In theory, people are allocating attentional resources to some eye fixations but not all of them, see Section 4.2 in the following. In the current work, those fixations to which attention is paid are called critical fixations. Two independent parallel measurements were implemented to detect critical moments where participants are possibly engaged with a visually critical element of urban context: dual task and skin conductance response (SCR) approach. These were time synchronised with eye-tracking fixations to reveal critical fixations.

The current chapter begins with providing a literature review about dual task and SCR approaches including their potential use to find critical fixations, then description of current eye-tracking experiment method commences.

4.2 Dual task review

There is a close relationship between attention and visual behaviour (Livingstone et al., 2017). Olivers et al. (2006) found that visual distractors during a visual search task significantly reduced visual performance due to the diversion of attention (Turatto and Pascucci, 2016). Lim et al. (2015) also found that conducting a visual investigation task while simultaneously attempting to memorise the altitudinal positions of two dots on a panel reduced the performance effectiveness of both tasks.

In a virtual study of pedestrians, Rothkopf et al. (2007) concluded that one’s gaze direction is affected by other tasks commonly performed while walking. They further suggested that humans use attention as a core mechanism for filtering the vast amount of information collected from the environment every day. This information is acquired using the varied senses and processed into smaller, relevant sets of data that can be perceived and processed easily and quickly (Rothkopf et al., 2007). The human capacity of attention is limited, however, making it near impossible to interpret all the information received and filtered daily (Gaspar et al., 2016).

It is challenging for anyone to simultaneously perform two simple tasks, since their attention will be divided when attempting to accomplish both tasks (Lim et al., 2015). Similar conditions have since been recreated in scientific research, however, with Boot et al. (2005) positing that a secondary task performed simultaneously alongside a visual search task results in the cognitive efficiency of the individual being affected. This finding therefore goes to the amount of cognitive resources or capacity for attention are actually allocated to the secondary task and accordingly explains performance on the primary task. This conclusion is predicated on the fundamental assumption that human attention is limited (Turatto and Pascucci, 2016).

Carrying out two tasks simultaneously can alter the performance of both tasks due to the division of attention, reducing the effectiveness of both tasks. In some cases, however, cognitive instructions can also influence allocation of attention. For example, instructions to focus on a precise duty can result in increasing the performance on that task during dual-task contexts. This is due to the preferential allocation of attention towards, with participants selectively choosing which tasks to undertake at different times (Kelly et al., 2010).

The relationship between attention and gaze behaviour is assumed to be close which makes eye-tracking a valid method for assessing cognition (Rothkopf et al., 2007). However, the nature of this relationship is not entirely clear. Eye-tracking studies on reading tasks have demonstrated there is a gap between attention and visual patterns among participants; for example, the number of fixations found on a text does not always correlated with a higher understanding of the material being read (Foulsham et al., 2013).

Building on this research, a parallel measurement when using eye-tracking is needed to differentiate between critical fixations and other fixations which, understandably, are not always significant. This will help clarify the cognitive status of the participant and whether they are mentally engaged with the item fixated upon.

In a dual task context, devoting more attention to one task should, in theory, affect performance of the other. This could also occur involuntarily in a real world situation when more attention is given to a task for different reasons, namely avoiding risk or seeking leisure (Williams, 2006). This could also mean that preference for a task in terms of the allocation of attention may be dispersed across a group of tasks according to their criticality or urgency. Consequently, performance on those tasks will be affected.

In the current eye-tracking study on cycling reported in this and the subsequent Chapter, responding to the audio stimulus will be the concurrent task while the main task will be natural observation of the urban surroundings when cycling on a predefined route i.e. visual behaviour. Both tasks appear to be distinct in terms of modality; however, the literature suggests that the performance on both tasks will be related. For example, Boot et al. (2005) reported that conducting a subordinate task such as counting numbers affected the primary visual task. Therefore, a reduced performance on the secondary task is anticipated when a critical or unusual visual event is encountered by the participant.

A dual task approach has been used in previous eye-tracking work to discriminate critical fixations. Fotios et al. (2015b) studied pedestrians' visual behaviour and implemented a dual task method to discriminate critical fixations, moments when participants paid attention to what they are looking at, from normal fixations. Their method was to implement a reaction time task where a participant was required to press a button in response to audio stimulus.

In part 2 of their study Fotios et al. (2015c) responded to a common challenge of real world eye-tracking studies that is the indefinite number of times an item will be encountered by participants during trials. For example, many factors e.g. weather, time during the day, public events, etc., could influence the frequency of pedestrians walking on the pavement or the frequency of cars on the road, etc. Specifically, they analysed the effect of appearance frequencies of one visual target (other pedestrians) on the number of eye fixations generated. They compared three approaches: All fixations, critical fixations and probability.

The ‘all fixations’ approach is a direct count of the number of fixations falling on the encountered pedestrians during trials. This approach can lead to substantial noise in the data thus inaccurate interpretation: the more pedestrians that appear in the scene the more fixations labelled under pedestrians. In the probability approach the measure stands on dividing the number of pedestrians that participants fixated on at least one time by the total number of pedestrians that appeared within the visual field of participants during the analysed recording. There was a negative relationship between these two variables – the probability of fixating a pedestrian was lower when the number of pedestrians encountered increased. This could be correlated to the fact that with a higher frequency of individuals appearing in the scene it is hard to fixate on all of them, or there is less need to fixate on them.

The critical fixations approach depends on synchronising the fixations identified by the eye-tracking apparatus with participants’ delayed or missed reactions to the audio stimulus (the dual task). These delayed responses referred to as critical moments and were proposed to indicate significant visual events during the experiment that had caused diversion in participants’ attention from responding to the dual task. Fotios et al. conclude that critical fixations approach is less affected by the variation of pedestrian appearance than the all fixations and probability approaches. See Figure 4.1 indicating to this finding by the red horizontal line (critical fixations).

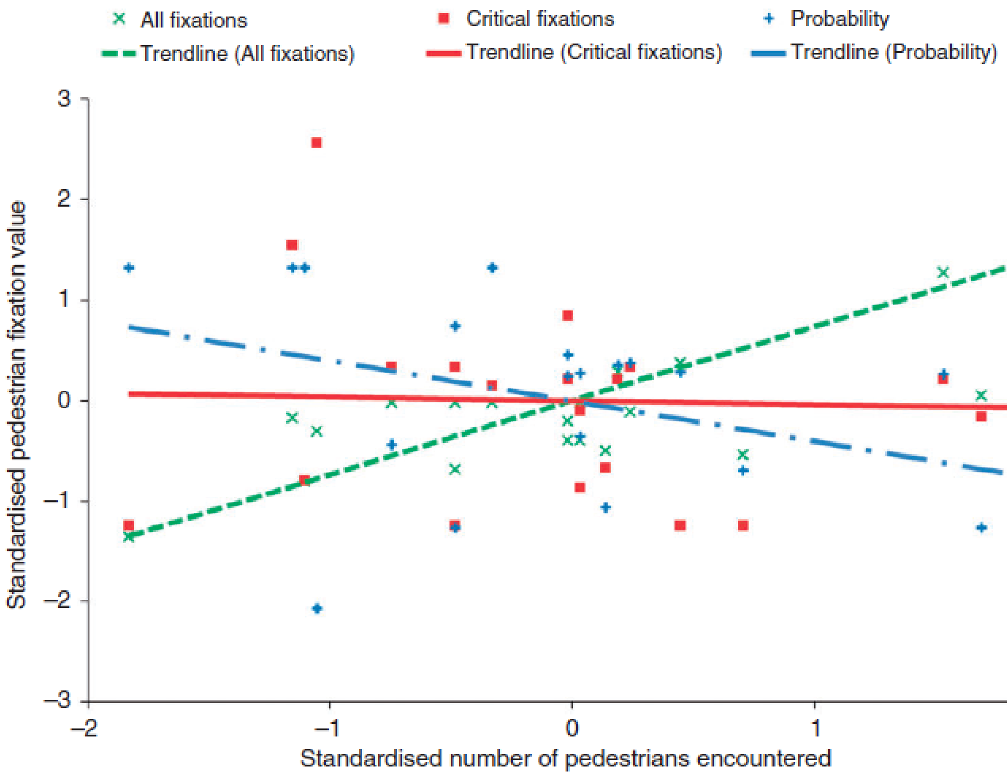

Figure 4. 1. Regression of measures of participants' fixation in respect to the rate of pedestrians encountered across daytime and after dark trials (from Fotios et al., 2015c)

4.3 SCR review

Skin conductance response (SCR) refers to the phenomenon where the skin becomes a better conductor of electricity, albeit momentarily, when an external or internal stimulus occurs in a way that is physiologically arousing (Rosebrock et al., 2016). It is also called electrodermal activity or galvanic skin response, and encapsulates a broad range of the overall activation and reaction of the human skin when exposed to certain stimuli.

Individual arousal resulting from a stimulus is an essential component of SCR and could be strong predictor of both attention and memory (Christopoulos et al., 2019).

According to White and Graham (2016), the varying situations in which skin conductance response is activated, and how it responds to varied stimuli, make it a critical resource in research. Specifically, an instrument which is able to detect physiological data is used to measure and monitor the electrodermal response (SCR) of participants as they are exposed to different stimuli, with Kuzinas et al. (2016) noting it could be useful to study skin reactions alongside other visual search tasks.

SCR is normally measured using silver or silver chloride electrodes placed on one's medial phalanx of both index and middle fingers, or thumb and little finger (van Dooren and Janssen, 2012) and which is fixed in location by double sided adhesive electrode collars. White and Graham (2016) reasoned that SCR is based on the primal fight or flight instinctive response in which the animal body readies itself for such exertions required to handle perceived threats. This increases the sweat activity to cool itself down, but in return the emotions get heightened.

This heightened sweating activity often accompanies the classic electrodermal activity of the skin. Specifically, Kuzinas et al. (2016) noted that such electrodermal activity in itself impairs the performance effectiveness of other activities, as in the case of car drivers observing other vehicles or land forms they pass by had, in that moment, a lower concentration on the road and the actual driving.

The SCR method was implemented in a social anxiety study alongside eye-tracking to evaluate involuntary responses arising from eye contact with strangers (simulated faces). SCR therefore helps to clarify what an eye fixation means (Wieser et al., 2009) i.e. critical fixation. This shows that SCR data can be used concurrently with an eye-tracking method to explain cognitive reactions of participants.

Kübler et al. (2014) contented that SCR is essential in similar studies due to its ability to facilitate the collection of biological data that reflects the electrical characteristics of the human skin. In their eye-tracking study on drivers with a visual deficiency they had utilised the measurement of skin conductance response (SCR) to assess participants' awareness of existing hazards. This is because, in the case of inattention or deficient visual ability, eye fixation alone will not provide sufficient information about hazards (Kübler et al., 2014). The study concludes that a combination of eye-tracking and SCR methods will therefore provide information about risk awareness on the road.

The primary objective of current study is to identify critical fixations in the participants and determine what factors, if any, contribute to them.

By pooling two parallel measurements for this study, dual task and SCR, it is hoped that more reliable data on critical visual events encountered by the participant during trials can be collected and analysed for more definitive conclusions to be made, and to improve the limitations of earlier eye-tracking studies discussed earlier, Section 2.4.4.

4.4 Eye-tracking method

Eye-tracking is a method for recording a person's gaze behaviour, that is where and on what a person is fixating. In a naturalistic study, eye-tracking is considered an objective way of investigating involuntary responses and gaze behaviour of cyclists to different visual stimuli within the urban environment. New eye-tracking models allow for better mobility making it suitable for real world studies.

Fixations which match moments of significant dual task (cognitive attention) or the SCR (high arousal of the skin electrical characteristics) are suggested to be critical fixations. Critical moments in dual task and SCR data were synchronised with the eye-tracking fixations to enable the coder (the main researcher) to identify critical fixations from the larger data of fixations i.e. all fixations.

Thus, the current study identifies three types of fixations: All fixations, Dual fixations, and SCR fixations, see Table 4.1.

Figure 4.2 illustrates the experiment design where critical fixations, either dual fixations or SCR fixations, were separately identified from all fixations, that is fixations identified by BeGaze software and mapped to target categories only.

Table 4.1. The three types of fixations identified in this study.

Fixation category	Data source
All fixations	Fixations as identified by the Begaze software (raw) and mapped to target categories.
Dual fixations	Fixations associated with impaired response to the audio dual task.
SCR fixations	Fixations associated with above-threshold SCRs.

4.5 Route and Bicycle

The cycling route was located across and around the University of Sheffield main campus - an urban location. The route comprised four different sections chosen to include variations in exposure to motorised vehicles, proximity to pedestrians, and urban characteristics (see Table 4.2 and Figures 4.3, 4.4). Two sections required on-road cycling (Sections A and C), one section followed a path through a public park (Section B), and the final section passed through a car park (Section D). All four sections were lit after dark. Table 4.2 provides information about the volume of other road users in each section of the route, evaluated by counting their presence in the eye-tracking recordings. This means the volume of pedestrians, cyclists, and cars corresponds to the mean of eye-tracking general fixations on these items across the day and night trials.

Each trial consists of two laps of the route with a total length of approximately 2.2 km. The length of the route, and hence the duration of each recording, was chosen as a compromise between ensuring sufficient data for analysis (i.e. opportunities to fixate upon a wide range of targets), time required by the experimenter to process the recorded data, and what was appropriate for participants in terms of their available time and physical exertion.

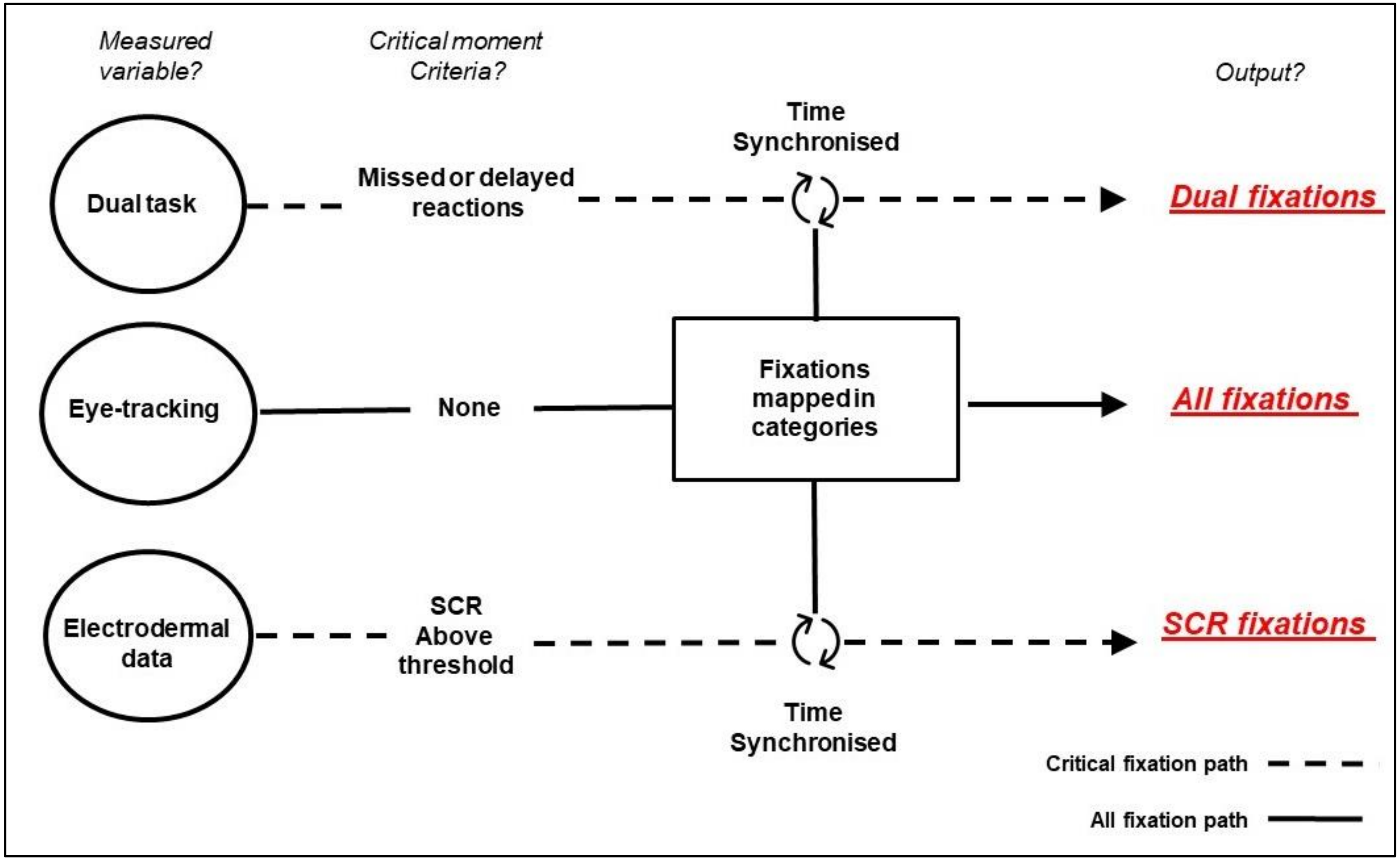

Figure 4.2. The experiment design illustrating the dual task and SCR measurements which were taken in parallel to eye-tracking; thus, critical fixations were identified from all fixations.

A graphic map of the experiment path was shown to the subject before each trial. The route took approximately six to eight minutes to complete, and data from both laps were used in the analysis.

Participants rode a standard city bicycle, Figure 4.5, borrowed for this experiment from the University's Department of Estates and Facilities. The saddle height was adjusted as necessary to suit each participant. A high-visibility vest and helmet were provided for those participants who did not have their own, and the bicycle was fitted with front and rear lamps. Two panniers attached to the rear of the bicycle housed the EDA and dual task equipment, including the BIOPAC data acquisition unit, laptop, audio unit (to produce sound stimulus of the dual task), and two lithium battery packs to power the equipment.

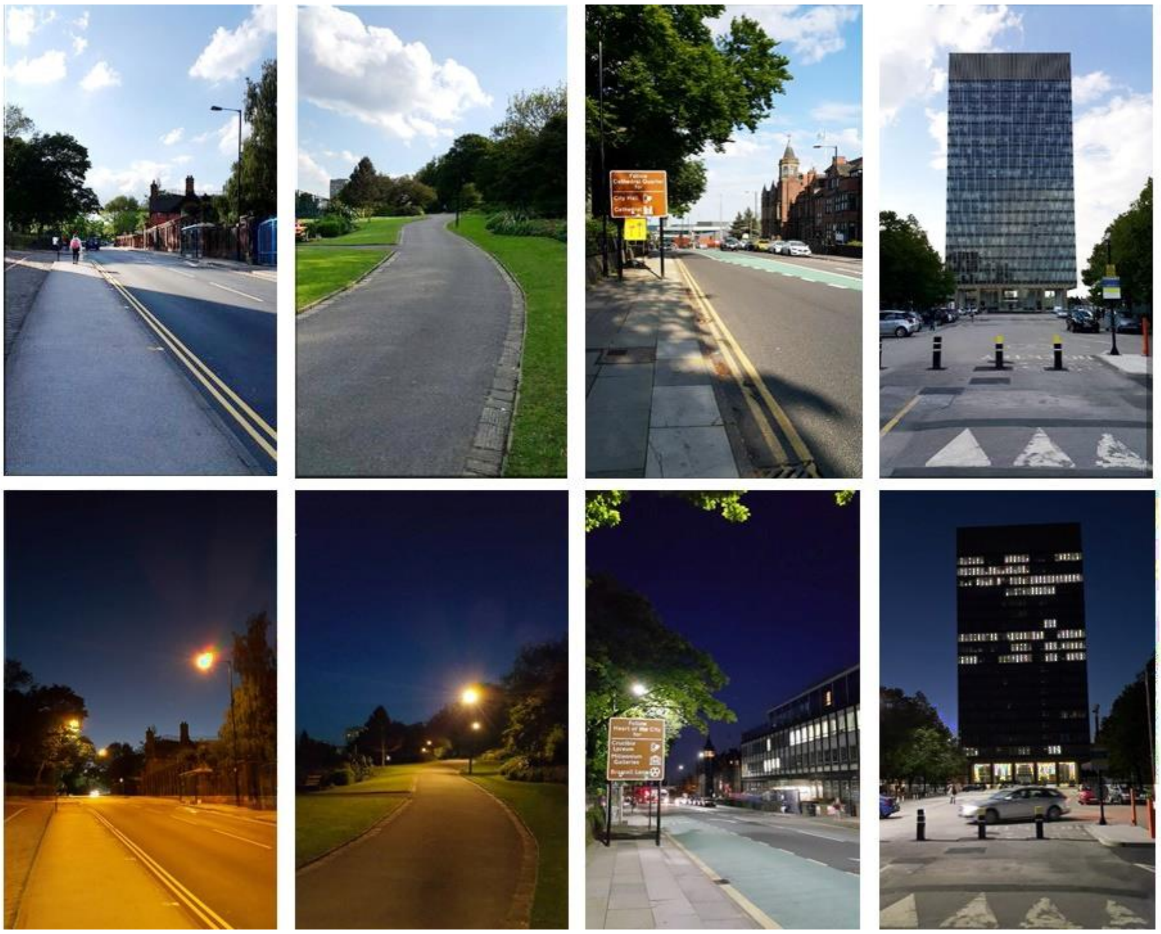

Figure 4.3. Images of the four sections of the experimental route during daytime (top row) and after dark (bottom row). From left to right, these are Sections A, B, C, and D.

Table 4.2. Description of the four sections of the route and the relative volume of other road/pavement users. All four sections were lit after dark.

Section	Length [1]	Description	Relative volume of pedestrians[2]		Relative volume of other cyclists	Relative volume of vehicles
			On pavement	Sharing or crossing		
A	217 m	A single carriageway with two traffic lanes; the surface quality is generally good, but there are some potholes, cracks, and unevenness.	High (69)	Low (17.5)	High (29)	High (109)
B	322 m	Pathway through a public park used by pedestrians and cyclists; no motorised vehicles; the path surface is smooth with no significant surface hazards.	N/A [3]	High (177.5)	Low (6.5)	None
C	355 m	Dual carriageway with four traffic lanes; a frequently used and busy area due to the proximity of a hospital and multiple university buildings. The surface quality is generally good, but there are some potholes, cracks, and unevenness.	High (81)	Low (28)	Moderate (15)	High (141.5)
D	194 m	Off-road area of university campus used for car parking and deliveries with a mix of pedestrians and cyclists; the surface quality is generally good, but there are some potholes, cracks, and unevenness. There are two speed bumps.	N/A	Moderate (42)	Moderate (11.5)	High (133)

[1] Section length measured using the ruler function of Google Earth.

[2] Volume of pedestrians evaluated by counting their presence in the eye-tracking recordings across day and after dark trials (this applies to cyclists and vehicles' columns).

[3] N/A refers to situations where pedestrians share the path with cyclists and there is no particular pavement for them to be separated from other people such as the situation in Section B (path through a park).

Figure 4.4. The experiment route was cycled anticlockwise starting at Section A. Line styles are differentiated to illustrate the four distinct route sections. The black lines at the start of each section demonstrate, approximately, the location where photos in Figure 4.3 were taken (facing anticlockwise).

Figure 4.5. The bicycle used in the experiment. The rear panniers contain the EDA data acquisition unit (SCR), laptop, and external batteries.

4.6 Participants and Procedure

Twenty-two participants were recruited for this experiment by sending an email to student lists, distributing posters around the University campus, and by word of mouth. An information sheet introducing the experiment and its general goal was sent to those people who expressed an interest in participating. Participants were advised about the nature of the activity they would be performing and the type of equipment they would be using. Ethical approval was obtained from the University Research Committee prior to the start of the experiment. Participants were informed that they could stop the experiment at any time if they feel they need to.

On the experiment day, three preliminary checks were carried out on participants: visual acuity, colour vision and hearing.

Foveal vision was checked using a Landolt ring acuity test from 2 m observation distance, see Figure 4.6. A Landolt ring is a circle with a gap (a missing part in the circle, similar to the letter ‘C’) where the stroke width of the ring and the gap are both one fifth of its overall diameter. Participants need to indicate the direction of the gap which could be in any of the four directions, up, down, right, or left. The rings are organised in rows, starting from the biggest rings (top) to smallest (bottom). The researcher chose a random ring from each row, starting from the top, and asked the participant to state aloud the direction of the missing part.

The participants wore their normal corrective lenses for the acuity test and for the test trials, if they would need to wear them while cycling (seven participants wore lenses). All the test participants registered a Snellen acuity between 6/10.4 and 6/8.2, equivalent to between +0.24 and +0.14 log MAR which is above the lowest acuity required for car driving in the UK (6/12 Snellen scale) (GOV.UK, 2018).

Second, an Ishihara colour perception test was used to check for the presence of colour blindness. The Ishihara test (and also the acuity test) were conducted under a D65 daylight simulating fluorescent light source. According to the Ishihara colour perception test, all participants had normal colour vision.

The third preliminary check was on the hearing ability of participants; this was confirmed by testing ability to detect the audio stimulus to exclude the possibility that a participant failed to respond due to inability to hear the sound. All participants confirmed before the trials that they were able to hear the dual task beep.

The participants were asked to report whether they considered themselves to be experienced or casual cyclists. Eleven of the twelve participants who were included in the analysis (see section 5.2) considered themselves to be experienced cyclists, and one a casual cyclist, see Section 5.2 in Chapter 5 for criteria used to filter out low quality recordings resulting in the current sample. The participants received a £20 incentive payment for contributing to this work.

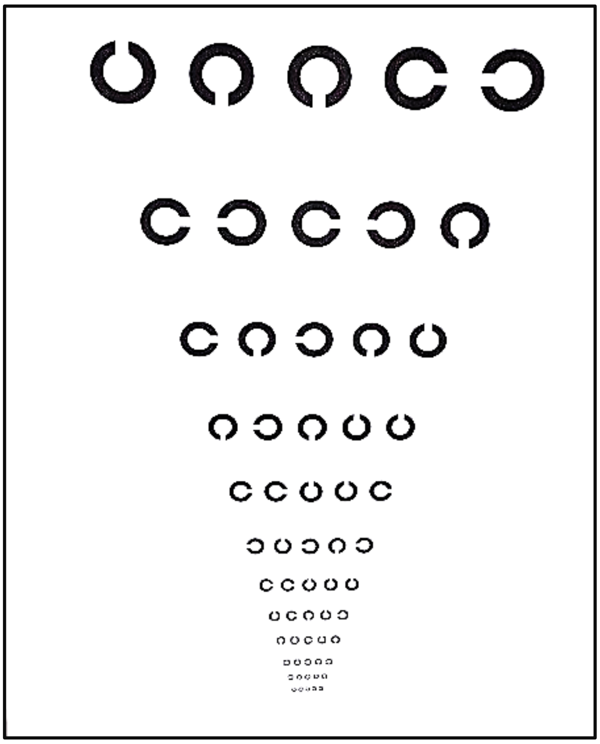

Figure 4. 6. Landolt ring acuity test sheet (A4 size page) used in the experiment. Participants observed the sheet from 2 m distance.

On arrival at the laboratory participants were asked to read the participant information sheet and sign the consent form. They were then asked to put on the eye-tracking glasses using a head strap to hold the glasses steady. Electrodes for measuring SCR were attached to the participants' fingers and the SCR system was started.

Following the manufacturer's instructions for the eye-tracking device, calibration was achieved by asking participants to fixate on a static object placed at a distance of approximately two metres. If there was any variation between the fixation mark and the target object, this was corrected by the experimenter by moving the on-screen gaze mark from its current inaccurate location to the target location. Following successful calibration, fixation recording commenced. The participant was asked to observe, at a close distance, the AcqKnowledge software display on the SCR laptop for at least three seconds. This is because the display included a running timestamp that would enable the eye-tracking video and data to be synchronised with the SCR data during post-trial processing. The laptop was then placed in a bicycle pannier and the participant and experimenter left the laboratory and went to the starting point on the cycling route.

To align the eye-tracking and dual task response times, the participant was required to look at the dual task response button and press it five times immediately before starting the trial. This provided a distinctive timestamp within the dual task data that could be synchronised with the eye-tracking video. The participants were instructed to respond to the dual task audio stimulus during the trial by pressing the button attached to the bicycle handlebar.

Cyclists followed the fixed urban route in both daytime and after dark. These two trials were conducted on separate days, to avoid the participants getting used to the route which may lead to less spontaneous eye fixations.

After dark trials were conducted between 18:00 and 21:00; daytime trials were conducted between 9:00 and 18:00. The experiment was conducted during February and March 2016, with sunset occurring between 16:48 (1st of February) and 19:39 (30th of March) (TimeAndDate, 2018).

4.7 Data Capture and Treatment

This section provides a description of the three parallel measurements used in the study, including details of their apparatus.

4.7.1 Eye-tracking apparatus

Gaze directions were captured using eye-tracking glasses (SMI ETG 2W analysis Pro) worn by the participant, see Figure 4.7. These were connected to a mobile recording device (Samsung Galaxy S4 GT-19506) and operated by iView ETG 2.1 software. This recording device was stored in a waist bag worn by the participant. Data were recorded using a sampling frequency of 60 Hz.

Figure 4. 7. SMI eye-tracking glasses and mobile recording device used in the study.

The recorded data were then downloaded to a laptop running Begaze SMi experiment suite 360°. This software analyses the recording and generates a more comprehensive data file, which provides details about fixations, saccades, blinks, and the coordinates of the gaze position. It has a semantic mapping feature enabling fixations to be placed into different target categories, see Section 4.7.2 and Figure 4.8. The data can automatically be extracted to Excel for further analysis.

In this study, only eye fixations were used (saccades or blinks were not used). These instances where the participant’s gaze settles on a location in the scene for a specific time were identified using the event detection method of Begaze, which calculates a variety of eye metrics including fixations (SMI, 2016). This automated process has an advantage over the traditional method of calculating the dwell time or gaze coordinates when identifying fixations, as it is both time-efficient especially for long experiments and excludes human errors that are likely to occur when manually identifying eye fixations. This method has been implemented previously (Mantuano et al., 2017; Vansteenkiste et al., 2013; Viaene et al., 2016; Zeuwts et al., 2016).

The method is based on identifying two consecutive saccades, and the period between them is considered a fixation (Holmqvist et al., 2011; SMI, 2016). Thus, each fixation is bordered by two saccades. As per the Begaze software manual, fixations of under 50 milliseconds are removed within the event detection process. Using a fixation duration threshold of 50 milliseconds and above in eye-tracking studies is acceptable (Inhoff and Radach, 1998).

4.7.2 Semantic mapping: defining target categories

As explained earlier, eye fixations are the main eye-tracking data utilised to assess cyclists’ visual behaviour in current study. For these fixations to be meaningful, they need to be mapped with a reference describing what the participant is looking at; thus 8 categories were used in the semantic mapping stage.

These categories were derived from previous eye-tracking studies (Fotios et al., 2015b; Fotios et al., 2015c; Foulsham et al., 2011; Vansteenkiste et al., 2014a), in addition to a pilot analysis conducted on a sample of recordings to assess the frequency and nature of items which appear in the experiment environment and thus to determine the most suitable target categories’ titles.

Table 4.3 provides a description and literature justification for the eight target categories. These categories were used to analyse cyclists' visual behaviour, that is to identify where cyclists look and whether there are differences between critical fixations (either dual or SCR fixations) and all fixations' pattern.

Fixations' categorisation was performed by using the semantic mapping function of BeGaze, which enables classifying each fixation to a target category. The software will show two screens where the right screen is showing the scene observed by the participant with the gaze mark on an item, that is where the participant was looking at this moment, while the left screen shows the target categories. The researcher makes a judgment about which category best suits a fixation and clicks on a coded area on the left screen i.e. target category (the area of interest: AOI). This will map each fixation with a target category, see Figure 4.8.

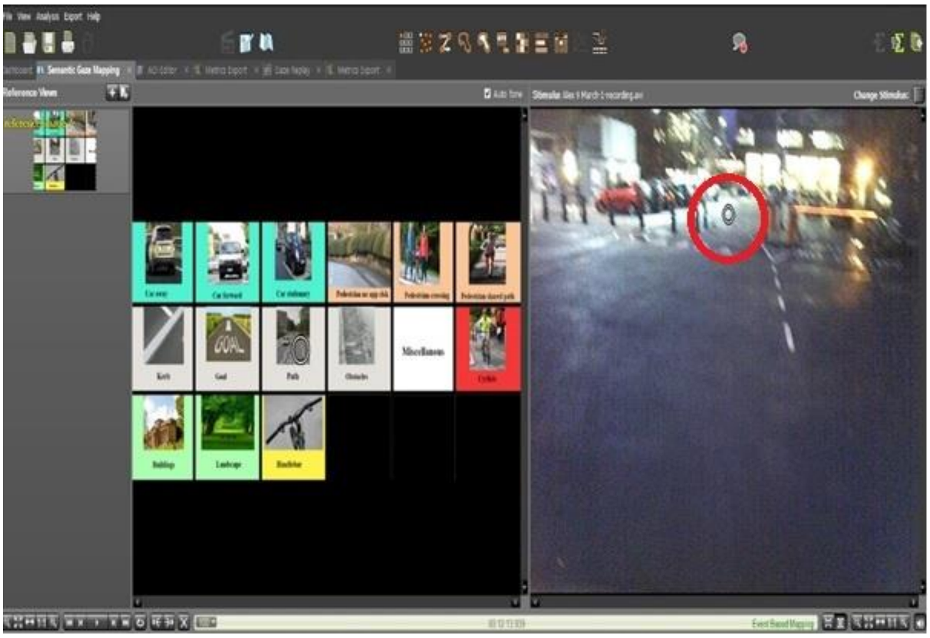

Figure 4. 8 Screenshot showing semantic mapping function two widows of Begaze. The right part of the screen shows the scene observed by the participant during the trial with the gaze mark (inside red circle). The left part shows the coded area of interests (target categories) where the researcher can link each fixation to a designated target category.

To assess the consistency of the experimenter's allocation of fixations to different target categories, 17% of all trials were analysed independently by a second person (Dr James Uttley – research associate). When considering allocation to all eight categories, the two coders agreed on 65% of trials. This is below the level of agreement found in other studies (e.g. coding agreement > 90% as found by Foulsham et al., 2011).

Table 4.3. Description and literature justification of the eight target categories.

Target category	**Description**	**Justification**
Path	Fixations on the road surface ahead of the bicycle	Previous studies on cyclists have indicated the importance of fixating on the road path (Mantuano et al., 2017; Vansteenkiste et al., 2014a; Vansteenkiste et al., 2017).
Goal	A way finding fixations above street level	This is essential for fixations related to navigating and planning ahead. This category appeared in previous research (Fotios et al., 2015b; Vansteenkiste et al., 2013).
Obstacles	Any object or irregularity on the path which may cause an accident if not detected including small posts	Used before in studies on pedestrians, it is proposed vital for cyclists' safety on the roads. It is therefore anticipated to influence gaze behaviour (Fotios et al., 2015b).
Kerb	Pavement/edge of footpath	The expectation is that being aware of kerb distance is vital for cyclists to avoid accidents.
Cars	Moving, crossing and stationary cars which participants encounter on the experimental route	Cars are a major source of cycling accidents on the roads; thus, they are visually important objects in the steering decisions made by cyclists. They are therefore expected to have an effect on gaze behaviour (Werneke et al., 2015).
Cyclists & pedestrians [1]	Either on shared path in the distance or crossing the road	Cyclists usually encounter other cyclists and pedestrians while riding; thus, fixations on this category will explain their visual criticality to cyclists (Dozza and Werneke, 2014; Mantuano et al., 2017; Werneke et al., 2015).

Table 4.3 (Cont.)

Buildings	Fixations on facades of buildings	Separating buildings in an independent category could be of benefit in explaining how cyclists observe the built environment (Forsyth and Krizek, 2011). In urban environment buildings constitute a large portion of surfaces/objects in the participants surround.
Miscellaneous	All other objects or surfaces	All other fixations which do not fit the previous categories (Foulsham et al., 2011).

[1] **Note that ''Cyclists & pedestrians'' will be considered as one target category throughout the thesis.**

General Fixations (miscellaneous) were a notable source of disagreement between the coders. However, when the categories were collapsed into the 3 categories utilised by Foulsham et al. (person, path and miscellaneous), the coder agreement was similar (87%) to that of other studies (Foulsham et al., 2011; Uttley, 2015). This suggests, perhaps unsurprisingly, that more categories lead to less agreement in fixation categorisations between coders.

4.8 Dual task

4.8.1 Reaction time

The dual task required the cyclist to press a button, fixed to the left bicycle handlebar, close to the cyclist's thumb to allow use without taking hands off the handlebar, each time a beep was heard, a method used in previous research (Fotios et al., 2015b). A loudspeaker, fixed to the helmet strap, provided the audio stimulus at intervals which varied randomly in length between one and three seconds. An Arduino micro-controller generated the stimuli and detected button presses through an interrupt function and logged these events on an SD card, the data is logged in an excel sheet to be used in the analysis phase.

Failure or slow response to the beep is interpreted to reveal a diversion of attention to something significant in the environment. In each individual trial, moments when participants' reaction times to the audio stimulus were more than or equal to two standard deviations above the mean reaction time (MRT) were considered critical. Those moments are identified as outliers of the overall reaction during the trial, a method that complies with the procedures described by Field (Field, 2013). In this study, outliers are slow reaction incidents to the beep.

Mean and its associated measure of variance, the standard deviation, are used here as a cut-off threshold to identify outlying reaction times that are particularly large. The mean is not being used here simply as a measure of central tendency and therefore considerations of whether the reaction time data is normally distributed are therefore not warranted. Indeed, reaction times are known to generally be skewed to the left with a long positive tail indicating a number of possible outliers (Whelan, 2008). This applies even in the most controlled conditions (Harald Baayen and Milin, 2010). Use of mean and standard deviations are a commonly applied approach in psychology research to filtering reaction time data (e.g.Lachaud and Renaud, 2011; Ratcliff, 1993), and the use of median reaction times has been warned against (Miller, 1988). Using two standard deviations above the mean to identify outliers has been adopted in previous research (Whelan, 2008), including in research similar to the current study to identify outlying reaction times on a dual task to identify critical fixations of pedestrians (Fotios et al., 2015b).

In addition, a pilot study (see Appendix A) was conducted to assess the use of dual task and SCR approaches in the current study where 2 standard deviations above the mean was found suitable to define outliers. The mean plus two standard deviations method for identifying outlying, long reaction times was therefore used in the current study.

4.8.2 Dual fixations

Dual fixations are eye-tracking fixations that fall within the time window of a critical dual task response, that is a slow or missed response to the audio stimulus. These fixations were classified into eight visual categories.

Visual events or items in the environment likely to divert participants' attention may have occurred shortly before or after the audio beep, so the moment the button was pressed would not reveal precisely the visual stimulus causing a slow or missed response, that is where the participant was looking at that time. To overcome this problem, a two-second window was allowed for inspecting simultaneous eye-tracking fixations, one second on each side of the audio beep occurrence. This time span was chosen because the minimum interval between beeps was one second, and any larger window would possibly have resulted in an overlap between the critical responses of two adjacent beeps.

The synchronisation is done in Excel software where all fixations identified by Begaze are plotted, and its time is matched precisely within the dual task two-second window. If the start time, end time, or both start and end time of a fixation occurred within the dual task two-second window, the fixation was defined as a dual fixation.

4.9 Skin Conductance Response

4.9.1 SCR apparatus

The BIOPAC system consists of electrode patches and a transmitter unit (BIOPAC Bionomadix). The single electrode patch is a 2 x 1 cm plastic piece, which has adhesive gel to enable attaching it to the determined location on the participant’s skin. The patch consists of a galvanised tip directly in contact with the skin, thus passing the electrodermal signal to the transmitter unit by a wired connection, Figure 4.9 and 4.10.

The electrode patches were attached to the tips of the cyclist’s thumb and little finger (van Dooren and Janssen, 2012), allowing the other three fingers to remain free to operate the brake lever. The electrodes pass a steady low current where fluctuations in their characteristics indicate changes in skin conductance which is measured in micro-Siemens (µS). The transmitter is a wireless unit which transfers the participant’s electrodermal activity data to the data acquisition unit.

Through pilot testing, it was confirmed that a good electrodermal signal, a sharp signal without noise (for details about signal clarity see Section 4.9.2), is obtained at these locations, in the current study they were thumb and little finger, which were suggested to provide a clear signal (Dawson et al., 2007).

The electrodes were connected by wire to the EDA slot of the transmitter unit which was attached to the participant’s right-hand wrist using an adjustable strap, see Figure 4.9. The EDA signal was then sent wirelessly to the Data Acquisition Hardware which was connected to a laptop running AcqKnowledge 4.4 software. During trials, the MP150 laptop and power source for the equipment were positioned inside a pannier fitted to the rear of the bicycle, see Figure 4.5.

Data were recorded at 200 Hz which is within the region considered to provide an accurate representation of signal shape (Figner and Murphy, 2011). AcqKnowledge 4.4 software was used to display and record data for this measurement, and later in the analysis phase.

Figure 4.11 illustrates SCR data capturing and processing system. In this experiment, all potential hazards and other objects were natural and non-specific; the experimenter did not deliberately introduce any events such as non-specific SCR: NS-SCR.

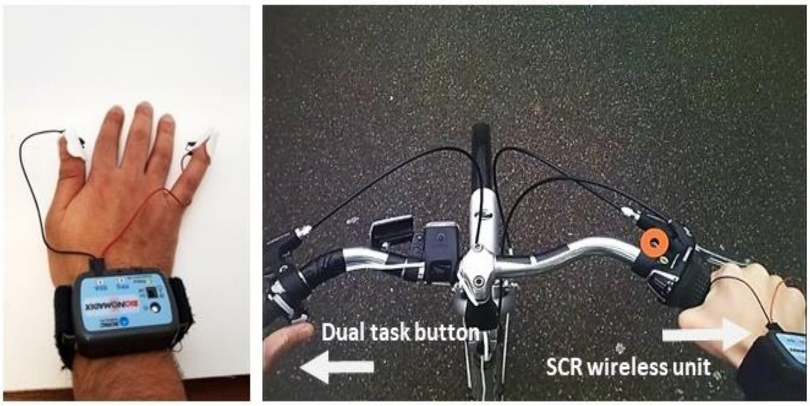

Figure 4.9. (Left) Electrodes for measuring SCR attached to the thumb and little finger of the right hand. (Right) Photograph of the bicycle handlebar to show the dual-task button and SCR wireless unit.

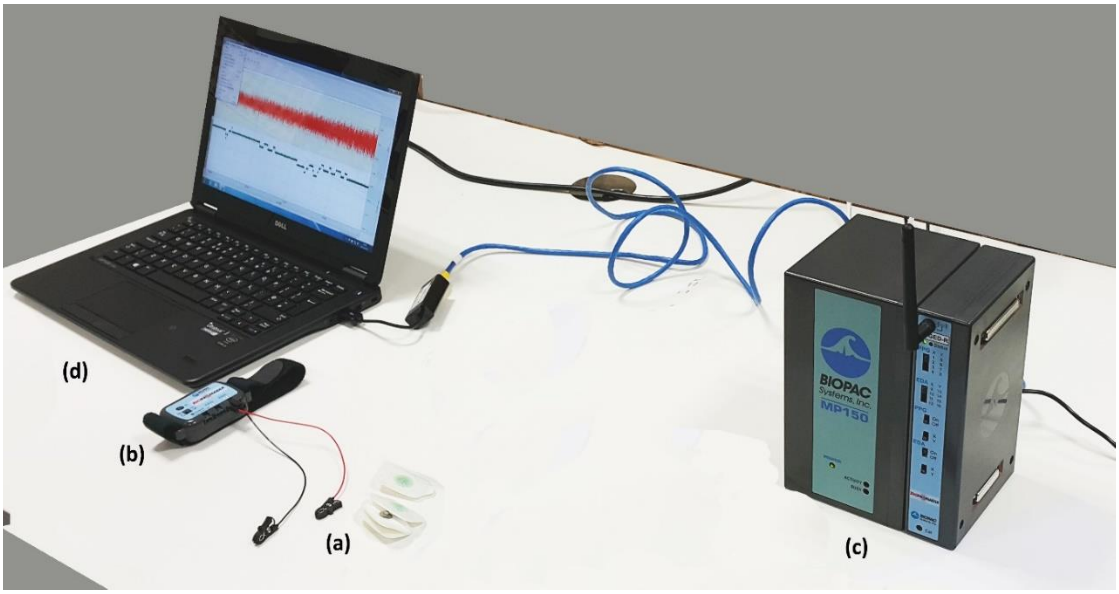

Figure 4.10. Main parts of the BIOPAC system: a) electrodes and patches b) transmitter unit c) acquisition hardware d) Laptop.

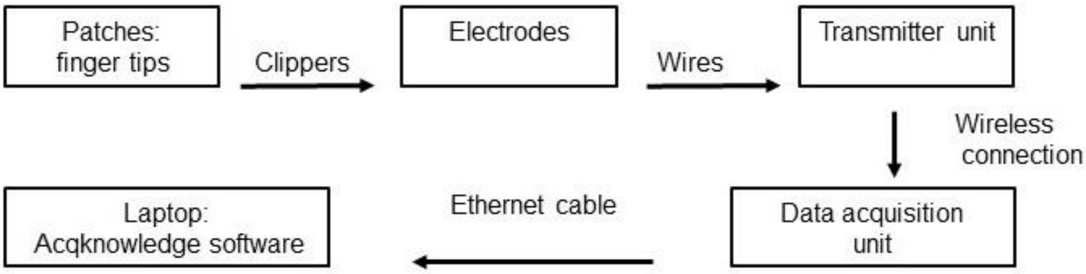

Figure 4. 11. The electrodermal activity (SCR) data capturing and processing system.

4.9.2 SCR analysis

Within the recorded SCR, artefacts or noise may exist. A potential source of noise is the contact point between the skin and the device electrode which could be affected by participants' excessive movement (e.g. finger clenching) or by the electrodes being struck. If these artefacts are not removed from the data, they could wrongly be counted as SCR (Taylor et al., 2015).

To reduce possible artefacts and noise, the data waveform was re-sampled and a low pass filter was used following procedures recommended by Braithwaite et al. (2013). An automated computations function ("cycle routine") in AcqKnowledge was then followed to identify SCRs with using an amplitude threshold of 0.05 µS (Braithwaite et al., 2013) (see Section 4.9.3 for more details about threshold selection and analysis). Figure 4.12 (top) shows screenshots of skin response at the raw stage and then after resampling, filtering and locating SCRs (bottom). Figure 4.13 provides an illustration of one SCR: start, peak, and an end.

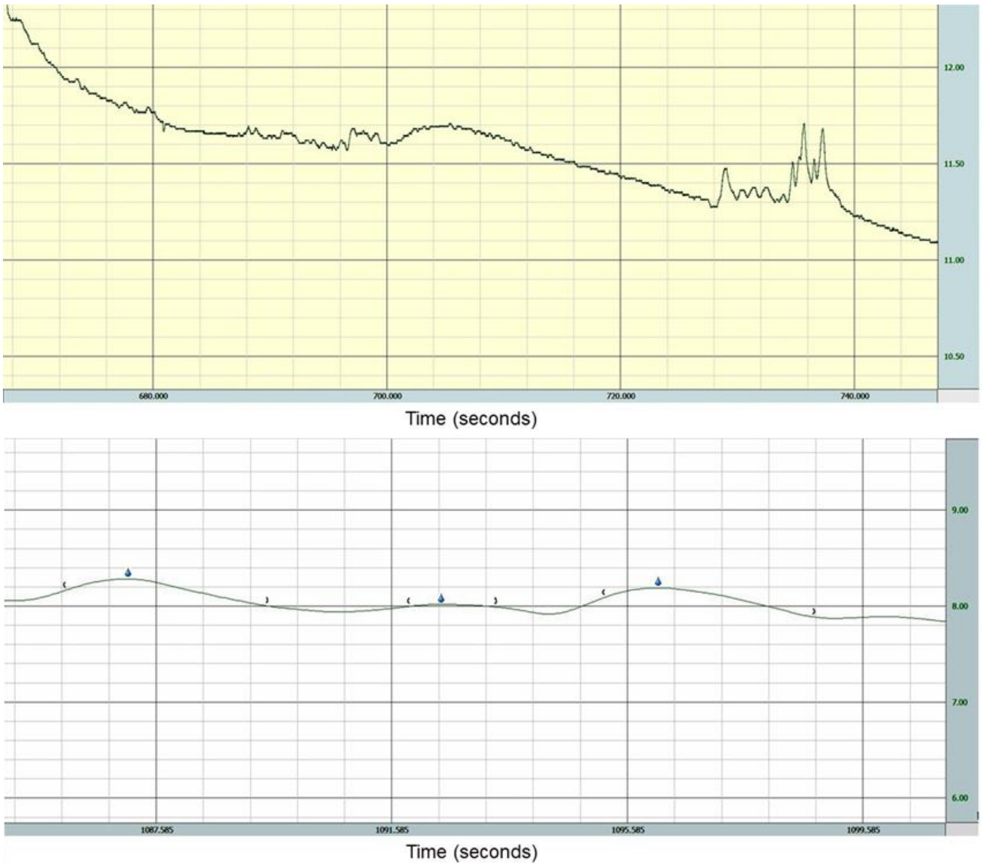

Figure 4.12. Examples of SCR data. (Top) Raw SCR data. (Bottom) SCR data after filtering and locating skin conductance responses where brackets refer to the start and end of each SCR. X-axis denotes (time elapsed in seconds). Y-axis denotes unit of electrodermal activity (SCR) in micro-siemens (µS).

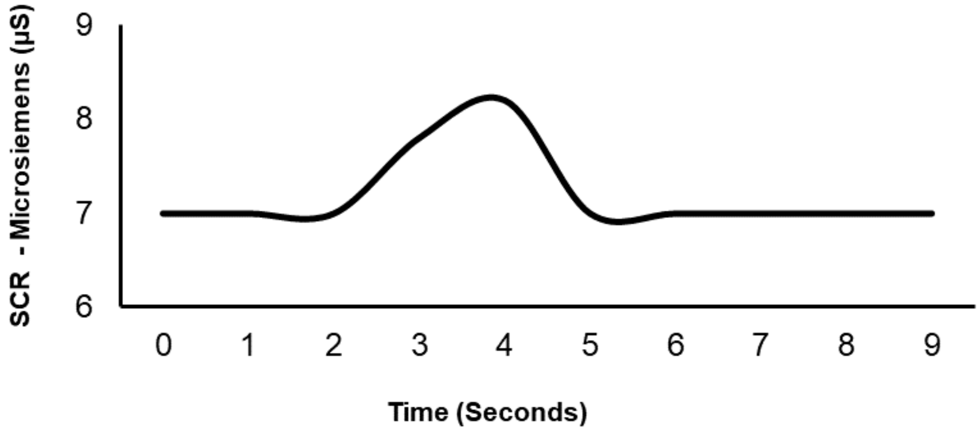

Figure 4.13. Illustration of one SCR taken from an actual trial showing the three phases of SCR: onset, peak, and end.

4.9.3 SCR Threshold

The number of SCRs produced in an experiment depends on the unique electrodermal activity of each individual and the level of physical activity during the study, that is the individual arousal level.

Take first the individual differences, SCR being a result of complex neural/biological processes could exhibit different electrodermal characteristics between participants; for example, amplitude level and number of responses produced for each individual when a sample of people is re-examined under the same stimuli and conditions could vary (Braithwaite et al., 2013).

SCR is individually unique, even in highly-controlled studies. This uniqueness is the product of individual differences in sweat-gland activity of the skin and dissimilarities in the cognitive processing of information sent from the sympathetic nervous system. Some people do not produce SCR at all, or do so at a very marginal level (Dawson et al., 2007). The study's participants were all SCR responsive and this was confirmed from their EDA recording.

Using a threshold is an essential procedure in studies implementing the SCR method. The idea behind using a threshold stands on eliminating weak responses with low amplitude changes in skin conductance. The researcher in such cases is interested in SCRs with amplitudes higher than the threshold which, in theory, indicate the more critical events (Braithwaite et al., 2013).

For a physically intense study, the researcher should pay attention not to include irrelevant SCR data from low-amplitude skin responses in a study where plenty of stronger responses exist. This explains that the SCR amplitude is dependent on each study context and activity level. For example, including 50 responses above a 0.02 µS threshold where there are another 150 responses above a 0.05 µS threshold would include relatively non-significant events in the analysis.

SCR thresholds of 0.01 to 0.05 µS have been considered acceptable, depending on the level of activity and the type of experiment (Dawson et al., 2007).

To examine the effect of variation in SCR threshold, the mean number of SCRs with different threshold was checked for 5 test subjects. Table 4.4 provides a comparison between SCR thresholds of 0.04 and 0.02 µS for a sample of five participants. The reason these thresholds were used in the comparison instead of 0.01 and 0.05 µS, for example, is a pilot estimation that a narrower gap is better for illustrating the sensitivity between thresholds than using extreme thresholds. At an early stage of the experiment, using two thresholds for comparing five participants was a time-efficient option. Table 4.4 illustrates the individual differences between participants in the number of SCRs identified under each threshold (fewer SCRs are identified under higher threshold e.g. 0.4 µS). The data are for several participants during one trial in similar light conditions (after dark).

Table 4. 4. Comparison of the number of SCRs identified when applying thresholds of 0.02 and 0.04 µS, using a sample of 5 participants.

Participant ID	Threshold 0.02 µS	Threshold 0.04 µS
1	84	61
2	220	184
3	163	36
5	27	7
6	164	136
Mean number of SCRs	131.6	84.8
Standard deviation	76	73

Participant 1, who achieved the median number of SCRs under the 0.04 µS threshold (being the more conservative threshold in this comparison), was selected for further analysis. Figure 4.14 compares the effects of five common thresholds (0.01 - 0.05) found in the SCR literature on the number of SCRs identified in the same trial of Participant 1; the larger the threshold value, the smaller the number of SCRs identified as those responses below the threshold are filtered out. Although using threshold above 0.05 is not common in the literature, using the power trend line (the dotted line Figure 4.14) showed using a higher threshold than 0.05 will not overly affect the number of SCR identified. As the trend line had a very high R^2 value (0.9965) we can be confident in its use to extrapolate estimates of SCR numbers beyond 0.05 µS.

Based on the previous pilot analysis of the SCR threshold and considering the level of physical activity during this study (outdoor cycling), the threshold used for the main analysis was 0.05 µS. This means that smaller SCR amplitudes were filtered out of the analysis.

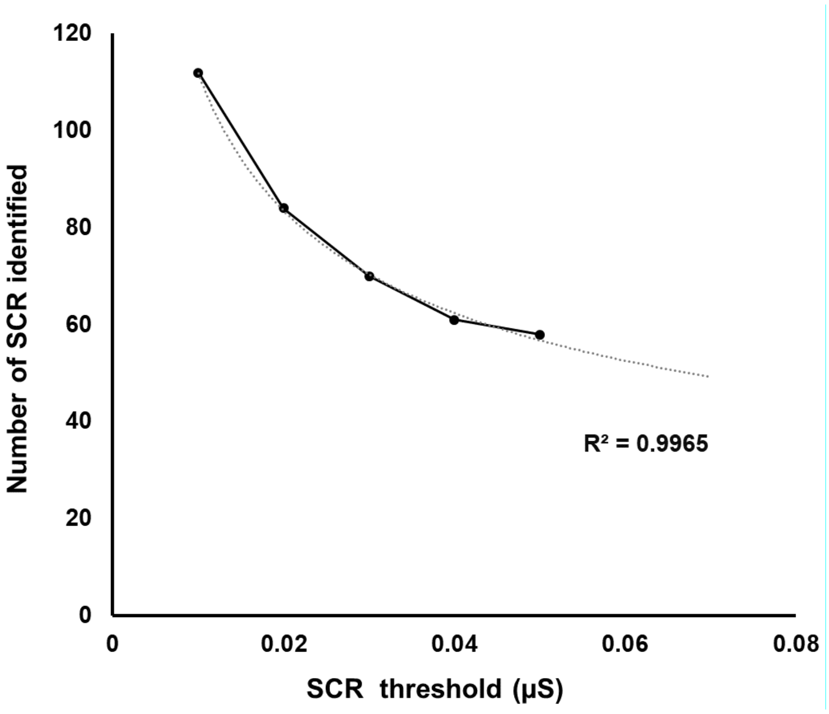

Figure 4. 14. The number of SCRs identified when altering the threshold for changes in skin conductance; data obtained from the same participant during one trial. The dotted line illustrates the best fit line using power trend line function (two forecast units).

This threshold is considered conservative compared with previous SCR studies (Armel and Ramachandran, 2003; Braithwaite et al., 2014). Having said that, a level of subjectivity exists when deciding the threshold for the analysis; however, this remains an acceptable procedure left for careful consideration by the researcher (BIOPAC, 2014). To offset this subjectivity, the chosen threshold was used for analysing the data of all participants. Initial examination of the data using the 0.05 µS threshold showed that a reasonable number of SCRs were retained even when using this conservative threshold. A smaller threshold may have led to an inappropriately large number of SCRs being included in the analysis, which would not have been reflective of the purpose of using the SCR threshold in this context – to identify critical moments that may be relatively rare.

Some relevant SCR may be filtered out by choosing a 0.05 µS threshold, but this is a similar situation for all studies implementing the SCR method, and is ultimately related to the complex neural processes when an SCR is produced. Filtering out some relevant SCRs should be less harmful to the reliability of the analysis compared with including less significant SCRs.

4.9.4 Latency and SCR fixations

Latency is the period of time (in seconds) between the stimulus onset and initiation of the SCR. The skin takes usually between one and four seconds before reacting to a stimulus (Braithwaite et al., 2013; Dawson et al., 2007).

When synchronising the recorded SCRs and eye-tracking fixations, consideration was given to the latency aspect of SCR. To determine those fixations associated with a significant change in SCR, this latency means looking for the item fixated one to four seconds before the onset of SCR to check if this factor matters, two latency periods were considered for a test sample of four participants: for window A, these were the items fixated one to three seconds before the SCR was recorded, and for window B, the items from two to four seconds before. The proportions of fixated items are shown in Figure 4.15. For this non normally distributed the Wilcoxon test (non-parametric, repeated measure) did not indicate significant variations in the proportions between these two windows. Therefore, window A was used, meaning that the coders looked for objects fixated in the one to three-second period before the beginning of the SCR response.

The identified SCRs were time synchronised with eye-tracking fixations following the same procedure described under dual fixations, Section 4.8.2. This is a necessary step as it enables the investigation of where a participant was looking at the moment an SCR was produced.

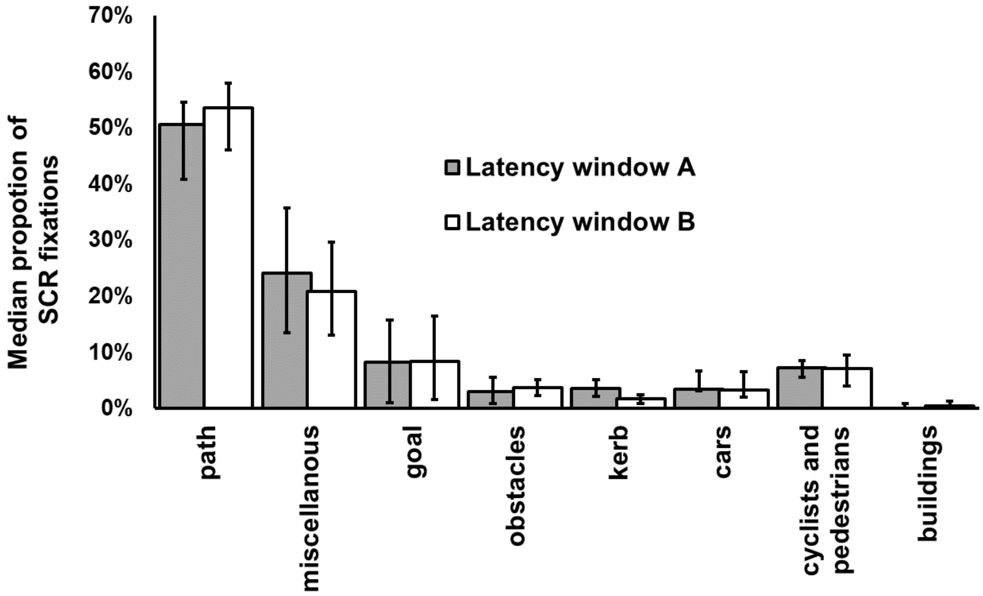

Figure 4. 15. Comparison of latency windows A and B: Median proportions of SCR fixations in target categories for four participants during after dark trials. The interquartile range represented by error bars.

4.10 Summary

This chapter described the method used to measure cyclists' gaze behavior using eye-tracking apparatus. Dual task and SCR approaches were used to explore methods for establishing critical fixations from all fixations. The 2.2 km route included four sections to enable analysis of predicted differences in visual behavior following changes in urban characteristics of each sections. Three types of data validation were carried: Validation of target categories coding; the effect of different SCR thresholds on the number of SCR identified and latency window influence on SCR data.

The next chapter focuses on results of the eye-tracking experiment investigating what visual tasks are important for cyclists while cycling in urban environment; whether there is a difference in visual behavior when cycling during daytime or after dark; the effect of the urban surround on visual behavior, and similarities and dissimilarities between dual and SCR fixations, concluding with a discussion on findings.

Chapter 5. Eye-tracking: Results and discussion

5.1 Approach to analysis

Chapter 4 described the method with which eye-tracking was utilised to record the visual behaviour of cyclists in a natural urban context. In addition to eye-tracking, skin conductance response (SCR) and responses to an audio dual task were recorded to identify critical visual fixations. Critical fixations are assumed to be important for safe cycling, hence the priority features for lighting after dark. This extends past work on eye-tracking with cyclists (Boya et al., 2017; Mantuano et al., 2017; Vansteenkiste et al., 2014a; Vansteenkiste et al., 2017) by conducting trials in a natural setting and by using a parallel measure to discriminate between casual and critical visual fixations. This chapter presents the results and discussion for eye-tracking, the dual task, and the SCR recordings, and uses these data to determine the critical visual task for cyclists.

5.2 Analysis of eye-tracking data: Sample and data quality

While 22 participants completed both trials (during the day and after dark), missing data in the eye-tracking recordings led to the removal of responses from 10 participants. Data loss, low tracking ratio, and gaze mark inaccuracy may sometimes occur in eye-tracking recordings, especially in studies involving high levels of movement or those conducted in a real world context where numerous environmental and personal factors can affect the quality of the data thus in eye-tracking studies. Data loss in the recordings, either partially or fully, is thus the principal reason for excluding trials from analysis (Holmqvist et al., 2011). However, SMI eye-tracking equipment does not provide reasons for this loss. In previous eye-tracking studies comparable to the current study, the reduction in the experiment sample was predicted e.g. 50% (Vansteenkiste et al., 2014a); 31% (Vansteenkiste et al., 2017); 19% (Mantuano et al., 2017).

Reasons for the loss of the fixation marker include external factors such as sun glare, heavy rain, and logistical complexity (Holmqvist et al., 2011). Sun glare, for example, could cause data loss; either because the participant closes their eyes partially or completely to avoid the glare, or because attrition occurs in the process of producing the video. It is recommended in future real world eye-tracking studies to ask participants to wear a shading cap to avoid direct sun falling on their eyes or the tracking glass[2].

Table 2.1 in Chapter 2 presented the details of eye-tracking data omitted in previous studies including the context where the experiments were conducted and the actual sample size after excluding low quality trials, for comparability.

In the current study the resulting set of data comprised of 20 trials in the after dark condition and 13 trials in the day condition. The current study utilised a repeated measures design whereby the same sample was subjected to comparable conditions to study the effect of different ambient light levels on cyclists' visual behaviour. Equal sample size for each light condition meant homogeneity was better for the comparison. This is important as the reliability of post hoc tests is reduced and statistical problems may arise when comparing unequal sample sizes under each condition (Field, 2013).

Twelve participants yielded good quality data in both day and after dark eye-tracking videos and were hence used for the current analysis. This sample comprised of 11 males and one female, eight of whom were aged 18-29 years, three participants were 30-49 years old, and one participant who was more than 50. While this is a smaller sample than employed in the trials, loss of data is common in eye-tracking studies and the resultant sample is comparable to previous studies, see Table 2.1 in Chapter 2.

To determine data quality, a three-step trial inclusion procedure was applied, a process derived from previous eye-tracking literature, see Figure 5.1 below.

First; trials with a tracking ratio below 80% were excluded (Mantuano et al., 2017; Vansteenkiste et al., 2017). The tracking ratio is the percentage of frames in which the eye tracker could determine the direction of gaze (Mantuano et al., 2017; Vansteenkiste et al., 2017). For example, when eye-tracking a participant gaze at 60 Hz, if the apparatus was able to measure the direction of the eye at 50 frames per

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[2] As recommended by Dr Richard Lilley, the Tracksys company representative (provider of SMI eye-tracking equipment).

second, the tracking ratio would be 50/60 = 83.33%. However, this does not guarantee that the measure is accurate.

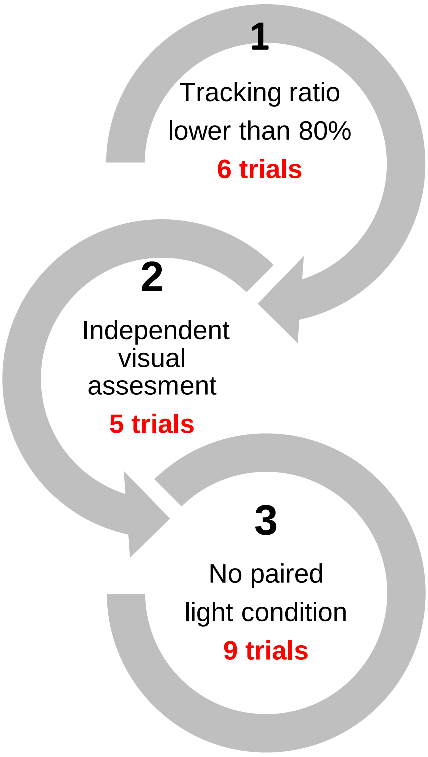

Figure 5. 1. The three-step inspection procedure used to assess the quality of eye-tracking recordings. The numbers in red font denote the number of trials omitted in each step.

For instance, when the system detects something else as the 'pupil' (e.g., eye makeup) the data quality is low even if the tracking ratio is high. Tracking ratio is, therefore, one of the measures of data quality but cannot be relied upon solely; visual validation is also required.

In this study, the tracking ratio for the trials included in the analysis ranged from 83.4% to 98.99%. Although some trials had a tracking ratio above 80%, the accuracy of the gaze mark was poor, namely a jumpy or fuzzy cursor. A visual inspection of all eye-tracking videos was therefore conducted by the experimenter and validated separately by a second reviewer, this as the second filtration step [3].

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[3] Researcher Dr Jim Uttley, lighting research group (University of Sheffield).

Third; any remaining trials that did not have a paired light condition (i.e. the participant yielded good quality day and after dark trials) were also excluded. This reduced the sample of good quality data by 27% from 33 (13 daytime trials and 20 after dark trials) to 24 trials (paired trials number for 12 participants.

Table 5.1 shows the number of trials excluded in each of the three quality inspection steps.

Table 5.1. Tracking ratio details and whether a trial was used or excluded from the analysis. Note: shaded cells are the participants who were excluded.

Participant ID	After dark trials		Day trials	
	Tracking ratio (%)	**Used or reason for omission**	**Tracking ratio (%)**	**Used or reason for omission**
1	***98.99***	***Used***	***96.2***	***Used***
2	95.1	No paired trial	75.13	Low tracking ratio
3	92.32	Unclear gaze mark	91.5	Unclear gaze mark
4	96.7	No paired trial	77.22	Low tracking ratio
5	92.56	Unclear gaze mark	90.2	No pair
6	***83.4***	***Used***	***89.1***	***Used***
7	***89.5***	***Used***	***97.5***	***Used***
8	95.2	No paired trial	57.3	Low tracking ratio
9	***97.6***	***Used***	***97.9***	***Used***
10	***96.4***	***Used***	***87.8***	***Used***
11	***97.8***	***Used***	***88.3***	***Used***
12	95.32	No pair	91.63	Unclear gaze mark
13	***92.4***	***Used***	***92.1***	***Used***
14	***88.8***	***Used***	***82.9***	***Used***
15	96.7	No paired trial	79.38	Low tracking ratio
16	***98.5***	***Used***	***97***	***Used***
17	***97.1***	***Used***	***96***	***Used***
18	95.9	No pair	97.68	Unclear gaze mark
19	***98.4***	***Used***	***97.3***	***Used***
20	***96.8***	***Used***	***96.5***	***Used***
21	92	No paired trial	50.64	Low tracking ratio
22	97.5	No paired trial	55.35	Low tracking ratio

A reduction in sample size may affect the overall pattern of fixations recorded in a survey. However, this does not appear to be the case for the current study. Figure 5.2 below shows the distribution of all fixations across the target categories for the 20 participants completing after dark trials (the original sample). These were similar to the figures obtained for the retained sample (12 participants). Similarly, Figure 5.3 shows the results for the 13 participants completing daytime trials and for the reduced sample of 12 participants. If the data retention process had had a significant impact on the results, the two datasets within each figure would have exhibited different trends. This was not the case as both the original and the reduced samples exhibited very similar trends. Wilcoxon signed rank tests were conducted to confirm this finding and no significant differences were found between the samples in either day or after dark trials.

Results for the after dark comparison were as follows: (path p=0.05; miscellaneous p=0.201; goal p=0.212; obstacles p= 0.619; kerb p=1.000; car p= 0.309; cyclists & pedestrians p=0.789; buildings p=0.121) while results for the day trials were as follows: (path p=0.678; miscellaneous p=1.000; goal p=0.919; obstacles p=0.905; kerb p=0.527; car p=0.798; cyclists & pedestrians p=0.919; buildings p=0.472). The reduced dataset was therefore assumed to be a satisfactory representation of the original data.

The main concern of checking possible differences between the original and the retained samples is to assess if the overall trend of fixation distribution over target categories would differ between sample sizes. Wilcoxon paired comparisons found almost no significant difference between samples in either the day or after dark trials, except in one case where path category after dark gave near to significant value (p=0.050) but this was assumed marginal to the objective of this statistical comparison and not to affect the validity of using the 12 participant sample.

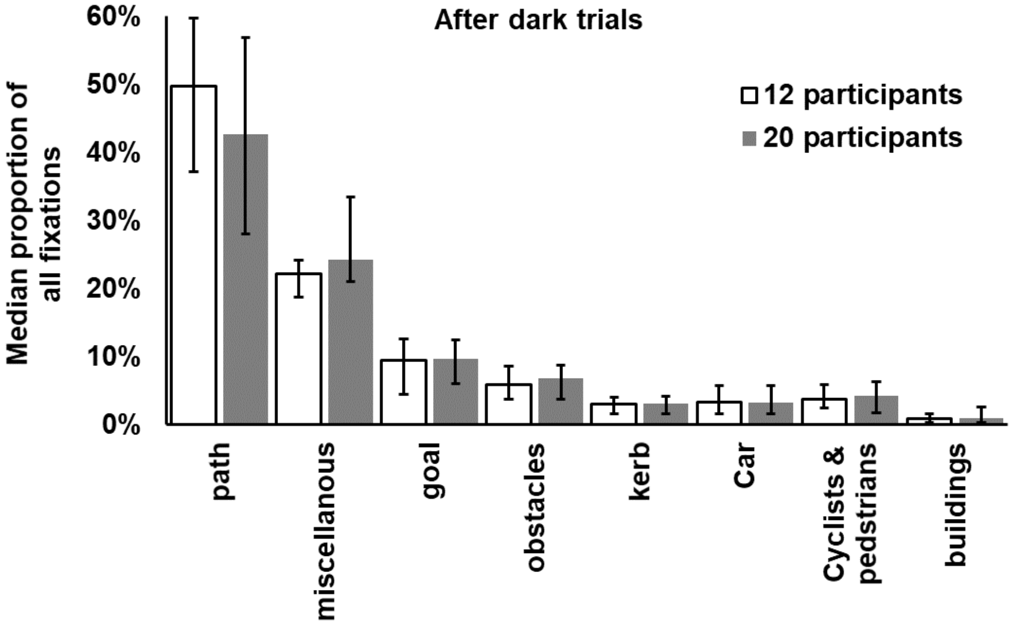

Figure 5. 2. The median proportion of all fixations over target categories (after dark trials) for the original sample (20 participants) and the retained sample (12 participants). The interquartile range represented by error bars.

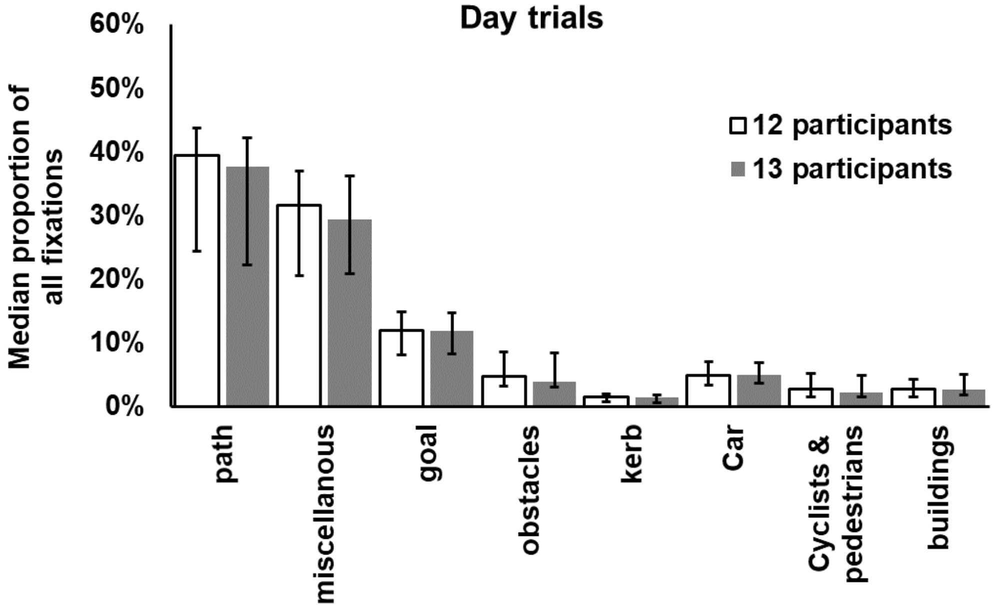

Figure 5. 3. The median proportion of all fixations over target categories (day trials) for the original sample (13 participants) and the retained sample (12 participants). The interquartile range represented by error bars.

5.3 Analysis of eye-tracking data: All fixations

All fixations refer to the visual fixations extracted by the eye-tracking software (BeGaze) without further refinement through the dual task or SCR data. As was described in Chapter 4, Table 4.1, these fixations were allocated to one of the eight target categories using the semantic mapping function of BeGaze. This allocation process was validated by an independent coder (see Chapter 4, Section 4.7.2).

Overall, analysis of All fixations allocations to categories suggested they were not drawn from normally distributed populations (see Appendix B for results of data normality analysis).

Thus, when looking for the central distribution of the data, the median was used to report the results. This is because extreme values are common in data that is not normally distributed and the median is less influenced by such values than the mean (Field, 2013). The interquartile range was used to determine the dispersion of values around the median (rather than standard deviation as is commonly used with normally distributed data) and is defined as the difference between the upper quartile and lower quartile. The former provides a value at 75% of the data range (above the median), whereas the latter provides a value at 25% of the data range (under the median). One advantage of using the interquartile range is that it avoids the possibility of extreme values influencing the results (Field, 2013).

In line with previous work (Fotios et al., 2015b), analyses were carried out using the proportion of fixations on each category of the target rather than the absolute frequency. This was because the number of fixations (all, dual, or SCR) within a trial varied between participants. The use of proportions instead of frequencies also allowed for better comparability, between target categories, when collating the sample data. For example, if a participant conducted 80 fixations during a trial, 20 of which were categorised as obstacles, the obstacle category will constitute 25% of the total fixations in that trial.

Figure 5.4 shows the median of the distribution of all fixations across the eight target categories for across both light conditions. These show that the tendency for cyclists to fixate on each visual category differs, with the highest proportion of fixation being on the path. The Friedman's test (non-parametric data, repeated measures) suggested that the distribution of fixation proportions between the categories was significantly different ($p<0.001$).

Table 5.2 presents the results of Wilcoxon signed rank (non-parametric data, repeated measures) paired comparisons between target categories for all fixation data, where the goal, path, and miscellaneous categories were found to differ significantly from all other categories.

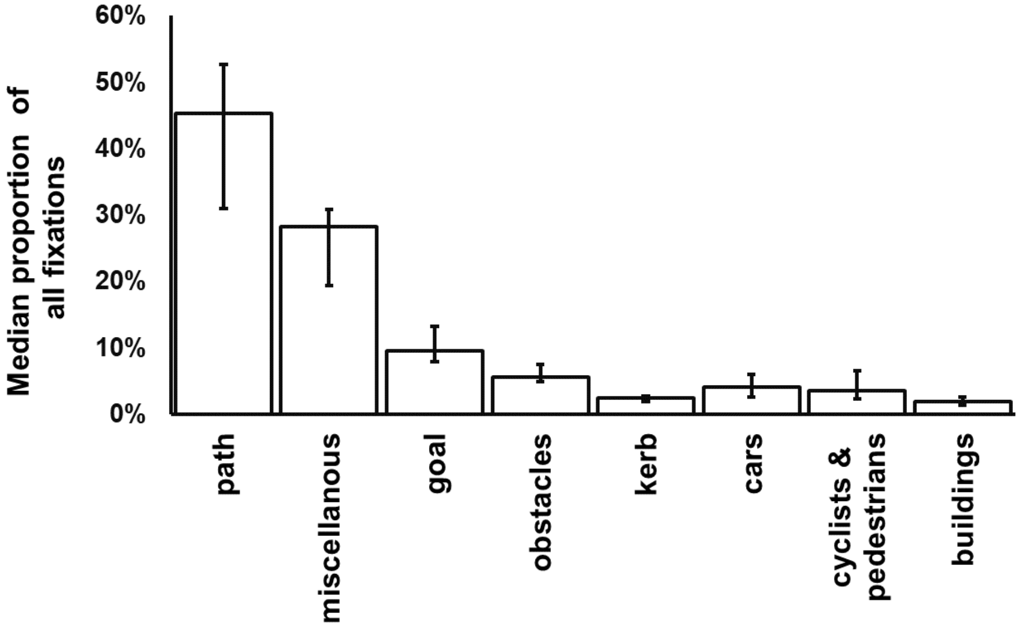

Figure 5. 4. The median proportion of all fixations over target categories across day and after dark. The interquartile range represented by error bars.

Table 5. 2. Wilcoxon paired comparisons of target categories (proportion of all fixations) for day and after dark data combined.

Category	Path	Obstacles	Kerb	Car	Cyclists & pedestrians	Miscellaneous	Buildings
Goal	**(0.002)**	**(0.026)**	**(0.003)**	**(0.002)**	**(0.002)**	**(0.002)**	**(0.002)**
Path	-	**(0.002)**	**(0.002)**	**(0.002)**	**(0.002)**	**(0.025)**	**(0.002)**
Obstacles	-	-	**(0.003)**	0.264	0.208	**(0.002)**	**(0.010)**
Kerb	-	-	-	**(0.045)**	0.066	**(0.002)**	0.605
Car	-	-	-	-	0.653	**(0.002)**	**(0.011)**
Cyclists & pedestrians	-	-	-	-	-	**(0.002)**	0.074
Miscellaneous	-	-	-	-	-	-	**(0.002)**

*P-values in bold and between brackets indicate a significant difference ($p<0.05$).

5.4 Reaction time data

An impaired response to the dual task (either missed or delayed) was used to mark moments of assumed cognitive attention to something more important than the dual task: responding to the beep (Chapter 4, Section 4.8). Fixations occurring at these moments were assumed to be critical and were labelled as dual Fixations.

Delayed reactions were those for which the reaction time was equal to or more than two standard deviations above the mean reaction time to the audio stimulus per individual trial: these are data outliers. This outlier threshold was determined individually for each of the 24 cases (12 participants, day and after dark trials).

The distribution of reaction times to the dual task is shown in Figure 5.5 (all test participants, day and after dark trials combined) and Figure 5.6 (participant #1 only, after dark trial). The dotted line in Figure 5.6 presents the reaction time threshold for participant #1 after dark (MRT + 2 Standard deviations = 1013 ms). Chapter 4, Section 4.8.1 provides a justification for using the mean + 2 standard deviation threshold with reaction time data.

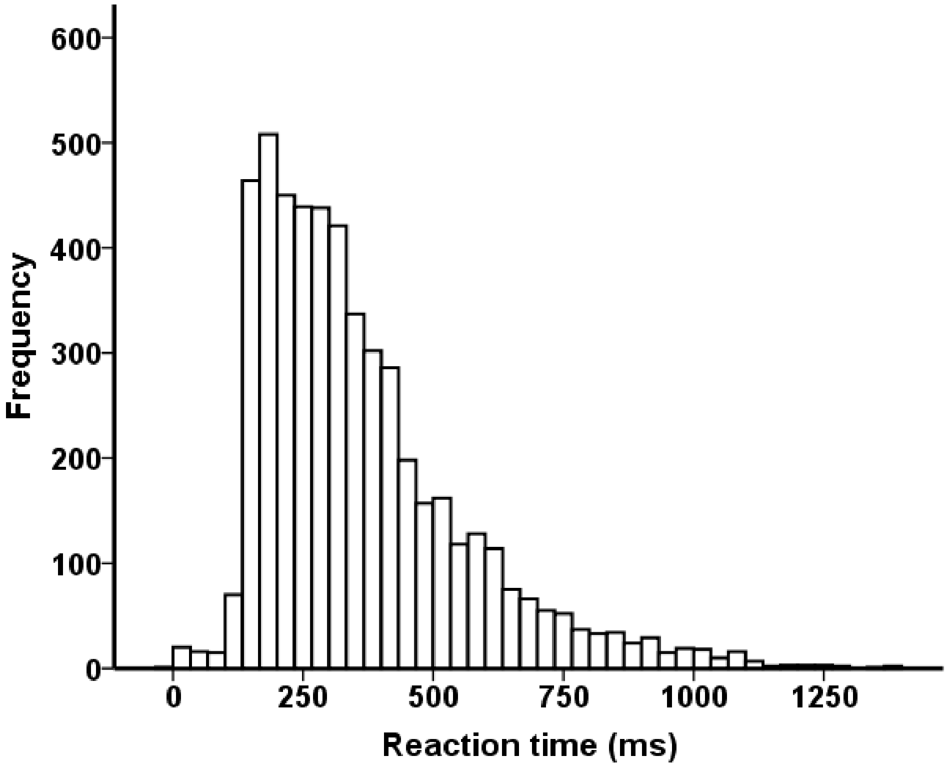

Figure 5. 5. Reaction time data for all participants for day and after dark trials combined.

Table 5.3 below presents the reaction time data for the 12 participants, including the number of beeps produced throughout the trial: missed responses; delayed responses; and the percentage of successful responses. An analysis of the data distribution did not suggest the data were drawn from normally distributed populations (see Appendix B).

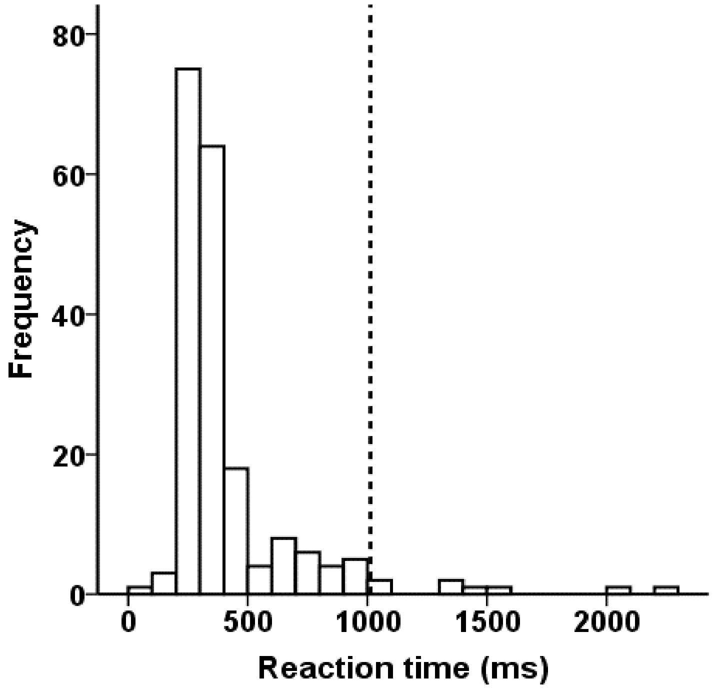

Figure 5. 6. Distribution of reaction time to dual task for participant #1, after dark trial. The dotted line denotes the critical response threshold (mean RT + 2 standard deviations), which in this case was 1013 ms.

Table 5.3 shows that the number of beeps per trial ranged from 173 to 343 across the day and after dark trials. This variance is a result of two factors; the amount of time each participant needed to cycle the two laps of the test route and the randomised time interval between each beep. Thus, if a participant took longer to finish the experiment (e.g., a slower cyclist), more audio stimuli were produced.

The median successful response rates (all responses including delayed responses divided by the total number of beeps produced during the trial) for the day and after dark trials were 95% and 92%, respectively, see Table 5.3.

One of the participants (ID = 20) had a notably lower successful response percentage (45% and 48% for the day and after dark trials, respectively).

Figure 5.7 below illustrates the effect on the distribution of dual fixations both with and without participant (20). Both distributions exhibit largely similar trends. To confirm this, a Wilcoxon signed rank test was conducted to compare possible differences between target categories when participant (20) was included/excluded from the sample. No significant difference was identified in any of the categories (P=1.000 for all paired comparisons). Participant #20 was therefore retained in the dataset.

Table 5. 3. Reaction time data for the day and after dark trials.

Participant ID	Day trial responses				After dark trial responses			
	Beeps total [1]	Missed [2]	Delayed [3]	Successful % [4]	Beeps total	Missed	Delayed	Successful %
1	233	12	12	95%	210	14	6	93%
6	293	69	14	76%	274	66	13	76%
7	261	32	4	88%	259	32	8	88%
9	235	5	5	98%	255	13	7	95%
10	256	10	11	96%	253	19	9	92%
11	294	5	8	98%	261	8	7	97%
13	286	33	12	88%	340	29	18	91%
14	173	18	8	90%	242	51	7	79%
16	251	5	14	98%	248	29	13	88%
17	225	3	7	99%	257	21	10	92%
19	235	12	9	95%	235	11	8	95%
20	343	187	8	45%	313	163	7	48%
Median	253	12	8.5	95%	256	25	8	92%

[1] The total number of audio stimuli produced during a trial.
[2] Missed responses = participant not responded to the beep stimulus by pressing the dual task button.
[3] Delayed responses = participant’s response was > the trial reaction time response mean + 2SD.
[4] Successful responses % = the number of total reaction time responses, both delayed and not delayed, divided by the number of beeps produced in the whole trial.

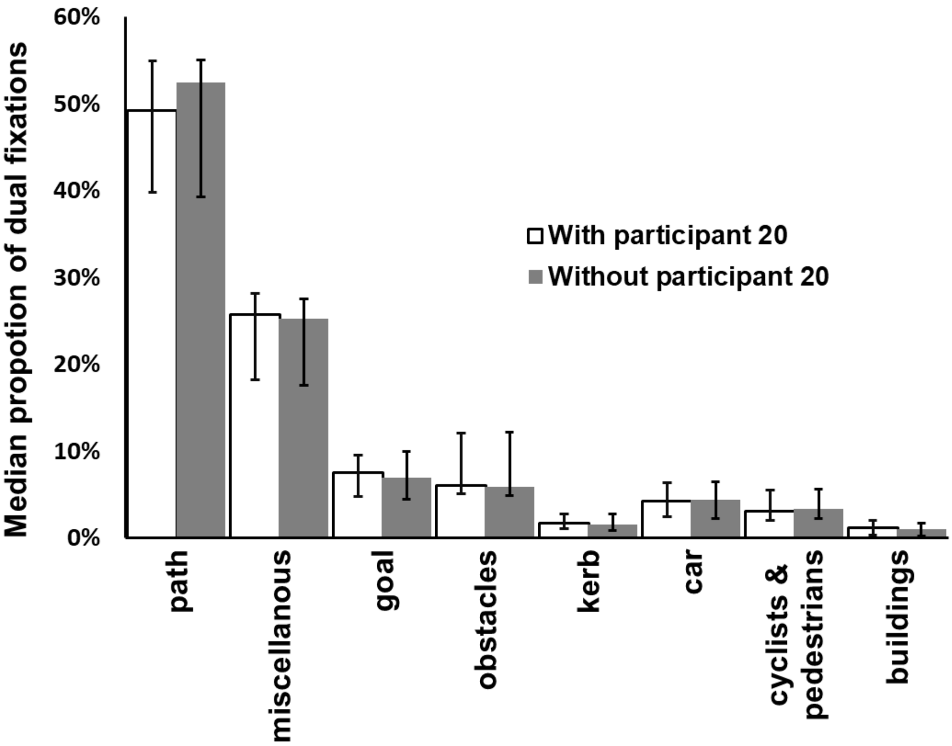

Figure 5. 7. The median proportion of dual fixations across the day and after dark trials, once with participant (20) included and once without. The interquartile range represented by error bars.

5.5 Analysis of eye-tracking data: Dual fixations

Impaired responses to the dual task may not have occurred at the exact moment of fixation on a visually critical object thus identification of the object associated with an impaired dual task response was determined by identifying fixations in close temporal proximity to the dual task. Specifically, a two-second window was established, commencing one second before and ending one second after the onset of the critical audio stimulus (The exact beep moment which the identified delayed or missed response is associated with). This section of the eye-tracking recording was then searched for the likely visual fixation. The time span chosen as the smallest period between beeps was one second: a larger window may have resulted in an overlap between two adjacent beeps.

The median proportion of dual fixations over target categories was compared across day and after dark trials, see Figure 5.8. Application of a Friedman’s test suggested there was a significant difference (p=0.001).

Table 5.4 shows Wilcoxon pair comparisons between different categories. The proportion of dual fixations differed significantly between the compared target categories. However, only two categories were significantly different throughout all comparisons: path and miscellaneous (for p<0.05). The rate of dual fixations was significantly higher in the path category than in the other categories, the same was true for the miscellaneous category, although the rate of dual fixations was lower than for the path category.

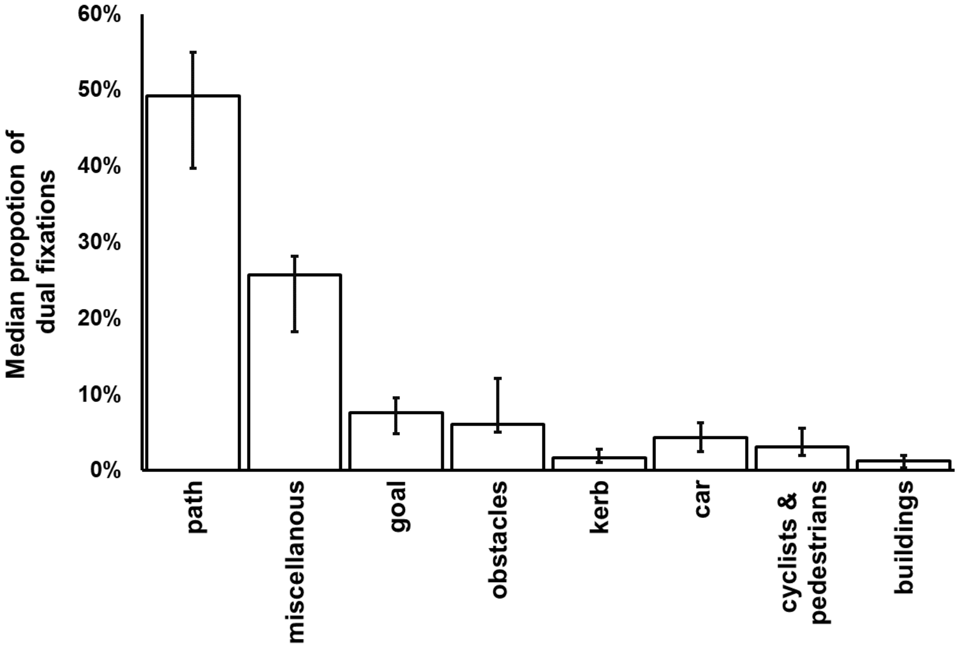

Figure 5. 8. The median proportion of dual fixations in each target category across day and after dark trials. The interquartile range represented by error bars.

Figure 5.9 shows the distribution of dual fixations for the day and after dark trials, separately. A difference between the patterns in each light condition was particularly noticeable in the path category.

The Friedman test revealed significant differences between target categories for both light conditions when comparing the distribution of dual fixations for day and dark trials separately (p<0.001) between target categories. Further paired comparisons were therefore conducted using the Wilcoxon signed rank test for day versus after dark conditions. Only the path category exhibited a significant difference (P = 0.032), see Table 5.5, with a higher dual fixations rate after dark.

One possible reason why cyclists are more likely to look at the path surface during after dark time than the day is that a lower light level means they need to be more vigilant in their search for hazards. A similar trend was found in a previous study on pedestrians where more dual fixations toward path were revealed after dark than day time (Fotios et al., 2015b).

Table 5. 4. Paired comparisons of target categories using the Wilcoxon test for day and after dark data combined.

Category	Path	Obstacles	Kerb	Car	Cyclists & pedestrians	Miscellaneous	Buildings
Goal	**(0.002)**	0.964	**(0.011)**	0.109	**(0.045)**	**(0.002)**	**(0.002)**
Path	-	**(0.002)**	**(0.002)**	**(0.002)**	**(0.002)**	**(0.005)**	**(0.002)**
Obstacles	-	-	**(0.002)**	0.134	**(0.041)**	**(0.004)**	**(0.002)**
Kerb	-	-	-	**(0.038)**	0.218	**(0.002)**	0.159
Car	-	-	-	-	0.305	**(0.002)**	**(0.002)**
Cyclists and pedestrians	-	-	-	-	-	**(0.002)**	**(0.018)**
Miscellaneous	-	-	-	-	-	-	**(0.002)**

* P-values between brackets indicate a significant difference (p<0.05).

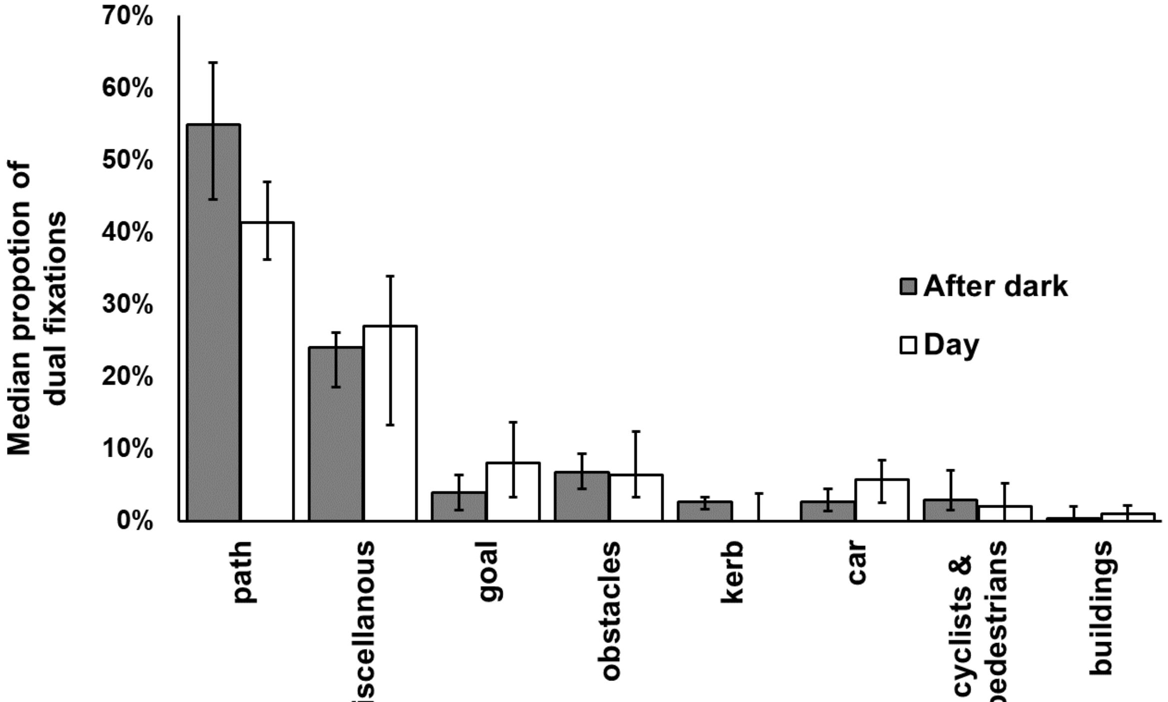

Figure 5. 9. The median proportion of dual fixations in each category for both day and after dark conditions. The interquartile range represented by error bars.

Table 5. 5. Dual fixations in both day and after dark trials. Results of Wilcoxon signed rank test for day versus after dark comparisons for each visual category.

Target category	Day median	After dark median	P<0.05
Path	0.41	0.55	**(0.032)***
Miscellaneous	0.27	0.24	0.414
Goal	0.08	0.04	0.183
Obstacles	0.06	0.07	0.635
Kerb	0	0.03	0.121
Car	0.06	0.03	0.114
Cyclists & pedestrians	0.02	0.03	0.573
Buildings	0.01	0	0.611

* p-values between brackets indicate a significant difference (p<0.05).

The path category was investigated further using the paired Wilcoxon tests (p<0.05), this time comparing day and after dark trials for each section of the route (see Table 4.2 in Chapter 4 for description of each section). This revealed that, when comparing dual fixations as determined for day and after dark trials for path category only, only sections A and B exhibited a significant difference between light conditions (p= 0.005 and 0.023, for day and after dark respectively). Section C was slightly over the significance level (p=0.056) and no effect was found in section D (p=0.114). This suggests an effect of urban context on cyclists' tendency to fixate on the path when ambient light level is varied.

The effect of the route section on dual fixation distribution was then considered. Figure 5.10 demonstrates the median proportions of dual fixations in each of the eight target categories for each of the four sections compared. The graph suggests that the distribution of dual fixations over target categories varied between route sections.

The data suggest there to be a difference between the four routes: this difference was expected given differences in urban characteristics and the traffic flow in each section, see Table 4.2. For example, route section C has a larger proportion of dual fixations in the car category than sections A, B and D: this was expected because route section C was situated along a dual carriageway which, by its nature, carries a high volume of traffic.

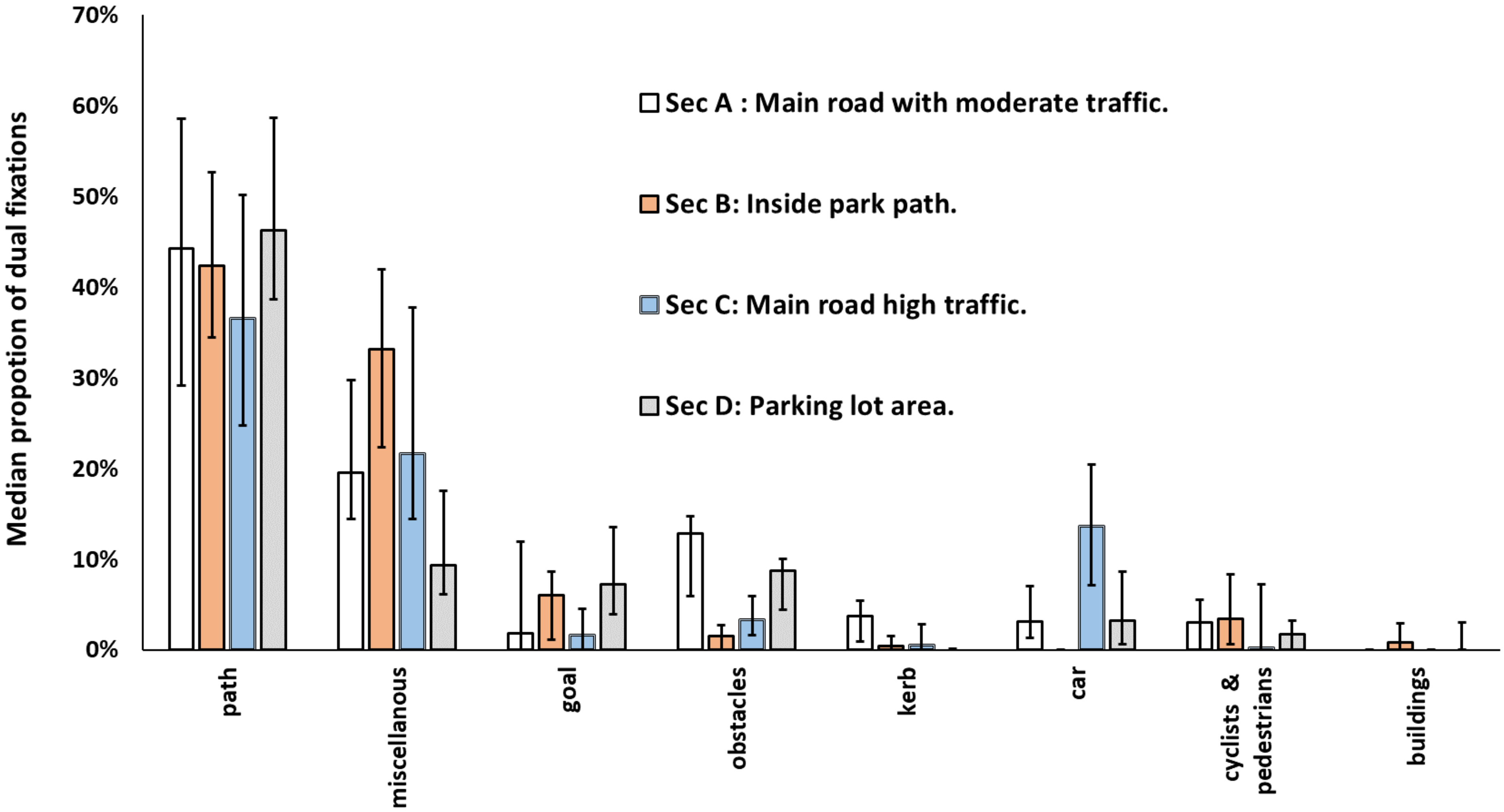

Figure 5. 10. The median proportions of dual fixations over target categories for sections A, B, C, and D. Data are for both day and after dark trials. The interquartile range represented by error bars.

Friedman’s test was used to compare differences in the proportion of dual fixations across route sections in each individual category. Significant differences (p<0.05) were found in six categories: goal (p=0.041); obstacles (p=0.015); kerb (p=0.09); car (p=0.002); miscellaneous (p=0.031); and buildings (p=0.003). There were no significant differences between road sections in two categories: path, and cyclists & pedestrians. Post hoc tests were carried out using the Wilcoxon signed rank test to identify the significant differences between route sections in the target categories suggested earlier by Friedman’s test to be significantly different. These are shown in Table 5.6.

For significant differences (p<0.05), Section A had significantly higher dual fixations than sections B and C in both obstacles (p=0.010 and 0.041, respectively) and kerb (p=0.019 and 0.007, respectively), whereas sections C and D had significantly higher dual fixations than B in the obstacles category (p=0.029 and 0.012, respectively). This suggests that section B yielded the lowest number of dual fixations toward obstacles, possibly due to the better quality of the path surface.

Section C yielded a higher dual fixation rate in the car category; however, no significant difference was found when compared with section A. This could be because both sections carry a higher level of car traffic than the other sections. Section B yielded a significantly higher rate of dual fixations in the buildings category than sections A and C (p=0.018 and 0.028, respectively): Considering that section B yielded the lowest rate of dual fixations in the obstacles category, this could have reflected more cognitive capacity available to look toward a non-safety category such as buildings.

These results suggest considerable differences exist between different route sections with respect to the proportion of dual fixations toward different target categories.

Table 5.6. Wilcoxon paired comparisons between the road sections in the target categories that yielded significant results ($p<0.05$) for data across day and after dark.

Route Section	**A**	**B** [1]	**C**	**D**
A		Obstacles (0.010) A[2] Kerb (0.019) A Buildings (0.018) B	Obstacles (0.041) A Kerb (0.007) A Car (0.016) C	Miscellaneous (0.019) A
B			Obstacles (0.029) C Buildings (0.028) B	Obstacles (0.012) D Miscellaneous (0.003) B
C				Obstacles (0.021) D Car (0.016) C Goal (0.041) D

[1] Car category were omitted from section B comparisons as cars were not permitted in this section.

[2] The letters after p-value indicate the section with higher dual fixations.

5.6 Analysis of eye-tracking data: SCR fixations

SCR was the second method implemented to find critical moments during trials. Eye fixations associated with these moments are termed SCR fixations, see Table 4.1. Investigating SCR fixations is suggested to reveal whether these patterns agree with dual fixations when comparing fixation rates over target categories across the day and after dark; day versus after dark, and between route sections (Data distribution was not normal for all comparisons, see Appendix B). Should the two fixations types provide similar trends of distribution, this could be considered as a validation to the findings; namely, the results are suggested to be robust being reached from two independent paths.

Figure 5.11 below shows the distribution of SCR fixations over target categories across the day and after dark trials. The application of Friedman’s test ($p<0.05$) suggested the rate of SCR fixations significantly varied between target categories ($p<0.001$). Table 5.7 presents the paired comparisons results for the Wilcoxon signed rank test between target categories. Median SCR fixation proportions in the goal, path, and miscellaneous were significantly different when compared with the other categories almost all the time.

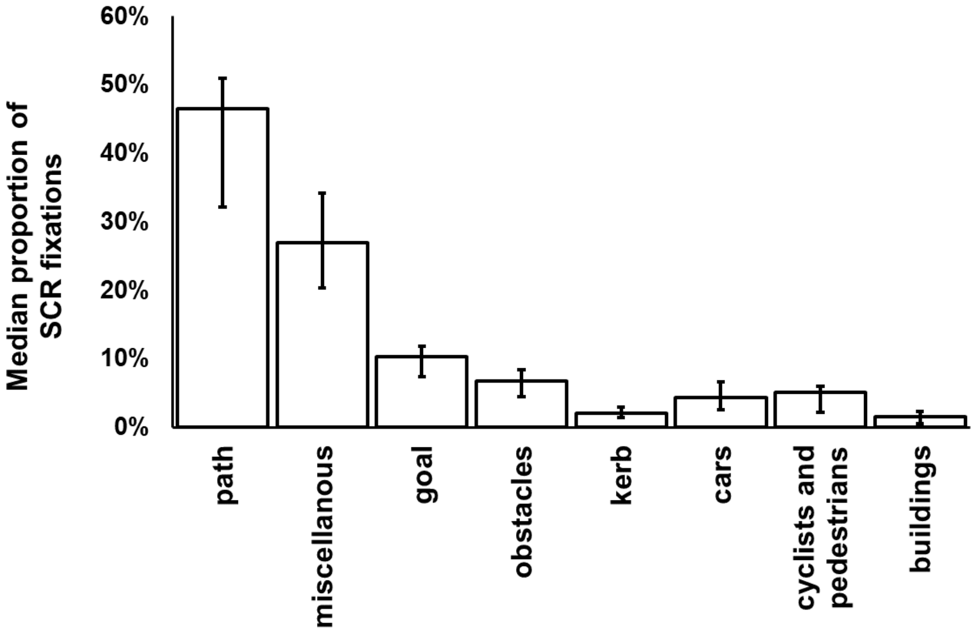

Figure 5.11. The median proportion of SCR fixations over target categories across both day and after dark trials. The interquartile range represented by error bars.

Figure 5.12 presents distribution of SCR fixations during day and after dark over target categories, similarity in distribution pattern is observed comparing to dual fixations day and after dark conditions, Figure 5.9.

The Friedman test revealed significant differences between target categories for both light conditions when comparing the distribution of SCR fixations for day and dark trials separately ($p<0.001$). The rate of SCR fixations in each category, day vs after dark trials, was then compared using the Wilcoxon signed rank test ($p<0.05$). No significant differences were identified, although the value for the path category was almost significance ($p=0.050$).

The trend in the SCR comparison was almost similar to the day vs after dark trials comparison of dual fixations, which was reported in Section 5.5.

In both cases, there was a propensity to critically fixate on the path after dark rather than during the daytime. Since the p-value for path category comparison in SCR fixations was nearly significant this suggests a similarity between the parallel dual task and SCR measurements. Possible differences between parallel measurements will be investigated further in Section 5.7.

Table 5. 7. Wilcoxon Paired comparisons of the distribution of SCR fixations over target categories using combined day and after dark data.

Category	Path	Obstacles	Kerb	Car	Cyclists & pedestrians	Miscellaneous	Buildings
Goal	**(0.002)**	**(0.049)**	**(0.002)**	**(0.020)**	**(0.003)**	**(0.002)**	**(0.002)**
Path	-	**(0.002)**	**(0.002)**	**(0.002)**	**(0.002)**	0.050 [1]	**(0.002)**
Obstacles	-	-	**(0.007)**	0.265	0.195	**(0.002)**	**(0.006)**
Kerb	-	-	-	**(0.040)**	0.106	**(0.002)**	0.537
Car	-	-	-	-	0.357	**(0.002)**	**(0.010)**
Cyclists and pedestrians	-	-	-	-	-	**(0.002)**	**(0.018)**
Miscellaneous	-	-	-	-	-	-	**(0.002)**

* p-values between brackets indicate a significant difference (p<0.05). [1] p-value close to significance (p<0.05)

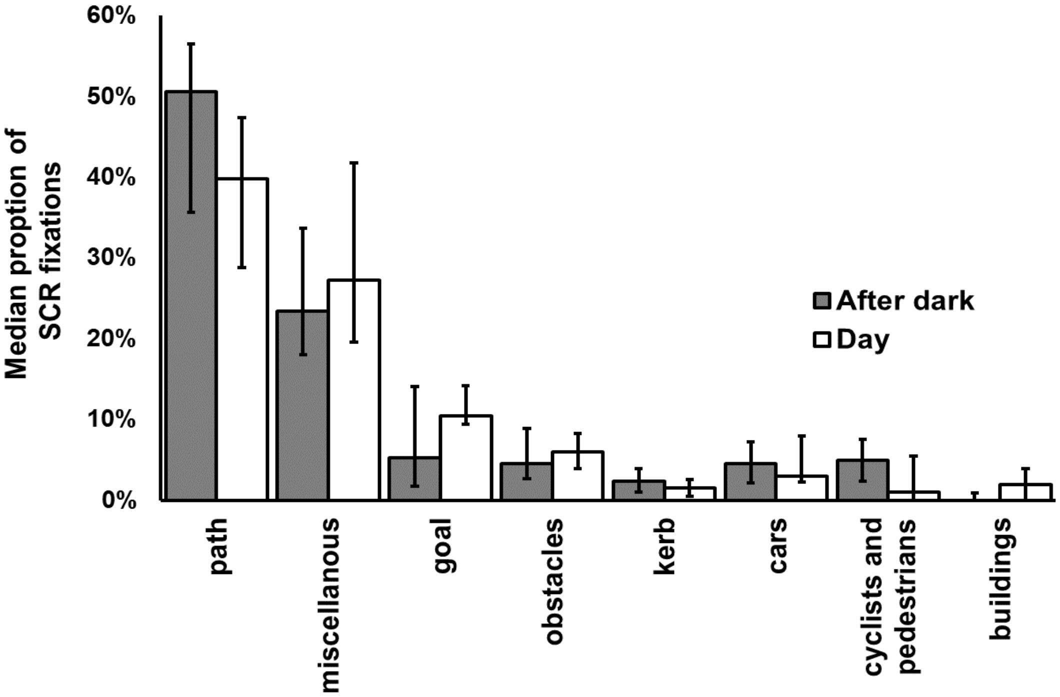

Figure 5. 12. The proportion of SCR fixations over target categories for day and after dark conditions. The interquartile range represented by error bars.

Table 5.8 presents the results of testing using Wilcoxon signed rank ($p<0.05$) to compare the day and after dark proportions of SCR fixations distribution over target categories.

Table 5. 8. Wilcoxon paired comparison ($p<0.50$) of the distribution of SCR fixations proportion over target categories, day versus after dark trials. Medians of target categories in each light condition are presented.

Target category	Daytime trials median	After dark trials median	Wilcoxon results (P<0.05)
Path	0.40	0.51	**(0.050)**
Miscellaneous	0.27	0.23	0.255
Goal	0.10	0.05	0.289
Obstacles	0.06	0.05	0.753
Kerb	0.02	0.02	0.343
Car	0.03	0.04	0.858
Cyclists & pedestrians	0.01	0.05	0.154
Buildings	0.02	0	0.182

* Path category achieved the closest value to significance, as indicated in bold and brackets ($p<0.05$).

The distribution of SCR fixations was then considered over the four distinct sections of the route. The aim was to see whether variations of features of the urban context are reflected in different SCR fixation rates over target categories. Figure 5.13, therefore, presents the distribution of SCR fixations over target categories in each of the four route sections.

Friedman's test showed that SCR fixations in the following categories were significantly different between route sections: obstacles ($p=0.001$); kerb ($p=0.004$); cyclists & pedestrians ($p=0.008$); miscellaneous ($p=0.001$); buildings ($p=0.010$). However, goal, path, and car were not significantly different ($p= 0.754$; 0.825; and 0.535, respectively).

This suggests that the latter categories were equally important in each of the four road sections. (Note that in the car category, section B was not included in the Friedman's comparison as no motorised vehicles are permitted in this section). This is a similarity here with Table 5.6 (road sections: dual fixations) as there was no significant difference between road sections for path category also. However, the other non-significant categories found in the current SCR fixations comparison, namely, goal and car, were not replicated in the dual fixations results.

These results suggest considerable differences exist between different route sections with respect to the proportion of SCR fixations toward different target categories.

The significant p-values for Wilcoxon pair comparisons of SCR fixations between road sections are presented in Table 5.9.

For significance level ($p<0.05$), section A was higher than section B ($p=0.007$) in the obstacles category, however, it was not significantly higher than section D, the latter of which was higher than section B ($p=0.031$) and section C ($p=0.004$) in obstacles category.

Section A yielded a higher rate of SCR fixations than section D in the kerb category ($p=0.005$).

Similar to the comparison of dual fixations on different road sections (Section 5.5), the results suggest that different urban contexts will have an influence on cyclists' visual behaviour.

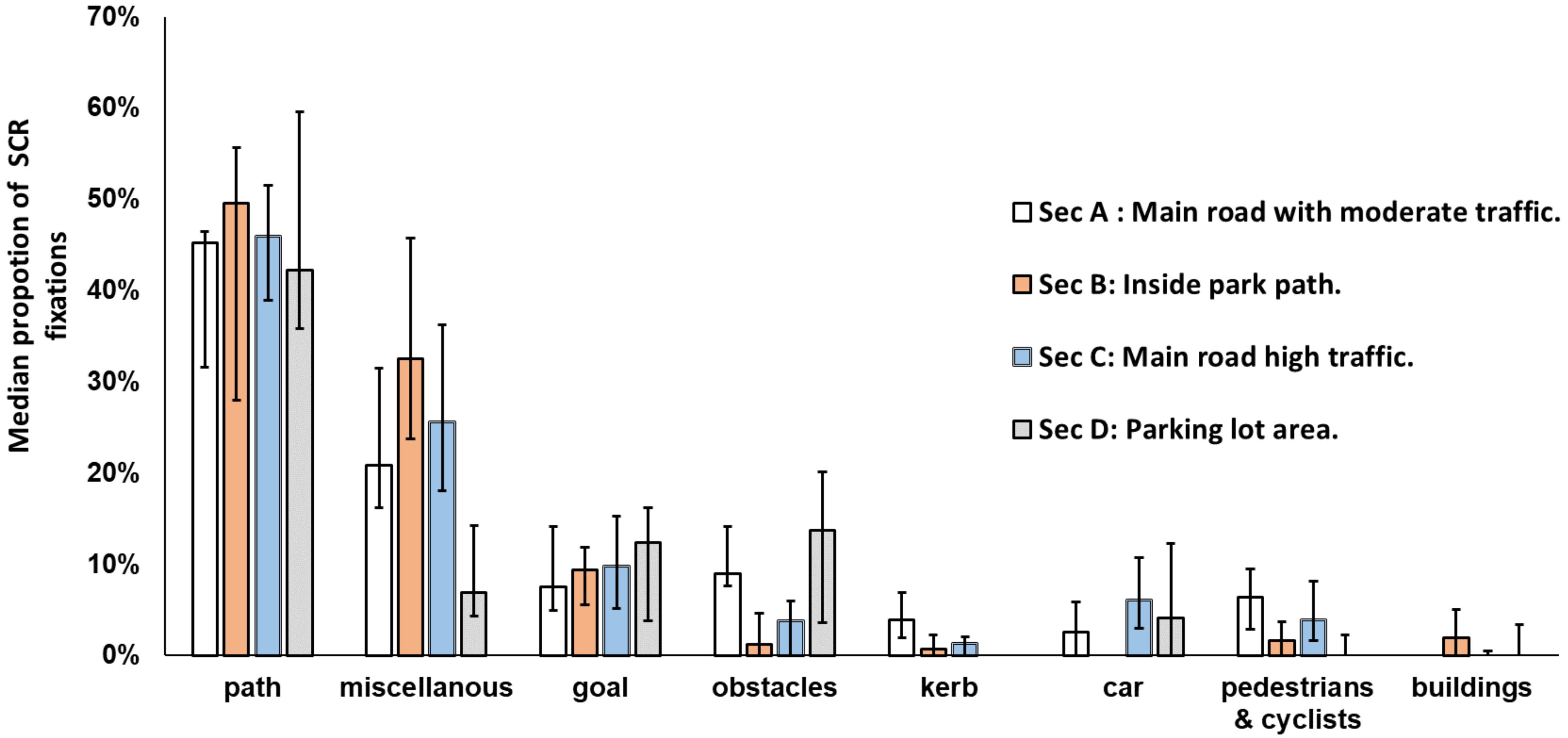

Figure 5. 13. The median proportions of SCR fixations in target categories for sections A, B, C, and D. Data are across both light conditions. The interquartile range represented by error bars.

Table 5. 9. Significant values of paired comparison of SCR fixations for different route sections using Wilcoxon signed rank test (p<0.05).

Route Section	**A**	**B**[1]	**C**	**D**
A		Obstacles (0.007) A[2] Cyclists & Ped. [3] (0.033) A Buildings (0.012) B	Obstacles (0.003) A Buildings (0.035) B	Miscellaneous (0.023) A Cyclists & Ped. (0.013) A Kerb (0.005) A
B			Kerb (0.036) C	Obstacles (0.031) D Miscellaneous (0.002) B
C				Obstacles (0.004) D Cyclists & Ped. (0.009) C Miscellaneous (0.028) C

[1] Section B was omitted from the car category comparisons as cars are not permitted on this section.
[2] The letter indicates the section with a higher SCR fixations rate.
[3] Cyclists & Ped. = cyclists & pedestrians.

5.7 Comparing fixation types

The three types of fixation, all, dual and SCR, were compared under each target category of the eight to check for possible differences or similarities in their distribution over target categories, using data of the whole route, see Figure 5.14. Friedman's test did not reveal any significant difference between measurements in all target categories.

A possible reason why no substantial differences between the three measurements were identified is that this analysis was conducted on a relatively large amount of data, comparing data of the whole route. This large amount of data, compared to individual section length (see road sections analysis Sections 5.5 and 5.6), might have mitigated possible differences between the three types of fixations. In contrast, in previous comparisons between the rate of fixations between road sections, the findings of dual and SCR approaches were not identical. For example, in a dual fixations road sections comparison, two categories were not found to be significantly different between road sections: path and cyclists and pedestrians. Whereas in the SCR approach goal, path and car categories were not found to be significantly different between road sections (see Sections 5.5 and 5.6 for road section comparisons). This highlights a variation between dual and SCR fixations findings.

Another thing to consider is the fact that the route length used in this study (2.2 km) was longer than that used in comparable eye-tracking studies: i.e. 650 m (Mantuano et al., 2017) and 256 m (Vansteenkiste et al., 2014a). This additional length suggests a need to compare dual and SCR fixations under each individual road section to see if any significant differences between parallel measurements emerge when a shorter segment of the road is analysed compared to the whole route.

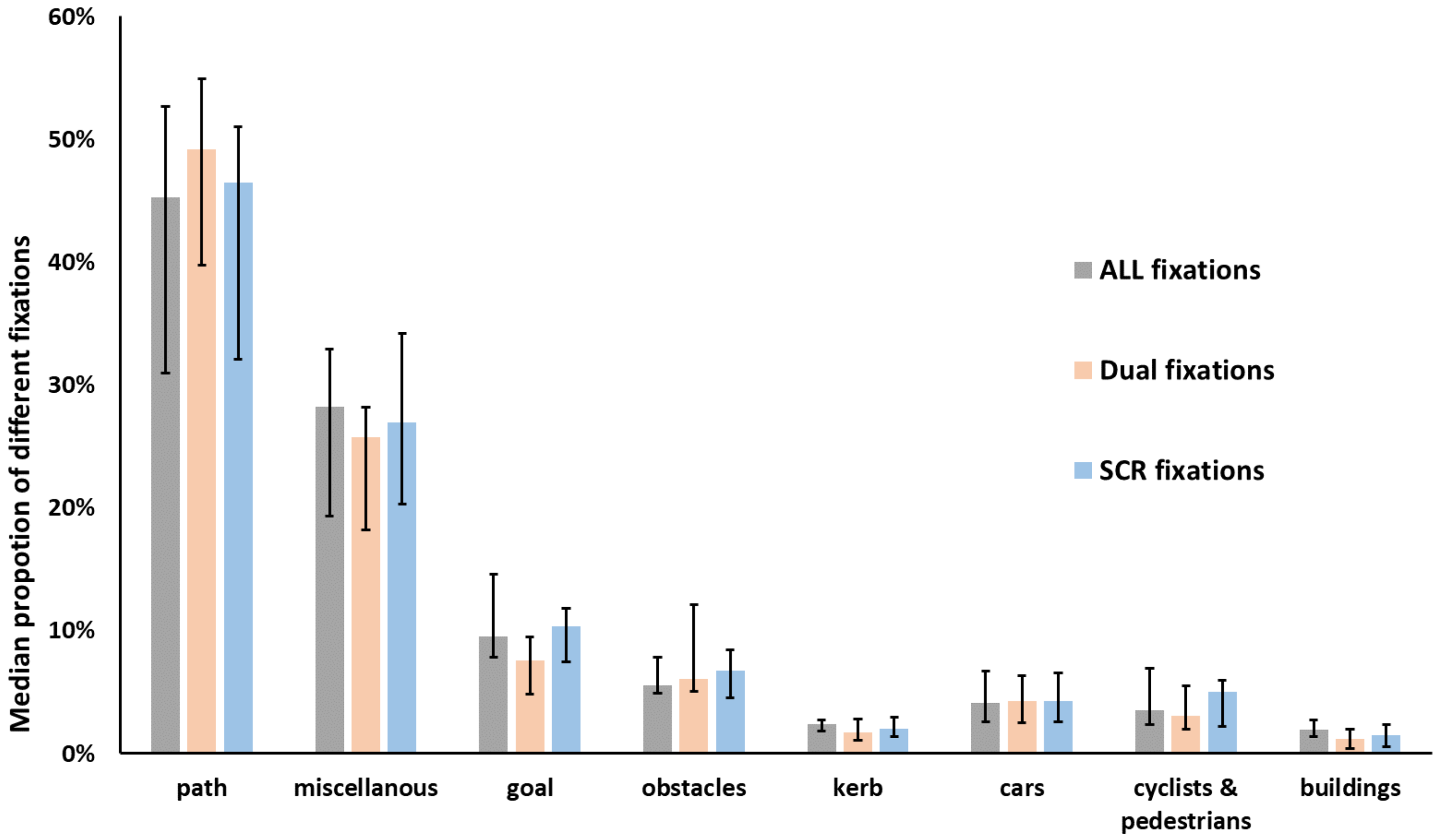

Figure 5. 14. The median proportion of the three fixation types distributed over target categories across the day and after dark trials for the whole route data. The interquartile range represented by error bars.

Table 5.10. provides Wilcoxon comparisons between dual and SCR fixations data of the 12 participants for each of the four sections, for data across day and after dark trials. Generally, similarities between both measurements exist, however significant differences were also found in two categories, goal, and ‘cyclists & pedestrians’, under each section as follows:

Section A (cyclists & pedestrians, p=0.018) with higher rate in SCR fixations; section B (goal, p=0.031) higher in SCR fixations and (cyclists & pedestrians, p=0.036) higher rate in dual fixations; section C (goal, p=0.041) higher rate in SCR fixations data. There was no significant difference found in section D, both measurements exhibited similar patterns of fixations in this section. This suggests that using the dual task and SCR to establish critical fixations may lead to different conclusions. The measurement which achieved a higher rate in the categories found significant is indicated in bold in Table 5.10 below.

Table 5. 10. Dual and SCR fixations rate comparison on each section of the four of the experiment route using Wilcoxon signed rank test (P<0.05).

Target category	**Wilcoxon results (p<0.05)**			
	Section A	**Section B**	**Section C**	**Section D**
Path	0.814	0.937	0.387	0.875
Miscellaneous	0.504	0.247	0.610	0.504
Goal	0.247	**(0.031) SCR**	**(0.041) SCR**	0.504
Obstacles	0.476	0.438	0.474	0.224
Kerb	0.788	0.438	1	1
Car	0.763	0.593	0.195	0.307
Cyclists & pedestrian.	**(0.018) SCR**	**(0.036) Dual**	0.476	0.384
buildings	1	0.483	0.221	0.917

* P-values between brackets indicate a significant difference (p<0.05) with an indication of which measurement achieved a higher rate (In bold font).

A further analysis was conducted to test whether the three fixation measurements, the ‘all fixations’ was included in this comparison, yield significantly different results when each measurement is compared individually between two sections of the route under widely different urban conditions.

The 8 target categories used throughout the analysis, see Section 4.7.2, were collapsed into two broader categories: safety and non-safety. This division was designed to overcome the low fixation rate of some categories; for instance, buildings and kerb, and to inspect whether a clear variation between all, dual and SCR fixations exist when comparing broader categories instead. The re-categorisation process was based on previous studies which were used initially to establish the 8 target categories (See Chapter 2, Table 2.1) those studies describe/justify whether a category is of safety or non-safety nature. The re-categorisation was then validated independently by a co-researcher[4]. The 8 categories were re-categorised as follows:

- Safety: Goal, path, obstacles, kerb, cars, and ‘cyclists & pedestrians’.
- Non-safety: Miscellaneous, buildings[5].

The comparison was between sections B and C, see Table 4.2. Section B is a path that passes through a park where no vehicles are permitted, while section C is a main road that carries a high volume of traffic. Normality assessment for data of sections B and C and both safety and non-safety categories were tested and found not normal (See Appendix B). The hypothesis was that more safety-related fixations would be found at section C (main road) than at section B (path through a park).

As anticipated, a higher rate of dual fixations under the safety category was found at section C during the day and combined trials but not for the after dark trials. Safety fixations were also significantly higher at section C than at section B for all fixations, whereas non-safety all fixations were significantly higher at section B than at section C. This also supports the hypothesis that section B is less challenging in terms of safety than section C as it is a path where motorised vehicles are not allowed (public park path).

Table 5.11 shows that the methods used to identify critical fixations could reveal different patterns when comparing data captured in different urban contexts. This was found when comparing all fixations and dual fixations data but not when comparing SCR fixations data. This implies that the dual task, a method used to locate critical

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[4] Dr. James Uttley – research associate.

[5] Note that only fixation towards pedestrians with no apparent risk e.g. pedestrians located far from the cyclist path with no expected interaction, were extracted from cyclists & pedestrians category and placed under the non-safety category.

fixations, could be more sensitive than the SCR approach in terms of identifying differences in visual behavior when cycling through varied urban contexts.

Table 5. 11. Comparison of all, dual, and SCR fixations proportions between sections B and C for safety and non-safety categories. Using Wilcoxon signed rank test ($p<0.05$). Using data for day, after dark and combined.

Light condition	Category	Wilcoxon result (p<0.05) All Fixations	 Dual Fixations	 SCR Fixations
Day	Safety	0.195	**(0.009**) **C**	0.388
Day	Non-safety	0.195	0.182	0.388
After dark	Safety	**(0.036) C**[1]	0.937	0.099
After dark	Non-safety	**(0.036) B**	0.937	0.099
Combined [2]	Safety	0.077	**(0.034) C**	0.224
Combined	Non-safety	0.077	0.556	0.239

[1] The letter after the p-value indicates the section with a higher rate.

[2] The mean fixations proportion of the day and after dark trials.

The statistical comparisons suggest that dual task and SCR approaches used in the current study to discriminate critical fixations yielded different trends when comparing road sections with distinctive urban contexts. However, such differences were not in all comparisons which suggest good general agreement between both approaches, this implies both approaches could be used to validate the findings of each other, however generally as some variations between fixations pattern were identified.

This analysis suggests that all three approaches (all fixations, dual and SCR) led to similar estimates of fixation proportion for each target category when comparing fixation proportions across the whole route. This disagrees with the finding from pedestrian eye-tracking (Fotios et al., 2015b) of differences in fixation between the all-fixation and dual task approaches.

There are two caveats associated with this conclusion. The first caveat is that whilst the proportions are similar, this does not mean that the dual and SCR identified the exact same items as being fixated. For example, the dual approach may have indicated items that were not recorded using SCR. The second caveat is associated with the relatively high number of fixations devoted towards the path ahead (45%, higher than the 22% found for pedestrians (Fotios et al., 2015b) which may have indicated a greater need for cyclists than pedestrians to scan for approaching hazards. This high proportion reduces the fixations available to other items, these smaller samples reducing the ability to reveal differences.

In this sense, the very high frequency of 'all fixations' classified under path category may have mitigated the chance of finding a radical difference between the three fixation types because the probability a critical moment identified by either dual or SCR methods will be more likely to coincide with a fixation classified under this category, or under miscellaneous category which also achieved a high all fixations frequency, see Figure 4.2 for a demonstration of how each type of fixations was established.

5.8 Discussion

5.8.1 Critical observations – where cyclists look?

In this study, the critical visual tasks of cyclists in natural settings were identified using dual and SCR fixations. Both fixations exhibited similar patterns in the eight target categories; however, they ultimately confirmed the path as the most critical visual category during cycling since it achieved higher dual and SCR fixations rates than the other seven categories.

In comparing the day and after dark trials, the only notable difference was found in the path category where a larger proportion of critical fixations, dual and SCR fixations, occurred after dark.

The path category achieved a significant higher dual fixation rate during after dark trials than in the day trials, Figure 5.9. A similar trend was identified in the SCR fixation data where the path was the only category to achieve close to a significant difference between the daytime and after dark trials (p=0.050), with a higher rate in the latter light condition (Figure 5.12). This may indicate the logical difficulty of cyclists observing the path clearly after dark than during the daytime owing to lower light levels.

In this experiment, the routes followed by cyclists were specifically chosen to include variations in the urban contexts: cycling on a main road (section C) and on a minor road (section A) where the need for personal safety is intensified due to the presence of moving and parked motorised vehicles, and cycling through a park (section B) and a campus parking lot (section D), see Table 4.2. The study results revealed significant differences in cyclists' gaze behaviour between these sections. This means that the distribution of both dual and SCR fixations across the target categories were not similar in the four road sections.

In the four road sections, the path category achieved higher all, dual, and SCR fixation rates compared to the remaining categories. No significant difference was revealed between the sections in comparing the path for all types of fixations, suggesting that this category was equally important across all sections. Observing the path more than other categories can be attributed to the desire among cyclists to avoid obstacles or such road irregularities, thus averting injuries from swerving toward an adjacent vehicle or falling on the road.

Vansteenkiste et al. (2014a) argued that the road surface could have a vital influence on cyclists' safety more than for other road users such as pedestrians and drivers.

This is a logical claim, for example, pedestrians often use the sidewalk or pavement where motorised vehicles are not permitted, compared to cyclists who are mostly on the main roads near car drivers, which makes falling on the road a considerable risk. Further, pedestrians have more freedom of movement and can thus avoid road obstacles more easily than cyclists who are restrained by the bicycle's movement capacity. Also, given the size and structure of a car compared to a bicycle, maintaining adequate balance on the road is more challenging when cycling than when driving a car. These factors make observing the path critical for cyclists to avoid encountering a surface irregularity or obstacle.

Observing the path for cyclists was substantiated as an important visual task in previous studies. For instance, Vansteenkiste et al. (2014a) compared cyclists' visual behaviour when cycling on a road with low surface quality to another with high surface quality. More fixations were found in the immediate region, the region correlated with fixations toward the path, this is when travelling on the low-quality road than the high-quality road.

Similarly, the miscellaneous category which was second to path, also achieved significant higher dual and SCR fixations than the other categories, except for the path. It could be argued here that the miscellaneous category is extremely broad and necessitates reclassification into sub-categories to provide the precise locations of fixations. Having said that, the miscellaneous category was however intentionally used to address fixations toward general items in the environment that for example are not distinctively related to the cycling task or personal safety, which are both the main focus of this study. Hence, subdividing this category may have altered the main focus of this experiment to non-safety related fixations which diverge from the scope of this study. Addressing general fixations in an unrelated category to that of the investigation was common in previous studies. For example, (Fotios et al., 2015b) confirmed such fixations using a category denoted as the ‘general environment’ whereas (Foulsham et al., 2011) depicted the category as ‘other objects’. In all cases, the study results suggest that the path is the most critical visual category during cycling.

5.8.2 Differences and similarities: Dual task and SCR methods

To evaluate the similarities between dual task and SCR fixations, three models of comparisons were performed. The data of the whole route was first compared and Friedman’s test ($p<0.05$) revealed no significant difference between the three types of fixations: all, dual, and SCR fixations, see Section 5.7. Thus, a second comparison was done to evaluate dual and SCR fixations for each of the four sections individually, see Table 5.10.

The results show a significant difference between the two approaches but only in two categories: goal and ‘cyclists & pedestrians’ for sections A, B, and C only. Section D did not indicate any significant difference. This suggests that a shorter road could better reveal differences between the dual and SCR approaches than a comparison of data of the whole route, as larger amounts of data may mitigate differences between the dual task and SCR approaches.

The results also suggest that particular elements in the environment, including in the target categories could stimulate the dual task and SCR critical responses differently. This could be a function of the distinct nature of each measurement. For example, dual task is a reaction measurement to determine the moments when a participant’s attention is diverted, whereas the SCR approach is a physiological measurement that depicts variations in skin response characteristics when reacting to proposed visual stimulus. This implies that a visual element could divert a participant’s attention but may not necessarily stimulate an SCR reaction and vice versa. Consequently, it is reasonable not to expect a critical reaction in both measurements for each visual stimulus encountered in the experiment.

The third comparison as shown in Table 5.11 entails contrasting the three fixation types between two sections of the route in distinct urban contexts (section B versus section C) as well as collapsing the initial eight categories into two broader categories (safety and non-safety). No difference was found in SCR fixation data between the sections, however, dual fixations showed significant differences in the safety category for daylight condition and for a combination of both the day and after dark trials. This illustrates a difference between dual and SCR when comparing distinctive routes, and dual task is suggested to be more sensitive in revealing such differences.

The effect of different urban contexts on visual behaviour was also found in previous eye-tracking studies (Fotios et al., 2015b; Mantuano et al., 2017; Vansteenkiste et al., 2014a).

5.8.3 Comparison with other studies

In previous eye-tracking studies, data validation has rarely been attempted. For example, no validation was reported in Vansteenkiste et al. (2014a) or Mantuano et al. (2017).

Vansteenkiste et al. (2017) distinguished differences in the visual behaviour of a sample of children and adults. For the adult group, validation of the results was carried out using previous study data (Vansteenkiste et al., 2014a), where a similar experiment and model were used to study adults’ visual behaviour when cycling on a low quality vs high-quality path. However, this was only mentioned in general terms and no quantitative comparison was provided.

In comparison, Boya et al. (2017) conducted a meta-analysis comparison with research by (Gegenfurtner et al., 2011) to validate their findings.

Further, to validate their results, Fotios et al. (2015b) compared the proportion of observations of two visual categories, path and person, that were found to be significant for pedestrians with the same categories of two previous studies (Davoudian and Raynham, 2012; Foulsham et al., 2011).

As discussed previously in this study, observing the path was suggested to be critical for cyclists. To determine whether the rates of dual and SCR fixations related to path category in current study are similar to the rates found by previous studies on eye-tracking and cycling (e.g.Vansteenkiste et al., 2014a; Mantuano et al., 2017), fixations identified within path category were extracted from the two previous studies' results for approximate comparability, see Figure 5.15.

It is worth mentioning that the two comparable studies were carried during daytime only, so no after dark trials exist in those.

In Mantuano et al. (2017), the proportion of fixations toward path was estimated by summing fixation frequencies of categories involving participants fixating on the road surfaces such as intersections, crosswalks, and road surface adjacent to discontinued pavement. The resulting number was then divided by the total fixation frequencies of all reported categories to get path fixation proportion. The study reported results of two road segments distinguished by a major quality: whether the cycle path is shared with pedestrians or not. The study then concluded that cycling on a road shared with pedestrians causes more attention diversion and less fixation on elements related to cycling safety such as fixating on the path. The proportion of fixations toward path reported in Figure 5.15 corroborates this statement as more fixation toward path was found on the cycle path not shared with pedestrians, which was also referred to as 'separate' in Figure 5.15.

In Vansteenkiste et al. (2014a), cyclists' visual behaviour on high quality and low quality paths was compared. The former path is a renewed part of the road mainly paved with bricks where minimum deficiencies could be found, whereas the latter path comprised large tiles that either had shifted or were missing.

Fixations related to the path category found on the low quality path had a proportion of 0.63 from the total fixations, on the high quality path this proportion equalled 0.25. These proportions suggest that cyclists were keen to observe the path surface more while on the low quality path.

In the current study, the dual and SCR fixation rates under path category were almost similar to the ranges reported by previous studies. For the after dark trials, the proportion of fixations towards path were 0.54 and 0.47 for dual and SCR fixations, respectively. These proportions were lower during the daytime, 0.41 and 0.39 for dual and SCR fixations, respectively.

Participants' inclination to observe the path more during the after dark is logically due to the lower visibility than that of daytime, another indication of the importance of light properties for safe cycling.

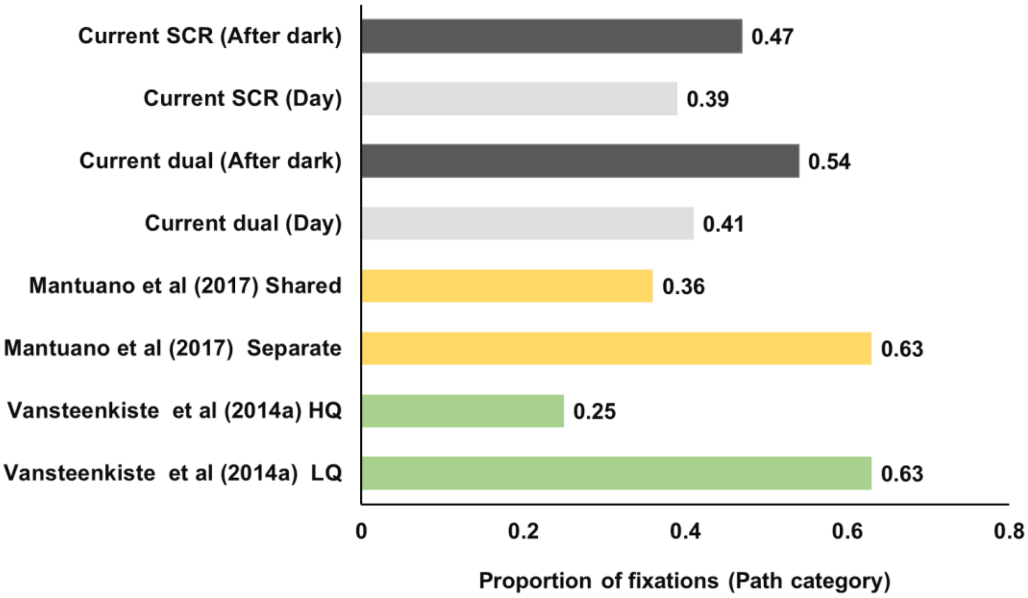

Figure 5. 15. Proportion of fixations classified under the path category in current and previous studies. In Mantuano et al. (2017) 'Shared' refers to cycle path which is shared with pedestrians whereas 'Separate' indicates the path without pedestrians. In Vansteenkiste et al (2014a), HQ = high quality path, and HL= low quality path.

5.9 Summary

This chapter reported results of the eye-tracking experiment conducted in the real world context to determine important environmental elements that cyclists are more likely to observe. This was conducted to provide empirical evidence about where light should be provided for cyclists to increase safety levels.

One essential objective in the current study was to overcome limitations in previous eye-tracking studies where critical fixations, moments where participants paid genuine attention to what they are looking at, were not discriminated from the overall fixation data. Another aspect which the current study responded to was the literature lacking comprehensive eye-tracking studies on cycling in real world settings.

Through synchronisation with the fixations produced by the eye-tracking apparatus, critical moments identified by either the dual task or SCR methods yielded critical fixations which were denoted as dual fixations and SCR fixations according to each method.

Analysis of the dual and SCR fixations suggested looking at the path is the most critical visual task while cycling. Participants fixated more on the path after dark than during the daytime, however, this was found to be significant in the dual fixations analysis only. It suggested a similar trend that was near significant in the SCR fixations analysis. Generally, dual and SCR fixations showed similar patterns in the target categories. This confirms the robustness of the findings in this study which were reached from two independent paths.

Chapter 6. Ambient light and perception of architectural features

6.1 Introduction

Chapters 4 and 5 reported an eye-tracking experiment that investigated the visual behaviour of cyclists within an urban context. The aim was to find where cyclists look, a prerequisite for knowing where and how to provide road lighting for this category of road users. The results suggested that looking at the path ahead is the most critical visual task, perhaps enabling cyclists to search for possible surface irregularities such as obstacles or potholes, thus mitigating accidents. Improving safety on the road is believed to encourage more people to adopt cycling (Fotios and Castleton, 2017a), a primary focus of this research. However, another way to increase the number of cyclists is to improve the cycling experience and make it more enjoyable: the presence of visually appealing features (categorised as features of the urban environment not directly related to the safety of the cyclist) has been found to correlate with an increase in cycling and walking (Borst et al., 2008; Titze et al., 2007). Other than the enjoyment factor this type of perception was deemed beneficial for personal restoration i.e. recovering from stress and fatigue (Nikunen et al., 2014) hence an added value to cyclists' life quality aspect.

However, the safety aspect is still important as the presence of visually appealing features alone is insufficient if the route travelled is challenging in terms of safety. In such cases cyclists will be occupied with observing safety alerting features, for instance negotiating vehicles or avoiding an obstacle, thus reducing the cognitive capacity available to observe attractive features.

Several elements could determine the safety of a route, amongst which are the type of cycle path and light conditions (see Sections 2.5.1 and 2.5.2 for a review of these variables, respectively).

It was proposed that, when given the opportunity to do so, cyclists will exhibit more visual attention to visually interesting features of the environment. This opportunity arises in those parts of the route where safety was expected to be higher, i.e. sections of the route which did not involve cycling alongside motorised vehicles. It was also hypothesised that cycling would be perceived as safer in daytime than after dark. In the current chapter this proposal was tested through a post hoc analysis of the main eye-tracking experiment data (the experiment reported earlier in chapters 4 and 5).

In the current study the perceived safety and task demands for cyclists were varied by comparing two types of route (pedestrianised routes versus on-road routes) and two types of light condition (daylight versus after dark).

Given that this is an exploratory study, rather than confirmatory where a solid hypothesis suggested by previous literature is being tested (Wagenmakers et al., 2012), the study tentative hypothesis is that more observations toward non-safety elements of the environment, including architectural features, should be obtained when cycling during daytime than after dark, and when cycling on pedestrianised path than on-road path.

The analysis first assessed cyclists' visual behaviour toward the non-safety features of the environment while varying safety conditions, then the analysis moves to evaluate participants' visual behaviour towards one specific item of the broader non-safety category, that is architectural features (being aesthetic elements).

Among a choice of several aesthetic features that exist in the urban environment such as landscapes, sky, street furniture, etc. Architectural features were selected as the unit of analysis for the following reasons:

- Two buildings with distinctive architectural styles on each route section were located at a position that allowed an equal cycle path length at each section, offering a good comparable case.

- Choosing an item other than an architectural building such as trees or greenery would not provide suitably comparable sizes: for example, they may extend across larger areas along the route. A tree, for example, also lacks the distinctive quality needed as a number of similar trees were distributed along the paths whereas the method stands on comparing visual behaviour toward a precise visual target.

- Another reason for choosing architectural features as visual targets is the existence of previous studies on visual engagement with architectural and aesthetic urban features and its relation to improving people experience of urban context, see Section 6.2 below, thus the findings are proposed to be relevant to existing literature.

6.2 Perception of architectural features

In this respect, architecture can be viewed as fulfilling human psychological needs through both aesthetic and purely functional means. In precise terms, this is accomplished through attributes designed to stimulate perception, examples of which include: light, colour, rhythm, scale, and texture. This is a pertinent consideration given that the human mind is constantly engaged in the visual interpretation of various entities present in the immediate environment (Roth, 1993).

Shemesh et al. (2017) argued that architectural features of the environment have a positive influence on our experience. This is reflected in the physiological and cognitive responses we make to the environment. Many researchers have employed behavioural and cognitive measures to determine the nature of people's perception of and response to certain urban features (Dieleman et al., 2002; Saelens et al., 2003; Shemesh et al., 2017). Enshrined within the theory of Cognitive Architecture, to objectively evaluate such an influence constitutes an effective way to ascertain the effect of architectural design and the urban environment (Sussman and Hollander, 2014). The theoretical implication of this is that people respond differently to the urban environment based on their interpretation of the architectural characteristics within their environs.

The 'visual appropriateness' of the urban environment is therefore deemed critical to public wellbeing (Wadley and Gore, 2016). As part of a small-scale pilot study, Sussman and Hollander (2014) assessed the emotional state of participants in different urban environments by measuring their brain responses. This was achieved by attaching an Electroencephalography monitor (EEG) to participants while they walked through two different neighbourhoods in Boston, US. When their brain waves were measured, it was found that the brain activity produced was more positive in response to certain architectural characteristics (e.g. edges, shapes, patterns).

EEG was also used by Shemesh et al. (2017) to assess people's responses to internal spaces. Specifically, they investigated participants' cognitive responses to different architectural spaces using a combination of virtual reality technology and a measurement of brain activity through EEG. The results showed that when people experience symmetrical space, they produce brain patterns that are different to those produced when experiencing asymmetrical space.

As noted previously in Chapter 2: Section 2.4.2, recent advances in mobile eye-tracking technology have facilitated the recording of visual behaviour in real world environments and this is especially useful in the investigation of human responses to urban design and architecture. For example, Dupont et al. (2017) explored how visual behaviour may differ when viewing rural or urban landscapes, while Viaene et al. (2016) explored how people view landmarks located within buildings when navigating their way around. Research exploring the effect the urban environment has on the visual behaviour of cyclists, however, remains scarce. Furthermore, as outlined earlier in the literature review: Section 2.5, the research that does exist has primarily been concerned with cycling task-related aspects such as path quality (Vansteenkiste et al., 2014a; Vansteenkiste et al., 2017) or individual differences in the visual behaviour of experienced and novice cyclists (Boya et al., 2017). Thus the current study should provide an insight about how ambient light level and cycle path characteristics contribute positively to the quality of the ride, this is investigated by assessing perception toward architectural features in each situation, with such perception deemed important for improving cycling experience, particularly at the after dark (BSI, 2013; Boyce, 2019).

6.3 Method

6.3.1 Overview

Participants cycled a 2.2 km route during daylight and after dark conditions that included two distinct sections which varied in terms of task demands and perceived safety. Each section also exposed the participant to a distinctive, visually interesting architectural buildings. Participants’ gaze behaviour was recorded throughout using a mobile eye-tracking apparatus. Fixations towards the architectural building on each section were quantified along with fixations towards other features of the environment.

The analysis started by categorising eye fixations into two broader categories: Safety and non-safety, to provide a broader sense about how cyclists observe non-safety elements when safety conditions altered comparing to safety elements. The focus of the analysis was then narrowed to investigate visual behaviour toward one particular non-safety element: the facades of the two architectural buildings (aesthetic elements).

6.3.2 Route and participants

Participants cycled a short circular route close to the University of Sheffield campus, as described in Section 4.5. In the current chapter, only two distinct sections of that route were included in the analysis, see Figure 6.1. Cycling along these sections involved passing two buildings with distinctive architectural styles.

The sections used in the current study are shorter parts of sections B and D which were described earlier in Chapter 4: Table 4.2, in the current study these will be referred to as pedestrianised and On-road paths, respectively. Figure 6.1 depicts the pedestrianised and On-road paths on section B and D and illustrates their location on the map.

The pedestrianised path passed the Weston Park Museum, a well-known Sheffield landmark that has a neoclassical appearance along with several modern renovations. This path was located within a park and the path cycled by participants was vehicles restricted. The On-road path passed the Arts Tower, a 21-storey grade II listed University of Sheffield building and another iconic Sheffield landmark that was built in the 1960s. This path passed through a car park and therefore exposed the participant to potential interactions with vehicles. The path surface was relatively poor and included two speed humps that each participant had to cycle over. Viewing landmark buildings has been suggested to elicit a sense of comfort among observers as they exhibit a sense of direction (Kaplan et al., 1998).

Images of the two buildings are presented in Figure 6.2. Each cycle path was approximately 100 m in length and was defined as extending from the point at which the building became visible to the cyclist to the point at which the cyclist had passed the building.

The route was cycled twice by each participant in both daylight and after dark sessions, which meant they passed through each cycle path twice under each light condition. Data for both laps were aggregated. Details of the number of participants yielding good data quality who were included in the analysis are presented in Chapter 5: Section 5.2.

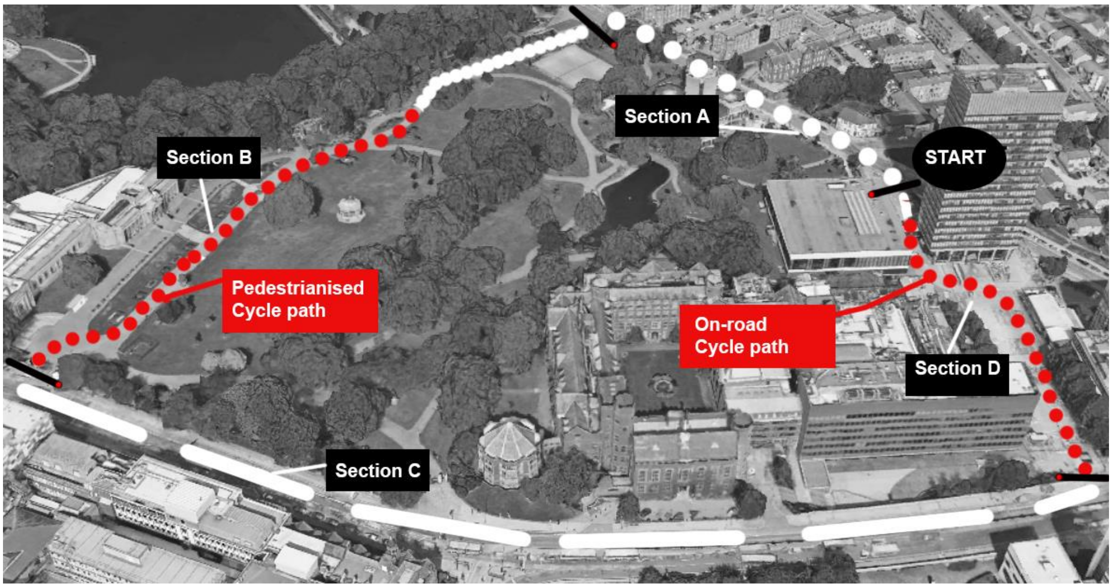

Figure 6. 1. An aerial view of the experimental route showing the initial four sections: A, B, C and D used in the main eye-tracking study (Chapters 4,5) with the black lines at the start of each section demonstrate the start and end of each section (anticlockwise). The shorter segments used for the current study, namely, the pedestrianised and On-road paths are marked by the red dotted lines. These sections are shorter parts of Sections B and D.

Figure 6. 2. Images of the Arts Tower (left) and Weston Park Museum (right) accompanied by example images of architectural details that could possibly attract visual fixations.

Figures 6.3 and 6.4 show a number of screenshots captured from the eye-tracking recording of one participant on each section. The gaze mark (red circle) indicates where the participant was looking at this particular moment.

Figure 6. 3. Screenshots of the on-road path in chronological order, starting from top left, with the gaze mark indicating where the participant was looking at that moment.

Figure 6. 4. Screenshots of the pedestrianised path in chronological order, starting from top left, with the gaze mark indicating where the participant was looking at that moment.

6.4 Results

This analysis considers the all fixation data, in order to capture fixations towards both safety-critical and non-safety-critical items. Dual and SCR fixations are not relevant to this analysis as these capture on safety-critical items, see Table 4.1 for description of the three fixation types used in this thesis. Further, the perception of pleasant elements was suggested to be deemed to the involuntary type of attention where a lower cognitive effort is paid (Nikunen et al., 2014), this is in contrary with the essence of critical fixations where moments of high levels of voluntary attention are used to identify them.

6.4.1 Analytical procedure

The eye-tracking data recorded on pedestrianised and On-road paths (Figure 6.1) were identified and then extracted from the entire set of route data. Eye fixations and fixation durations were used to assess visual behaviour in this study; however, for this to be meaningful, a reference for the fixated object was needed. Categorisation of fixations was achieved using the semantic mapping function of BeGaze software, where 8 target categories were used to reference fixations (see Section 4.7.2). A detailed description of the eight categories is provided in Table 4.4.

The fixations data that were previously categorised into eight categories were then collapsed into two larger categories: safety and non-safety. This re-categorisation procedure is the same as procedure described under Chapter 5, Section 5.7.

Because both cycle paths were of the same length and all participants were not aware as to which section of the route will be used for the analysis, the proportion and duration of fixations towards non-safety elements was an objective measure used to quantify changes in visual behaviour when the independent variables (path type / light condition) were altered. It was proposed that there would be fewer fixations towards non-safety features when cycling after dark (when path visibility is impaired) and/or when cycling on the on-road path where vehicles are allowed. This is because participants were expected to be cognitively and visually engaged with safety features; for example, looking at vehicles or observing the road surface for possible obstacles. Conversely, cycling through a pedestrianised path and/or during the day was expected to reduce the cognitive load. This would allow for more fixations towards non-safety features in the environment, including architectural features.

Re-categorising to larger safety and non-safety categories was assumed to reveal the general tendency of cyclists to observe each category when cycling in conditions that differ in terms of safety alertness and task demands: pedestrianised vs on road paths and/or day vs after dark light conditions. Another reason for re-categorising is the fact that some of the initial 8 categories yielded a low rate of fixations. Combining similar categories together was therefore more likely to reveal alterations in visual behaviour when the test conditions change.

Two dependent variables were calculated from the fixation – the median proportion of all fixations; and the median of fixations durations. These were then compared for safety and non-safety fixations, path type (pedestrianised vs on-road), and light condition (daylights vs after dark). Assessment of histograms and the Shapiro-Wilk test did not suggest that the data were normally distributed (see Appendix C for normality tests results).

The analysis then moves from exploring the general tendency to fixate towards safety or non-safety elements to assessing fixations specifically towards architectural buildings (a non-safety feature). These data were subsequently extracted and analysed separately. It was hypothesised that observing such aesthetic elements, such as the facades of architecturally interesting buildings, can improve the cycling experience (see Sections 2.5 and 6.2). Investigating how fixations towards such features may be influenced by the path type or ambient light condition can provide insights into how to design cycling infrastructure that is not only safe but also allows the cyclist to enjoy their surrounding environment.

Moving the investigation from a broad (non-safety) category to a specific element (architectural features) could be of benefit to the general understanding of the subject. For example, fixations distributed within a broad category could exhibit general trends with no exact information as to which particular items participants fixate upon. Assessing fixations towards a particular object therefore adds precision to the investigation.

A Wilcoxon signed rank test (repeated measure, nonparametric) with the standard threshold assumed $p<0.05$ was used to assess the effect of the independent variables (the characteristics of cycle path and light conditions) on visual behaviour.

6.4.2 Safety vs non-safety fixations

Figure 6.5 compares the median proportion of all fixations categorised as non-safety by path type and light condition (the remaining proportion of fixations were categorised as safety-related). This indicated differences between the two cycle paths and light conditions in respect to the proportion of fixations under the non-safety category.

For the after dark trials, the pedestrianised path yielded a higher fixation rate (Median 0.37, Inter-Quartile range (IQR) = 0.33 - 0.42) than the on-road path (Median = 0.08, IQR= 0.07- 0.12). This was also the case for day trials where the fixation rate on the pedestrianised path (Median = 0.43, IQR = 0.33 - 0.53) was higher than on the on-road path (Median = 0.17, IQR = 0.11- 0.20). The Wilcoxon signed rank test shows that there were a significantly greater proportion of non-safety fixations on the pedestrianised path than the on-road path during after dark (p= 0.002) and daytime (p= 0.003) trials. No effect of light conditions was found in either the pedestrianised (p = 0.060) or on-road (p = 0.158) paths when each was compared separately for light conditions, although it was close to significant on the pedestrianised path.

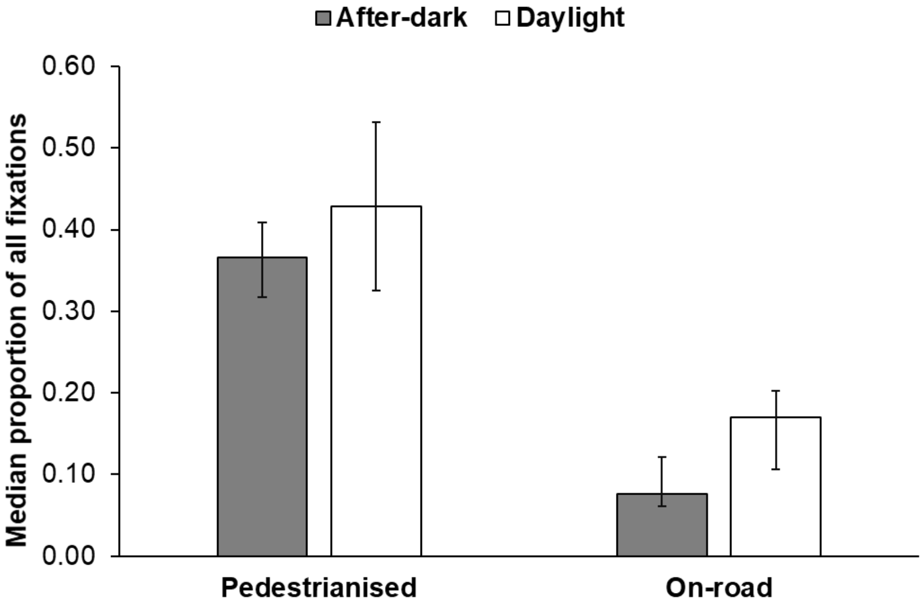

Figure 6. 5. The median proportion of all fixations defined as non-safety by path type and light condition. The interquartile range represented by error bars.

This suggests a higher rate of fixations towards non-safety features when cycling on a pedestrianised path, this is in line with the current hypothesis that cycling on a pedestrianised path will encourage more fixations toward non-safety items. It also suggests that the majority of fixations will be devoted to the safety category when cycling on the on-road path whereas the difference between safety and non-safety fixations is smaller on the pedestrianised path for both light conditions suggesting increased fixations toward non-safety elements, see Table 6.1.

The fixation duration variable was then analysed. This is the median of all fixations durations produced during trials, for day and after dark conditions. Table 6.2 presents fixations durations data in milliseconds (ms) for the 12 participants included in the analysis for both day and after dark trials.

The difference in fixation durations in the non-safety category between day and after dark conditions were larger for the pedestrianised path (after dark median = 245 ms, daylight median = 185 ms) than for the on-road path (after dark median = 201 ms, daylight median = 178 ms).

Table 6. 1. Median and interquartile values of the proportion of fixations in safety and non-safety categories in day and after dark trials.

	Non-safety				**Safety**			
	After dark		**Day**		**After dark**		**Day**	
Measurement	Ped.[1]	On-road	Ped.	On-road	Ped.	On-road	Ped.	On-road
Median	0.37	0.08	0.43	0.17	0.63	0.92	0.57	0.83
Lower quartile	0.33	0.07	0.33	0.11	0.59	0.92	0.47	0.80
Upper quartile	0.42	0.12	0.53	0.20	0.68	0.93	0.67	0.89

[1] Pedestrianised.

This trend is more obvious in the safety category where differences in fixations durations between light conditions on the pedestrianised path (after dark median = 295 ms, daylight median = 202 ms) were much larger than on the on-road path (after dark median = 243 ms, daylight median = 202 ms). It is worth noting that the median of both paths was the same for day trials, which suggests that an increased ambient light level have mitigated the effect of characteristics of cycle path on fixations rate.

The median fixation durations towards safety and non-safety categories, by light condition and path type, are shown in Figure 6.6. These suggest participants may have generally fixated on safety and non-safety features for less time during the day than after dark, with this difference being more obvious on the pedestrianised cycle path.

The non-safety data revealed an effect of light condition on fixations durations for the pedestrianised path, where the difference was significant (Wilcoxon p= 0.028) with a longer fixation duration in the after dark condition. This suggests that the participant needed less time to retrieve visual information during daylight. This agrees with one previous research finding where higher level of ambient illuminance produced shorter reaction time than lower illuminance (Benedetto et al., 2014).

The difference between light conditions was not found to be significant for the on-road path for the non-safety category (p = 0.209). No significant effect was found when comparing pedestrianised and on-road paths for day and after dark trials separately (p= 0.132 and 0.814, respectively).

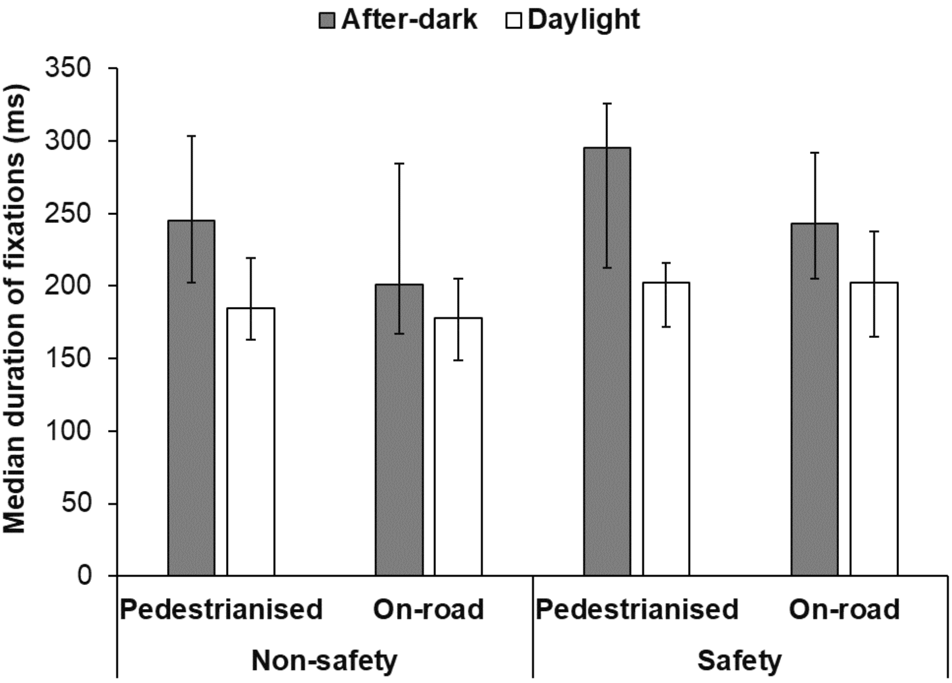

Figure 6. 6. Median duration of fixations towards safety and non-safety related features by path type and light condition. The interquartile range represented by error bars.

For fixations durations in relation to the safety category, there was a significant difference when comparing light conditions for each of the pedestrianised and the on-road paths (p= 0.002 and 0.010, respectively) with a longer duration after dark. This also suggests an effect of light condition whereby participants needed to fixate longer after dark.

The difference in duration between the two paths was found to be significant for the safety category in the after dark trials only (p= 0.015) with longer duration on the pedestrianised path.

This suggests that, while on the pedestrianised path, participants shifted their gaze less frequently when visually engaging with safety related features than when they were on the on-road path. This is perhaps related to the good safety condition of the pedestrianised path as participants did not need to shift their gaze frequently probably due to less safety related features on this path.

Table 6. 2. Median fixation duration (ms) for day and after dark light conditions; pedestrianised and on-road paths and safety and non-safety categories.

	Non-safety				Safety			
	After dark		Day		After dark		Day	
Measurement	Ped.[1]	On-road	Ped.	On-road	Ped.	On-road	Ped.	On-road
Median	245	201	184	178	295	243	202	202
Lower quartile	203	168	163	149	212	205	172	165
Upper quartile	303	284	218	305	325	291	215	236

[1] Pedestrianised.

6.4.3 Fixations towards architectural buildings

A key aim of this chapter is to explore the gaze behaviour of cyclists towards non-safety features of the urban environment, with fixations directed towards architectural buildings being deemed a good representation of the aesthetic/appealing features of this environment (see Chapter 2: Section 2.5.2; and Section 6.2).

The rate of fixations towards architectural buildings was generally low, which is reasonable considering the length of both paths (100 m) and the fact that this is a subcategory of the non-safety category that initially attracted a lower fixation rate than the safety category. Having said that, quantifying fixations proportion and duration toward this element would still provide an objective data about visual behaviour toward this aesthetic feature.

Figure 6.7 shows the median of all fixations towards architectural buildings: Weston Park Museum and the Arts Tower, by path type and light condition. This suggests participants were more likely to look at architectural features during the day than when it is dark, and when they are on the pedestrianised path rather than the on-road after dark. Table 6.3 illustrates the proportions of all fixations towards the architectural buildings on each cycle path.

The Wilcoxon signed ranked test revealed no significant difference between light conditions on the pedestrianised path (p = 0.099). This was not the case for the on-road path where after dark and day conditions were significantly different (p = 0.004) with more fixations towards the architectural building facade (the Arts Tower) during the day suggesting an effect of ambient light level on perception.

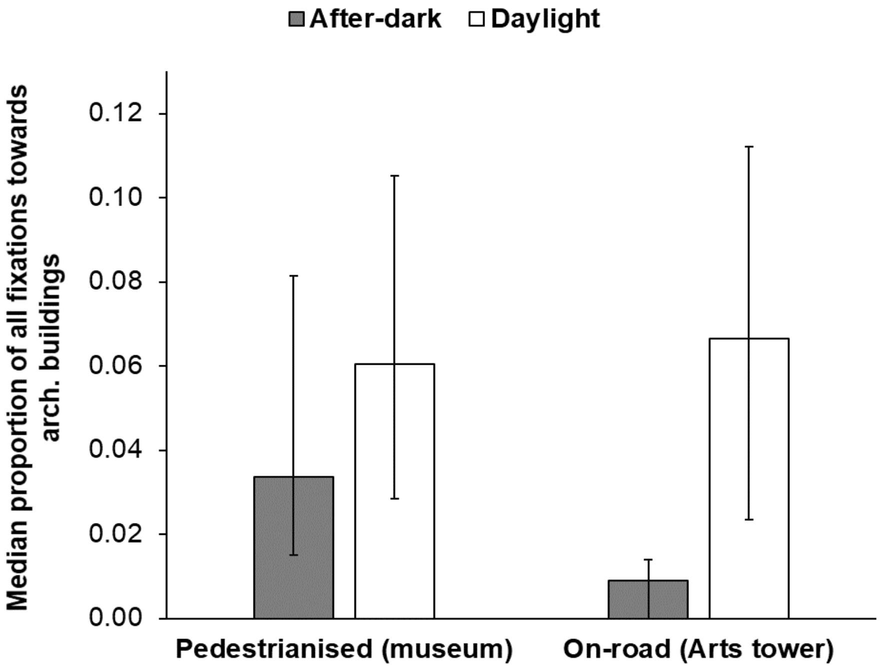

Figure 6. 7. Median proportion of all fixations towards architectural buildings by path type and light condition. The interquartile range represented by error bars.

Table 6. 3. All fixations proportions towards the architectural buildings on each section of the route.

	All fixations proportions toward architectural buildings			
	After dark		**Day**	
Measurement	Ped[1] (Museum)	On-road (The Arts tower)	Ped[1] (Museum)	On-road (The Arts tower)
Median	0.03	0.01	0.06	0.07
Lower quartile	0.01	0	0.03	0.03
Upper quartile	0.08	0.01	0.10	0.12

[1] Pedestrianised.

When comparing the two paths by light condition, a significant difference was only found for after dark trials (p = 0.012), with the pedestrianised achieving more fixations. This suggests higher light levels of day time may eradicate the influence of the characteristics of cycle path on visual behaviour towards architectural features.

Figure 6.8 shows the median of fixations durations towards buildings by path type and light condition. On the pedestrianised path, the all fixations durations towards the architectural building was significantly longer during after dark trials than during the day (p = 0.005, medians = 149ms (day), 174 ms (dark)); This was not the case for the on-road path where no significant difference was found between light conditions (p = 1.000, medians 158 ms (day), 141 ms (dark)).

No significant effect was found when comparing the all fixations durations between the two paths in either after dark (p = 0.173) or day conditions (p = 0.508).

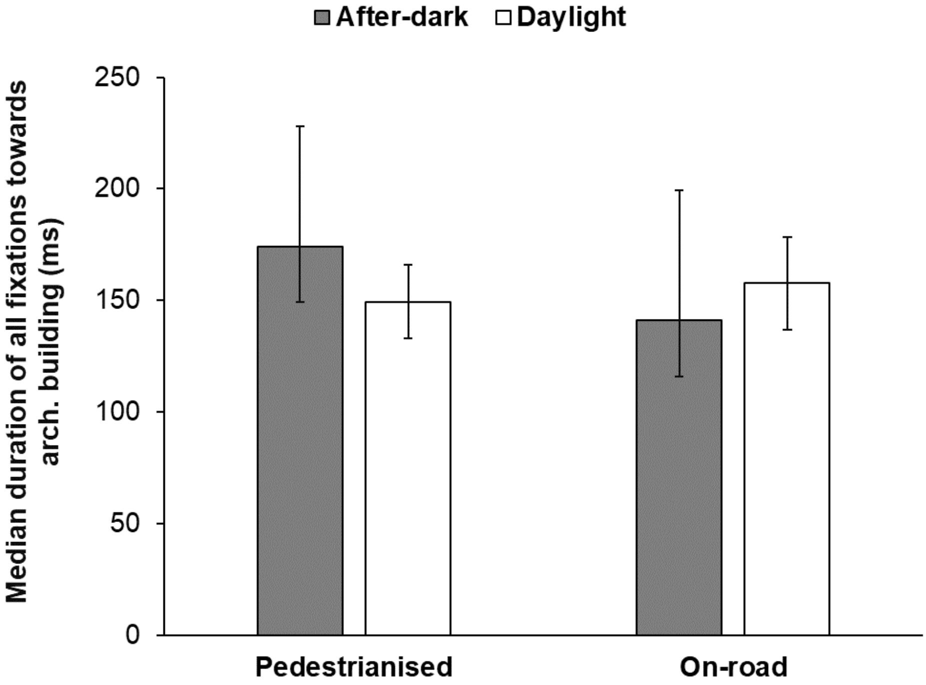

Figure 6. 8. Median of all fixations durations towards the architectural buildings by path type and light condition. The interquartile range represented by error bars.

In general, fixation duration was similar for both path types and light conditions with one exception, the pedestrianised path, where fixations durations was longer after dark than during the day. Table 6.4 provides a summary of significant p-values of Wilcoxon signed rank test found above with findings and implications from these results.

6.5 Discussion

6.5.1 Proportion of fixations: safety/non-safety

The all fixations comparison revealed an effect of path type on the rate of non-safety fixations with higher non-safety fixations found on the pedestrianised path than on the on-road path for both light conditions. For both paths, most of the fixations were devoted to the safety category; however, the gap between safety and non-safety fixations was smaller on the pedestrianised path, an indication of increased fixations towards non-safety elements.

This supports the initial hypothesis that, on a pedestrianised cycle path where no vehicle is permitted, visual interaction between cyclists and non-safety features of the environment increases. This is possibly because cyclists have a reduced cognitive load in terms of searching for safety threats i.e. moving car, or it may be that cycling tasks are less demanding; thus, more capacity is available for observing other visual features in their surroundings. No significant difference was found when comparing light conditions for each path separately.

Table 6. 4. Wilcoxon signed rank test significant values (p<0.05) with the findings and implications from the statistical analysis.

Section(s) Comparison	**Type of data**	**Category**	**Light condition**	**P<0.05**	**Higher at**	**Findings/implications**
Pedestrianised vs On-road	Fixations proportion	Non-safety	After dark	0.002	Pedestrianised path	Cycling on the pedestrianised path generates more fixations toward non-safety features.
Pedestrianised vs On-road	Fixations proportion	Non-safety	Day	0.003	Pedestrianised path	Findings similar to (Fixation proportion) Pedestrianised Vs On-road.
Pedestrianised	Fixations durations	Non-safety	Day vs After dark	0.028	After dark	Longer fixations durations after dark were found for the pedestrianised path. Cyclists were able to fixate longer, possibly due to a less demanding environment.
Pedestrianised	Fixations durations	Safety	Day vs After dark	0.002	After dark	Longer fixations durations in the after dark condition. There is therefore an effect of light.
On-road	Fixations durations	Safety	Day vs After dark	0.010	After dark	Findings similar to the fixations durations of Pedestrianised section.
On-road	Fixations proportion	Architectural building	Day vs After dark	0.004	Day light	An increase in the amount of light encourages more fixations towards architectural building when on the on-road path.
Pedestrianised vs On-road	Fixations proportion	Architectural building	After dark	0.012	Pedestrianised path	Cycling on the pedestrianised path encourages more fixations on the architectural building after dark. This indicated a positive cycling experience.
Pedestrianised	Fixations durations	Architectural building	Day vs After dark	0.005	After dark	Longer fixations durations after dark than during the day. particularly on the pedestrianised path. This implies that participants were more comfortable fixating for longer on the building. There was fewer safety related elements on this path thus less temptation to shift their gaze from the building.

6.5.2 Fixations durations: safety/non-safety

The non-safety fixations durations revealed an effect of light with longer durations in after dark trials, but only on the pedestrianised path. This suggests that participants needed less time to retrieve visual information during daylight than when it was dark. Furthermore, the longer after dark fixations durations on the pedestrianised path could be justified to participants having more time resources available to fixate on non-safety features as they did not need to shift their gaze frequently towards safety features at this time.

The light effect is more obvious when comparing the safety category for both paths separately, as the all fixations durations was significantly longer after dark for each path type. This obviously could be explained by the considerably lower light levels during the after dark.

Path type comparisons only yielded a significant difference in the after dark condition, with a longer fixation duration on the pedestrianised path than on the on-road path toward safety features. This suggests that cyclists fixated longer on safety related features when travelling on a pedestrianised path. This could possibly be related to a tendency among cyclists to shift their gaze more frequently towards safety related elements while at the on-road path, whereas on the pedestrianised path better safety conditions provide the capacity to fixate for longer on safety features i.e. a cyclist could take his time looking on safety concerning features.

6.5.3 Proportion of fixations: architectural buildings

There were more fixations towards architectural buildings after dark on the pedestrianised path than on the on-road path. However, this effect of path type was mitigated during the day. This suggests that cycling after dark on the pedestrianised path may encourage more fixations towards architectural buildings.

An effect of light condition was found for the on-road path only with significantly more fixations falling on the Arts Tower during the day than after dark. This suggests that cyclists are less likely to fixate on architectural buildings when cycling on an on-road path after dark, being the extreme safety condition. Furthermore, there is an effect of light as more light encourages fixation on architectural buildings.

The reason no light effect was found on the pedestrianised path could be that, because this path is theoretically safer (no vehicles permitted), and that the increased fixations towards the architectural building after dark had mitigated the possible difference between light conditions.

Both path types produced a similar rate of all fixations during the day. This suggests an increased amount of light had encouraged more fixations towards architectural buildings on the on-road path. However, there was a significant difference between the paths during after dark with higher fixations at the pedestrianised.

6.5.4 Fixations durations: architectural buildings

In general, fixations durations were similar for both path types and light conditions with one exception, the pedestrianised path where there were longer durations of all fixations after dark than during the day. This matches the trend found for the durations of fixations towards safety and non-safety categories, where the durations were significantly longer on the pedestrianised path during the after dark than the day.

There are several limitations in this study, however, that need to be addressed. The first is the fact that this was a field study carried out in a real world environment, it was not possible to keep all aspects of the two cycle paths equivalent. One limitation was therefore that the Weston Park Museum (pedestrianised path) was located on the right side of the path whereas the Arts Tower (On-road path) directly faced the participant. These differences in position relative to the direction of the cyclist may have had some influence on how often they were observed. The natural direction of a cyclist's gaze is ahead, in their direction of travel e.g. (Vansteenkiste et al., 2014a). This may increase the likelihood that a building directly ahead of a cyclist (e.g. the Arts Tower in On-road path) is fixated compared with a building to the side of the cyclist (e.g. the Weston Park Museum in pedestrianised path). The implication of this is that the difference in proportion of fixations towards the buildings on the pedestrianised path and the on-road path may actually be an underestimate – had Weston Park Museum been positioned straight ahead of the cyclist, the proportion of fixations towards this building may have been even higher.

The analysis conducted thus provides only a conservative estimate; however, it is suggested to open a useful pathway for future research.

6.6 Summary

A post hoc analysis on data obtained from the main eye-tracking experiment (the experiment reported in chapters 4 and 5) was carried in the current chapter to investigate how the characteristics of cycle path and different ambient light conditions influence cyclists’ perception of non-safety features of the urban environment including architectural features being aesthetic elements that were deemed important for positive cycling experience in the literature review chapter.

An increased observation toward such aesthetic features is thought to indicate a positive cycling experience. The findings of the current study add to the general output of the thesis for three reasons: first, the type of path a cyclist travels on has an influence on gaze behaviour (see Section 2.5.2), hence an essential element in cycling context was investigated. Second, understanding the influence of light levels on this type of perception is deemed important for implications to current road lighting guidelines. Third, previous cycling research had focused mainly on the perception of safety related features; thus, little is known about non-safety features, for instance aesthetic elements such as architectural features, this is a limitation highlighted in the literature chapter (See section 2.5). In overall, understanding such perception will inform about the quality of cycling experience thus aid cycling promotion efforts.

Two cycle paths, pedestrianised and on-road, were compared in respect to the proportion and duration of fixations after dark and during the day. Light conditions were compared on each path separately to isolate the light effect from the cycle path variable.

The results of this analysis, although exploratory, have demonstrated that cyclists are generally more likely to fixate on non-safety elements including architectural features on a pedestrianised path than on an on-road path. There was also an effect of light on the fixation proportion and fixations durations.

Based on the findings from this study cycling on pedestrianised cycle path and during daytime is suggested to improve the quality of cycling experience by increasing the observations of aesthetic elements of the surround environment.

Chapter 7. Obstacle detection: Method

7.1 Introduction

Previously in chapter 5 the eye-tracking experiment revealed that fixating on the path was suggested to be the most critical visual task while cycling than other target categories. This could be explained by a tendency among cyclists to search for irregularities or obstacles likely to exist on the road surface (Schepers and den Brinker, 2011; Thompson and Rivara, 2001; Werneke et al., 2015).

Avoiding such obstacles is important considering the risky consequences such as a cyclist falling or swerving while on the road where motor vehicles are present. After dark, the ability of cyclists to detect approaching obstacles is affected by the characteristics of, and interaction between, road lighting and bicycle lighting. An experiment was conducted to investigate detection performance under different lighting conditions. Thus this work had four objectives:

- Investigate whether an increased amount of road light illuminance improves detection performance.
- Assess the effect of bicycle lighting luminance intensity on detection performance.
- Understand the combined effect of road lighting and bicycle lighting characteristics on participants' obstacle detection performance.
- Explore the influence of bicycle lamp mounting position on obstacle detection.

The method of this experiment is explained in the following.

7.2 Apparatus

Obstacle detection was tested using the apparatus shown in Figure 7.1 below. This is a modified version of the apparatus previously used to investigate obstacle detection for pedestrians (Uttley et al., 2017). The modifications are (1) test participants were seated on a cycle rather than walking on a treadmill, and (2) bicycle lights were included in addition to overhead lighting representing road lighting. The apparatus is a chamber that is open on one side, where the participant was located and lit from two overhead arrays of LEDs (road light). The chamber has a raised floor containing a cylinder that could be raised above the surface by varying heights to simulate different sizes of an obstacle.

The dimensions of the chamber are 2.4 m wide, 2.4 m high and 3.8 m long, with the three walls covered in black cotton cloth. The false floor was made from a medium density fibre (MDF) board and painted in Munsell N5 grey paint (reflectance = 0.2). This paint has a uniform (flat) spectral reflectance and hence a near neutral effect on the colour properties of the reflected light. Surfaces with low reflectance were used to ensure a low light level, typical of the mesopic range of the current experiment.

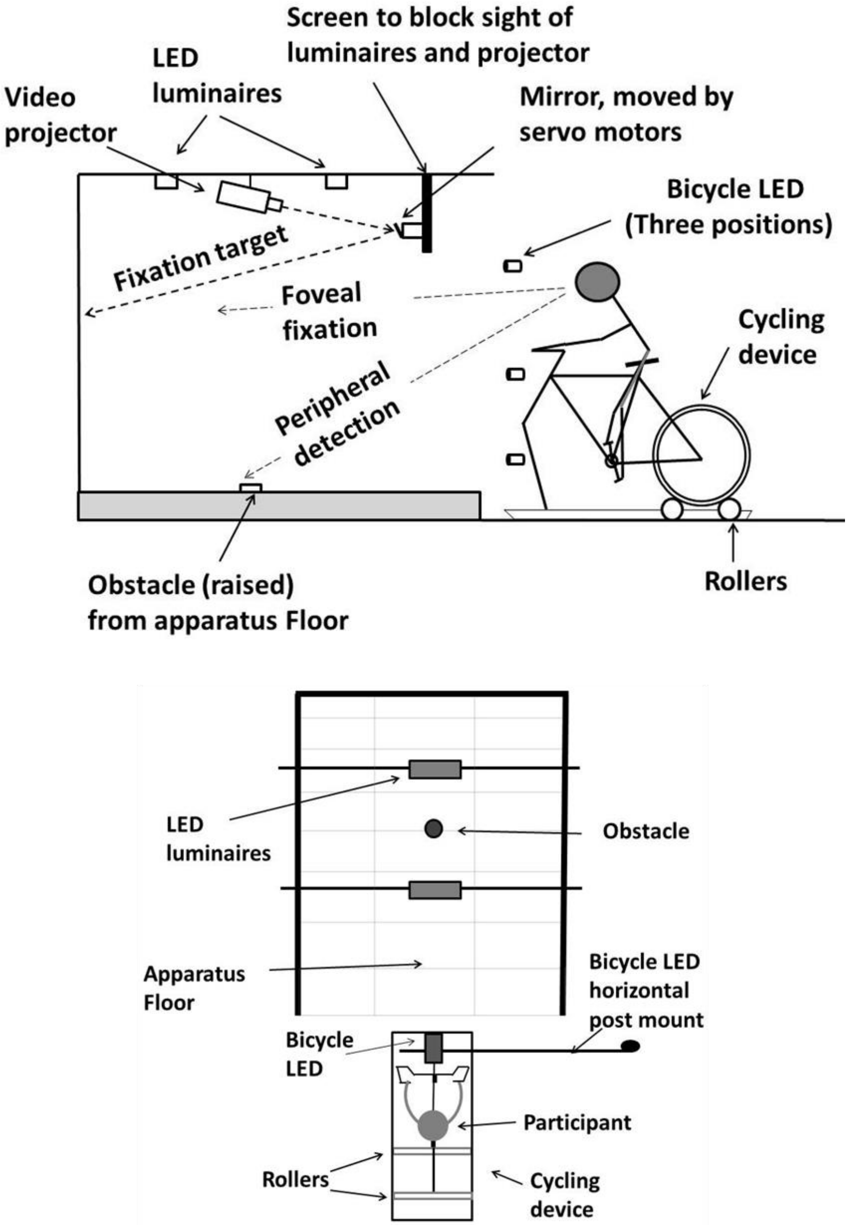

Figure 7. 1. Section (Top) and plan (Bottom) of apparatus.

The static bicycle, Figure 7.2, was placed at the open end of the chamber. During trials, participants sat upon this bicycle to replicate the head/eye posture of a cyclist and the cognitive load associated with the physical activity of pedalling. To allow pedalling the bicycle was mounted on rollers, but for safety, it was held upright using a frame. During trials, participants were instructed to pedal. To encourage pedalling at a reasonable speed an alarm sounded if the rotational speed was not within the region of 50 to 80 revolutions per minute.

Figure 7. 2. The static bicycle used in the experiment.

7.3 Task details

This experiment used one obstacle cylinder, of diameter 200mm, located at the centre of the false floor. The top and side surfaces of this obstacle were painted with the same grey paint as the surrounding floor surface.

Figure 7.3 shows the servo motor which controls the movement of the obstacle located underneath the apparatus floor, the motor is controlled by a computer software (python) via a Pololu micro-controller. In this study, only the obstacle at the centre of the floor was used (Indicated by the red arrow in Figure 7.3).

This cylinder was normally flush with the surrounding floor but could be raised to one of seven heights (0.5, 2.8, 4.5, 7.1, 11.3, 17.9 and 28.4 mm) to simulate an obstacle.

The smallest height 0.5 was used as a null condition, meaning participants should not be able to detect it. This was intentional to find random responses like when a participant keeps pressing the button even without seeing the obstacle raised.

The cylinder heights followed a geometric progression ratio of 1.59 (0.2 log unit steps), the geometric progression as used for the acuity chart developed by Bailey and Lovie (1976).

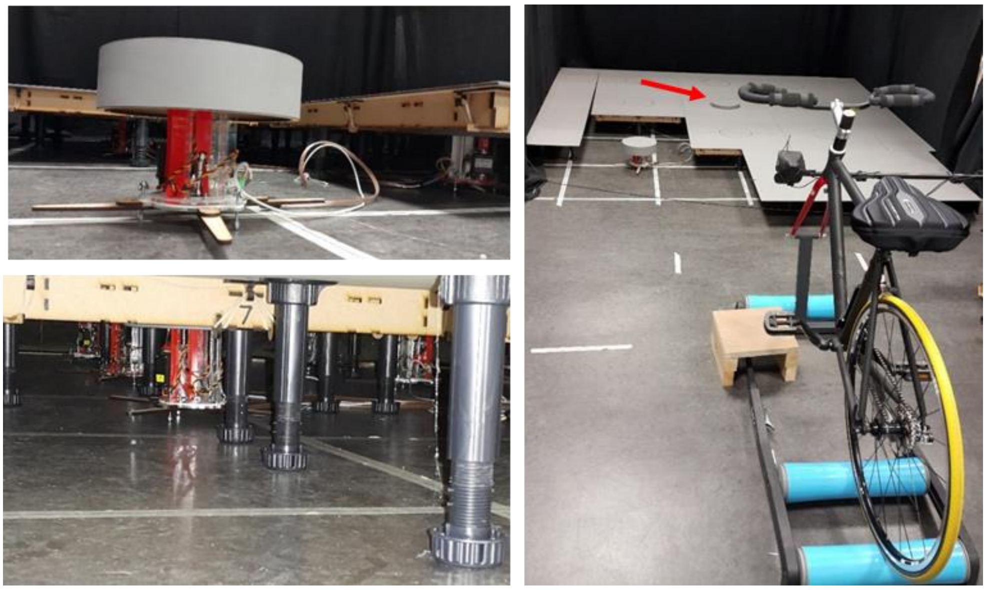

Figure 7. 3. (Left, top and bottom) The servo motor controls the simulated movement of the central obstacle. (Right) The static bicycle facing the apparatus. Part of the floor was removed for demonstration.

The same logarithmic progression was implemented in previous studies of obstacle detection (Fotios and Cheal, 2009, 2013; Uttley et al., 2017). The range of heights was chosen to include response rates of near zero at the smallest height and lower light levels to near 100% for the greatest height and higher light levels. Such performance trends were found in earlier detection studies, for example a study by Uttley et al. (2017) found that detection mean at the smallest obstacle (0.5 mm) was generally near zero in all illuminance levels tested (0.2,0.6, 2, 6.3 and 20 lux), whereas for the largest obstacle (28.4mm) mean detection reached 100 % for all S/P ratios and age groups (young/old) assessed in the experiment.

Findings by Uttley et al. suggest that the range of heights would produce an escarpment of performance, i.e. progressively changing performance as the height and light increased. It is in this escarpment that we would expect the other variables being investigated (e.g. bicycle lamp mounting position, road light illuminance, bicycle luminance) to influence performance.

For example, a similar approach of including test conditions where no response is expected i.e. the obstacle deliberately not raised during the trial to check for false alarms, was implemented by Fotios and Cheal (2013) in whose obstacle detection experiment a total of 160 null conditions (for all of the four participants) were introduced to check for false responses and only in 34 occasions false responses were registered (a false rate of 0.21) suggesting that participants intended to only respond when the obstacle was actually raised.

In the current study, the centre of the obstacle was positioned 1.2 m from the far wall and approximately 2.6 m from the participant's position on the cycle, giving an eye to obstacle distance of approximately 3 m. At this distance, and for an eye level of 1.75m, the obstacle subtended a visual size ranging from 0.01° to 0.43° for the range of the seven obstacle heights tested in the experiment, see Table 7.1 [6].

Table 7. 1. Calculations of visual size of the seven obstacle heights tested in the experiment (visual angle width is 3.65° for all heights).

Obstacle height	Visual angel height
28.4 mm	0.43°
17.9 mm	0.27°
11.3 mm	0.17°
7.1 mm	0.11°
4.5 mm	0.07°
2.8 mm	0.04°
0.5 mm	0.01°

Each of the seven obstacle heights was presented at two rising speeds (1 and 2 mm/s) giving 14 trials per lighting condition. The order in which these 14 trials took place was randomised for each lighting condition.

Using seven obstacle heights necessitated raising the obstacle almost immediately, for the detection task to be accurate, and this has to be done several times during each trial. Two considerations here: 1) Raising the obstacle at higher speeds than the fastest speed used may have resulted in generating distracting noise by the servo motors carriers; 2) The quick movement of the obstacle may stimulate the physiological motion

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[6] For all heights, the obstacle width was constant, approximately 3.65°.

detection systems of the participants and this may have affected the detection performance hence producing unrelated data giving that motion detection was outside the scope of the current study.

Therefore, 1 mm/s and 2 mm/s speeds were used to raise the obstacle. The reason why two speeds were used instead of one was to validate that there was no effect of motion detection between the speeds should no significant difference between them will be found when analysing the data.

The emergent height of the obstacle replicates the visual angle subtended by a static obstacle when approached by a cyclist in a real world situation.

Participants indicated detection by pressing a hand-held response button. If detection occurred before the obstacle reached its maximum height it would immediately return to lie flush with the surrounding surface (the home position), and a successful detection would be recorded. If the obstacle reached its maximum height without the button being pressed it would remain at this height for 2 seconds, or until the button was pressed (whichever was sooner), before returning to the home position. If the button was pressed within this 2 seconds period a detection was recorded, but if not, a miss was recorded. For the control condition (0.5 mm obstacle height) the exposure time at maximum height was increased to 8 seconds, representing the typical average time of other trials, including random time interval and time to reach and remain at the maximum height. It was predicted that the 8 seconds control condition would capture false positive responses from guessing or pressing the response button randomly.

A dynamic fixation mark was projected onto the rear wall of the test chamber by reflection from a gimbal-mounted mirror. ‘Dynamic’ here means that the location of the fixation mark moved (by operation of the mirror gimbal), and the fixation mark changed at random intervals from a crosshair (the normal status) to a digit (1 to 9) at random intervals between 2 to 6 seconds for 0.2 second duration before returning to the crosshair. Participants were instructed to read these numbers aloud, this response being recorded and used as a measure of fixation maintenance. The fixation mark moved randomly within an ellipse on the far wall, this ellipse having a height of 1.05 m and width of 2 m (15.7° x 29.5°) with its centre 1.5 m above the false floor. The maximum possible visual angle between the fixation target and the obstacle was 41.4° (when at the top of the ellipse), the minimum 18.6° (when at the bottom of the ellipse).

Figure 7.4 below illustrates experiment equipment attached at the top of the chamber: gimbal-mounted mirror (location is indicated by letter A), the mirror covered by black screening and surrounded by cardboard to prevent unwanted light reflections. The mirror reflects the fixation mark emitted from the projector (C). The two arrays of LED used to replicate road lighting are indicated by the letter (B). During the experiment, the normal room light was switched off till the end of the experiment.

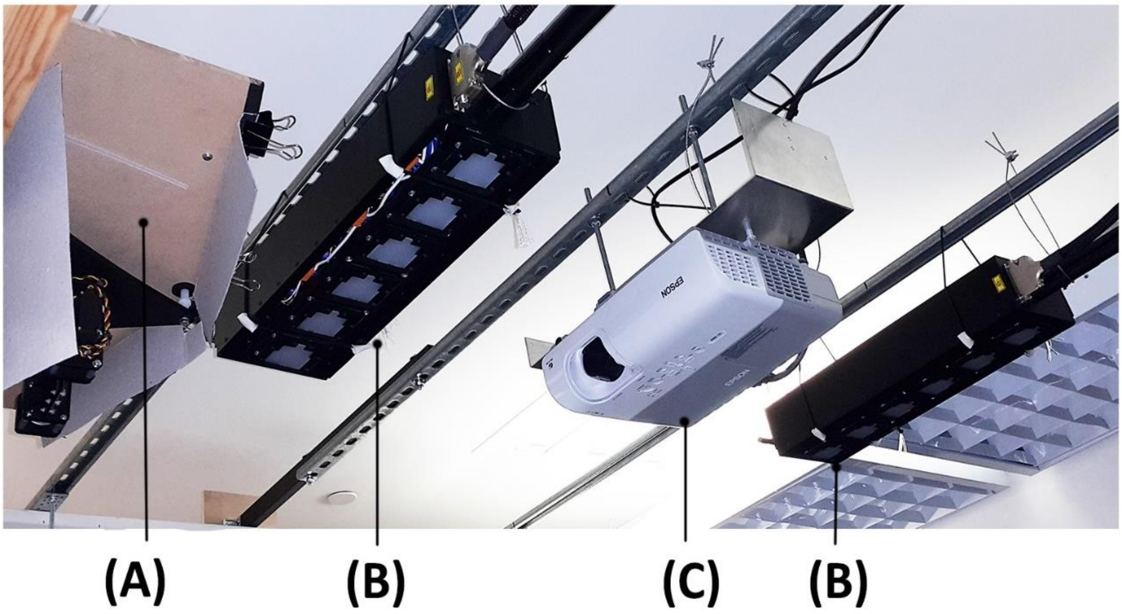

Figure 7. 4. View of the underside of the ceiling of the test chamber to show experiment equipment: (A) location of a gimbal-mounted mirror (B) Two arrays of LEDs simulating overhead road lighting (C) Fixation mark projector.

The fixation target moved with a speed between 14.7° and 36.4° visual arc per second on the far wall. The speed was varied randomly each time the target changes direction. Figure 7.5 illustrates an example of the path taken by the fixation target from the start of a light condition session for 60 seconds period for one trial.

Many peripheral detection studies have employed a static fixation mark (e.g.Bullough and Rea, 2000) and there has been little if any, validation of the degree to which fixation was maintained. The purpose of this dynamic fixation target was to maintain foveal fixation on the fixation mark, better ensuring the peripheral vision was used for the obstacle detection task (Fotios et al., 2016).

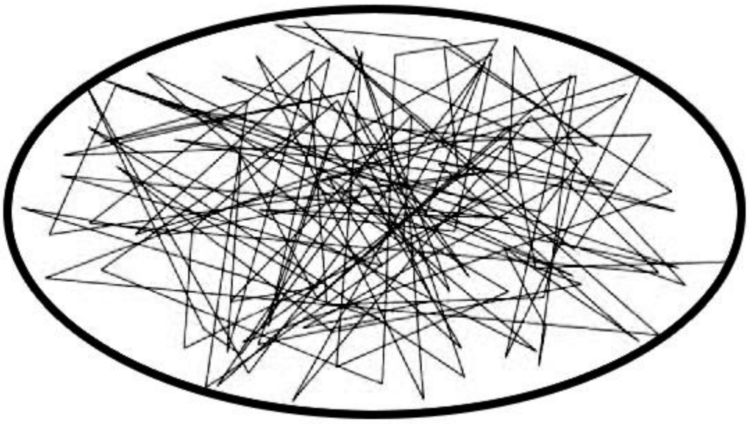

Figure 7. 5. The fixation target moved randomly and changed speed every time the direction is changed, the path of the target during a trial is shown.

7.4 Lighting

The test area was lit from above by two arrays of LEDs as shown in Figures 7.1 and 7.4. Each array was comprised of six clusters of four types of LED, red, green, blue and amber. Acrylic casted diffusers (3 mm thick) were positioned before each LED group to enhance the uniformity and colour mixing of the light emitted.

The control system allowed the intensity of each type of LED to be independently modulated, thus allowing a wide range of unique spectra to be set. The illuminance provided by these arrays was varied but only one SPD and colour coordinates were used (S/P=1.6; x= 0.46 and y= 0.42, respectively) this value falls within the traditional range of S/P ratios found in road lamps (Boyce, 2014). The SPD patterns of road and bicycle lighting are shown in Figure 7.6. Tests were carried out under three horizontal illuminances, 0.2, 2.0 and 20.0 lux, as measured at the centre of the obstacle, and a fourth condition in which the LED array was switched off. The three road lighting illuminances bracket the illuminances recommended in UK road lighting guidelines e.g. BS 5489-1:2013 (BSI, 2013).

To measure the light falling on the obstacle several metrics can be used e.g. luminance, semi-cylindrical, illuminance, etc. In this study, horizontal illuminance was used to characterise road lighting, this being the metric used in road lighting guidelines (e.g.BS 5489-1:2013), while luminance was used to describe intensity of bicycle light, to enable better distinction.

Furthermore, the illuminance values tested are replicating values tested in earlier studies (Fotios and Cheal, 2009, 2013; Uttley et al., 2017), to enable comparability.

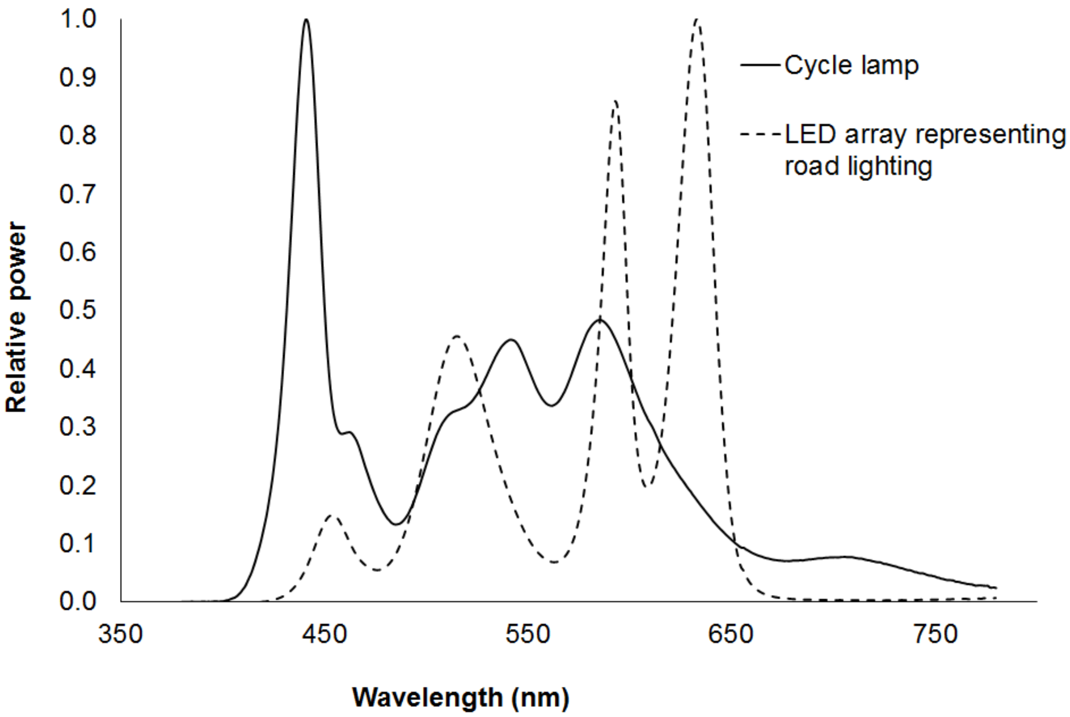

Figure 7. 6. Spectral power distributions SPD (normalised to a peak response of unity) for the LED array simulating overhead road lighting and for the bicycle lamp.

A second light source simulated a forward-facing bicycle-mounted lamp (LED Lenser model H14R.2), the bicycle lighting introduces many additional variables: mounting location on the bicycle, beam angle and direction, luminance and SPD.

Careful consideration of these variables may lead to improved lamp design and guidelines. Improving the performance of the bicycle lamp was the focus of some recent studies (Cai et al., 2014). In the current experiment, two variables of bicycle light were investigated; mounting height and luminance (light intensity). The three mounting positions were the wheel hub, handlebar or cyclists' helmet, these giving heights above ground level as shown in Table 7.2.

Table 7. 2. Description of mounting positions of the bicycle lamp and the length of the shadow cast from the raised obstacle at 28.4 mm height.

Location	Height of lamp above floor (mm)	Beam direction	Length of obstacle shadow
Handlebar	1370	20° below horizontal	100 mm
Helmet	1830	35° below horizontal	40 mm
Hub	565	Horizontal	150 mm

Changing the bicycle lamp mounting position is hypothesised to influence the contrast between the facing side of the raised obstacle and its surround area.

Figure 7.7 shows the influence of changing light source projection angel on the side, top and surround of an object. The (left) image was taken while the light source was projected from the helmet position while the (right) image representing lighting from the hub projection angel. The changes in appearance and conspicuity of the object in the figure demonstrate the influence that different bicycle lamp mounting positions might have on the object visibility.

Figure 7. 7. The light projected from the helmet position (left) and from the hub (right) demonstrating how a change in bicycle light position influences the contrast between the side, top and surround of an object hence its conspicuity.

These positions were in a single vertical line, 1370 mm from the obstacle centre, at the centre line of the bicycle. At the three locations, the bicycle lamp was aimed so that the obstacle was approximately in the centre of the beam, with the leading edge in the same position.

The difference in mounting position had an influence on the length of shadow cast from the raised obstacle, Figure 7.8 demonstrates the shadow cast onto the floor when the obstacle is raised to the maximum height (28.4 mm) with bicycle lamp set at 1.0 cd/m² and road light switched off for the three mounting positions.

Figure 7.9 shows the arm used to alter bicycle light position, as well as the bicycle lamp covered partially by black cardboard to prevent glare. Changing the mounting position of the bicycle lamp created different beam patterns on the floor surface ahead of the cyclists as shown in Figure 7.10.

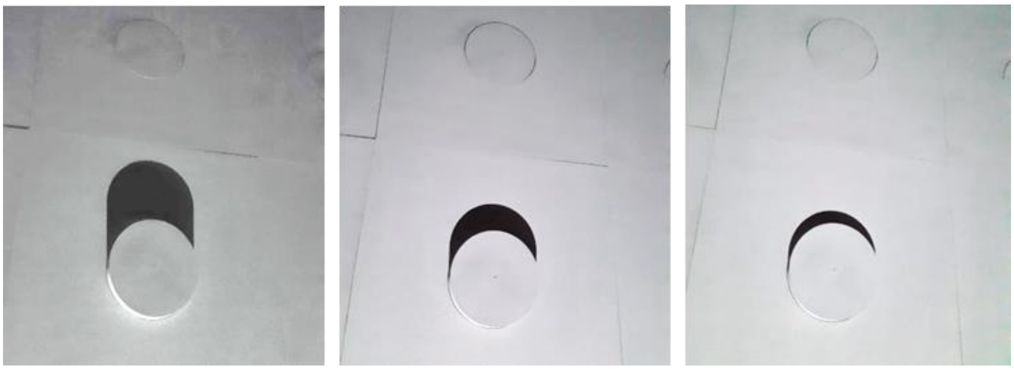

Figure 7. 8. Obstacle shadow patterns of the hub, handlebar, and helmet positions, respectively.

For luminance values, the bicycle lamp was either switched off or set to 0.1, 0.32 and 1.0 cd/m² as measured on the side of the raised obstacle facing the observer.

As with road lighting illuminances, these luminances were chosen to offer an interval of one log unit (0.1 to 1.0 cd/m²) and the halfway point (0.32 cd/m²). These levels were tested in previous studies. For example, Bullough and Rea (2000) tested a range of light luminance (3, 1, 0.3 and 0.1 cd m²) against peripheral detection task and found no large improvement in performance after 1 cd m² level. Also, He et al. (1997) found that reaction performance does not improve significantly beyond 1.0 cd m².

In the current study, using luminance levels that replicate or fell in the range of levels assessed previously allows for comparability with previous studies. Using luminance level of 1.0 cd m² and lower enables the production of performance escarpment that progresses from lower to a higher level allowing the demonstration of the effect of different light properties on performance, on the contrary using levels above 1 cd/m² will diminish this opportunity as no improvement in performance was found by earlier similar studies.

Change in luminance was achieved using the lamp's built-in control, with a neutral density filter (25% light transmission) placed directly in front of the lamp at all times to reduce its light output. A fibre optic cable located in the periphery of the beam, light sensor (TSL2591 and Arduino microcontroller) allowed accurate adjustment to predetermined intensities and corresponding to luminances of the obstacle side, and monitoring/logging of the intensity during trials. The bicycle lamp spectrum had a correlated colour temperature of 6500K, a general colour rendering index of Ra=75, and a S/P ratio of 2.1.

For the current purpose, it would have been ideal if the two sources of lighting (road and bicycle) had the same SPD so that any differences in detection could be ascribed fully to light source location and light level. However, this was not possible given that the bicycle lamp has a higher S/P ratio (2.1) than the road lighting (1.6) this would be expected to increase the detection of peripheral obstacles as a higher S/P was found beneficial for such detection performance (Uttley et al., 2017).

For contrast calculations either between the side of the raised obstacle and the surrounding area for all light combinations see Appendix E. The contrast between these surfaces, in theory, should have a role in detection ability, this meant a higher contrast value could be better for detection and vice versa (Akashi et al., 2014). This was tested in the experiment and compared against detection performance as will be discussed in the following chapter.

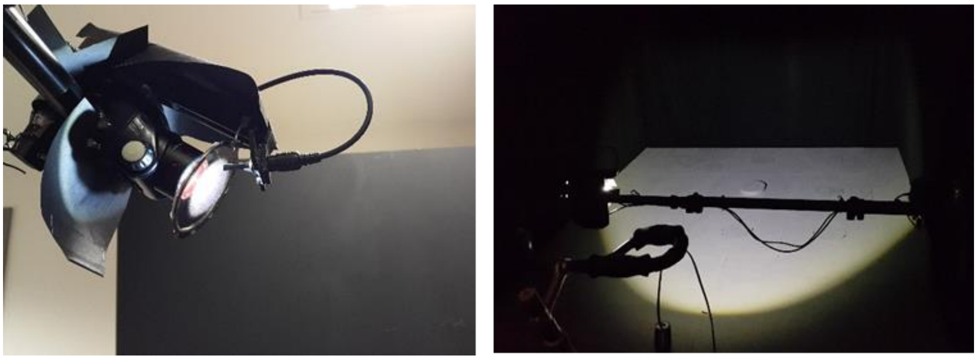

Figure 7. 9. (Left) The bicycle lamp covered partially by black cardboard to prevent glare also a neutral density filter placed in front of it to reduce its light output. (Right) the arm used to alter the bicycle lamp position.

Figure 7. 10. Beam pattern on the floor surface ahead of the cyclists when the bicycle-mounted lamp was located at the helmet (left), handlebar (middle) and wheel hub (right).

7.5 Procedure

Three experiments were carried out, each using ten participants, and each were paid a small fee as an incentive. The thirty test participants included twelve males and eighteen females, and their ages ranged from 18 to 36 years with an overall mean age of 26 years. Thirteen participants wore their normal corrective lenses during experiment.

Initially, the normal vision was confirmed using a Landolt ring acuity chart and the Ishihara test for colour blindness (Same procedures as those described under Section 4.6). A twenty-minute period was allowed for dark adaptation; during this time the test procedure was explained and participants were given time to become accustomed to pedalling the bicycle.

A practice session was included to introduce the fixation task and the obstacle detection task (pressing the response button if they noticed a raised obstacle). Practice trials consisted of 12 sessions. The practice period sessions progressed from easy to more demanding. For example, the obstacle height was reduced gradually reaching the lowest height at the end of the practice. The fixation target follows the same progressive difficulty, in the beginning, it was static and closer to the obstacle then altered to moving mode and or changed to numbers.

In trials, participants were instructed to fixate upon the fixation target, stating aloud any digits that appeared, whilst pedalling and pressing the response button if they detected a raised obstacle. To encourage participants to maintain a foveal gaze on the moving fixation target the experimenter stated that the fixation target task should be their primary focus.

For each lighting condition, a period of approximately three minutes was required to complete the 14 detection trials. If the participant requested a break, or if four consecutive conditions had been completed, a short rest period was taken (approximately 3-4 minutes) until the participant was ready to resume.

Experiment 1 examined variations in road lighting and bicycle lighting but the latter was retained in only one position, mounted on the handlebar, this being a common location for bicycle lamps. The ten test participants (6 males, 4 females, aged 18-36 years, an age mean of 27 years, four wore corrective lenses) each completed trials under the 16 conditions (4 road lighting illuminances: 0, 0.2, 2.0 and 20 lux; 4 bicycle light luminances: 0,0.1,0.32, 1.0) in a random order within a single two-hour test session see Figure 7.11.

Experiment 2 examined the effect of varying the location of the bicycle lamp (change in vertical height) and did so with only one bicycle light luminance, 0.32 cd/m^2, the middle of the three cycle lamp settings used in experiment 1. The four road lighting illuminances were retained (0, 0.2, 2.0 and 20 lux). The three vertical positions of the bicycle lamp were equivalent to the cyclist's helmet, the handlebars, and the wheel hub. The ten test participants (2 males, 8 females; aged 19 to 36 years, an age mean of 27 years, three wore corrective lenses) each completed trials under all twelve conditions in random order, see Figure 7.11.

The results of experiments 1 and 2 were analysed to devise a hypothesis to be tested in experiment 3. Initially, a small number of conditions were chosen to confirm the apparent benefit of the hub-mounted bicycle lamp over a handlebar or helmet mounted lamp, in terms of increasing obstacle detection rate, with further conditions included to replicate conditions used in experiments 1 and 2 to enable cross-checking of the results. These conditions fell into a repeat of experiment 1 but with the bicycle lamp mounted on the wheel hub rather than the handlebar. Thus Experiment 3 examined variations in road lighting and bicycle lighting with the latter lamp mounted on the wheel hub. The ten test participants (4 males, 6 females; aged 18 to 35 years, an age mean of 24 years, six wore corrective lenses) each carried out trials under all 16 conditions (4 road lighting illuminances: 0, 0.2, 2.0 and 20 lux; 4 bicycle light luminances: 0,0.1,0.32, 1.0) in random order.

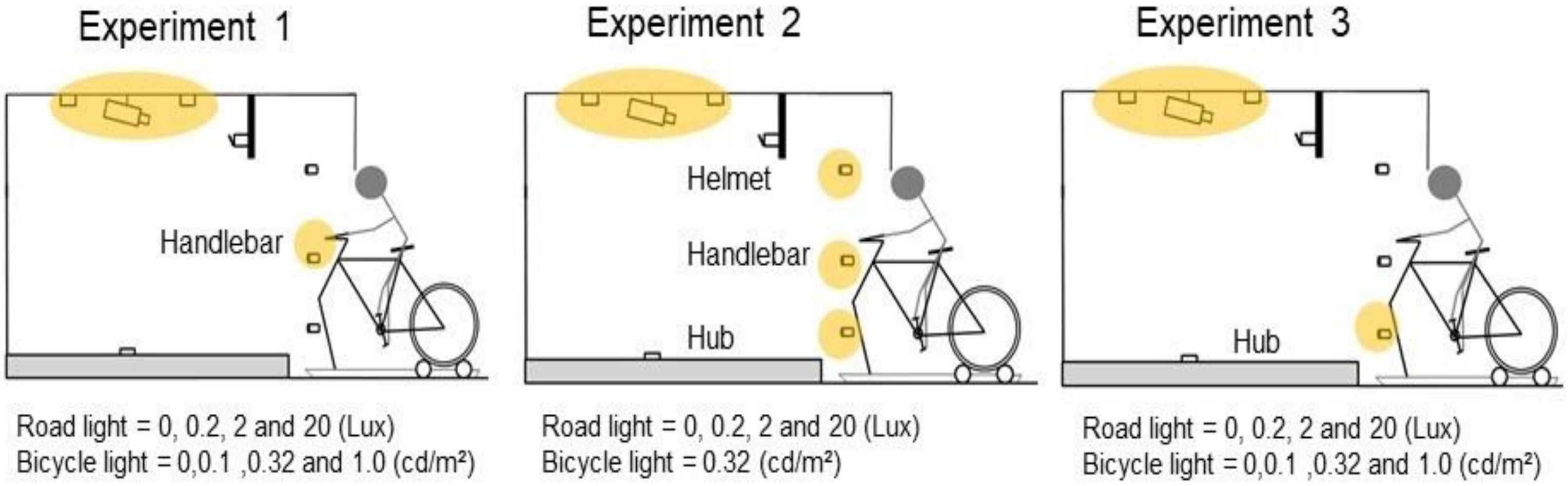

Figure 7. 11. Experiments 1, 2 and 3 showing road light illuminances, bicycle light luminances and bicycle lamp position(s) at each experiment.

7.6 Summary

The method implemented to measure obstacle detection performance under variations of: road light; bicycle light, and mounting position was described in this chapter. The mounting position of the bicycle lamp was varied to three locations: the hub, handlebar and helmet, to evaluate the effect on participants' detection ability. The study was divided into three consequent experiments (1,2 and 3). The aim was to study the effect of the previously described variables on obstacle detection, being a critical visual task for cyclists as per the results of the main eye-tracking experiment (Chapter 5). In the next chapter, the results and discussion of the obstacle detection experiment will be provided.

Chapter 8. Obstacle detection: Results and discussion

8.1 Introduction

Chapter 7 described the apparatus used in the experiment, the aim of which was to investigate cyclists' ability to detect an approaching obstacle using peripheral vision under different combinations of road light illuminance and bicycle light luminance. This chapter reports and discusses the results. The objectives were to reveal whether different intensities of road light and bicycle light aid cyclists' visual detection performance when used separately and/or together. The effect of bicycle lamp mounting position on detection performance was also evaluated.

Three sequential experiments were conducted. Experiment 1 tested variations of road and bicycle light when the latter was mounted on the handlebar position. Experiment 2 used only one bicycle luminance and three mounting positions: helmet, handlebar, and the hub. Based on the findings of experiments 1 and 2, experiment 3 repeated the light combinations tested in experiment 1 but with the bicycle lamp mounted on the wheel hub. This was to establish whether detection improves when the position of the bicycle lamp changes.

Normality analysis was performed using a range of statistical and graphical measures (central tendency, distribution, Kolmogorov-Smirnov, and Shapiro-Wilks). These showed that experiment 1 data, as well as data for experiments 2 and 3, were not drawn from a normally distributed population (see Appendix D). Hence, statistical analyses were conducted using non-parametric, repeated measures tests.

8.2 Fixation target identification

During trials, the fixation mark changed at random intervals from a crosshair to a single-digit number. This occurred 40 times on average in each test condition. Test participants were required to read this number aloud. The degree to which test participants could accurately read these numbers provided an estimate of their attention towards the fixation task and hence ensured that the detection target was maintained in peripheral vision. The overall correct identification rate for all three experiments was 88% (Standard deviation= 4.2 %). The rates for each separate experiment were 91% (experiment 1), 90% (experiment 2), and 84% (experiment 3). This indicates satisfactory attention towards the fixation target. It was therefore deduced that there was a tendency for participants, as instructed, to direct their gaze towards the fixation mark; thus, the obstacle is suggested to had been detected using peripheral vision.

8.3 Obstacle speed

In each trial, the seven obstacle heights were raised twice, once at a speed of 1 mm/s (slower speed) and another at 2 mm/s (faster speed). Detection performance under each speed was compared to determine whether this influenced detection.

Normality assessments were conducted on two datasets: the *detection rate* for all obstacle heights (seven heights) and the *detection height* for the largest obstacle (28.4 mm): the height of the obstacle at the moment of detection even before reaching its maximum at 28.4mm. The largest obstacle will be referred to as the ‘emergent obstacle’. Neither data sets were drawn from a normally distributed population (see Appendix D).

Detection rate data were analysed using the McNemar test (non-parametric, ordinal data) (Field, 2013). This analysis included all the seven obstacle heights (190 comparisons conducted for all experiments). The results indicated no significant difference in the detection rate between the two speeds.

Emergent obstacle data was then analysed using the Wilcoxon signed rank test (non-parametric, repeated measures). For experiment 1, this was carried out for the 15 light conditions (no light condition was removed). The effect of obstacle speed on detection performance was significant ($p < 0.05$) in 12 conditions. The slower obstacle speed (1 mm/s) yielded a lower detection height (median = 4.2 mm) across all conditions than the faster speed (median = 6.8 mm).

In experiment 2, comparisons of obstacle speed revealed significant differences in 4 out of 12 light conditions, with the slower speed producing lower detection heights (median = 4.45 mm across all conditions) than the faster speed (median = 6.6 mm).

Experiment 3 yielded a significant difference between the two speeds in six of the 15 light conditions. Again, the slower speed produced lower detection heights (median =

3.1 mm) than the faster speed (median = 4.1 mm). Experiments 1 and 3 tested the same light combinations while varying the mounting position of the bicycle lamp from the handlebar to the hub. The smaller number of significant conditions in experiment 3 (6 conditions) compared to experiment 1 (12 conditions) could therefore be related to an improvement in detection performance caused by a better bicycle lamp mounting position (see Section 8.6.2).

Tables 8.1, 8.2, and 8.3 show the median detected height of the emergent obstacle under each light condition and the two speeds.

Table 8. 1. Experiment 1 median detection height (mm) of the emergent obstacle under all light conditions for the two speeds: slower = 1mm/s and faster = 2 mm/s.

Road light (lux)	Speed	Median detection height (mm) of the emergent obstacle under varied bicycle luminance			
		0	0.1 cd/m^2	0.32 cd/m^2	1.0 cd/m^2
0	1 mm/s	N/A[1]	6	6.1	3.9
	2 mm/s	N/A	10.05	7.45	7.2
0.2	1 mm/s	5.45	8.9	5.45	4.8
	2 mm/s	7.6	11.75	8.85	6.8
2	1 mm/s	3.25	5.85	5.9	4.25
	2 mm/s	5	5.75	9.05	7.75
20	1 mm/s	3.2	2.75	2.85	3.4
	2 mm/s	4.95	4.35	4.6	4.45

[1] The condition where the road light and bicycle light was switched off was excluded.

Table 8. 2. Experiment 2 median detection height (mm) of the emergent obstacle under all light conditions for the two speeds: slower = 1mm/s and faster = 2 mm/s.

Road light (lux)	Speed	Median detection height (mm) of the emergent obstacle under varied bicycle luminance		
		Helmet	Handlebar	Hub
0	1 mm/s	11.75	5.35	2.3
	2 mm/s	13.2	6.45	4.25
0.2	1 mm/s	8.65	6.9	2.35
	2 mm/s	10.6	8.8	5.2
2	1 mm/s	6.45	5.3	3.95
	2 mm/s	10.2	9.85	6.35
20	1 mm/s	3.8	3.65	3.55
	2 mm/s	5.05	5.2	5.3

Table 8. 3. Experiment 3 median detection height (mm) of the emergent obstacle under all light conditions for the two speeds: slower = 1mm/s and faster = 2 mm/s.

Road light (lux)	Speed	Median detection height (mm) of the emergent obstacle under varied bicycle luminance			
		0	0.1 cd/m^2	0.32 cd/m^2	1.0 cd/m^2
0	1 mm/s	N/A[1]	2.8	2.05	3
	2 mm/s	N/A	3.75	3.9	3.6
0.2	1 mm/s	5	3	2.2	2.3
	2 mm/s	6.7	3.8	3.8	2.6
2	1 mm/s	3.8	4.55	4.75	2.7
	2 mm/s	4.35	6.8	6.35	4.1
20	1 mm/s	2.75	3.4	3.05	2.8
	2 mm/s	2.65	4.5	4.9	5.9

[1] The condition where the road light and bicycle light were switched off was excluded.

The difference in detection performance between speeds is suggested to be a function of a latency effect (Uttley et al., 2017). This occurs when the obstacle travels for a greater distance under the faster speed than the slower speed, even if the participant visually detects the obstacle at the same moment for each speed. This effect is explained by Uttley (2015) who used the same apparatus employed in the current study. In Uttley's study, the latency difference between speeds was 1.25 seconds between the moment the obstacle was noticed and the moment the participant pressed the response button to register detection. During this latency period, the obstacle travelling at 2 mm/s covered an additional distance of 1.25 mm compared with the obstacle travelling at 1 mm/s.

When this distance was deducted from the detection height data for 2 mm/s in the three experiments and the Wilcoxon test was reapplied, the difference between the two speeds was no longer suggested to be significant.

Thus, the difference between detected heights under each of the two speeds found in the three experiments was attributed to the extended distance covered by the obstacle at the faster speed and did not necessarily reflect an impact of speed on detection performance.

It was therefore concluded that the increasing speed of the obstacle did not have a significant effect on detection performance. Consequently, in the subsequent analyses of detection rate and detection height, the data used will be the mean outcome of the two speeds for each height of the seven and light condition across the study sample.

8.4 Results of experiment 1

Experiment 1 examined 16 light combinations (4 road light illuminances and 4 bicycle light luminances) with the bicycle lamp mounted on the handlebar, see Table 8.4.

Table 8. 4. Road light and bicycle light levels tested in experiment 1 with the bicycle lamp always mounted on the handlebar.

Tested variables	Values
Road lighting illuminance (lux)	0, 0.2, 2.0 and 20
Bicycle lighting luminance (cd/m²)	0, 0.1, 0.32 and 1.0
Bicycle lamp position	Handlebar

8.4.1 Detection rate

As stated earlier in Section 8.3, the detection rate data were not normally distributed. Moreover, because the data were essentially discrete and not continuous (ordinal data), which means the value for any participant will be 0, 0.5, or 1 rather than any value between 0 and 1, it will never appear to be 'normally' distributed.

Non normally distributed data traditionally calls for use of the median rather than the mean when reporting results. However, this was not the case when producing the graphs in Figure 8.2. This was because the mean provides clearer curve lines and thus demonstrates with greater clarity the correlation between increased detection rate and the increased height of the obstacle.

If the median was used the curves would have generally overlapped (not seen) as the result would have = 1 in most conditions. Using a median in such situations is therefore not recommended. For example, Fagerland et al. (2011) argued that using the median to report the results of a discrete numerical variable could yield an inaccurate measure of central tendency giving the limited number of possible values it could report (similar to the detection rate variable in the current study). Moreover, the mean is still able to give a good indication of the central tendency in the data.

To further illustrate the difference between using the median or the mean, Figure 8.1 reports the median and can be compared with the graphical use of the mean in Figure 8.2.

However, when conducting statistical comparisons between the two speeds (1 and 2 mm/s), a non-parametric McNemar test was used. This emphasises that the use of the detection mean for each of the seven obstacle heights in Figure 8.2 was ultimately illustrative. The author is aware that using the median for non-parametric data has more support in the literature than using the mean; however, for a discrete numerical variable such as the detection rate its use is debateable (Fagerland et al., 2011).

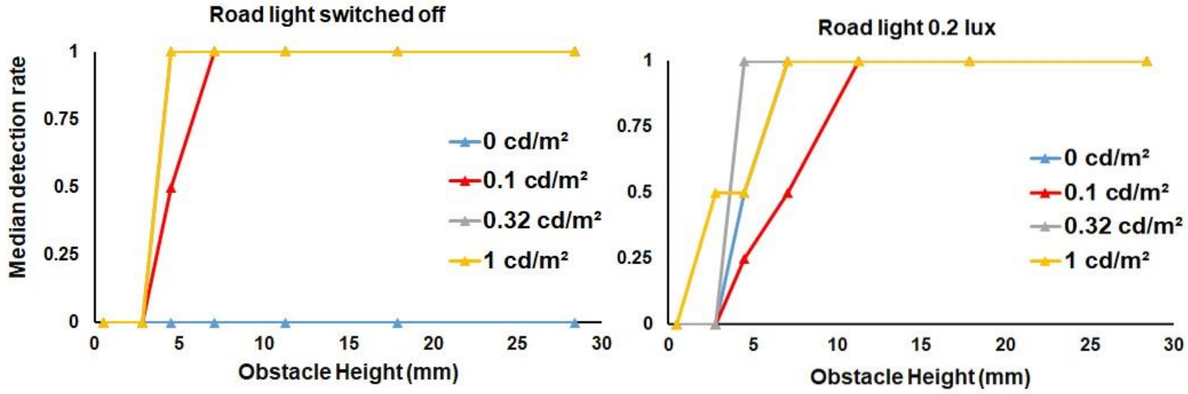

Figure 8. 1. Median obstacle detection rate when i) road light is switched off and ii) at 0.2 lux under varying bicycle luminances for the seven obstacle heights tested in experiment 1.

Figure 8.2 shows the mean detection rate plotted against the seven obstacle heights for all combinations of road illuminances and bicycle luminances. It indicates that the detection rate increased to almost 100% with larger obstacle heights, compared with almost 0% detection rate for the smaller heights.

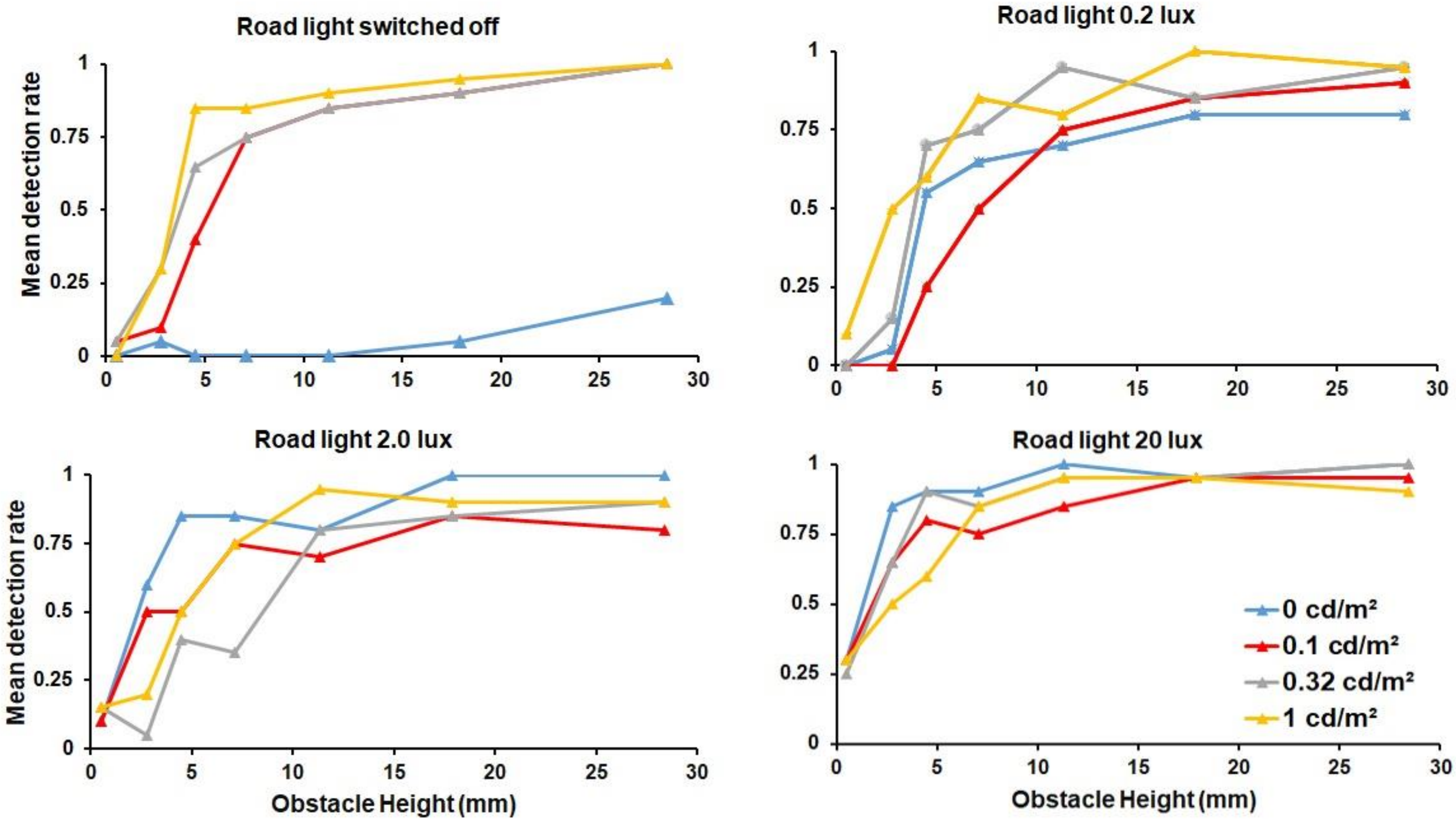

Figure 8. 2. Mean obstacle detection rate plotted against obstacle heights for experiment 1. The four separate graphs display the four road light illuminances while the four lines in each graph display the bicycle light luminance.

8.4.2 Detection height

The analysis reported in this section includes height at the moment the emergent obstacle was detected, as participants had usually detected the obstacle before it reached its maximum height.

Only data for the largest obstacle were used (28.4 mm), reducing the possibility of a floor effect that is predicted have lower obstacle heights were used instead and no detection is made before the obstacle reaches its maximum height. In such cases, ‘no detected height’ will be recorded as the opportunity for detection will be minimised by the lower height of smaller obstacles comparing to using the maximum height.

Figure 8.3 and Table 8.5 present the median detection height for each light condition in experiment 1. If only 0 cd/m² bicycle light is considered, a higher illuminance level clearly allows smaller obstacles to be seen; this is similar to the results found in previous research (Fotios and Cheal, 2013; Uttley et al., 2017). At each of the three road light illuminances, switching on the bicycle lamp provided no benefit as obstacle detection performance did not improve. At lower road light illuminances (0.2 and 2.0 lux), there was a clear difference in performance between the three bicycle light luminances; however, this difference disappeared at a higher road light illuminance (20 lux). For the lowest bicycle light luminance (0.1 cd/m²), there was a steady improvement in obstacle detection as road light illuminance increased. Nonetheless, obstacle detection first decreased and then increased for the two higher bicycle light luminances (0.32 and 1.0 cd/m²), indicating a possible impact of contrast reversal on detection. Contrast reversal is the result of bicycle light reducing the difference in luminance level between the side of the obstacle and the area immediately ahead of it (surround). This makes the obstacle less conspicuous (see Appendix E for luminance measurements at the surround and the side of the obstacle for the three experiments; and Section 8.9.3 for detailed discussion of the contrast effect on detection performance).

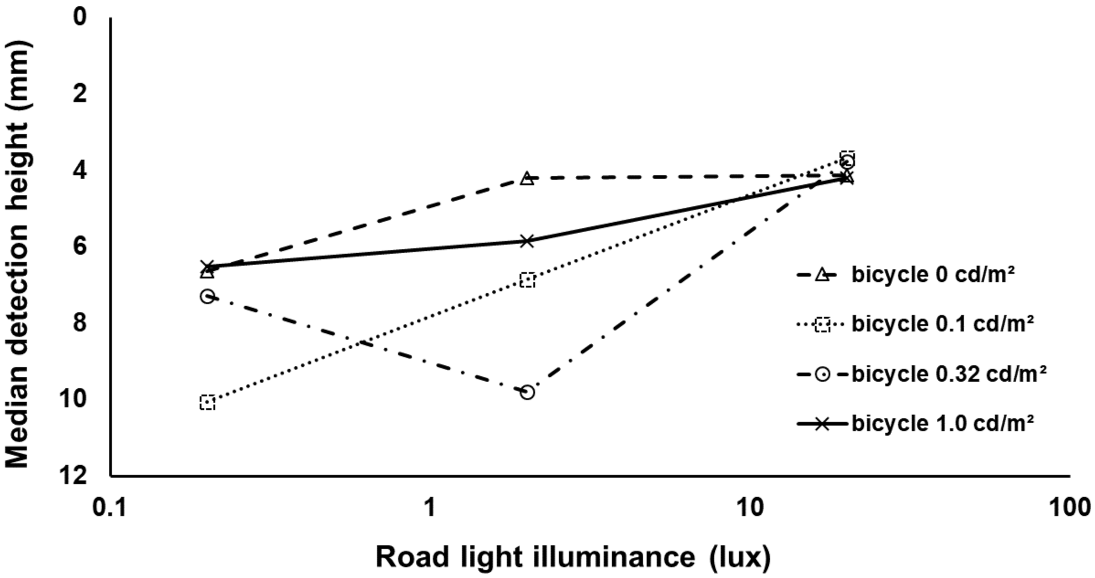

Figure 8. 3. Results of experiment 1: Median detection height of the emergent obstacle for varying levels of illuminance and luminance. The bicycle light was located on the handlebar.

Table 8. 5. Results of experiment 1: Median detection height of the emergent obstacle for each light combination. The bicycle light was located on the handlebar.

Road light (lux)	**Median detection height (mm) of the emergent obstacle under varied bicycle luminances**			
	0	**0.1 cd/m^2**	**0.32 cd/m^2**	**1.0 cd/m^2**
0	25.1	7.12	7.02	5.25
0.2	6.65	10.0	7.28	6.52
2	4.20	6.85	9.80	5.85
20	4.12	3.68	3.78	4.20

The data for 15 of the 16 test conditions were statistically analysed. The results from trials with no road or cycle lighting were omitted as they were used for a validation comparison, see Section 8.8.

A standard threshold of $p < 0.05$ was used to indicate significant effects for all statistical tests and no adjustments were made. Rather than focus on any single test, the overall pattern of results is considered when drawing conclusions about significance.

Comparing the 15 conditions using Friedman's test (non-parametric, repeated measures test) suggested that changes in road and bicycle lighting were significant in all light combinations ($p < 0.05$), except when bicycle light was at the highest luminance ($p = 0.072$) or the road illuminance was highest ($p = 0.435$), see Tables 8.6 and 8.7. In such situations where no significant difference was identified, changes in road light levels or bicycle light levels resulted in similar detection performance.

Using the Wilcoxon test (non-parametric, repeated measures test), while the bicycle light was switched off, when increasing road illuminance from 0.2 lux (median = 6.65 mm) to a higher level of 2.0 lux (median = 4.20 mm) or 20 lux (median = 4.12 mm) resulted in a significant increase in detection, with p-values of 0.012 and 0.017, respectively. Conversely, increasing road light above 2.0 lux did not result in any significant increase in detection (p =0.8), as shown in Table 8.6.

A similar effect was found in previous studies where detection reached a performance plateau at 2 lux level (Fotios & Cheal, 2013; Uttley et al., 2017).

At 0.2 lux, adding bicycle light resulted in either a significant decrease or no improvement in detection (Friedman's p = 0.054, Wilcoxon p = 0.036 when changing from 0 cd/m² (median = 6.65 mm) to 0.1 cd/ m² (median= 10 mm), which indicated reduced detection. For the same level of road light, altering the bicycle light from 0 cd/m² to either 0.3 (median= 7.28 mm) or 1.0 cd/m² (median= 6.52 mm) did not improve detection (Wilcoxon p = 1.000 and 0.674 for these conditions, respectively).

In general, switching on the bicycle light did not increase detection regardless of the luminance level. With 2 lux road lighting, the addition of bicycle lighting at any luminance level significantly decreased detection performance, as shown by the Friedman's result for all combinations at this road light level (p= 0.027). Wilcoxon paired test p-values when bicycle light was adjusted from 0 cd/ m² (median= 4.20 mm) to 0.1 (median= 6.85 mm), 0.3 (median= 9.80 mm), or 1 cd/m² (median= 5.85 mm) were 0.008, 0.038, and 0.021, respectively (see Table 8.7).

At 20 lux road light, using bicycle light (all luminance levels) had no significant effect on detection (Friedman's p = 0.435), as shown in Table 8.7.

Switching from 0.2 to 20 lux significantly improved detection at all cycle light levels (Wilcoxon $p < 0.05$, see Table 8.6). However, this was likely to be due to the increase in road light level from very low to very high, it is not necessarily an influence of bicycle light.

If the increase in illuminance was small (e.g., 0.2 to 2.0 lux, or 2.0 to 20 lux), then the increase at all bicycle light luminances was inconsistent, as shown in Table 8.6.

The findings of experiment 1 suggest that bicycle light did not improve detection; on the contrary, it reduced detection on several occasions.

Table 8. 6. Friedman and Wilcoxon tests of the effect of constant bicycle light and varied road light (experiment 1) on the detection of the emergent obstacle.

Bicycle light (cd/m^2)	**Light combinations (No).**	**Friedman's ($p < 0.05$)**	**Wilcoxon paired comparisons ($p < 0.05$)**					
			0 - 0.2 lx	**0 - 2.0 lx**	**0 - 20 lx**	**0.2 - 2.0 lx**	**0.2 - 20 lx**	**2.0 - 20 lx**
0	3	**(0.008)**	-	-	-	**(0.012)**	**(0.017)**	0.8
0.1	4	**(0.001)**	0.110	0.170	**(0.007)**	**(0.012)**	**(0.008)**	**(0.03)**
0.3	4	**(0.008)**	0.44	0.26	**(0.009)**	0.401	**(0.005)**	**(0.028)**
1.0	4	0.072	0.103	0.515	0.08	0.767	**(0.021)**	0.139

Note: Values in bold and between brackets indicate significant p-values

Table 8. 7. Friedman and Wilcoxon tests of the effect of constant road light and varied bicycle light (experiment 1) on the detection of the emergent obstacle.

Road light (lux)	**Light Combinations (No).**	**Friedman's ($p < 0.05$)**	**Wilcoxon paired comparisons ($p < 0.05$)**					
			0 - 0.1 cd/m^2	**0 – 0.3 cd/m^2**	**0 – 1.0 cd/m^2**	**0.1 – 0.3 cd/m^2**	**0.1 – 1.0 cd/m^2**	**0.3 – 1.0 cd/m^2**
0	3	**(0.014)**	-	-	-	0.508	**(0.005)**	0.114
0.2	4	0.054*	**(0.036)**	1.000	0.674	**(0.021)**	**(0.008)**	0.114
2.0	4	**(0.027)**	**(0.008)**	**(0.038)**	**(0.021)**	0.123	0.327	0.214
20	4	0.435	0.959	0.799	0.26	0.575	0.722	0.441

Note: Values in bold and between brackets indicate significant p-values.
* P-value on the edge of significance threshold.

8.5 Results of experiment 2

Experiment 2 examined 12 lighting combinations comprising four road lighting illuminances, one bicycle light luminance (0.32 cd/m^2), and three bicycle light positions: helmet, handlebar, and hub. The experiment aimed to determine whether the mounting position of a given bicycle lamp would affect detection. One luminance was intentionally selected instead of testing the three, like the case in experiment 1 and 3, to better isolate the effect of bicycle light mounting position, see Table 8.8.

Table 8. 8. Road light levels and one bicycle light level were tested in experiment 2 with the bicycle lamp in three positions: handlebar, helmet, and hub.

Tested variables	Values
Road lighting illuminances (lux)	0, 0.2, 2.0 and 20
Bicycle lighting luminance (cd/m²)	0.32
Bicycle lamp positions	Handlebar, helmet ,and hub

8.5.1 Detection rate

Figure 8.4 shows the mean detection rate for the three bicycle light positions. The graphs illustrate the advantage of the hub position over other mounting positions, this is specifically true at 0.2 lux and no road light. In general, the detection rate was enhanced by both larger obstacle heights and higher road light illuminance, which is similar to the patterns of experiment 1.

8.5.2 Detection height

Detection height data for the emergent obstacle are presented in Figure 8.5 and Table 8.9. Both figures show that, at lower road lighting illuminances, detection was best for the hub mounted position and poorest for the helmet. This difference disappeared at the highest road light levels suggesting that the effect of mounting position is mitigated at these levels.

The Friedman test indicated that the mounting position had a significant effect in two cases, when the road lighting was switched off and at the lowest illuminance (0.2 lux), with p-values = 0.002 and 0.001, respectively. However, no significant effect was found at higher illuminances (2.0, 20 lux), with p-values = 0.202 and 0.407, respectively, as shown in Table 8.11. This was confirmed for each pair of mounting locations using the Wilcoxon test (see Tables 8.10 and 8.11). The hub mounted lamp was best for detection at no road light and 0.2 lux, whereas the poorest detection was found for the lamp in the helmet position.

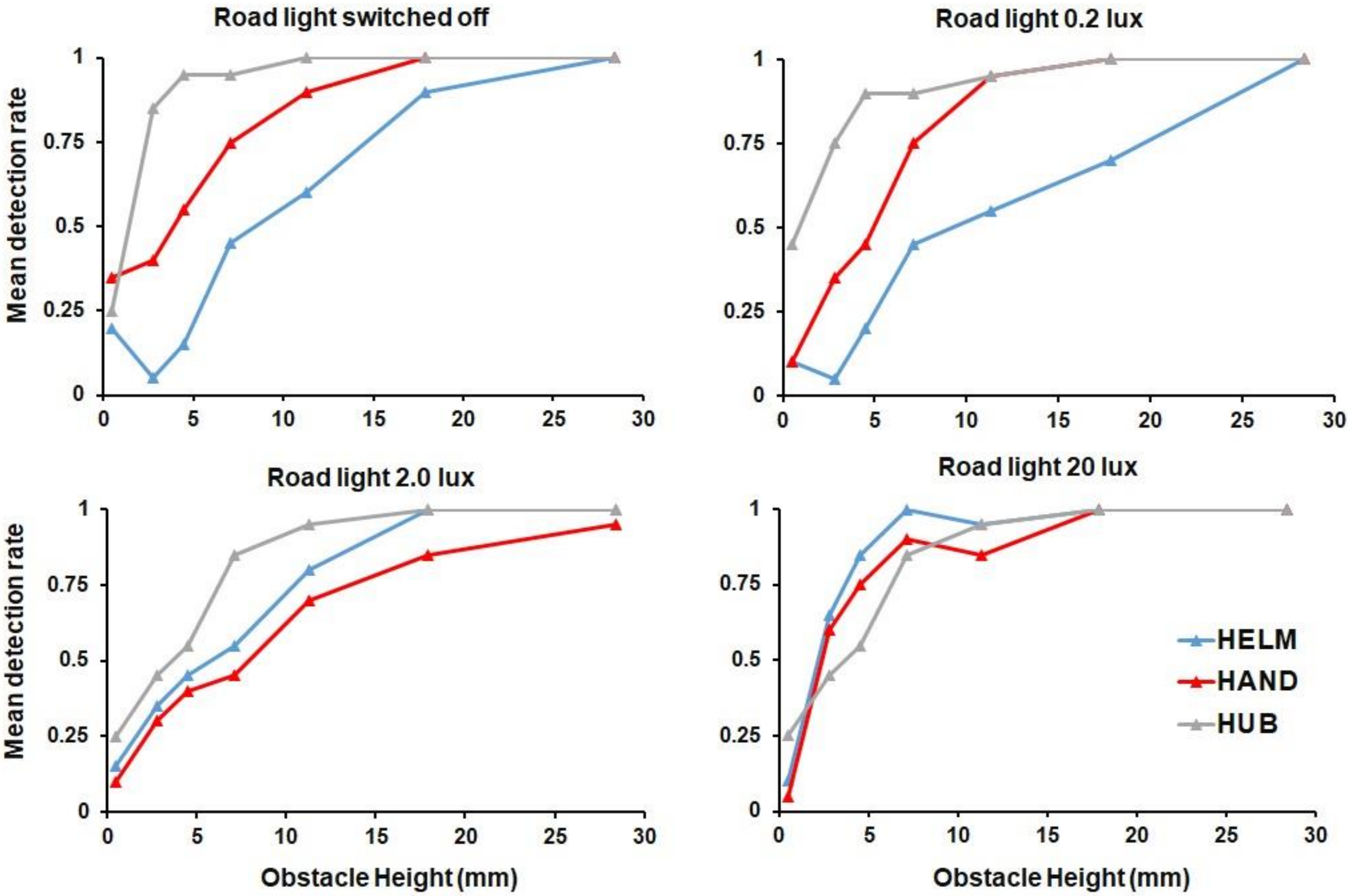

Figure 8. 4. Mean obstacle detection rate plotted against obstacle heights. The four separate graphs display the four road light illuminances: the three lines in each graph display the bicycle light mounting position. (HELM = helmet, HAND = handlebar and HUB = wheel hub).

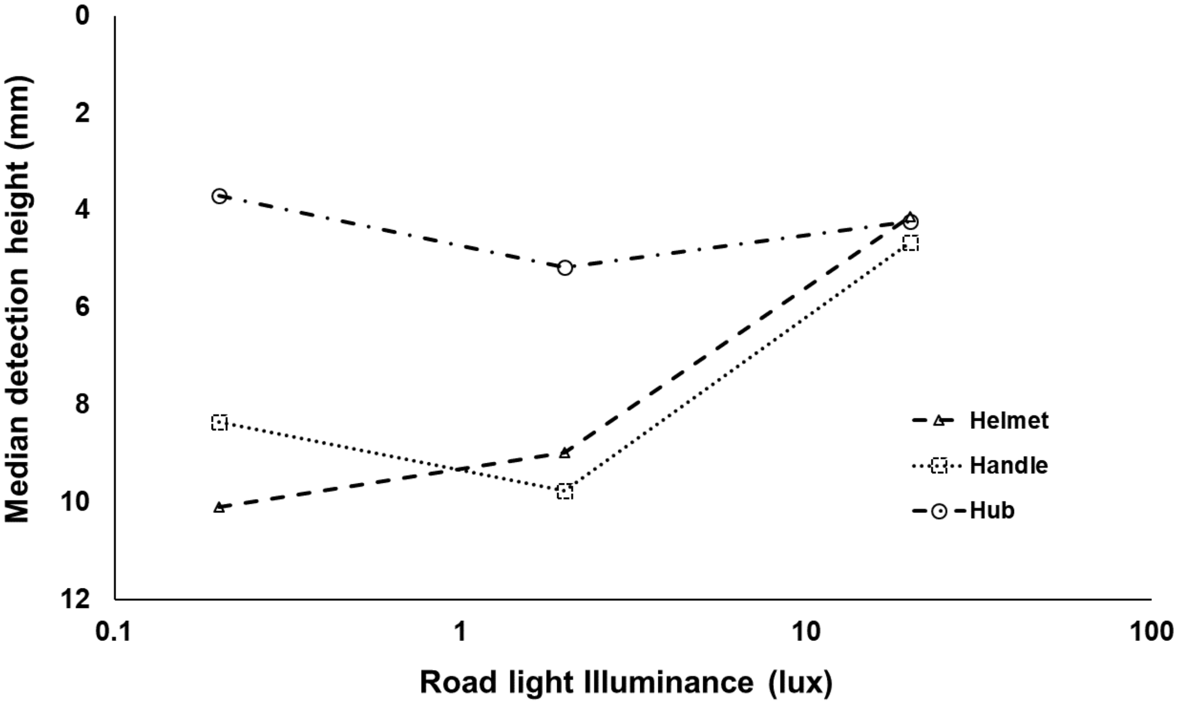

Figure 8. 5. Results of experiment 2: Median detection height of the emergent obstacle in respect to varied illuminance levels when the bicycle lamp was mounted on either the helmet, handlebar, or wheel hub. The bicycle light was set to provide a target luminance of 0.32 cd/m² for all trials.

Table 8. 9. Results of experiment 2: Median detection height of the emergent obstacle for each combination of road light illuminance and bicycle light position. The bicycle light was set to provide a target luminance of 0.32 cd/m² for all trials.

Road light (lux)	**Median detection height (mm) of the emergent obstacle under varied luminances**		
	Helmet	**Handlebar**	**Hub**
0	12.5	6.3	3.32
0.2	10.1	8.35	3.7
2.0	8.98	9.78	5.18
20	4.12	4.65	4.22

Table 8.10 presents the results of Friedman and Wilcoxon tests for the three mounting positions and varied road light.

When the bicycle light was in either the helmet or hub position, changes in road light illuminances were significant (Friedman's p = 0.002 for both positions). However, no significant effect was found for handlebar position (p = 0.142).

Wilcoxon paired tests ($p < 0.05$) for helmet position showed that increasing road light from no road light (median= 12.5 mm); 0.2 lux (median= 10.1 mm), or 2 lux (media= 8.98 mm) to 20 lux (median= 4.12 mm), yielded significantly better detection performance (p = 0.013, 0.005, and 0.007, respectively).

The better detection performance at 20 lux was assumed to be a function of the substantial increase in road illuminance rather than an effect of bicycle light position, and was similar to the pattern in experiment 1.

A significant decrease in detection perfromance was found in the hub position when illuminace was increased to 2 lux (median = 5.18 mm) from no road light (median = 3.32 mm); or from 0.2 lux (median = 3.7 mm) (p = 0.005 and 0.013, respectively). This decrease was believed to be casued by contrast reversal i.e., a reduced contrast between the obstacle side and the surround area.

Table 8. 10. Friedman and Wilcoxon tests of the effect of fixed bicycle lamp position and varied road light (experiment 2) on the detection of the emergent obstacle. The bicycle light was always on 0.32 cd/m².

Bicycle light position	**Number of light combinations**	**Friedman's (p < 0.05)**	**Wilcoxon paired comparisons (p < 0.05)**					
			0 - 0.2 lx	**0 - 2.0 lx**	**0 - 20 lx**	**0.2 - 2.0 lx**	**0.2 - 20 lx**	**2.0 - 20 lx**
Helmet	4	**(0.002)**	0.959	0.139	**(0.013)**	0.083	**(0.005)**	**(0.007)**
Handlebar	4	0.145	0.169	0.878	0.285	0.646	**(0.037)**	0.241
Hub	4	**(0.002)**	0.26	**(0.005)**	0.093	**(0.013)**	0.285	0.139

Note: Values in bold and between brackets values indicate significant p-values

Table 8.11 presents statistical comparisons at constant road light and varied bicycle light positions. Altering the bicycle lamp mounting position was significant only when the road light was switched off or at 0.2 lux (Friedman's p= 0.002 and 0.001, respectively). Wilcoxon paired comparisons ($p < 0.05$) for no light and 0.2 lux conditions revealed significant effects for all positions, with paired comparisons showing the hub position achieving the best detection performance, particularly at no road light (median= 3.32 mm) and 0.2 lux (median= 3.7 mm). It was significantly better than the handlebar position which at no road light (median= 6.3 mm) was p= 0.013 and at 0.2 lux (median = 8.35 mm) p = 0.009. Wilcoxon comparisons also showed that the hub was better than the helmet position at no road light and 0.2 lux (p = 0.007 and

0.005, respectively). The results demonstrated that at no road light and 0.2 lux levels, mounting the bicycle light at hub position improved detection performance.

Table 8. 11. Friedman and Wilcoxon tests of the effect of constant road light and varied bicycle light positions (experiment 2) on the detection of the emergent obstacle. The bicycle light was always on 0.32 cd/m².

Road light (lux)	**Number of light combinations**	**Friedman's ($p < 0.05$)**	**Wilcoxon paired comparisons ($p < 0.05$)**		
			Helmet – handlebar	**Helmet – Hub**	**Handlebar - Hub**
0	3	**(0.002)**	**(0.013)**	**(0.007)**	**(0.013)**
0.2	3	**(0.001)**	**(0.015)**	**(0.005)**	**(0.009)**
2.0	3	0.202	0.646	**(0.022)**	0.575
20	3	0.407	0.241	0.169	0.610

Note: Values in bold and between brackets indicate significant p-values

8.6 Results of experiment 3

Experiment 3 examined 16 lighting combinations using the same conditions as in experiment 1; however, the bicycle lamp was mounted on the wheel hub rather than on the handlebar, see Table 8.12.

Table 8. 12. Road light and bicycle light levels tested in experiment 3 with bicycle lamp mounted on the hub position.

Tested variables	**Values**
Road lighting illuminances (lux)	0, 0.2, 2.0 and 20
Bicycle lighting luminances (cd/m²)	0, 0.1, 0.32 and 1.0
Bicycle lamp position	Hub

8.6.1 Detection rate

Figure 8.6 shows the mean detection rate plotted against the seven obstacle heights. As found in experiments 1 and 2, the detection rate increased with larger obstacle heights and higher road light levels.

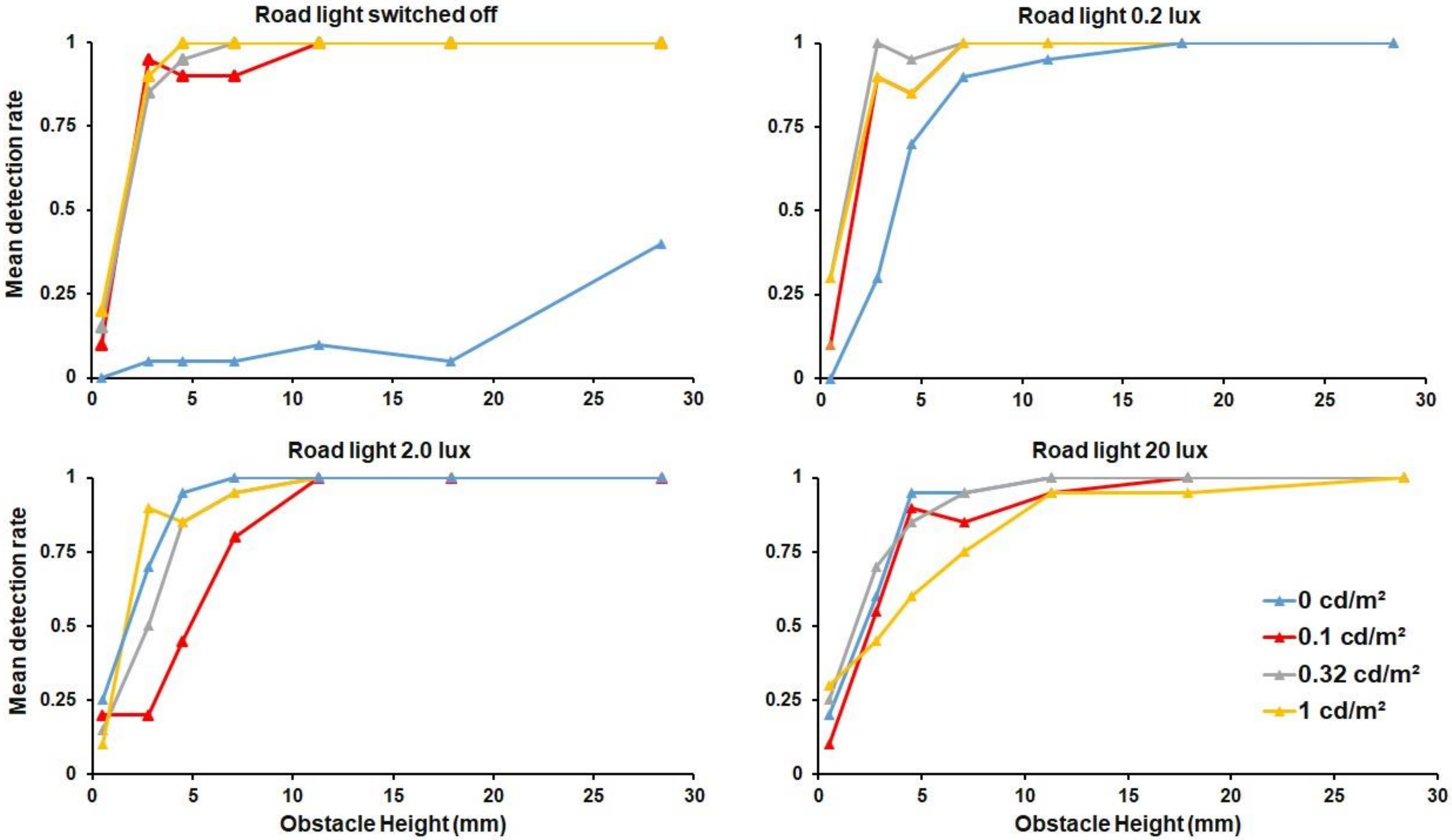

Figure 8. 6. Mean obstacle detection rate plotted against obstacle height. The four separate graphs display the four road light illuminances: the four lines in each graph display the bicycle light luminances. The bicycle light was mounted on the hub only.

8.6.2 Detection height

Data for detection height at the emergent obstacle are presented in Figure 8.7 and Table 8.13.

When the bicycle light was turned off, the curve in Figure 8.7 displays a trend similar to that in experiment 1, see Figure 8.3. Under this bicycle condition, increasing the road illuminance from 0.2 lux (median= 5.32 mm) to 20 lux (median= 3.15 mm) significantly increased detection performance, The Wilcoxon test confirmed this (p= 0.005). However, this was not the case when increasing road illuminance from 0.2 lux to 2.0 lux (median= 3.68 mm, p= 0.139) although detection height was reduced. Similarly, increasing the illuminance level from 2.0 to 20 lux did not have a significant effect (p = 0.074). These findings replicated those of experiment 1 in the no bicycle light condition where performance not improved after 2 lux i.e. performance plateau.

In contrast to experiment 1, switching on the hub mounted bicycle lamp (to any luminance level) when the road light was 0.2 lux significantly increased detection performance, see Table 8.15. This was confirmed by both the Friedman's test (p = 0.006) and Wilcoxon signed rank test (p= 0.009, 0.013, and 0.037 when altering luminance level from 0 cd/m² to 0.1 (median= 3.48 mm), 0.32 (median= 3.32 mm), and 1.0 cd/m² (median = 2.75 mm), respectively. Nevertheless, Wilcoxon paired comparisons indicated no significant difference in detection performance when the three luminance levels were compared at 0.2 lux (0.1 vs 0.3 cd/m² (p = 0.575); 0.1 vs 1.0 cd/m² (p = 0.093) and 0.3 vs 1.0 cd/m² (p = 0.445).

At 2.0 lux road light, using a simultaneous bicycle luminance of 0.1 (median= 5.70 mm) or 0.32 cd/m² (median= 5.55 mm) significantly reduced detection performance compared to when the bicycle light was turned off (median= 3.68 mm), Wilcoxon p-values = 0.059 and 0.047, respectively. However, using 1.0 cd/m² (median = 3.40 mm) showed that performance remained the same (Wilcoxon p = 0.574).

When the road light increased to the highest level (20 lux) all bicycle luminances resulted in reduced performance regarding the detected heights, see Table 8.13. However, this reduction was not found to be significant (Friedman's p = 0.145), as shown in Table 8.15.

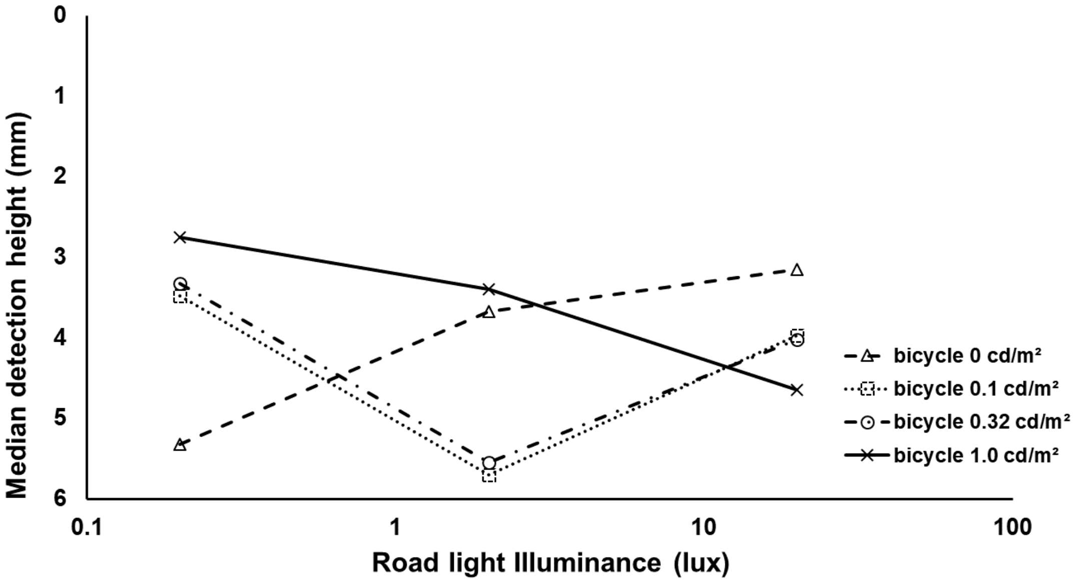

Figure 8. 7. Results of experiment 3: Median detection height for the emergent obstacle plotted in respect to varied illuminance and luminance levels. The bicycle light was located on the hub for all trials.

Table 8. 13. Results of experiment 3: Median detection height of the emergent obstacle for each combination of road light illuminance and bicycle light luminance. The bicycle light was located always on the wheel hub.

Road light (lux)	**Median detection height (mm) of the emergent obstacle under varied luminances**			
	0	**0.1 cd/m^2**	**0.32 cd/m^2**	**1.0 cd/m^2**
0	22.3	3.52	3.20	3.30
0.2	5.32	3.48	3.32	2.75
2	3.68	5.70	5.55	3.40
20	3.15	3.98	4.02	4.65

Figure 8.7 shows that luminances of 0.1 and 0.32 cd/m^2 resulted in a similar pattern as both significantly decreased detection performance when the road lighting was altered from 0.2 to 2.0 lux (Wilcoxon p-values = 0.022 and 0.015, respectively). This was followed by an increase in performance at the highest road light level. However, this increase was not significant (Wilcoxon p-values = 0.139 and 0.114 for 0.1 and 0.32 cd/m^2, respectively). This was similar to the trend found for the handlebar position when the bicycle light luminance was 0.32 cd/m^2 in experiment 1 (Figure 8.3) and experiment 2 (Figure 8.5). For the higher bicycle luminance level (1.0 cd/m^2), there was a gradual reduction in detection ability as road lighting illuminance increased

(Table 8.14), but this was significant only when the road light illuminance changed from 0.2 to 2.0 lux (Wilcoxon p =0.013), as shown in Table 8.14.

Table 8. 14. Friedman and Wilcoxon tests on the effect of constant bicycle light and varied road light (experiment 3) on the detection of the emergent obstacle.

Bicycle light (cd/m²)	**Number of light combinations**	**Friedman's (p < 0.05)**	**Wilcoxon paired comparisons (p < 0.05)**					
			0 - 0.2 lx	**0 - 2.0 lx**	**0 - 20 lx**	**0.2 - 2.0 lx**	**0.2 - 20 lx**	**2.0 - 20 lx**
0	3	**(0.003)**	-	-	-	0.139	**(0.005)**	0.074
0.1	4	**(0.033)**	0.139	0.114	0.721	**(0.022)**	0.139	0.139
0.3	4	**(0.013)**	1.000	**(0.007)**	0.168	**(0.015)**	0.093	0.114
1.0	4	**(0.041)**	0.059	0.878	0.114	**(0.013)**	0.074	0.415

Note: Values in bold and between brackets indicate significant p-values.

Table 8. 15. Friedman and Wilcoxon tests on the effect of constant road light and varied bicycle light (experiment 3) on the detection of the emergent obstacle.

Road light (lux)	**Number of light combinations**	**Friedman's (p < 0.05)**	**Wilcoxon paired comparisons (p < 0.05)**					
			0 - 0.1 cd/m²	**0 – 0.3 cd/m²**	**0 – 1.0 cd/m²**	**0.1 – 0.3 cd/m²**	**0.1 – 1.0 cd/m²**	**0.3 – 1.0 cd/m²**
0	3	0.407	-	-	-	0.202	0.683	0.386
0.2	4	**(0.006)**	**(0.009)**	**(0.013)**	**(0.037)**	0.575	0.093	0.445
2.0	4	**(0.009)**	0.059*	**(0.047)**	0.574	0.646	0.074	0.059*
20	4	0.145	0.333	0.114	**(0.019)**	0.646	0.646	0.221

Note: Values in bold and between brackets indicate significant p-values.
* P-values near significance threshold.

8.7 Detection height for 50% probability (h50)

In previous sections, the detection rate and detection height of the largest obstacle (emergent obstacle) were used to assess performance under different road light and bicycle light combinations. To validate the previous findings, an alternative approach was implemented where the obstacle height for 50% detection probability (h^{50}) was calculated to further assess detection performance. In this case, h^{50} for each light combination was extracted across the seven obstacle heights (0.5 - 28.4 mm).

h^{50} was computed by implementing the four parameter logistic equation (4 PLE), Equation 8.1, which provides the mean detection rate across the seven obstacle heights for each light combination. This equation has been used in previous studies

(Fotios and Cheal, 2009, 2013; Harris, 2006). Figure 8.8 illustrates the 4PLE best-fit curve for one light condition, which is calculated as shown in Equation 8.1:

$$y = 100 - \frac{100}{1 + \left(\frac{h}{h50}\right)^{s}}$$

Equation 8. 1

Where y = detection rate; h = obstacle height; h^{50} = height of the obstacle at 50% detection probability, and ^{s} = Curve slope.

It is important to note that h^{50} values are statistical results derived from the detection rate data of all participants; as such, further statistical comparisons are not a valid option for this type of data.

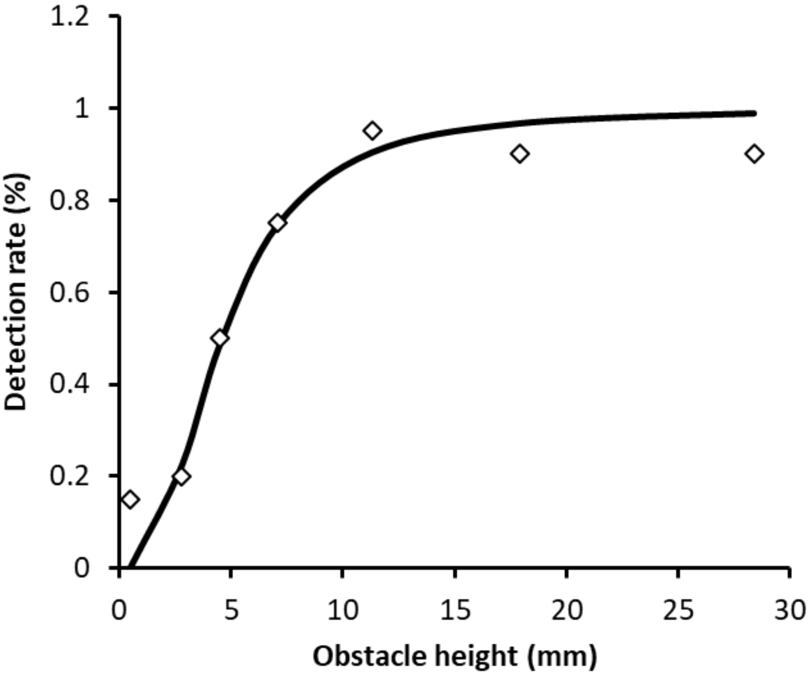

Figure 8. 8. Example of 4PLE best-fit curve for 2.0 lux and 1 cd/m² condition (experiment 1). Data points show the actual mean detection rate of the sample at each of the seven heights.

Figure 8.9 shows the height required for 50% detection probability (h^{50}) of all light combinations tested during the three experiments, as calculated by 4PLE. The smaller heights indicate better detection performance at each light condition. For validation, data for the emergent obstacle (the 28.4 mm obstacle) were plotted in dotted grey lines.

In experiment 1, the bicycle light did not result in better detection at lower illuminances. Switching off the bicycle light was better for detection at 2 lux and the addition of bicycle luminance did not improve detection at 20 lux. Overall, this pattern matches that of the emergent obstacle data, see Figure 8.3.

Trends in experiment 2 corroborated the previous analysis as the hub mounting position improved detection than the other two positions. One noticeable difference between h50 and the emergent obstacle data is the better performance of the helmet position at 2.0 lux in h50 data; other than this the trend lines in both approaches were almost similar. In experiment 3, bicycle light improved detection at 0.2 lux, confirming earlier findings based on the emergent obstacle data.

The reason the trend lines of the h50 data in Figure 8.9 were not identical to those of the emergent obstacle data was that each data set was established using a different method. For instance, the median height at detection moment was taken for the emergent obstacle (interval data) whereas the h50 data were established based on the mean detection of the obstacle at each of the seven heights (ordinal data). To predict the obstacle height needed for 50 % detection, the value was then computed using the 4PLE equation for each light condition. Despite this difference in approach, the trend lines for both data sets showed reasonable agreement across the three experiments, which suggests the data are robust.

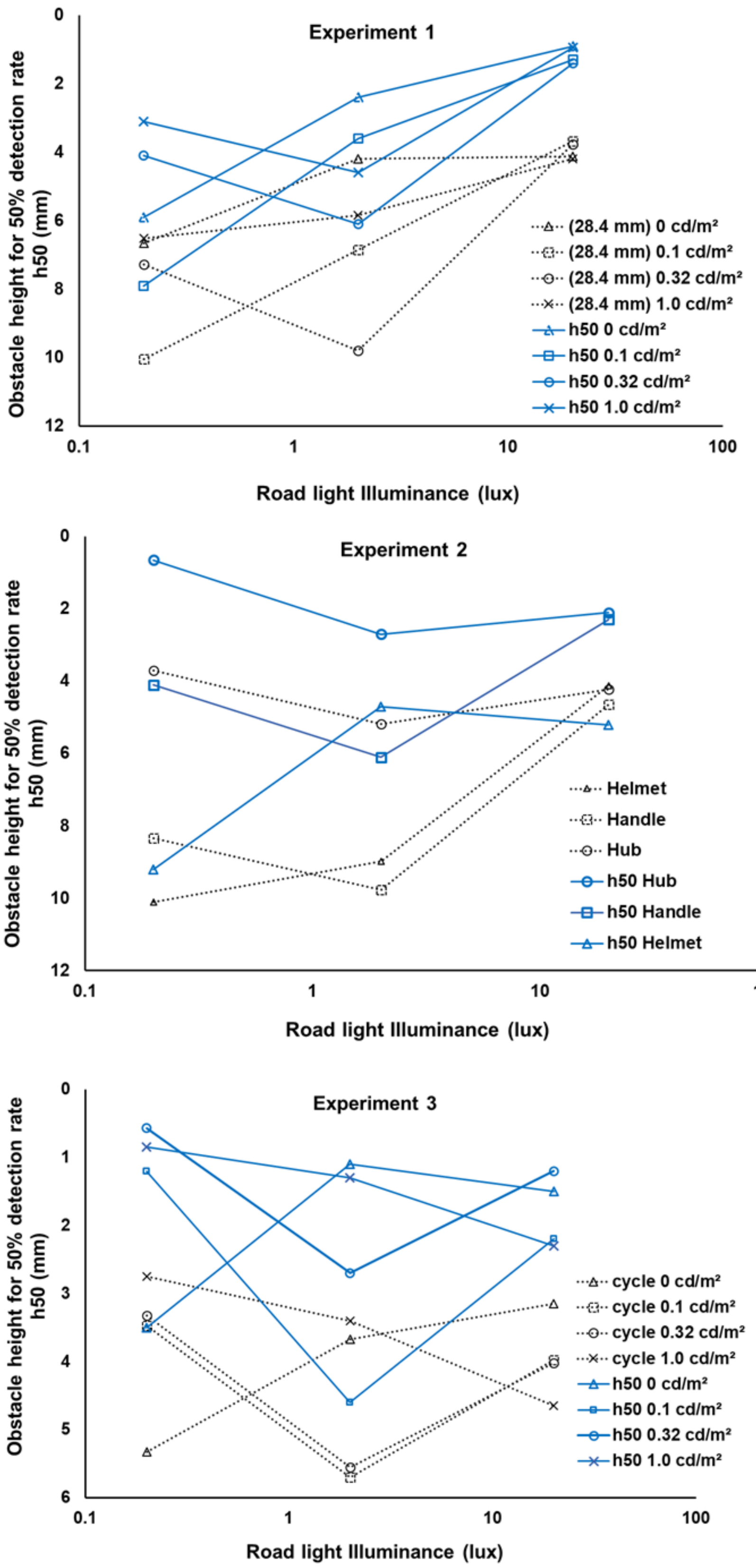

Figure 8. 9. Obstacle height needed for 50% detection rate is presented in blue curves. For comparison, the median of the detected height of the emergent obstacle is plotted in dotted grey lines.

8.8 Validation of Results

To provide a degree of validation, two conditions were compared: no-light trials, where tests were conducted without road and bicycle lighting (experiments 1 and 3), and 0.2 lux trials (the next lowest level, for comparability). This involved trials for all heights. The second null condition used is detection rate of the smallest obstacle height (0.5 mm). An almost zero detection rate is anticipated in both cases (no light and 0.5 mm height), whereas a high rate of detection would indicate false positives; for example, participants pressing the detection button randomly.

Table 8.16 presents the outcomes of these trials. Detection probability for the no-light trials was 0.07 over experiments 1 and 3, Furthermore, the 28.4mm obstacle (emergent obstacle) had to attain a height greater than 22mm to be identified. For comparison, Table 8.16 depicts outcomes of the trials with road lighting fixed to 0.2 lux (lowest road light level). In this instance, the detection rate increased to 0.6, the mean of experiments 1 and 3, while the median detection height of the emergent obstacle reduced to approximately 6 mm. The considerable variation in detection responses between the two conditions implies there was no tendency to give false alarm responses. However, the fact that, in a minimal number of trials, the obstacle in the no-light trials could be identified implies that some stray light was present; for instance, scattered light emanating from a projected fixation mark.

It was anticipated that the detection probability for the 0.5 mm obstacle height would be considerably lower than that for the higher obstacle heights. The 0.5 mm obstacle was identified on 135 occasions out of 840 in the three experiments. This represents an overall detection rate of 0.16. By comparison, the next smallest obstacle within this range (2.8 mm) yielded an overall detection rate of 0.51 across all three experiments. The 0.5 mm obstacle was identified on only a small number of occasions; this also implied there was no tendency for test participants to give false alarm responses.

Table 8. 16. Summary of results for the three experiments using validation conditions of light and obstacle height to check data robustness.

Experiment No.	**Light conditions validation**				**Smallest obstacle validation**	
	No-light trials		**0.2 lux trials**		**Detection rate [3]**	
	Detection rate[1]	**Detection height [2]**	**Detection rate**	**Detection height**	**0.5 mm obstacle**	**2.8 mm obstacle**
1	0.043 (6/140 trials)	25.1 mm (range 20.6 to 26.0 mm, n=4)	0.51 (71/140 trials)	6.65 mm (range 5.0 to 11.2 mm, n=16)	0.12 (37/300 trials)	0.36 (108/300 trials)
2	-	-	-	-	0.18 (44/240 trials)	0.45 (109/240 trials)
3	0.10 (14/140 trials)	22.3 mm (range 18.4 to 28.4 mm, n=8)	0.69 (97/140 trials)	5.32 mm (range 2.8 to 14.4 mm, n=20)	0.18 (54/300 trials)	0.69 (208/300 trials)

[1] Detection rate: proportion of the detection rate of trials across all seven obstacle heights for a particular light condition.

[2] Detection height: median detected height (range and number of detections) for the 28.4 mm obstacle (emergent obstacle).

[3] Detection rate for 0.5 mm and 2.8 mm obstacles: including trials of all light conditions and the two obstacle speeds, except for no-light trials in experiment 1 and 3.

To further validate the robustness of the three experiments, three pairs of identical conditions were compared, with each condition tested in a separate experiment – these were road light only conditions (experiments 1 and 3), handlebar position with the bicycle lamp at 0.32 cd/m^2 (experiments 1 and 2), and hub position with the bicycle lamp at 0.32 cd/m^2 (experiments 2 and 3). The results are shown in Figure 8.10. In each case, the results from the two separate experiments tended to exhibit the same pattern.

The Mann–Whitney test ($p < 0.05$) for independent samples did not indicate any significant differences between experiments for the identical conditions, see Table 8.17. This agreement between identical conditions demonstrates the robustness of the three experiments.

Table 8. 17. Mann-Whitney independent sample results ($p < 0.05$) for the three pairs of identical conditions across experiments.

Compared experiments	Compared condition	Mann-Whitney test ($p < 0.05$)
1 and 3	Road light only	p = 0.131,0.880 and 0.082 for 0.2 lux, 2 lux, and 20 lux, respectively.
1 and 2	Handlebar at 0.32 cd/m^2	p = 0.910, 0.870, and 0.520 for 0.2 lux, 2 lux, and 20 lux, respectively.
2 and 3	Hub at 0.32 cd/m^2	P = 0.364, 0.762, and 0.345 for 0.2 lux, 2 lux, and 20 lux, respectively

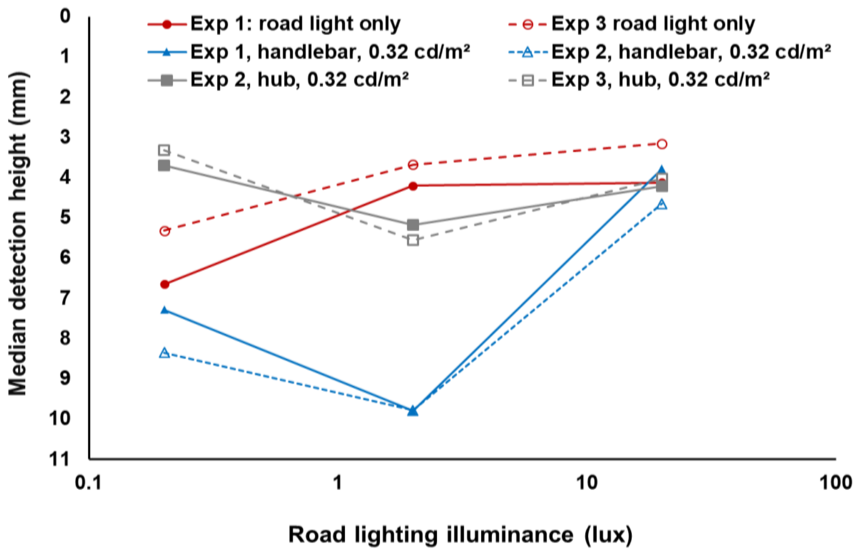

Figure 8. 10. The three paired identical conditions in the three experiments. The similarity between the trend lines suggests robustness.

8.9 Discussion

Previous research on lighting and detection performance (Eloholma et al., 2006; Alferdinck, 2006; Fotios & Cheal, 2013; Uttley et al., 2017) has mainly focused on sources projecting light downward on the horizontal plane, such as road lighting, and evaluated detection performance under varied light properties. Thus, limited investigations have been conducted on light sources perpendicular to the road surface, such as bicycle lighting. However, a few studies on driving had been performed to evaluate the influence of car headlamp on detection (e.g.Akashi et al., 2007). The effect of road lighting and bicycle lighting on detection performance, when used separately or simultaneously, is discussed in the following section.

8.9.1 Bicycle light intensity

In experiment 1, turning on the bicycle light did not aid detection; on the contrary, it reduced detection compared to when the bicycle light was switched off, particularly at 0.1 cd/m². Detection was also significantly reduced by all luminances at 2 lux road light (see Section 8.4.2 and Table 8.5).

The third experiment repeated the same light conditions tested in experiment 1 but with the bicycle light mounted on the hub instead of the handlebar, as the hub appeared to be the best position for detection in experiment 2.

At 2 lux, increasing the bicycle light to 1 cd/m² prevented the reduction in detection caused by 0.1 or 0.32 cd/m², although the performance was similar to that in the no bicycle light condition. At 20 lux, using bicycle light either did not improve detection at 0.1 and 0.32 cd/m² or significantly reduced it at 1 cd/m² (see Section 8.6.2).

Mounting the bicycle light on the hub (all luminances) has been demonstrated to aid obstacle detection only when the road light is turned off or at 0.2 lux.

8.9.2 Bicycle lamp mounting position

Experiment 2 only tested bicycle luminance at 0.32 cd/m² and showed that the hub mounting position was better for detection than the handlebar or helmet positions. Experiment 3 revealed that the advantageous performance of the hub position persists when bicycle luminance was altered from 0.32 (the only luminance used in experiment

2) to 0.1 or 1.0 cd/m². This was most notably the case when the road light was switched off or at 0.2 lux, see Figure 8.7.

To further assess the benefit of hub mounting position, data from experiments 1 and 3 (independent samples) were compared and plotted in Figure 8.11. The hub curve indicated better detection performance than the handlebar curve, particularly at 0.2 lux.

The results from the two experiments were compared using the Mann–Whitney test for independent samples. These suggested that the hub mounting position offered significantly better detection performance ($p < 0.001$) than the handlebar at 0.2 lux for all luminances. At 2 lux, only the 1 cd/m²-hub was significantly better than the same luminance value for the handlebar position ($p < 0.05$). No significant difference was found at 20 lux. These data reinforce the benefit of the hub light in low road light illuminance.

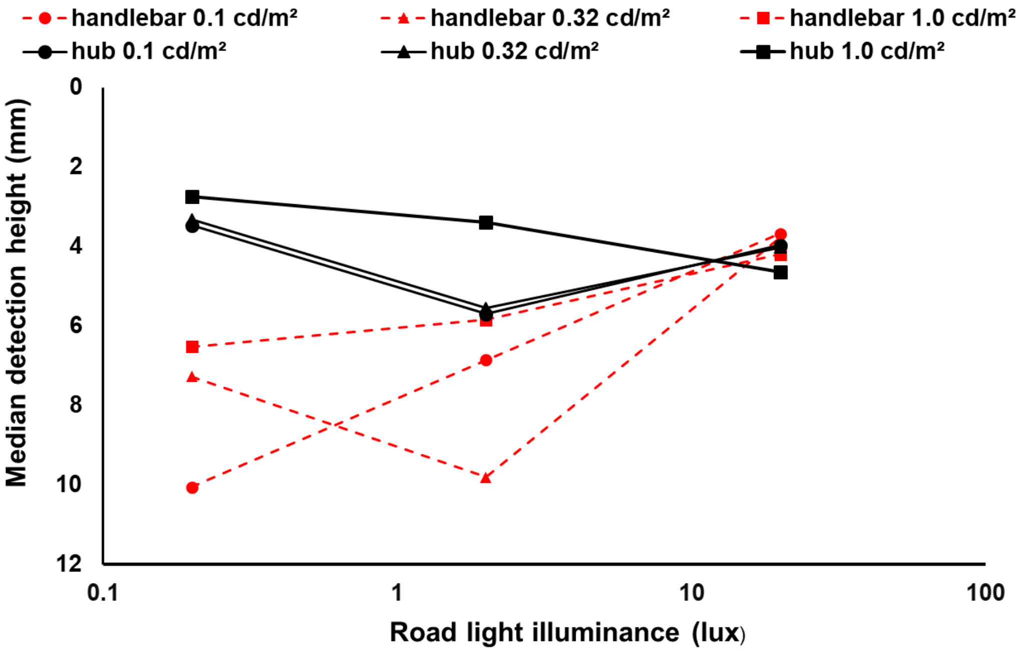

Figure 8. 11. Comparison of handlebar (experiment 1) and hub (experiment 3) for the emergent obstacle data using a combination of road and bicycle light.

Figure 8.12 presents the interquartile ranges found in experiment 2 for the handlebar and hub mounting positions. The Wilcoxon signed rank test ($p < 0.05$) showed that the hub position resulted in a significantly better performance than the handlebar position at 0.2 lux (p = 0.009), whereas the performance was not significant at 2 lux (p = 0.575) or 20 lux (p = 0.610), see Table 8.10.

Figure 8.13 shows all light conditions tested in the three experiments. When evaluating bicycle light mounting location and the detected height of the emergent obstacle, conditions in which road light and bicycle light were switched off were omitted. The helmet position was tested only in experiment 2, which explains why the shorter dotted lines in the figure for experiments 1 and 3 do not extend to the helmet mark. The trend lines demonstrate better performance of the hub compared to other positions.

To provide a clearer comparison, Figure 8.14 illustrates only light conditions where the bicycle light was set at 0.32 cd/m² and road light levels where bicycle light was found to be significantly useful for detection (0 and 0.2 lux).

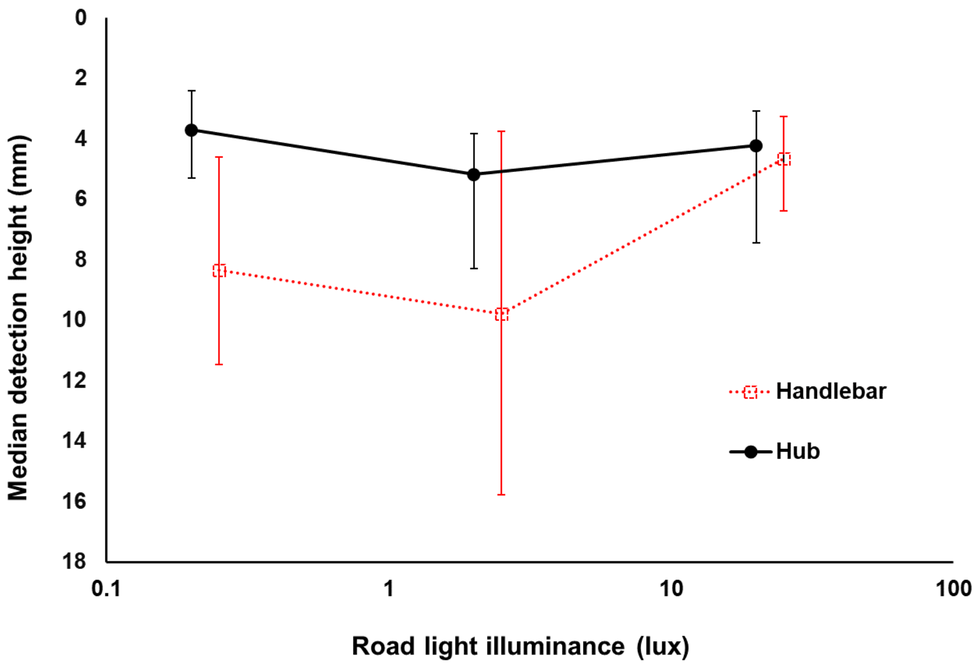

Figure 8. 12. The hub and handlebar positions (experiment 2) for median detection height of the emergent obstacle plotted against the illuminance levels (bicycle light = 0.32 cd/m²). The interquartile range is indicated by the error bars. Data of the handlebar were shifted an equal distance but in opposite directions, and only by enough to separate the vertical lines.

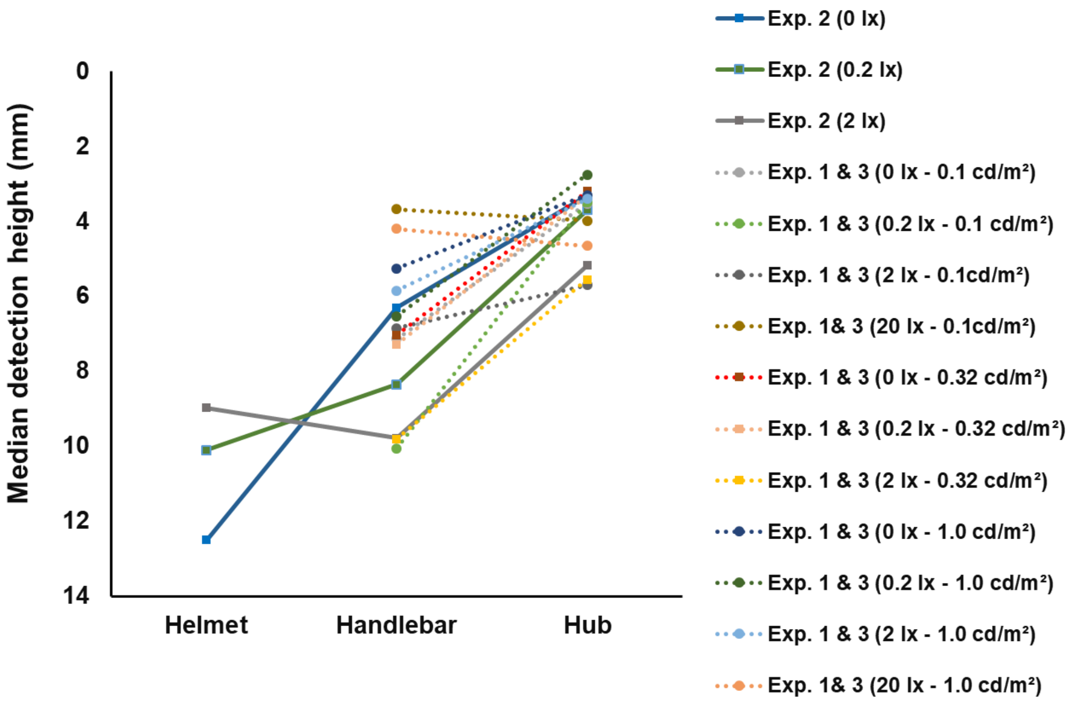

Figure 8. 13. All light combinations tested in the three experiments in regard to bicycle light mounting position, with lower detection height of the emergent obstacle indicating better performance.

In all these conditions, the hub mounting position significantly outperformed the handlebar and helmet positions. Furthermore, the handlebar position was significantly better than the helmet position; this indicates that mounting the bicycle light on the helmet is likely to result in low obstacle detection performance.

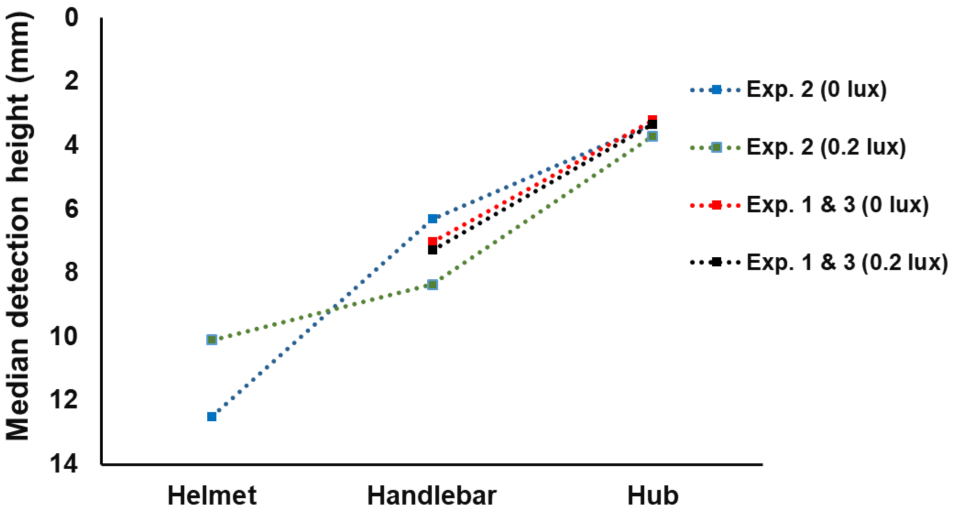

Figure 8. 14. Detection height of the emergent obstacle at lower road light levels and when bicycle light was set at 0.32 cd/m² with respect to the three mounting positions across the three experiments for comparability.

8.9.3 Contrast effect

In this experiment, the LED array (representing road lighting) illuminated the obstacle from above – creating relatively bright surfaces at the top and in the surrounding area compared with the side of the obstacle. Because the bicycle light was projected toward the obstacle from the side, the side of the obstacle was brighter than the surrounding horizontal surface provided the former had received a higher light intensity.

When the relative intensities of the road and bicycle light were changed, the relative contrast of the obstacle against the background (side versus surround) was also altered – exhibiting a larger contrast when either road or bicycle lighting were dominant and a smaller contrast (reduced detection) when they presented a luminance of similar magnitude (see Appendix E for detailed contrast calculations for the three experiments).

This is illustrated in Figure 8.15, where detection height was plotted against obstacle contrast. Contrast was defined using Equation 8.2 which calculates the light contrast between the side of the obstacle and the surrounding area.

Luminance was measured from the participant's observation point, with obstacle luminance measured on the raised side of the obstacle and surround luminance measured from the surface floor immediately in front of the obstacle.

$$Contrast = (Lo - Ls) / Ls$$

Equation 8. 2.

Where Lo = obstacle side luminance and Ls = surround luminance.

The relationship between detection height and contrast was explained using the approximate results of a second order polynomial equation – with R^2 values of 0.52, 0.40, and 0.42 for experiments 1, 2, and 3, respectively.

These trend lines depict the expected relationship between detection height and obstacle contrast and indicated better detection performance at higher contrast.

In Figure 8.15, a negative contrast implies that the surround was brighter than the side of the obstacle and vice-versa for positive contrast. For a given magnitude of absolute contrast, a negative contrast value permitted the detection of smaller obstacles. For instance, the results from experiment 1 showed that a contrast of 0.25 required a detection height of 7 mm, whereas the required detection height reduced to approximately 5.5mm with a contrast of -0.25, indicating an improvement in detection performance.

This suggests that having a bright surround (obstacle seen in silhouette) is better than a bright obstacle, thus road lighting is more effective than bicycle lighting.

The trend line in experiment 3 illustrates the superior detection performance of the hub mounting position compared to the handlebar (experiment 1).

The possible effect of shadows on obstacle detection should also be noted. Mounting the bicycle light at different positions (i.e., varying vertical heights) affected the length of the shadow cast by the obstacle on its back surround, which was larger for the hub-mounted lamp (approximately 150 mm from the far edge of the obstacle to the tip of the shadow) and smaller for the helmet-mounted lamp (approximately 40mm) and handlebar (100 mm), as shown in Figure 7.8 and Table 7.2.

This may provide an alternative explanation as to why the hub mounting position resulted in better detection than the handlebar and helmet positions.

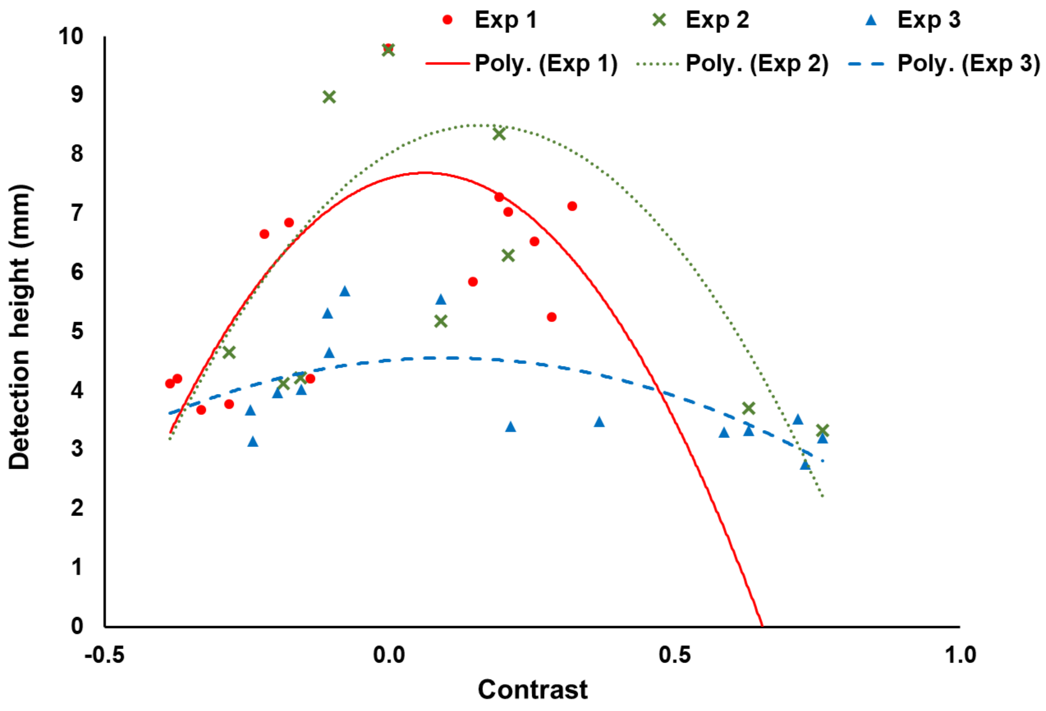

Figure 8. 15. Contrast value plotted against detected height of the emergent obstacle for the three experiments.

8.9.4 Road light level and detection

Experiments 1 and 3 showed that, following an increase in road light levels, detection performance increased when the bicycle light was switched off. However, this performance reached a plateau at 2 lux, beyond this level no significant improvement was found. This plateau effect has also been observed in previous studies (Eloholma et al., 2006; Alferdinck, 2006; Fotios & Cheal, 2013; Uttley et al., 2017).

Figure 8.15 depicts the similarity in performance between the current study and earlier studies (Fotios & Cheal, 2013; Uttley et al., 2017) that used illuminance to measure the effect of light intensity on obstacle detection.

The comparison was established using normalised performance values (NPVs), where an estimation for the individual study was calculated and plotted against different levels of road light illuminance, as shown in Figure 8.16. The NPV at each Illuminance was quantified as the ratio of the difference between the value of the performance measure (e.g., h50, reaction time, etc.) for a specific illuminance and the worst performance measure across all illuminances, and the general difference between the best and worst performance across all illuminances:

$$NPVi = \frac{|Pi - Pw|}{Pb - Pw}$$

Equation 8. 3.

Where, for a particular luminance of i, NPVi = Normalised Performance Value; Pi = Performance at illuminance I; Pw = Worst performance across all illuminances tested, and Pb = Best performance across all illuminances tested.

For example, to measure detection performance under varied illuminances, Fotios and Cheal (2013) used the height needed for 50% detection probability (h50). The best performance was 0.92 mm at 20 lux. The worst performance was 2.80 mm at 0.2 lux. The difference between the best and worst performances was therefore 1.88 mm. If a particular illuminance yielded a performance of 1.80 mm, the difference between this and the worst performance would be 1.00 mm. Thus, the NPV would be 1/1.88 = 0.53.

Based on that, the worst performance is continuously NPV= 0, in the other hand the best performance NPV = 1, constantly.

One benefit of counting NPV for multiple studies is it enables a comparison between those studies irrespective of the sort of data used in each and determines the relationship between light level and performance.

The NPVs for all three studies, including the current experiment, are demonstrated in Figure 8.16. The pattern exhibits a considerable consistency in respect to the relationship between illuminance level and detection performance, demonstrating the plateau found at 2 lux.

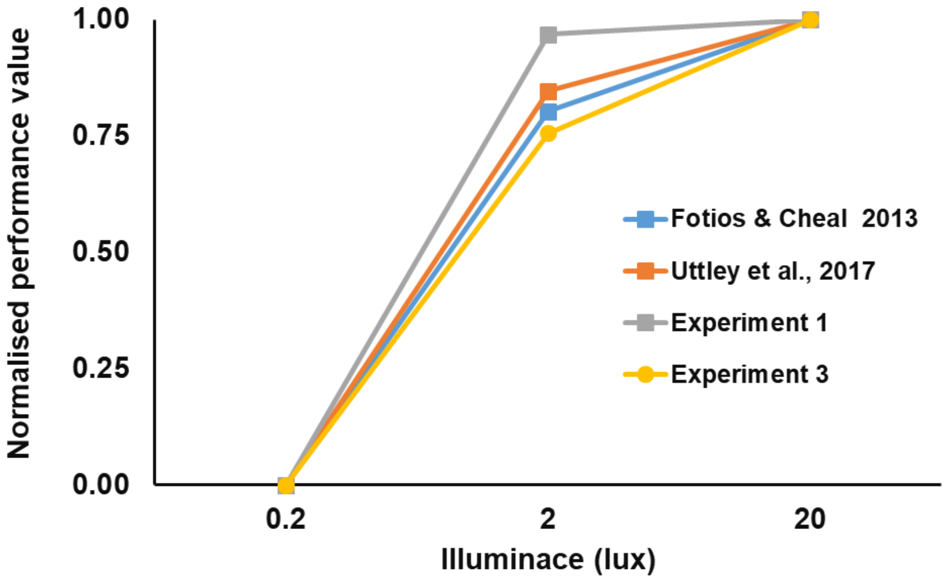

Figure 8. 16. Normalised performance values by illuminance for Fotios & Cheal (2013), Uttley et al. (2017), and the current study.

However, other studies that examined detection under variations of light intensity have not identified a performance plateau (e.g.Bullough and Rea, 2000; He et al., 1997; Lingard and Rea, 2002).

The current study showed that an increase in road light level improved detection performance when the bicycle light was switched off. However, an increase in road light beyond 2 lux did not significantly improve detection.

8.10 Summary

This study explored how cyclists identify an obstacle on the road surface using their peripheral vision; and investigated the impact on such detection of varying the levels of light from bicycle and road lighting. The height at which a rising obstacle was detected constituted the main dataset that was analysed.

The outcomes indicate that, when cycling on a lit road, bicycle lighting often confers no advantage for peripheral detection and may even aggravate the situation. Furthermore, the position of the light did not have any significant effect. However, a hub mounted bicycle lamp improved detection over a handlebar mounted lamp at low illuminances. This advantage was enough to offset the reduction in detection that was found when reducing road lighting from 2.0 lux to 0.2 lux.

Chapter 9. Summary, implications and limitations

9.1 Introduction

Previous chapters of the thesis presented the research conducted on cycling and road lighting. The main aim of this research was to discriminate the key visual tasks undertaken by cyclists then to explore how certain properties of lighting influence one task in particular which was identified to be critical for cyclists by eye-tracking main experiment (Chapters 4 and 5), that is obstacle detection (Chapters 7 and 8). Further, the effects of ambient light on both the decision to cycle and the perception of aesthetic visual items of urban environment (architectural features) were also investigated, however the latter two studies were an explorative observation and a post hoc analysis to the main eye-tracking data, thus their findings should be taken by indicative sense.

This chapter starts with a summary of this research. Each of the four studies conducted in this thesis will then be discussed in details with the approach followed in this research, along with the implications for current road lighting guidelines for cyclists and the limitations of each study.

9.2 Summary of the thesis

Chapter 1 provided an overall background regarding the benefits of increasing the size of the cycling population and highlighted the fact that, in the UK, this population remains below the rate of similar developed countries. The high rate of casualties and fatalities among cyclists in the UK was suggested to be the main reason why the public are reluctant to take up cycling.

Lighting was proposed as a means to overcome several safety challenges facing cyclists on the roads (particularly traffic safety), the main focus followed for promoting cycling in this thesis as it was elaborated on earlier in Chapters one and two, and thus the current road lighting guidelines for cycling were reviewed. This highlighted the need for additional empirical evidence to either support current lighting specifications or establish new ones.

The chapter also highlighted another path believed to be influential in promoting cycling, namely improving the quality of the cycling experience, the secondary focus in this thesis to promote cycling. The chapter therefore showed that it is essential to understand the visual behaviour of cyclists under varying levels of ambient light within different urban contexts.

Chapter 2 reviewed existing studies that utilised eye-tracking methodology and highlighted a limitation in that there was often no information on whether participants were cognitively engaged with the visual objects at which they were looking. Another limitation that was noted was the lack of naturalistic eye-tracking research on cycling.

The literature also discusses other important dimensions of lighting and cycling, one of which is the relationship between ambient light and the decision to cycle. Another dimension covered by the literature is that previous studies established a correlation between aesthetic elements and an increased level of cycling while other studies investigated the effect of aesthetic features of the environment, including architectural features, on participants' quality of life. However, the effect of ambient light levels on the perception of such features, especially when cycling on different types of cycle paths, has rarely been investigated.

The final section of the literature review focused on studies that explained the effect of specific lighting properties on detection performance. This helped establish what aspects of lighting could be investigated to improve current road lighting guidelines for cyclists.

Chapter 3 reported the findings of a study conducted in Sheffield that used a seasonal daylight-saving hours event in UK to investigate the effect of ambient light on the number of people cycling where a positive correlation was found between an increased ambient light level and the tendency to cycle.

Chapter 4 then reported the methodology used in the main eye-tracking experiment, which was conducted in a natural setting using two parallel measurements: dual task and skin conductance response, with literature provided for these two approaches and their eligibility to be used to reveal critical eye movements (fixations). These were used to reveal points during the experiment where the participant either gave a significant attentional reaction (dual task) or a significant physiological reaction (SCR).

The results of the eye-tracking experiment were then reported in chapter 5, where observing the path was found to be the most significant visual task performed by cyclists. This finding was confirmed by both dual and SCR fixations. This will accommodate cyclists' tendency to search for obstacles on the roads (Schepers and den Brinker, 2011; Thompson and Rivara, 2001; Werneke et al., 2015).

This obstacle detection task was then explored in the obstacle detection experiment reported in chapters 7 (method) and 8 (results and discussion). But prior to this, chapter 6 presented a post hoc analysis on part of the main eye-tracking experiment data to evaluate first cyclists' perceptions of elements not considered to be related to the safety aspects of cycling then perception of specific aesthetic element (architectural features), where the increased observation of such items was deemed to indicate a positive cycling experience. The findings demonstrated that when the ambient light level is high (daylight) there are increased observation towards non-safety elements of the urban environment, including architectural features. This was also the case when cycling on a pedestrianised cycle path compared to the on-road path.

Chapter 7 reported the method of the obstacle detection experiment. This was a simulation of a real world situation where an obstacle is approached by a cyclist. The light characteristics studied were road light intensity, bicycle light intensity, and the effect of the mounting position of the bicycle lamp.

The results of the experiment were presented in chapter 8. These showed that obstacle detection is better when there is a degree of road lighting than when there is none at all. This was the case up to a plateau of 2 lux and when bicycle light was switched off. In relation to bicycle lighting when used simultaneously with road lighting, detection only improved at the highest level of road light (20 lux). This indicates that, at this level, road lighting is more dominant than bicycle lighting. However, at lower levels of light (0.2, 2.0 lux), turning on the bicycle light either reduced detection or had no effect at. The only time this was not the case was when the bicycle lamp was mounted on the hub and the level of road lighting was set to 0.2 lux. The influence of the combined use of road lighting and bicycle lighting on detection performance, a gap in the existing research, had therefore been addressed.

The current chapter provides further discussion of the findings of the four studies, including the implications for current road lighting guidelines accompanied by the limitations of each study. Chapter 10 will present the conclusions for this thesis and potential areas of future research along with recommendations to cyclists and the policymakers.

9.3 Approach of current research

Establishing evidence that informs about the influence of light properties on cyclists' visual behaviour is a task not without complications (Chapter 2: Section 2.2).

One approach in this quest would be using subjective assessments e.g. rating questions, interviews, etc. where concerns related to the possibility of collecting biased responses from participants thus inaccurate conclusions were raised (Poulton, 1977, 1982). Another concern in this light is whether participants are forced to respond to a phenomenon that they usually unaware of initially (Fotios et al., 2015a). Finally, less than credible or reliable design of surveys could lead to collecting inaccurate responses (Toomingas et al., 1997).

Having said that, subjective assessments including questionnaires and rating scales, for example, when accurately fit the context of the study and sensibly designed are indeed a credible instrument to collect data and understandably a valid research method.

Subjective assessments were used by a number of studies investigating the effect of illuminance levels on pedestrians' reassurance (feeling safe in a location under specific illuminance level) (e.g.Boomsma and Steg, 2014; Loewen et al., 1993; Rea et al., 2015). For example, Fotios et al. (2018) have implemented a rating scale method to compare between pedestrians' reassurance levels in 10 locations in an urban environment by asking participants to complete almost the same questionnaire one time during the daytime and another during the after dark. This method, to a good extent, isolates road lighting factor from other existing variables which might have affected the rating if the questionnaire only conducted during after dark. In such an instance, there will be no baseline point (daylight) to establish the effectiveness of road lighting.

Having said that, another concern of subjective assessments is the gap between the stated behaviour and the actual behaviour. Keskin (2019) conducted a study to assess the effect of daylight on seating preferences in a University library. The study consists of two parts, first, the author asked the sample to respond to a survey questionnaire wherein the second part observed participants' seat preference from a distant. Although the results suggested the influence of daylight on seating choice the effect between the survey and the distant observation was not identical illustrating a difference between what the respondents say and their actual behaviour.

In subjective surveys, participants' responses are restricted by the range of answers available in the survey and the way these are designed and structured, this is referred to as range bias (Poulton, 1977).

Consequently, and based on these concerns a decision had been made to follow an approach where participants have minimum influence on the collected data. That is to say, the aim was to capture the involuntary responses of participants. This was the base the four studies conducted in the current thesis sought to follow as it was considered more appropriate to understand such a complex phenomenon i.e. the relationship between lighting and cyclists' visual behaviour.

9.4 Statistical considerations

Applying several statistical comparisons implies that the P-value should be adjusted (corrected), to reduce the probability of type 1 error (false positives), however, such adjustment could escalate the probability of type 2 error (false negatives) (Field, 2013). In this light, Rothman (1990) explained that such adjustments are not critical since it could eliminate important findings, he advanced that the essence of empirical research is studying systematic rules of nature rather than coincidental numbers, in other words, understanding the pattern of the phenomena rather than restrict the findings to statistical results.

Some studies stated that P-values must be utilised to interpret the results, and should not be taken strictly for granted, as conducting statistical tests can mitigate an existing effect through the test processes (Nuzzo, 2014).

In assessing the results, it is essential to be mindful of the conditions and the settings in which this experiment was conducted. Specifically, this study investigated a considerably inconstant behavioural form e.g. the eye movement in eye-tracking study. In this sense, conducting experiments involve the assessment of naturalistic human behaviour and not necessarily pure statistical calculations.

The relatively high degree of variations in this type of research is symbolised by the wide interquartile range of dual and SCR fixations across the target categories.

The fluctuation observed in both fixation types suggests that the results of P-values should be understood together with other criteria available in the data such as patterns of target categories and bionomic cogency. Resultantly, the absence of a significant difference between after dark and day trials in SCR fixation data, for example, toward path category should be considered carefully to prevent overriding a real pattern that may exist between light conditions, specifically the result was near significant (Wilcoxon, p=0.050). Observing the path after dark is a logical manner as it could be harder to notice surface hazards while cycling.

The same statistical approach was kept in the obstacle detection experiment (Chapters 7 and 8) and the post hoc study (Chapter 6) where no corrections to the p-value were carried.

9.5 Implications and limitations

The implications from the thesis four studies to the current road lighting guidelines are presented in this section along with the strengths and limitations of each study.

9.5.1 Ambient light and cyclist frequencies

The field study reported in chapter 3, which investigated the influence of ambient light level on the desire to cycle, found there was a higher number of cyclists during daylight hours than after dark. This aligns with earlier findings from studies based on data from the USA (Fotios et al., 2017b; Uttley and Fotios, 2017). Thus, there is a correlation between the tendency to cycle and increased outdoor light levels. The field study, therefore, showed that light levels, daylight levels compared to after dark, could matter for the decision to cycle or not.

The study strength emerges from its ability to isolate the effect of ambient light levels on the cycling frequencies. This is done by comparing cyclists' numbers during a specific hour of the day in a week before the daylight saving event where this hour will be in dark then to compare cyclists' numbers in the same hour of the day in a week after the DST in daylight condition). By doing so, other factors that might affect cyclist numbers were isolated e.g. commuting routine, daily activities during this hour of the day, etc. This method had been applied previously in traffic collision context (Sullivan and Flannagan, 2002) when an effect of ambient light levels was found.

Having said that, other variables such as the weather or temperature may still have an influence over cyclists' numbers at the observation location. The use of control hours where light condition remained the same during the before and after weeks was used along with the data of main case hours to calculate the odds ratio and the confidence interval, both used to count the effect of such variables and by that provide robustness to the results (See sections 2.2, 3.2, 3.3 and equations 2.1, 3.1).

Table 3.2 compares the results of the current study with findings from (Fotios et al., 2017b; Uttley and Fotios, 2017) all found more cycling rates during daylight time than after dark.

This pilot study is not without limitations. For example, only an hour during the evening time was observed and whether a different trend would be found should a morning hour was included in the analysis is not known.

The small number of observation locations used, only two, could be considered a limitation as it might not represent the cycling behaviour of the entire city. Another concern is that the observations had only occurred in the weeks before and after the spring clock change (daylight saving time) thus result could be affected should the autumn DST event was included or if the data of the whole year were used instead (e.g. Fotios et al., 2017b); or when using data of 5 consequential years (Uttley and Fotios, 2017).

The study also could have used other methods than the observation to validate the findings. For example, Robbins and Fotios (2020) assessed the elements causing distractions to car drivers by using a dual method: interviews and real world observations. Using interviews in the current study would have provided more insights about the reasons people have chosen to cycle during the observation hour e.g. commuting, leisure, sport, etc. Thus further explaining the motive behind cycling.

9.5.2 Main eye-tracking study

Considering the time resource available to collect the data together with the fact a single trial consumes a long time (approximately 2 hrs from start to finish), both factors may demotivate some individuals from participating, thus recruitment strategy was to find a large number of participants as promptly as possible. This is to recruit any suitable individual who can use the bicycle effectively to complete the two laps on the experiment route.

This resulted in 22 participants (a total of 44 recorded trials) each participant completed two trials (day and after dark), however after inspecting the quality of the recordings (see Section 5.2, Figure 5.1 and Table 5.1) the experiment sample was reduced to 12 participants (a total of 24 trials). The result was a generic sample of cyclists where going further in the analysis to assess some previously suggested effects such as gender (Heinen et al, 2011) experience (Boya et al, 2017) and/or age (Boyce, 2014; Underwood et al., 2005) on the visual behaviour of cyclists was not viable due to lacking the suitable number of participants in each of these variables for the comparison to be meaningful.

The sample of 12 participants with a repeated-measures design allowed for an effect size of Cohen's D= 0.79 or larger to be detected using a Wilcoxon signed-rank test (matched pairs), assuming a power of 0.8 and an alpha of 0.05. This effect size is between the 'Medium' and 'Large' thresholds, which is defined by Cohen (1992) as acceptable. This was calculated using G*power software which is a tool to calculate the effect size of the study sample (Faul et al., 2007).

Both dual and SCR fixations were used to identify critical moments during trials. Similar patterns were exhibited by both fixations across eight target categories. However, amongst these categories, the path elicited higher dual and SCR fixations rates than the other seven target categories and was therefore suggested the most critical visual target for cyclists.

The reason for this might be that cyclists are keen to avoid obstacles or other irregularities in the road to prevent themselves from swerving into the path of an oncoming vehicle or falling on the road, obstacle detection was suggested vital by previous research (e.g.Schepers and den Brinker, 2011; Thompson and Rivara, 2001;

Werneke et al., 2015). This visual task was therefore investigated further, see Section 9.5.6.

This finding implies road lighting for cyclists should prioritise obstacle detection task when specifying lighting standards for cycling.

Having said that, both of the dual task and SCR approach should be viewed as intermediate measures of cognitive engagement with a significant visual event. It is likely that critical events recorded by these approaches result from influences other than important visual events/items. For example, acoustic distractors (SanMiguel et al., 2010) could divert participants' attention away from responding to the dual task; equally, they could stimulate SCRs not explicitly linked to the visual event.

Another source of noise in the data could arise from episodes of mind wandering during the trials, specifically affecting performance on the dual task. These are periods when the participant engages in internal thoughts (Smallwood et al., 2008).

The use of the SCR approach was therefore an attempt to overcome this limitation in attention performance that is correlated more to the dual task method as, in theory, SCR should be less affected by mind wandering as it is a physiological response that can be triggered subconsciously (Williams et al., 2004).

Another positive advantage SCR has over the dual task is that it is a continuous measurement that is not interrupted by non-stimulus periods, whereas in the dual task method audio beeps are produced at varying time intervals (see Chapter 4: Section 4.8). However, the SCR approach is not without its own limitations (see sections 9.5.3 and 9.5.4 for a further discussion of the limitations of both dual task and SCR approaches, respectively).

Previously, Section 2.4.2 discussed the advantages naturalistic studies have over the laboratory in providing more representative data of the real world. Nevertheless, extremely uncontrolled settings make internal validation in this type of research sort of a challenge.

In their eye-tracking study on pedestrians' visual behaviour within the urban environment, Fotios et al. (2015b) conducted post-trial interviews with the participants to further assess their eye movements, the data from the interviews were used to aid the understanding of fixations location thus not exactly to validate the data. Having said that, the post interviews could have been an option for internal validation in the current study, should more time resource was available. This is a limitation that should be improved in further research.

Another possible approach for internal validation would be asking the same participant to do the 24 trials. A problem in doing so is that the participant will become familiar with the experiment route thus providing unrealistic data. In a walking environment, Jovancevic-Misic and Hayhoe (2009) asked participants to walk 12 laps while other pedestrians were instructed to approach the main participants in different scenarios replicating real-life situations to study pedestrian visual strategy at such scenarios. They concluded that when participants learn the appearance probability of other pedestrians' their visual behaviour adapts accordingly hence data will not reflect real visual behaviour.

For external validation, Figure 5.15 in Chapter 5 provides the percentage of dual and SCR fixations of the current study toward the path category with the percentage of fixations toward this target category in two similar studies (Mantuano et al. 2017; Vansteenkiste et al.,2014a). This illustrated that the results of the current study fall within the ranges of previous studies.

9.5.3 Limitation of the dual task approach

In the dual task method, the reaction time to the audio stimulus was used to identify critical moments, the number of which varied considerably between participants. This demonstrates the lack of uniformity in participants' reaction to different visual stimuli or, more precisely their attentional capacity.

Such variation may arise for different reasons, one of which is participants' familiarity with the urban context of the study. Greater familiarity with a location will make a cyclist feel less inclined to shift his/her attention towards elements in the surrounding area, even though such elements may be visually critical. This is because these elements may have already been assessed during past experience travelling in this particular location. Thus, a participant familiar with the location will be less likely to divert his/her attention than another participant cycling through the location for the first time.

Jovancevic-Misic and Hayhoe (2009) argued that visual behaviour is influenced by the predictability of a context. Their research findings suggest that previous experience regarding the behaviour of other pedestrians in a given context will influence the length of time over which they are observed.

Another explanation for the differing rates of critical reaction moments between participants is the variation in a participant's capability to concentrate on one task, which denotes a capacity to respond to the audio beep while simultaneously remaining attentive to a potential visual element. This justification agrees with the findings of Fukuda and Vogel (2009) who identified variations in attentional capacity between participants exposed to the same stimulus in the surrounding environment.

In the eye-tracking experiment, the dual task method was implemented to determine significant moments by identifying responses to the secondary audio task (dual task) that were significantly slower than the overall response mean. The threshold at which this was defined was 2 standard deviations above the mean reaction time. The 2 standard deviations threshold was reported to be representative of 'outlying' values (Field, 2013); however, such a level may be fairly arbitrary. For instance, it may have been the case that responses exceeding this threshold were not caused by attention being diverted away from the reaction task e.g. participant simply forgot to response. Conversely, a diverting attention may have yielded responses less than 2 standard deviations above the mean. Although the threshold of 2 standard deviations has been used in other studies employing a dual task approach (Fotios et al., 2015b; Fotios et al., 2015c), its use therefore requires further explanation with reference to the pilot study (see Appendix A) where a threshold of 2 standard deviations was found acceptable.

The pilot study was carried to evaluate the appropriateness of the dual task and SCR approach for the eye-tracking experiment. The three tests reported in the study employed different types of stimuli (distracting images, short video clips, and full video) and were compared against periods where no stimulus was presented. For the images test, the non-stimulus mean reaction time (MRT) to the audio stimulus was 506 ms with a standard deviation of 54 ms. The MRT for the stimulus period was 555 ms, almost one standard deviation higher than the MRT for the non-stimulus period. For the video clips test, the non-stimulus MRT was 509 ms (standard deviation = 63 ms) whereas the MRT for stimulus periods was 663 ms, 2.5 times the standard deviation of the MRT for the non-stimulus period. The final test was a long video that contained salient events (stimulus) where the MRT during the non-stimulus period was 518 (standard deviation = 62 ms) and the MRT for the stimulus period was 627 ms, 1.8 times the standard deviation of the MRT for the non-stimulus period.

Table 9.1 presents the difference in MRT between non-stimulus and stimulus periods in terms of standard deviations.

Table 9. 1. The approximate number of standard deviations (non-stimulus period) embedded in the difference with the MRT of stimulus period in ms (the pilot study-Appendix A).

Test	**MRT** [1] non-stimulus period	**STD** [2] non-stimulus period	**MRT** stimulus period	**MRTs difference (ms) = MRT (stimulus) – MRT (non-stimulus)**	**How many STD (non-stimulus) could be incorporated in the MRTs difference?** [3]
Images	506	54	555	49	Approx. 1
Video clips	509	63	663	154	2.5
Full video	518	62	627	109	1.8

[1] MRT = mean reaction time.
[2] STD = standard deviation.
[3] This column represents the standard deviation(s) (non-stimulus period) that could be embedded in the difference of MRT (non-stimulus) – MRT (stimulus).

Based on these results, the difference between the MRTs for stimulus and non-stimulus periods could therefore be a function of the type of test, specifically the level of distractions presented. One objective of this analysis was to define a critical moment; however, using a threshold that is only 1 STD over the mean bears the risk of including a larger number of non-significant reactions in the data. Conversely, using a threshold of 3 STDs more than the mean may exclude many relevant reactions. Therefore, based on the results of the pilot study and previous studies that have implemented a dual task approach (Fotios et al., 2015b; Fotios et al., 2015c), two standard deviations threshold was proposed as a reasonable threshold at which to discriminate critical reaction times in the main eye-tracking experiment, hence critical fixations.

Having identified critical moments, critical fixations were then based on judgements as to the most important category of element within a 2-second window (one second before and after the critical response). This window was an arbitrary length of time in which to identify what had diverted participants' attention; it was based at least partly on the time period between beeps on the dual task. An appropriate window was considered to be a 1-second period prior and afterward the impaired reaction. Nevertheless, the possibility exists that the poor response may have been caused by something that happened a second or more before the button was pressed. However, this would probably have been taken by the response on the beep before it and thus would have been considered as a critical fixation. Conversely, it seems improbable that participants would have directed their gaze to whatever diverted their attention a second or more after an impaired response was registered. If a visual phenomenon attracts our attention, we will divert gaze towards it.

Researchers have found that latencies between the direction of our attention and our gaze are usually lower than 500 ms (Posner, 1980; Shulman et al., 1979). Thus, it does not seem likely that a person would take longer than a second to direct their gaze towards a visual stimulus that captured their attention.

A delayed response to the auditory beep in the eye-tracker experiment was attributed to attention being diverted away from the response task. It was always assumed that this had to be visual in nature, as to determine a critical observation every critical moment was included. It is possible, however, that attention was directed towards a non-visual stimulus, such as sounds or internal thoughts. Another possibility is that the reason for redirecting attention was visual but that this had no bearing on cycling safely.

The principal task of the main eye-tracking experiment was to therefore observe and identify objects or areas that enabled safer cycling. The dual task method, however, does not target visual behaviour where attention is diverted in response to events that have no bearing on safe cycling, such as nearby sporting events or social events. Yet it is by no means easy to distinguish ‘task-irrelevant’ critical moments from those that are of interest. This is therefore a limitation of the dual task method and indeed of the SCR approach that has to be accepted, having said that the method used in the study allows for categorising where the participant was looking during such critical moments and this should explain, even partially, whether a critical moment was relevant or not to the study focus. Nevertheless, the dual task and SCR approaches are an improvement over the traditional approach of previous eye-tracking studies of using all fixations only.

Categorising the critical observation within a 2-second window requires a subjective judgement on the part of the person devising the code whilst watching the videos. Because the average length of a fixation is approximately 330 ms (Henderson, 2003), multiple fixations are likely to have taken place during this period. It may have been the case that all fixations during the window interval were directed towards the same feature, which would mean that no decision needed to be made by the coder. Conversely, there may have been fixations on several items / areas, in which case the coder would have had to make a judgment as to which was the most important and therefore probably responsible for diverting the cyclist’s attention.

The higher level of agreement between coders when using the three categories proposed by Foulsham et al. (2011) appears to have reduced the subjectivity of the judgements made when categorising critical observations of the path.

As discussed previously, an inherent limitation of eye-tracking field experiments seeking to ascertain what is visually important to cyclists is that the extent to which different elements are present may affect the frequency with which they are observed. If a specific target category, such as cars has zero appearance during the course of a trial, the fact that it can never be observed does not mean that it is of no importance to cyclists. Similarly, an item may have been looked at multiple times purely because it frequently falls within the participant’s field of vision, irrespective of its perceived importance to the cyclist. Focusing solely on critical observations therefore addresses this limitation by measuring only what cyclists look at during critical moments.

These moments, identified using the dual task approach, have been shown to be a reliable way to account for the changes in frequency with which participants come into contact with different items during the trials (see Chapter 4, Figure 4.1), the same efficiency is assumed in the SCR approach as it enables critical physiological moments to be used for identifying critical fixations, thus mitigating the items appearance/frequency effect as well.

Nevertheless, the data obtained may continue to be influenced by the frequency with which various items are encountered. The method may not be able to account for variations in the frequency of other categories, which may have an effect on critical observations data if the values are extreme; for example, near to zero or an exceptionally high number of encounters. This is one of the negative features of a field experiment where stimuli cannot be rigidly controlled and may have a subsequent influence on visual behaviour.

9.5.4 Limitation of SCR approach

The second method implemented to identify significant moments in the study was the SCR approach, where the number of SCRs produced in a trial depend on the unique electrodermal activity of each person and the level of physical activity during the study is denoted as individual arousal level. SCR is the result of complex neural/biological processes that exhibit different electrodermal characteristics such as amplitude level. The number of SCR responses produced by different individuals within a sample therefore vary under the same stimuli and conditions (Braithwaite et al., 2013).

Even in highly controlled studies, SCR is unique owing to individual differences in the sweat-gland activity of the skin and divergences in the cognitive processing of information sent from the sympathetic nervous system. In fact, some people do not produce SCR at all or may do so at an exceptionally marginal level (Dawson et al., 2007). Nonetheless, all participants in the current study were SCR responsive as confirmed by their physiological records. Consequently, individual arousal level was proposed to have an influence on SCR fixations, thus affecting its agreement or disagreement with dual fixations.

Another factor that may affect SCR data is the chosen amplitude threshold level (see Section 4.7.3). This acts as a filter to allow the retention of SCRs with a larger amplitude while filtering SCRs with a lower amplitude. The threshold used in this study was 0.05 µS, which is considered conservative in the SCR literature (Braithwaite et al., 2013). The use of such a threshold may therefore have led to some relevant SCRs being ignored in the analysis. However, this is not inconsistent with similar studies implementing the SCR approach where complex neural processes accompanying SCR production were recognised during the interpretation of results. In all cases, eliminating relevant SCRs considered to pose less of a risk to the reliability of the results is preferable to including a greater number of SCRs that are less significant, which will be the consequence of using a lower threshold. This also contrasts with the purpose of using the SCR threshold in the current study, which was primarily aimed at identifying critical moments that are relatively rare.

The SCR literature recognises that, when threshold selection is left to the researcher's discretion (BIOPAC, 2014), some degree of subjectivity is inevitable. The application of this threshold to all study participants aimed to mitigate this subjectivity. Moreover, a pilot analysis of the sample using a 0.05 µS threshold resulted in the production of a substantial number of SCRs, even though this was a conservative threshold (see Chapter 4: Section 4.9.3).

The number of SCRs identified will eventually impact the rate of SCR fixations. This is another factor to consider regarding the variation between the outcomes of the dual task and SCR approaches. Both exhibited a generally similar distribution of critical fixations in the target categories; however, differences between the methods became apparent when the four road sections were compared. These distinctions were also observed when each approach was compared between two road sections, B and C, with each section of these exhibiting distinctively different urban features (Chapter 5, Section 5.7).

The results suggest that the dual task and SCR methods could be implemented to validate the findings of the other as they provide similar yet non-identical patterns. The implication of this for future research is that variations between the two approaches should be considered when using either of these methods to identify critical moments.

Events when a SCR is produced are considered imperative to a person's normal behaviour and have been proposed for use in related scientific studies. However, Najafpour et al. (2017) questioned the objectivity of SCR as a reliable metric in scientific studies, particularly given the different reactions a single instigator could elicit in different people. Therefore, while the SCR approach may benefit a given study, the unpredictability of its findings requires that a cautious approach be taken when drawing conclusions.

This limitation is suggested to be mitigated in the current study by the use of several procedures. First, critical moments within electrodermal activity recording (SCRs) were synchronised with eye-tracking fixations that were grouped into eight target categories. The median of SCR fixations in the overall sample was then used to report the results. This mitigated individual differences and eliminated the effect of extreme values, which is consistent with standard research where variation in responses and the data of individual participants within a sample is usually predicted. This is essentially what data normality tests as well as parametric and non-parametric statistical tests are designed to address.

The second factor that confirms the reliability of SCR data is the conformity between SCR fixation data and dual fixation data as both approaches validated each other in terms of triangulation (Thurmond, 2001).

9.5.5 Ambient light and perception of architectural features

This pilot study used data from the main eye-tracking experiment hence the recruiting strategy, sample population and sample size were the same (see Section 9.5.2).

The implications of this work for the current road lighting guidelines can be summarised as follows:

- A greater number of observations towards non-safety features of the environment, including architectural features, were found during daylight than after dark. The suggested implication for road lighting guidelines is that a higher level of ambient light correlates with increased observations of such features, thus a better cycling experience is proposed.

- Cycling on a pedestrianised path compared to an on-road path also is suggested to have encouraged observations of non-safety elements and architectural features. This indicates that cyclists are more comfortable while on a pedestrianised path – and perceived them as safer than paths shared with motorised vehicles. This tentatively proposed an evidence for the need to distinguish between the visual requirements of cyclists when cycling on each type of path. This variation should be reflected in the light properties recommended for each type of cycle path. The current road lighting guidelines recognise the differences between the different types of cycle path (Chapter 1, Section 1.5.1) but do not explain whether the recommendations provided for each are based on empirical evidence.

Considering the study limitations, the post hoc analysis involves testing an existing set of data against a hypothesis. In such a situation concerns about type 1 error (false positives) or type 2 error (false negatives) are escalated (Akobeng, 2016). The post hoc methodology is different from the orthodox research practice of establishing a hypothesis before data collection (Field, 2013). However, this exploratory study could still be regarded as a door opener for future investigations especially as most of the previous cycling research was devoted to the safety subject with a scarcity of studies covering the life quality aspect of cyclists i.e. cycling experience, as discussed in Chapter 2 under Section 2.5.

Having said that, being a common research practice and when done properly, post hoc analysis could lead to useful insights (Houser and Tiller, 2003). In this light, this analysis is exploratory, not confirmatory (Wagenmakers et al., 2012), and the data is used to explore a potential hypothesis that could be formally tested in a future experiment.

9.5.6 Road lighting guidelines for cycling - Obstacle detection

Similar to the main eye-tracking study the obstacle detection experiment did not investigate variables of gender, age, and experience hence the recruitment mostly targeted university students in overall approach (aged 18 to 35). This is arrived at a total of 30 participants, divided on the three consequent experiments (10 participants each).

For N=10 (comparing each experiment conditions individually) and assuming a power of 0.8 and an alpha = 0.05 with a repeated-measures design (Wilcoxon signed-rank test: matched pairs) the effect size of Cohen's D= 0.88 or larger was found. This is considered a large effect size (Cohen,1992). This means that the sample size of the experiment is acceptable in finding a large effect within the sample. Although smaller effects might be hard to detect according to this estimation, having said that the interest in the current experiment is to find extreme differences in detection performance under variation of light conditions hence this effect size was suitable.

The study also compared conditions between the experiment e.g. between experiments 1 and 3, this calls for using the Mann-Whitney test (two independent samples. When assuming a power of 0.8 and an alpha = 0.05 the calculated effect size = 1.18, which is considered large (Cohen,1992). The calculations of the effect size were produced using G*power software (Faul et al., 2007).

The internal validation of obstacle detection study is discussed under Section 8.8 (Chapter 8) and the results of detection for the validation conditions (lower detection performance) resembled a good tendency among participants to respond only when they see the obstacle i.e. genuine responses.

For external validation, data of the road light only conditions were depicted against the rates of two similar studies, in Figure 8.16, where similarity between detection performance for all studies was illustrated.

The effect of different intensities of road lighting and bicycle lighting, in addition to the mounting position of the bicycle lamp, on participants' ability to detect obstacles was assessed to provide objective evidence that can be used to validate certain aspects of the current road lighting guidelines for cyclists, or to recommend new ones. The main lighting properties that were tested were:

1) Road light intensity – represented by horizontal illuminance (lux), which follows the light metric used in current guidelines e.g., BS 5489-1:2013 and CEN/TR 13201-1:2014.
2) Bicycle lighting - the amount of light from this source was described using luminance (cd/m^2), which was to aid understanding and differentiate it from road lighting illuminance.
3) Bicycle lamp mounting position – three mounting heights representing the helmet, handlebar, and hub were used to investigate the effect of mounting position on detection performance (see Chapter 7, Table 7.2 for the exact height of each mounting position).

Other lighting properties may also have an influence on detection, such as the glare produced from the light source, for example. However, light intensities, road/ bicycle lighting, and bicycle lamp mounting position were selected for investigation as they were believed to have a more dominant influence on obstacle detection. Furthermore, there is no existing literature on the influence of bicycle light intensity and mounting position on cyclists' visual performance, especially when used simultaneously with road lighting. Consequently, the potentially important interplay between road lighting and bicycle lighting and their effect on visual performance has not been addressed before.

The implications this has for road lighting guidelines are that, if sole consideration is given to obstacle detection, an illuminance level higher than 2 lux (when the bicycle light is switched off) will be of little benefit to cyclists. From the point of view of energy conservation, an increase in illuminance beyond this road light level would therefore be against energy sustainability objectives.

This research attempted to address the gap in the literature regarding the combined effect of road lighting and bicycle lighting on visual performance (see Chapter 2: Section 2.6.2). When bicycle lighting was used in addition to road lighting, an increased rate of detection was noted, mostly at 20 lux – the highest illuminance, implying the dominance of road lighting over bicycle luminance. For road light levels of 0.2 and 2 lux, bicycle lighting either did not improve or reduced the level of detection.

The only time this was not the case was when a bicycle lamp was mounted on the hub and the road light was set to 0.2 lux. This applied irrespective of the level of luminance of the bicycle light, see Figure 8.6 in Chapter 8.

The results therefore showed that forward-facing bicycle lamps mounted on the hub facilitate better obstacle detection than those mounted on the handlebars. This is significant as the effect of the mounting position of the bicycle lamp on hazard detection had not previously been established in the literature.

The fact that only one S/P ratio of road light (1.6) and another of bicycle light (2.1) were tested is considered to be a limitation. To further enhance our understanding, it is therefore important to investigate the effect of other S/P ratios on cyclists' detection performance.

Another limitation is that the bicycle that was used in the experiment was static and maintained in an upright position by a frame. This was determined by the size of the laboratory and the need to ensure the safety of participants. A more realistic replication of a real world situation would be to allow participants to freely cycle on a roller (a common method of indoor cycling). Such conditions are suggested to influence the visual performance as they require a greater cognitive load than cycling on a static bicycle.

In the experiment, a fixation target was employed to ensure participants used their peripheral vision when detecting obstacles that required them to verbally state the numbers into which the fixation target had changed. However, such a method cannot ensure that detection always involved peripheral detection. A better approach would be to employ an eye-tracking apparatus that determines precisely where the participant was looking at the moment of detection. Further, eye-tracking equipment has now developed to the point where a real world obstacle detection study can be carried out to test road light and bicycle light parameters in outdoor settings.

The obstacle used in the experiment to assess detection remained the same throughout the trial, namely at the same location/distance. This might have enabled participants to guess that the obstacle will be raised at some point, this is a limitation that could be addressed by using multiple obstacles with different locations in the future. For example, Fotios et al. (2020) included more variables in their obstacle detection study: changing the location of the LED (road light); using several obstacles at different locations instead of one and tested obstacles below the floor level (resembling real-life potholes) this is in addition to the raised obstacles such as in the current study.

Table 9.2 presents the implications drawn from the two main experiments: eye-tracking and obstacle detection, and the two pilot studies: ambient light and cyclist frequencies; and light and the perception of aesthetic features of the urban environment (architectural features).

Table 9. 2. Implications for road lighting guidelines from the thesis studies.

Study	Related chapter/s	Implications for road lighting for cyclists
Ambient light influences cyclist frequencies	3	Higher light levels correlate with higher numbers of cyclists.
Main eye-tracking study	4, 5	Observing the path (obstacle detection) is the critical visual task performed by cyclists.
Perception of architectural features (post hoc analysis)	6	Higher light levels enhance observations of non-safety features of the built environment, including architectural features (aesthetic elements). A similar effect was found when cycling on a pedestrianised path compared to an on-road path.
Obstacle detection	7, 8	2 lux road light is the optimum level for obstacle detection when the bicycle light is switched off. Using the bicycle light simultaneously with road light did not improve detection but sometimes reduced detection, except when the road light was set to 0.2 lux and the bicycle lamp was mounted at the wheel hub position.

9.6 Summary

This chapter presented a summary of the research conducted, discussed the potential implications of the findings for the provision of road lighting for cyclists, and addressed several limitations inherent in the research. The use of an eye-tracking method in conjunction with novel dual task and SCR approaches have shown that observing the path, reflecting obstacle detection task, is a vital and essential visual task for cyclists. The process of detecting obstacles was then explored under different lighting properties.

The research in this thesis thus proposed an objective evidence in relation to cyclists' visual behaviour and peripheral detection under mesopic light conditions. Furthermore, the findings may be more bionomically valid than those of previous research considering the use of dual task and SCR methods both meant to overcome previous limitations identified in this field of research.

The research has also yielded constructive findings, however exploratory, about the following aspects of cycling and lighting: the extent to which ambient light influences numbers of cyclists, the influence of ambient light per se, and the influence of the characteristics of a cycle path on the perception of aesthetic features of the urban environment. These exploratory findings could potentially encourage further investigations in the future.

Nevertheless, certain limitations remain that represent areas of improvement for future research, the latter will be discussed further in Chapter 10 beside thesis conclusions and recommendations to cyclists and policymakers.

Chapter 10. Conclusion

10.1 Conclusions for this work

This research has explored four aspects, established from the literature review, about lighting and cycling during the after dark where it was indicated that improved road lighting has the potential to increase the rate of cycling in UK society as well as mitigating part of safety difficulties faced by cyclists on the roads - In the context of this study better detection of road obstacles. The literature also suggests that lighting can improve the experience of cycling by enabling more observations of aesthetic features of the urban environment such as architectural features which with such perception deemed positive to cycling experience by the literature.

One reason why this work is needed is that the recommendations and specifications in the current UK road lighting guidelines do not appear to be grounded in empirical evidence (Fotios and Gibbons, 2018). This means we do not know whether current guidance optimises lighting in terms of the cost (energy consumption) nor the benefits (propensity to cycle; safety whilst cycling, and enjoying the ride). This formed the basis of the current research which sought to provide an empirical evidence about the following dimensions: light levels and the desire to cycle; critical visual tasks of cyclists; the influence of light on perceptions of aesthetic features of urban environment (architectural features) when cycling on characteristically different cycle paths; and the detection of obstacles in the peripheral field of vision under variation of light characteristics.

The research findings aim to contribute to the development of future road lighting guidelines. Conclusions from this work are presented here in response to the main research questions (Chapter 2: Section 2.7, followed by recommendations and suggestions for future work in this area.

1) Does ambient light affect numbers of cyclists? (Chapter 3)

A field study was conducted in which the numbers of cyclists were counted for two one-hour periods per day, for five days before and after springtime clock change. A comparison of the number of cyclists was carried out using an odds ratio approach which isolates the influence of ambient light from amongst other environmental changes. The analysis suggested that, for the same time of day, there was a higher number of cyclists during daylight hours than after dark, which confirmed the findings of previous analyses of data from the USA (Fotios et al., 2017b; Uttley and Fotios, 2017), see Table 3.2. The current field study addressed a limitation about whether findings from USA studies will persist if the daylight-approach was carried in another country (UK) where weather, cycling infrastructure and cycling culture may be different.

2) What objective methods could be implemented to discriminate important visual tasks of cyclists? (Chapters 4 and 5)

A real world eye-tracking experiment was carried to determine the critical visual tasks of cyclists. In addition to eye-tracking apparatus as an objective method to study visual behaviour, two parallel measurements were implemented to reveal critical visual events during the experiment thus critical fixations were adopted; audio dual task and SCR approach. The use of parallel measurements aimed to overcome a limitation identified in previous eye-tracking studies where only general fixations were used in the analysis and whether a participant was cognitively engaged (i.e. paying attention) with the observed item was not quite known in these studies.

Through synchronisation with the fixations produced by eye-tracking apparatus, critical moments identified by either dual task or SCR methods yielded critical fixations, these were referred to as dual fixations and SCR fixations. Generally dual and SCR fixations showed similar patterns over target categories i.e. visual tasks, suggesting the findings of this study to robust with conclusions reached from two independent paths. The use of dual task and SCR parallel measurements was proposed to improve the ecological validity of previous eye-tracking studies where only all fixations were used in the analysis and whether a participant was paying genuine attention to the fixated visual item was not quite known.

3) What are the critical visual tasks of cyclists in urban environment? (Chapters 4 and 5)

The analysis of dual and SCR fixations suggested that looking at the path is the critical visual task for cyclists, more during after dark than daytime. Observing the path reflected a tendency amongst cyclists to search for possible road obstacles or irregularities to avoid the risk of swerving or falling.

The light effect, more critical fixations towards path during after dark than day trials, was found significant in dual fixations only, for SCR fixations the difference between day and after dark was near significant, however, it suggests a similar trend. Focusing on the path was confirmed higher than the remaining visual targets when comparing rates of dual and SCR fixations along the four sections of the study route.

The proportion of dual and SCR fixations toward the path fell within the range of rates found by previous studies (Mantuano et al., 2017; Vansteenkiste et al., 2014), see Chapter 5: Figure 5.15 for comparison with these previous studies. The study responded to a limitation identified in the literature review that a scarce number of naturalistic eye-tracking studies on cyclists exist.

4) How do ambient light and the characteristics of cycle paths influence cyclists' perception of aesthetic features of the urban environment with such perception proposed to be an indication of positive cycling experience? (Chapter 6)

More fixations toward non-safety items of the environment, including aesthetic elements: architectural features, were found during daytime cycling than after dark; and when traveling on the pedestrianised compared to the on-road cycle path. This is based on the findings from the post hoc analysis carried on the eye-tracking data, reported in Chapter 6.

The literature suggested that positive cycling experience could encourage cycling uptake (Sener et al., 2009a; Tight et al., 2004), enabling the visual clarity of aesthetic scenes in the urban environment deemed positive to the life quality aspect during after dark time (Boyce, 2019). Previously, this theme within cycling research had secured limited attention. The current study aimed to respond to this limitation and its findings, being an exploratory study, should be used as indicative rather than definitive.

5) What levels of road light illuminance improve visual performance of cyclists? (Chapters 7 and 8)

A laboratory experiment was conducted to investigate the detection of a road surface obstacle under various combinations of road light illuminance (0.2, 2.0, 20 lux), bicycle light luminance (0.1, 0.32, 1.0 cd/m²) and bicycle lamp position (helmet, handlebar or hub mounted).

Regarding the benefit of road lighting in the absence of bicycle lighting, some road lighting gives better target detection than no road lighting. This reached a plateau at 2 lux; further increase to 20 lux did not lead to a significant improvement. This plateau effect has also been observed in previous studies (Alferdinck, 2006; Eloholma et al., 2006; Fotios and Cheal, 2013; Uttley et al., 2017) see Chapter 8: Figure 8.16.

When bicycle lighting was turned on, an increase in detection was generally observed only at the highest road light level (20 lux), suggesting dominance of road lighting at this level over bicycle lighting. For lower road light levels (0.2, 2.0 lux) the addition of bicycle light either had no effect on detection or reduced levels of detection (but see below for one exception). The study suggested that a combined use of road and bicycle lighting can impair hazard detection.

The influence of the combined use of road lighting and bicycle lighting on detection performance was a limitation that this study addressed.

6) What level of bicycle light aids cyclists' visual performance? Does the mounting position of bicycle lamp matter? (Chapters 7 and 8)

For obstacle detection task, it has been established that with no road light illuminance (0 lux), turning on bicycle lighting will improve obstacle detection performance. But for other situations where bicycle lighting was used simultaneously alongside road lighting, at any illuminance, either no improvement or reduction in detection performance was revealed in most cases. One particular exception to this finding was when the road light was set on 0.2 lux and the bicycle lamp was mounted on the hub, this applies to the three levels of bicycle light luminance.

Experiment 2 assessed three mounting positions (hub, helmet and handlebar), with only one bicycle luminance (0.32 cd/m²), and found hub mounting position to be better for detection than the handlebar and helmet positions. Experiment 3 demonstrated that the efficacy of the hub mounted bicycle lamp position remained consistent when bicycle luminance was altered from 0.32 (the only luminance used in experiment 2) to 0.1 or 1.0 cd/m², this is in experiment 3 where the bicycle lamp was mounted at hub position only. This was particularly the case when road light was switched off or at 0.2 lux, see Chapter 8: Figure 8.11, 8.13 and 8.14.

The study concluded that forward-facing bicycle lamps mounted on the hub offer better obstacle detection than when mounted on the handlebar. The effect of the bicycle lamp mounting position on detection performance was not assessed previously in the literature.

10.2 Recommendations for cyclists and policymakers

10.2.1 Cyclists

For the obstacle detection task, being important for safe cycling as per the finding of the eye-tracking study, bicycle light is suggested to offer the best detection performance when mounted on the wheel hub location rather than the handlebar or cyclists' helmet. This is especially the case at no road light or 0.2 lux, which are common light conditions on unlit or lower lit cycle paths e.g. cycling in the countryside.

Other than that, using bicycle light simultaneously with different road light illuminances is suggested to either decrease or not improve detection in most cases. Hence the function of bicycle light should be devoted mainly to aid the conspicuity of cyclists to other road users, particularly car drivers.

10.2.2 Policymakers

The significance of mounting the bicycle light on the wheel hub when obstacle detection task becomes the priority to cyclists e.g. cycling on a low surface quality road is recommended to be integrated into new road lighting guidelines.

Observing the path was suggested to be an important visual task to cyclists reflecting a tendency to search for possible obstacles or irregularities hence this information should be indicated in the new road lighting guidelines.

Besides, cyclists should be considered as an independent group of road users. Currently, cyclists are grouped with pedestrians in one category, this could be due partially to previously lacking empirical evidence informing about cyclists’ particular visual needs.

In the light of government efforts aiming to promote cycling in the society, findings from the pilot studies had provided evidence, however in an indicative sense, that light matters to the decision to cycle or not (Cyclists frequencies study) and that higher light levels or cycling on a pedestrianised cycle path compared to on-road path (The post hoc study) both had encouraged more observations toward aesthetic features of the environment thus, in theory, adding positively to the cycling experience. This calls the policymakers to encourage and sponsor further research to confirm the findings from the pilot studies.

Policymakers are encouraged to direct/enforce bicycle light manufacturers to change their current approach to one that incorporates light properties of their products to the visual needs of cyclists. This could be done by providing scientifically based recommendations about how to gain optimum visual performance from their lighting products, with a reference to each visual task.

These recommendations have two caveats:

1) The findings from the obstacle detection study are based on a small sample of participants (N = 10 for each experiment of the three) hence the conclusions need to be validated by a study that uses a larger population.

2) The effect of mounting the bicycle light on the wheel hub on other aspects of safe cycling such as the conspicuity of cyclists to other road users e.g. car drivers or the influence on other visual tasks that cyclists need to perform was not assessed in this research thus further research is warranted before adopting these recommendations. Examples of other visual tasks which may be affected by mounting the bicycle light on the wheel hub include:

A) The overall visibility of the scene which is likely to influence reassurance i.e. feeling safe about a location while cycling.

B) Conspicuity of cyclists to nearby pedestrians and vehicles and vice versa.

10.3 Recommendations for further work

This research aimed to generate empirical evidence that specifies critical visual tasks of cyclists when in urban environments using eye-tracking methodology. Then the effects of lighting on identified critical visual tasks, obstacle detection, were also studied. In addition, the influence of ambient light level on the desire to cycle, and perception of features of the urban environment which is not related to safety (aesthetic features) were also assessed. Within that scope, potential future research is highlighted in this section.

In the pilot observation study, ambient light and cyclists number, although the study demonstrated that higher light levels encourage more cycling, it did not compare the tendency to cycle under variations of illuminance as those recommended by the road lighting guidelines. Thus a useful future investigation concerning the current road lighting guidelines would be to determine specific road light illuminance(s) at which a higher rate of cycling could be anticipated.

The analysis of the main eye-tracking study suggested an effect of route length, data of the whole route compared to a smaller section of it, that possibly had caused the anticipated difference between all, dual and SCR fixations trends to be partially mitigated unlike when comparing the smaller road sections where variations were more obvious between the three types of fixations. This is because recording visual behaviour on a longer path will reflect in larger data in contrary to the case of shorter section. Hence the next eye-tracking studies could further investigate the effect of route length on the trends of critical fixations.

Few eye-tracking studies that investigated cyclists' visual behaviour in natural settings could be found. This was highlighted in the literature review, Section 2.4.4. Within this small sample, however, they cannot be considered fully as naturalistic. Because they report data of only small segment of the cycled route so the findings cannot reflect the visual behaviour of a cyclist when traveling through several parts of the city as there would be variations in urban features and traffic conditions, including time spent cycling on the main road or in separated cycling lanes. More studies are required which investigate cyclists' visual behaviour in diverse real world contexts.

Another point to consider is the gap between the laboratory and real world eye-tracking studies (Dowiasch et al., 2015). The advantage of conducting naturalistic studies is also an opportunity to compare with laboratory studies, to either support or sustain its findings.

Although the literature investigating cyclists' visual behaviour using eye-tracking is in its infancy, there is a noticeable variation in the analysis protocol used in the previous studies e.g. (Mantuano et al., 2017; Vansteenkiste et al., 2014a). For example, each study used a different categorisation system, either in the number of categories used or the given title for a category. These variations could possibly lead to different interpretations of the data which is counterproductive to the accumulative progressing of this research theme. A key recommendation for future studies is, therefore, to follow a unified approach, perhaps focusing on one critical visual task e.g. fixations toward the path or establish a unified categorisation reference.

In the current study the approach followed was identifying critical visual tasks by implementing dual task and SCR approaches. It would be useful to explore the replicability of the current findings in the next studies when conducted in other locations and for varied route lengths.

Because the dual and SCR approaches exhibited considerable similarity, the SCR approach is proposed as a sound measurement for similar future studies.

The obstacle detection experiment had investigated the following light parameters: varied road light intensities, varied bicycle light intensities and three bicycle lamp mounting locations. In doing so, other possible parameters were not covered in the study, such as glare, colour rending index, more S/P ratios. Further, it would be of benefit to evaluate a wider range of bicycle light levels and the impact of these on detection.

The post hoc analysis of eye-tracking data reported in Chapter 6, looking toward architectural features of the environment, assessed fixations toward architectural features while light condition and cycle path characteristics were varied. It would be useful to experiment with the same type of perception against different road light illuminance to see what level motivates more observations of the aesthetic element.

Appendix A. Identifying critical visual tasks: Pilot study

A.1 Introduction

The development of eye-tracking technology has now made it possible to determine which visual features in the urban environment are important for cyclists, particularly in respect to their safety. Identifying where cyclists look when it is dark has useful implications for the development of current guidelines regarding the provision of road lighting for cyclists. Another potential beneficiary from this investigation is urban design as better road lighting will lead to safer travelling and better integration with the urban environment.

Previous eye-tracking studies have not shown whether an eye fixation identified by the apparatus is related to a critical visual task. For example, if the participant pays genuine attention to the fixated item, it is not unusual for people to look at an object or 'look into space' while they are cognitively disengaged, for example, when their mind is wandering (Rothkopf et al., 2007).

To address this question, some studies have used a parallel dual task while recording eye-tracking data (see Chapter 4, Sections 4.2 for literature review). A slow or missed response to an audio stimulus may indicate that an individual's attention has been diverted by a critical or unusual visual event (Fotios et al., 2015b). With synchronised measurements, potential critical visual tasks can be identified from the simultaneous drop-off in performance of the parallel response task. This method was reported to be more valid than previous techniques employed to assess eye-tracking data (Fotios et al., 2015c).

However, because the audio stimulus necessarily occurs at random intervals, the parallel measurement is not continuous and it is therefore difficult to identify the precise moment at which a participant's attention was diverted by a critical visual item. Another limitation of this method concerns the degree of cognitive demand required by this dual task which, in specific situations like busy roads would be risky to ask participant to perform it.

An alternative method for identifying critical visual tasks is the skin conductance response (SCR) (see chapter 4, Section 4.3 for literature review). This is a reflex physiological response that often accompanies significant emotional or cognitive processing. Previous research has used SCR to successfully detect hazards when driving (Kübler et al., 2014). A pilot study was therefore conducted here to validate the use of a dual task and skin conductance response methods to identify critical visual behaviour. This enabled the efficiency of both methods in interpreting eye fixations to be compared. It could therefore clarify whether the fixations identified were critical, namely if the participant was paying genuine attention to the object fixated upon at a certain moment in time during trials.

A.2 Method

In preparation for this study we have carried out a computer-based pilot test to confirm whether SCR can be used to indicate critical moments, while participants performed the dual task, both will be parallel measurements to be implemented in the real eye-tracking study (reported in Chapters 4 and 5). The test required participants to observe a computer screen whilst different visual stimuli were presented. During this time, participants were asked to reply to a semi-regular audio beep by pressing the spacebar on a keyboard as prompt as they could. The on-screen display, audio beep and measurement of response times were controlled through a Python program. Beeps happened at semi-random intervals, within 1 - 3 sec. To ensure participants closely observed the computer screen and did not direct all their attention to the audio response task, they were told that they would be asked a series of questions following the end of the experiment about what they had seen on the screen. This questioning did not actually take place however.

Three different types of visual stimuli were presented to participants, in three separate sessions:

A. Static images. Static, visually-distracting or salient images, interspersed with visual white noise. When the test began, the screen initially displayed visual white noise (visual static) for 20 seconds, before displaying a sequence of four distracting or salient images, see Figure A.1 for one image slide, each image displayed for 1.5 seconds. This pattern of 20 seconds of visual white noise followed by 4 images was repeated a further three times. After the final set of images had been presented, a further period of visual noise was shown before the test finished. This resulted in five periods of visual noise, and four periods in which images were displayed (four images in each period for a total of 16 images presented). Participants observed the screen for a total of approximately 2 minutes.

Figure A. 1. Examples of distracting images shown in the still images test.

B. Video clips. Periods of visual white noise (duration was randomly selected between 5 and 8 seconds) were interspersed with short (5 seconds) such as a bus going past, a group of pedestrians approaching. A total of eight video clips were shown, each preceded by the visual white noise. A screenshot from a video clip is shown in Figure A.2 (left).

C. Continuous video. Participants viewed a continuous video clip lasting 219 seconds, with no visual noise. Participants were asked to look out for three specific features in the environment, such as a particular word on a poster. See Figure A.2 (right).

Figure A. 2. Screenshots of critical events occurring in video clips (left) and one of the items participants were told to note in the full video part (right).

SCR was recorded during presentation of these stimuli. Participants also carried out a concurrent response task whilst observing the stimuli, pressing a key in response to a beep occurring every 1-3 s. This allowed comparison of the concurrent dual task method for identifying critical times with the SCR method, to confirm whether they provide similar results.

A.3 Results

Stimulus versus non-stimulus periods

In each of the three tests stimulus periods were defined for comparison against a non-stimulus period. For the static images test, stimulus periods were defined as beginning when the first image of an image set was presented, and ending 5 seconds after the final image of the set disappeared and the screen returned to white visual noise. For the Video Clips test, stimulus periods were defined from the beginning of each video clip, until 3 seconds after the end of the video clip. For the Full Video test, stimulus periods were defined as beginning when the salient feature first became visible within the video, and ending 5 seconds after the salient feature was no longer visible in the video. Non-stimulus periods were defined as all other times outside of the stimulus periods, for each of the three tests. The mean durations for stimulus and non-stimulus periods in the Images test were 44.0 and 72.3 seconds. In the Video Clips test, the mean durations for stimulus and non-stimulus periods were 75.8 and 40.6 seconds. In the Full Video test, the durations for stimulus and non-stimulus periods were 25.6 and 193.1 seconds.

Skin Conductance Response

The number of Skin Conductance Responses (SCRs) was calculated during each stimulus period for each participant, on each of the three tests. This frequency was normalised by converting to a rate of SCRs per 10 seconds of stimulus period. The same approach was taken to calculate a rate of SCRs per 10 seconds of non-stimulus period. These measures are presented in Figure A.3. The rate of SCRs during stimulus and non-stimulus periods does not appear to differ on the Video Clips and Full Video tests. However, the rate appears higher during stimulus periods versus non-stimulus periods on the Images test. These interpretations were confirmed with Wilcoxon signed-rank tests comparing stimulus and non-stimulus periods for each of the tests (p = 0.313 and 0.500 for the Video Clips and Full Video tests respectively, p = 0.001 for the Images test).

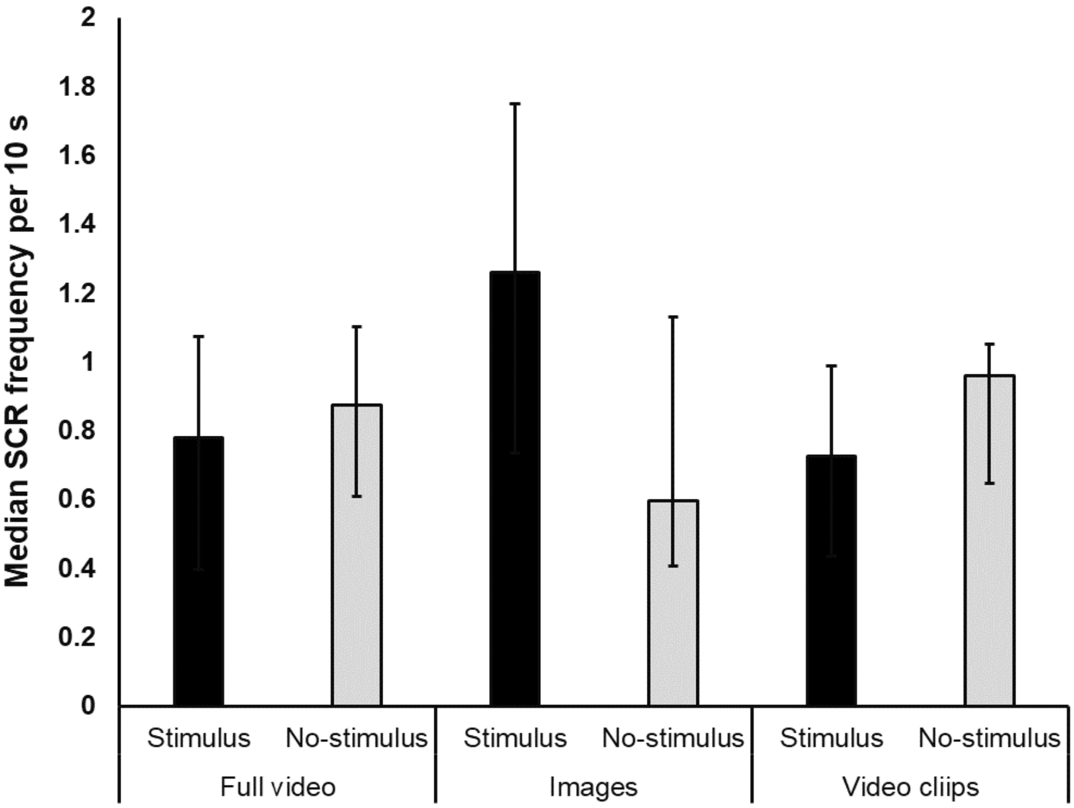

Figure A. 3. Median SCR frequency per 10 seconds for stimulus and non-stimulus periods, during Full Video, Images and Video Clips tests. Error bars show the interquartile range.

Dual task – reaction time

The mean reaction time (RT) to the concurrent response task was calculated during stimulus periods and non-stimulus periods for each participant, on each of the three tests. The total mean number of responses (number of times participant needed to respond to the beep) required on the concurrent task for stimulus and non-stimulus periods respectively was 9.6 and 33.3 for the Images test, 20.3 and 20.7 for the Video Clips test, and 12.2 and 98.6 for the Full Video test. Median RTs for stimulus and non-stimulus periods on each of the three tests are shown in Figure A.4. In all three tests RTs during stimulus periods are slower than RTs during non-stimulus periods. Wilcoxon signed-rank tests comparing stimulus and non-stimulus RTs suggested these differences were significant in all three tests (p = 0.001, 0.001 and 0.042 for the Images, Video Clips and Full Video tests respectively).

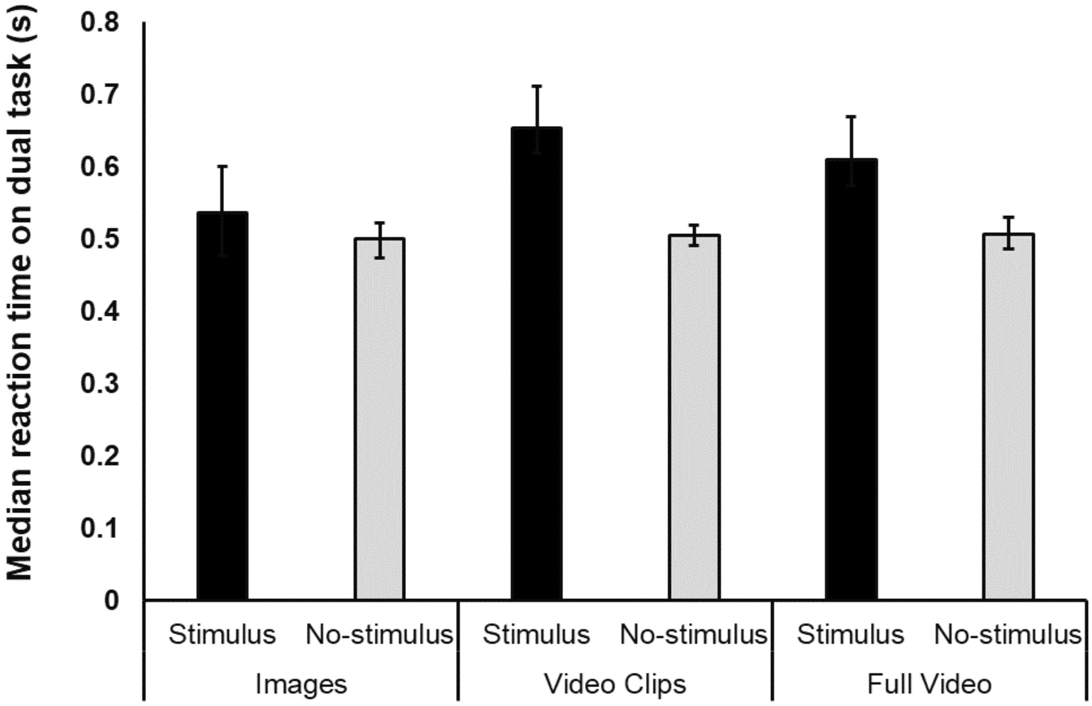

Figure A. 4. Median RTs to response task during stimulus and non-stimulus periods, during Full Video, Images and Video Clips tests. Error bars show the interquartile range.

Similarity between SCR and dual-task responding

To test whether there is a relationship between the SCR and dual task (RT) measures in terms of eliciting a reaction during stimulus and non-stimulus periods, the relative responsiveness of participants to stimuli in the three tests was measured and compared between the two methods of SCR and RT, to see if they were correlated. The relative responsiveness of participants was calculated by subtracting the participants' recorded value for each measure during the non-stimulus periods from their value during the stimulus periods. For example, the rate of SCR per 10 seconds during non-stimulus periods would be subtracted from the rate of SCR per 10 seconds during stimulus periods, and likewise for RTs. The larger the resulting value, the more responsive the participant was to the stimuli presented. This gives a responsiveness value for the SCR measure and for the RT measure. A scatterplot showing these two values, and their correlation, is shown in Figures A.5, A.6 and A.7 for the Images, Video Clips and Full Video tests. All three scatterplots suggest there may be a positive relationship between stimuli responsiveness as measured by the dual task approach and stimuli responsiveness as measured by the SCR approach. Spearman's correlation tests suggested the correlation in the Images test and the Video Clips test were significant (p = 0.006 and 0.037 respectively), whilst the Full Video test proved not significant (p = 0.441).

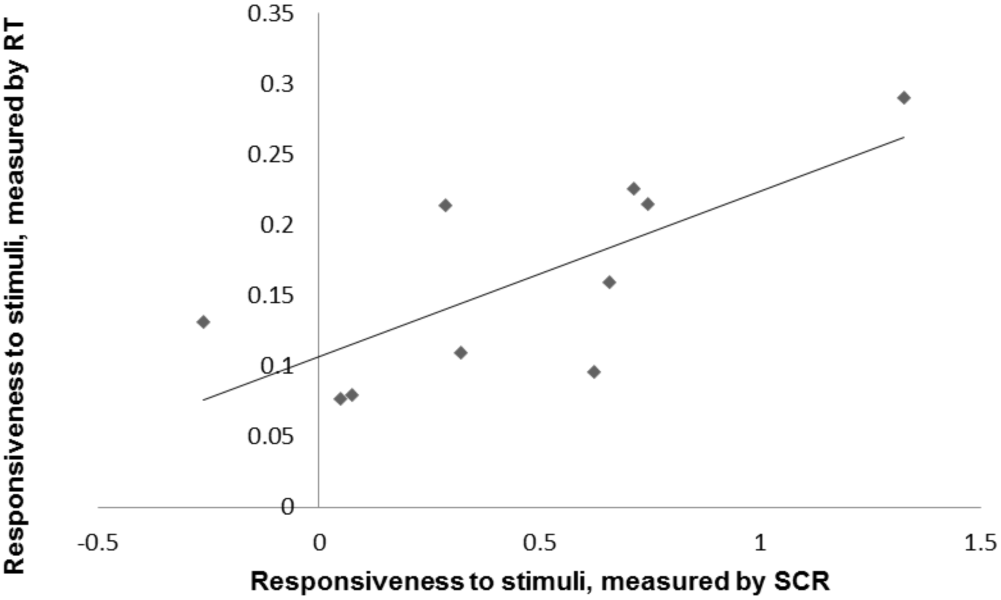

Figure A. 5. Correlation between responsiveness to stimuli measured by SCR and RT on Images test. Responsiveness to stimuli calculated by subtracting the value during non-stimulus periods from the value during stimulus periods, for SCR (rate per 10 seconds) and RT (mean RT).

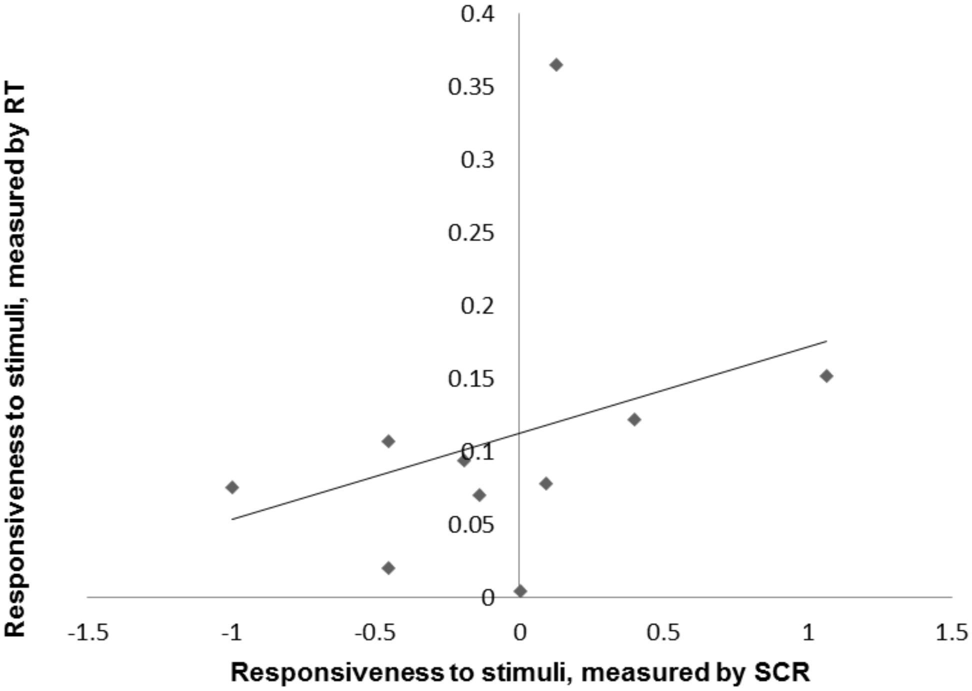

Figure A. 6. Correlation between responsiveness to stimuli measured by SCR and RT on Video Clips test. Responsiveness to stimuli calculated by subtracting the value during non-stimulus periods from the value during stimulus periods, for SCR (rate per 10 seconds) and RT (mean RT).

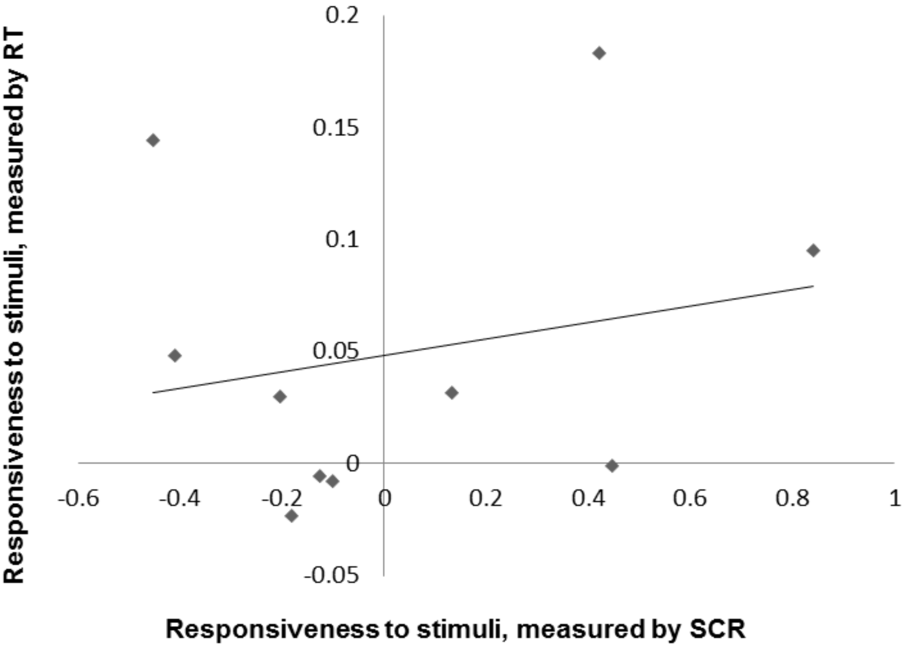

Figure A. 7. Correlation between responsiveness to stimuli measured by SCR and RT on Full Video test. Responsiveness to stimuli calculated by subtracting the value during non-stimulus periods from the value during stimulus periods, for SCR (rate per 10 seconds) and RT (mean RT).

A.4 Discussion

This pilot experiment had two purposes. The first was to assess whether SCR can be used to indicate when an individual is paying attention to something visually salient or distracting. The second was to assess whether SCR, as a measure of attention to a salient feature, provides the same outcomes as reaction times to an auditory dual task. Reaction time tasks have previously been used to successfully indicate critical times where attention may be focused on something visually salient or distracting (Fotios et al., 2015b; Fotios et al., 2015c). A correlation between the SCR measure and the reaction time measure would suggest that SCR could be used in place of or with the dual task reaction time to indicate critical times in circumstances where a dual task may be inappropriate or hazardous or to validate its results.

In the “Images” test, there was a higher rate of SCRs during stimulus periods compared with non-stimulus periods. This suggests that the distracting, conspicuous images presented during the stimulus periods resulted in an increase in SCR. However, this outcome was not seen in tests involving video clips or a full video with distinctive features to watch out for. Therefore, we conclude that using SCR to indicate critical times when a person is distracted by visual stimuli is feasible. Furthermore, results from the dual-task reaction time task confirm that this method of identifying critical times when salient visual stimuli are present is successful, as stimulus periods produced significantly slower reaction times than non-stimulus periods on all three tests. Two of the three tests conducted produced a significant positive correlation between responsiveness to the stimuli measured by SCR and responsiveness to the stimuli measured by reaction time. Therefore, participants displaying a larger difference in reaction times between stimulus and non-stimulus periods were also more likely to exhibit a larger difference in the rate of SCR between stimulus and non-stimulus periods. This implies that the two methods may be measuring similar effects and supports the use of SCR as an alternative or in parallel to the dual-task method in indicating critical responses to visual stimuli.

Cyclists' critical visual tasks are assumed to correlate strongly with safety. Events such as avoiding obstacles, uneven surfaces, pedestrians crossing or walking on the path, and other vehicles approaching, are all considered visually important events, in that a failure to perceive them will lead to a higher possibility of an injury or accident occurring while cycling.

The assumption in this study is that implementing a dual task approach in addition to an SCR approach is likely to reveal which eye-tracking fixations are critical, an important step in objectively determining cyclists' critical visual tasks. It is a method that relies upon identifying moments where a participant's attention is diverted from a concurrent task e.g., when responding to an audio stimulus. Moreover, physiological skin reactions (SCR) triggered by critical events are could also be synchronised with eye-tracking fixations.

Synchronising dual task and SCR data with eye-tracking fixations means that it is possible to identify which item in the visual environment the participant was fixating on during critical moments in each parallel measurement.

However, it is important to note that not all critical signals necessarily mean a safety-related item is being fixated on. It may simply be an attractive or an irregular item/event that has attracted the cyclist's attention. This could be considered a shortcoming of the proposed approach. This is because eye fixations alone, as identified by the eye-tracking system, provide information about the frequency with which participants have fixated on an item, but no indication as to the importance of this item. Thus, we lack information about the psychological status of the participant, which is important in determining the importance of a fixation.

Nevertheless, the two methods implemented in this study are likely to indicate critical visual events for participants and as such are an improvement on existing eye-tracking approaches.

A.5 Summary

The data collected (n= 10) indicate a critical SCR is more likely to occur during a stimulus event compared with other times, and there is a high degree of overlap between SCR and slower reaction times to a concurrent response task (dual task). These results suggest SCR can be employed as an alternative or parallel method to the dual task for identifying significant environmental features using eye-tracking data.

Appendix B. Main eye-tracking experiment: Normality assessments

Table B. 1. Normality assessment for all fixations proportion over target categories data (day and after dark combined).

Normality Test	Goal	Path	Obstacles	Kerb	Car	Cyclists & Pedestrians	Miscellaneous	Buildings
Central Tendency								
Mean	0.106	0.430	0.061	0.022	0.046	0.044	0.261	0.023
Median	0.095	0.450	0.055	0.020	0.040	0.035	0.280	0.020
Normality ?	NO	YES	YES	YES	YES	NO	NO	YES
Graphical								
Histogram	NO	NO	YES	YES	NO	YES	YES	NO
Box Plot	YES	YES	YES	YES	YES	YES	YES	NO
Q-Q Plot	NO	YES	YES	YES	YES	YES	YES	NO
Normality ?	NO	YES	YES	YES	YES	YES	YES	NO
Measures of dispersion								
Skewness (within +/- 0.5)	0.701	- 0.185	0.902	0.364	0.587	0.788	- 0.096	2.172
Kurtosis (within +/-1.0)	- 0.269	- 0.897	0.594	1.061	- 0.638	- 0.415	-1.291	6.201
Normality ?	NEAR	YES	NEAR	NEAR	NEAR	NEAR	NO	NO
Statistical tests								
Shapiro-Wilks Statistic Level of significance	0.482	0.690	0.357	0.394	0.323	0.178	0.602	0.004
Kolmogorov-Smirnov Statistic Level of significance	0.200	0.200	0.200	0.200	0.184	0.104	0.200	0.007
Normality? (not normal f p<0.05)	YES	YES	YES	YES	YES	YES	YES	NO
Overall assessment of Normality	**NO**	**YES**	**YES**	**YES**	**YES**	**YES**	**NEAR**	**NO**

Table B. 2. Normality assessment for dual fixations proportion data over target categories (day time trials).

Normality Test	Goal	Path	Obstacles	Kerb	Car	Cyclists & Pedestrians	Miscellaneous	Buildings
Central Tendency								
Mean	0.114	0.390	0.068	0.020	0.053	0.030	0.303	0.024
Median	0.105	0.400	0.060	0.015	0.030	0.010	0.270	0.020
Normality ?	NO	YES	YES	YES	NO	NO	NO	YES
Graphical								
Histogram	YES	NO	YES	NO	NO	NO	NO	NO
Box Plot	NO	YES	YES	YES	YES	NO	YES	NO
Q-Q Plot	YES	YES	YES	YES	NO	NO	NO	NO
Normality ?	YES	YES	YES	YES	NO	NO	NO	NO
Measures of dispersion								
Skewness (within +/- 0.5)	- 0.102	- 0.184	0.621	0.553	1.035	1.103	0.467	0.847
Kurtosis (within +/-1.0)	0.297	- 0.924	- 0.233	- 0.856	- 0.134	0.158	- 1.051	- 0.178
Normality ?	YES	YES	NEAR	NEAR	NEAR	NEAR	NEAR	NEAR
Statistical tests								
Shapiro-Wilks Statistic Level of significance	0.708	0.846	0.428	0.094	0.045	0.008	0.361	0.035
Kolmogorov-Smirnov Statistic Level of significance	0.200	0.200	0.200	0.151	0.032	0.009	0.200	0.079
Normality? (not normal f p<0.05)	YES	YES	YES	YES	NO	NO	YES	NEAR
Overall assessment of Normality	**YES**	**YES**	**YES**	**YES**	**NO**	**NO**	**NO**	**NO**

Table B. 3. Normality assessment for dual fixations proportion data over target categories (after dark trials).

Normality test	Goal	Path	Obstacles	Kerb	Car	Cyclists & Pedestrians	Miscellaneous	Buildings
Central Tendency								
Mean	0.078	0.471	0.057	0.027	0.051	0.051	0.251	0.009
Median	0.055	0.505	0.045	0.025	0.045	0.050	0.235	0.001
Normality ?	NO	YES	NO	YES	YES	YES	NO	NO
Graphical								
Histogram	NO	YES	YES	NO	YES	YES	NO	NO
Box Plot	YES	YES	YES	YES	NO	YES	YES	NO
Q-Q Plot	NO	YES	YES	YES	NO	YES	YES	NO
Normality ?	NO	YES	YES	YES	NO	YES	YES	NO
Measures of dispersion								
Skewness (within +/- 0.5)	0.589	- 0.348	0.444	0.735	1.339	0.684	0.108	1.704
Kurtosis (within +/-1.0)	- 1.146	- 0.468	- 0.782	0.278	2.509	0.278	- 1.166	1.670
Normality ?	NO	YES	YES	NEAR	NO	NEAR	NEAR	NO
Statistical tests								
Shapiro-Wilks Statistic Level of significance	0.135	0.135	0.548	0.560	0.140	0.597	0.739	0.001
Kolmogorov-Smirnov Statistic Level of significance	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.002
Normality? (not normal f $p<0.05$)	YES	YES	YES	YES	NO	YES	YES	NO
Overall assessment of Normality	**NO**	**YES**	**YES**	**YES**	**NO**	**YES**	**YES**	**YES**

Table B. 4. Normality assessment for dual fixations proportion data over target categories (Day and after dark combined trials).

Normality Test	Goal	Path	Obstacles	Kerb	Car	Cyclists & Pedestrians	Miscellaneous	Buildings
Central Tendency								
Mean	0.071	0.478	0.050	0.021	0.049	0.039	0.247	0.017
Median	0.075	0.490	0.060	0.020	0.040	0.030	0.255	0.010
Normality ?	YES	NO	NO	YES	NO	NO	YES	NO
Graphical								
Histogram	YES	YES	NO	NO	YES	NO	NO	YES
Box Plot	YES	YES	YES	YES	YES	NO	YES	YES
Q-Q Plot	YES	YES	NO	YES	YES	YES	NO	YES
Normality ?	YES	YES	NO	YES	YES	NO	NO	YES
Measures of dispersion								
Skewness (within +/- 0.5)	- 0.424	- 0.165	0.735	0.797	0.927	1.296	0.507	0.412
Kurtosis (within +/-1.0)	- 0.825	- 1.149	- 1.120	0.648	0.499	2.011	0.637	- 0.298
Normality ?	YES	NEAR	NEAR	NEAR	NEAR	NO	NEAR	YES
Statistical tests								
Shapiro-Wilks Statistic Level of significance	0.610	0.748	0.031	0.350	0.173	0.139	0.741	0.123
Kolmogorov-Smirnov Statistic Level of significance	0.200	0.200	0.001	0.200	0.140	0.200	0.200	0.061
Normality? (not normal f p<0.05)	YES	YES	NO	YES	YES	YES	YES	YES
Overall assessment of Normality	**YES**	**YES**	**NO**	**YES**	**YES**	**NO**	**YES**	**YES**

Table B. 5. Normality assessment for SCR fixations proportion data over target categories (Day time trials).

Normality Test	Goal	Path	Obstacles	Kerb	Car	Cyclists & Pedestrians	Miscellaneous	Buildings
Central Tendency								
Mean	0.114	0.390	0.068	0.200	0.053	0.030	0.303	0.024
Median	0.105	0.400	0.060	0.150	0.030	0.010	0.270	0.020
Normality ?	YES	YES	Yes	NO	NO	NO	NO	YES
Graphical								
Histogram	YES	NO	NO	NO	NO	NO	NO	NO
Box Plot	YES	YES	YES	NO	NO	NO	YES	NO
Q-Q Plot	NO	YES	YES	NO	NO	NO	NO	NO
Normality ?	YES	YES	YES	NO	NO	NO	NO	NO
Measures of dispersion								
Skewness (within +/- 0.5)	-0.102	- 0.184	0.621	0.553	1.035	1.103	0.467	0.847
Kurtosis (within +/-1.0)	0.297	- 0.924	- 0.233	- 0.856	- 0.134	0.158	- 1.051	- 0.178
Normality ?	YES	YES	NEAR	YES	NO	NO	YES	NO
Statistical tests								
Shapiro-Wilks Statistic Level of significance	0.708	0.846	0.428	0.094	0.045	0.008	0.361	0.035
Kolmogorov-Smirnov Statistic Level of significance	0.200	0.200	0.200	0.151	0.032	0.009	0.200	0.079
Normality? (not normal f p<0.05)	YES	YES	YES	YES	NO	NO	YES	NO
Overall assessment of Normality	**YES**	**YES**	**YES**	**NEAR**	**NO**	**NO**	**NEAR**	**NO**

Table B. 6. Normality assessment for SCR fixations proportion data over target categories (After dark time trials).

Normality Test	Goal	Path	Obstacles	Kerb	Car	Cyclists & Pedestrians	Miscellaneous	Buildings
Central Tendency								
Mean	0.078	0.471	0.057	0.027	0.051	0.051	0.251	0.009
Median	0.055	0.505	0.045	0.025	0.045	0.049	0.235	0.001
Normality ?	NO	NO	NO	YES	YES	YES	NO	NO
Graphical								
Histogram	NO	NO	NO	NO	NO	NO	NO	NO
Box Plot	NO	YES	NO	YES	YES	YES	YES	NO
Q-Q Plot	NO	YES	NO	YES	YES	YES	NO	NO
Normality ?	NO	NEAR	NO	NEAR	NEAR	NEAR	NO	NO
Measures of dispersion								
Skewness (within +/- 0.5)	0.589	- 0.348	0.444	0.735	1.33	0.684	0.108	1.70
Kurtosis (within +/-1.0)	-1.146	- 0.468	- 0.782	0.278	2.50	0.278	- 1.16	1.67
Normality ?	NO	YES	YES	NEAR	NO	NEAR	NEAR	NO
Statistical tests								
Shapiro-Wilks Statistic Level of significance	0.135	0.911	0.548	0.560	0.140	0.597	0.739	0.001
Kolmogorov-Smirnov Statistic Level of significance	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.002
Normality? (not normal f p<0.05)	YES	YES	YES	YES	YES	YES	YES	NO
Overall assessment of Normality	**NO**	**YES**	**NO**	**YES**	**YES**	**YES**	**NO**	**NO**

Table B. 7. Normality assessment for SCR fixations proportion data over target categories (Day and after dark combined trials).

Normality Test	Goal	Path	Obstacles	Kerb	Car	Cyclists & Pedestrians	Miscellaneous	Buildings
Central Tendency								
Mean	0.096	0.430	0.062	0.021	0.053	0.040	0.277	0.016
Median	0.105	0.465	0.065	0.020	0.045	0.050	0.270	0.015
Normality ?	YES	NO	YES	YES	YES	NO	YES	YES
Graphical								
Histogram	NO	YES	NO	YES	NO	NO	YES	YES
Box Plot	YES	YES	YES	YES	NO	YES	YES	YES
Q-Q Plot	YES	YES	YES	YES	NO	NO	YES	YES
Normality ?	YES	YES	YES	YES	NO	NO	YES	YES
Measures of dispersion								
Skewness (within +/- 0.5)	- 0.326	- 0.282	- 0.284	0.596	1.318	- 0.347	0.336	0.484
Kurtosis (within +/-1.0)	- 0.326	- 0.434	- 0.805	0.203	2.199	- 1.346	- 0.725	- 0.834
Normality ?	YES	YES	YES	NEAR	NO	NEAR	YES	YES
Statistical tests								
Shapiro-Wilks Statistic Level of significance	0.712	0.820	0.539	0.547	0.180	0.216	0.826	0.139
Kolmogorov-Smirnov Statistic Level of significance	0.200	0.200	0.124	0.135	0.200	0.140	0.200	0.200
Normality? (not normal f p<0.05)	YES	YES	YES	YES	YES	YES	YES	YES
Overall assessment of Normality	**YES**	**YES**	**YES**	**YES**	**NO**	**NO**	**YES**	**YES**

Table B. 8. Normality assessment for reaction time variables for the study sample (Day time trials).

Normality Test	Beeps total	Missed	Delayed	Successful responses
Central Tendency				
Mean	257	32	9.33	88
Median	253	12	8.5	95
Normality ?	YES	NO	YES	YES
Graphical				
Histogram	NO	NO	NO	NO
Box Plot	YES	NO	YES	NO
Q-Q Plot	NO	NO	NO	NO
Normality ?	NO	NO	NO	NO
Measures of dispersion				
Skewness (within +/- 0.5)	0.124	2.77	- 0.022	- 2.50
Kurtosis (within +/-1.0)	0.945	8.2	- 0.976	6.8
Normality ?	YES	NO	YES	NO
Statistical tests				
Shapiro-Wilks Statistic Level of significance	0.819	0.001	0.550	0.001
Kolmogorov-Smirnov Statistic Level of significance	0.200	0.001	0.200	0.002
Normality? (not normal f $p<0.05$)	YES	NO	YES	NO
Overall assessment of Normality	**NEAR**	**NO**	**NEAR**	**NO**

Table B. 9. Normality assessment for reaction time variables for the study sample (After dark trials).

Normality Test	Beeps total	Missed	Delayed	Successful responses
Central Tendency				
Mean	262	38	9.42	86
Median	256	25	8	91.5
Normality ?	NO	NO	YES	NO
Graphical				
Histogram	YES	NO	NO	NO
Box Plot	NO	NO	NO	NO
Q-Q Plot	NO	NO	NO	NO
Normality ?	NO	NO	NO	NO
Measures of dispersion				
Skewness				
(within +/- 0.5)	1.14	2.60	1.51	- 2.33
Kurtosis				
(within +/-1.0)	1.74	7.44	1.93	5.99
Normality ?	NO	NO	NO	NO
Statistical tests				
Shapiro-Wilks				
Statistic	0.099	0.001	0.014	0.001
Level of significance				
Kolmogorov-Smirnov				
Statistic	0.884	0.003	0.058	0.003
Level of significance				
Normality?	YES	NO	NO	NO
(not normal f p<0.05)				
Overall assessment of Normality	**NO**	**NO**	**NO**	**NO**

Table B. 10. Normality assessment for mean reaction time data (MRT) for study participants for day time and after dark trials.

ID	**Participant 1**		**Participant 6**	
Normality Test	**Day**	**Night**	**Day**	**Night**
Central Tendency				
Mean	362	374	363	338
Median	339	309	285	272
Normality ?	NEAR	NO	NO	NO
Graphical				
Histogram	YES	NO	NO	NO
Box Plot	YES	NO	NO	NO
Q-Q Plot	NO	NO	NO	NO
Normality ?	YES	NO	NO	NO
Measures of dispersion				
Skewness (within +/- 0.5)	1	1.9	1.62	1.33
Kurtosis (within +/-1.0)	2.8	3.1	2.19	1.52
Normality ?	NO	NO	NO	NO
Statistical tests				
Shapiro-Wilks Statistic Level of significance	0.001	0.001	0.001	0.001
Kolmogorov-Smirnov Statistic Level of significance	0.001	0.001	0.001	0.001
Normality? (not normal f p<0.05)	NO	NO	NO	NO
Overall assessment of Normality	**NO**	**NO**	**NO**	**NO**

Table B. 11. Normality assessment for mean reaction time data (MRT) for study participants for day time and after dark trials.

ID	Participant 7		Participant 9	
Normality Test	**Day**	**Night**	**Day**	**Night**
Central Tendency				
Mean	259	242	441	577
Median	231	215	404	566
Normality ?	YES	NO	YES	YES
Graphical				
Histogram	NO	NO	NO	YES
Box Plot	NO	NO	YES	YES
Q-Q Plot	NO	NO	NO	YES
Normality ?	NO	NO	NO	YES
Measures of dispersion				
Skewness (within +/- 0.5)	1.7	1.6	0.996	0.377
Kurtosis (within +/-1.0)	4.1	3.3	0.489	- 0.217
Normality ?	NO	NO	YES	YES
Statistical tests				
Shapiro-Wilks	0.001	0.001	0.001	0.001
Statistic				
Level of significance				
Kolmogorov-Smirnov	0.001	0.001	0.001	0.001
Statistic				
Level of significance				
Normality? (not normal f p<0.05)	NO	NO	NO	NO
Overall assessment of Normality	**NO**	**NO**	**NEAR**	**YES**

Table B. 12. Normality assessment for mean reaction time data (MRT) for study participants for day time and after dark trials.

ID	Participant 10		Participant 11	
Normality Test	**Day**	**Night**	**Day**	**Night**
Central Tendency				
Mean	471	548	177	180
Median	428	481	166	172
Normality ?	YES	NO	YES	YES
Graphical				
Histogram	YES	YES	YES	YES
Box Plot	NO	YES	NO	NO
Q-Q Plot	YES	YES	NO	NO
Normality ?	YES	YES	NO	NO
Measures of dispersion				
Skewness	0.871	0.773	0.75	0.909
(within +/- 0.5)				
Kurtosis	1.14	0.496	1.2	2.3
(within +/-1.0)				
Normality ?	NEAR	YES	NEAR	NO
Statistical tests				
Shapiro-Wilks	0.001	0.001	0.001	0.001
Statistic				
Level of significance				
Kolmogorov-Smirnov	0.001	0.001	0.001	0.001
Statistic				
Level of significance				
Normality?	NO	NO	NO	NO
(not normal f p<0.05)				
Overall assessment of Normality	**YES**	**NEAR**	**NO**	**NO**

Table B. 13. Normality assessment for mean reaction time data (MRT) for study participants for day time and after dark trials.

ID	Participant 13		Participant 14	
Normality Test	**Day**	**Night**	**Day**	**Night**
Central Tendency				
Mean	345	332	415	433
Median	314	318	374	382
Normality ?	NO	YES	NO	NO
Graphical				
Histogram	NO	NO	NO	NO
Box Plot	NO	NO	NO	NO
Q-Q Plot	NO	NO	NO	NO
Normality ?	NO	NO	NO	NO
Measures of dispersion				
Skewness (within +/- 0.5)	1.12	1.04	1.30	1.41
Kurtosis (within +/-1.0)	1.22	1.42	2.44	1.93
Normality ?	NO	NO	NO	NO
Statistical tests				
Shapiro-Wilks Statistic Level of significance	0.001	0.001	0.001	0.001
Kolmogorov-Smirnov Statistic Level of significance	0.001	0.001	0.001	0.001
Normality? (not normal f $p<0.05$)	NO	NO	NO	NO
Overall assessment of Normality	**NO**	**NO**	**NO**	**NO**

Table B. 14. Normality assessment for mean reaction time data (MRT) for study participants for day time and after dark trials.

ID	**Participant 16**		**Participant 17**	
Normality Test	**Day**	**Night**	**Day**	**Night**
Central Tendency				
Mean	518	518	260	328
Median	482	469	252	310
Normality ?	NO	NO	YES	YES
Graphical				
Histogram	YES	YES	YES	YES
Box Plot	NO	NO	NO	NO
Q-Q Plot	NO	NO	NO	NO
Normality ?	NO	NO	NO	NO
Measures of dispersion				
Skewness (within +/- 0.5)	0.788	0.693	0.714	0.909
Kurtosis (within +/-1.0)	0.769	0.89	1.75	2.06
Normality ?	NEAR	NEAR	NO	NO
Statistical tests				
Shapiro-Wilks Statistic Level of significance	0.001	0.001	0.001	0.001
Kolmogorov-Smirnov Statistic Level of significance	0.001	0.001	0.001	0.001
Normality? (not normal f p<0.05)	NO	NO	NO	NO
Overall assessment of Normality	**NO**	**NO**	**NO**	**NO**

Table B. 15. Normality assessment for mean reaction time data (MRT) for study participants for day time and after dark trials.

ID	Participant 19		Participant 20	
Normality Test	**Day**	**Night**	**Day**	**Night**
Central Tendency				
Mean	220	200	450	447
Median	185	173	335	351
Normality ?	NO	NO	NO	NO
Graphical				
Histogram	NO	NO	NO	NO
Box Plot	NO	NO	NO	NO
Q-Q Plot	NO	NO	NO	NO
Normality ?	NO	NO	NO	NO
Measures of dispersion				
Skewness (within +/- 0.5)	1.84	3.08	1.28	1.09
Kurtosis (within +/-1.0)	3.22	11.96	1.31	0.302
Normality ?	NO	NO	NO	NO
Statistical tests				
Shapiro-Wilks Statistic Level of significance	0.001	0.001	0.001	0.001
Kolmogorov-Smirnov Statistic Level of significance	0.001	0.001	0.001	0.001
Normality? (not normal f $p<0.05$)	NO	NO	NO	NO
Overall assessment of Normality	**NO**	**NO**	**NO**	**NO**

Table B. 16. Normality assessment for mean reaction time data (MRT) for all participants for day time and after dark trials.

ID	**12 participants together**	
Normality Test	**Day**	**Night**
Central Tendency		
Mean	350	371
Median	311	316
Normality ?	YES	NO
Graphical		
Histogram	NO	NO
Box Plot	NO	NO
Q-Q Plot	NO	NO
Normality ?	NO	NO
Measures of dispersion		
Skewness	1.46	1.30
(within +/- 0.5)		
Kurtosis	2.77	1.71
(within +/-1.0)		
Normality ?	NO	NO
Statistical tests		
Shapiro-Wilks	0.001	0.001
Statistic		
Level of significance		
Kolmogorov-Smirnov	0.001	0.001
Statistic		
Level of significance		
Normality?	NO	NO
(not normal f p<0.05)		
Overall assessment of Normality	**NO**	**NO**

Table B. 17. Normality assessment for safety and non-safety categories of section B (After dark trials).

Normality Test	**Safety All**	**Non-safety all**	**Safety dual**	**Non-safety dual**	**Safety SCR**	**Non-safety SCR**
Central Tendency						
Mean	0.69	030	0.72	0.27	0.65	0.34
Median	0.66	0.33	0.71	0.28	0.61	0.38
Normality ?	YES	YES	YES	YES	YES	YES
Graphical						
Histogram	NO	NO	NO	NO	YES	YES
Box Plot	YES	YES	YES	YES	YES	YES
Q-Q Plot	NO	NO	YES	YES	YES	YES
Normality ?	NO	NO	NEAR	NEAR	YES	YES
Measures of dispersion						
Skewness (within +/- 0.5)	0.29	- 0.29	0.013	- 0.013	0.32	- 0.326
Kurtosis (within +/-1.0)	- 0.71	- 0.71	- 1.42	- 1.42	- 0.121	- 0.121
Normality ?	YES	YES	NO	NO	YES	YES
Statistical tests						
Shapiro-Wilks Statistic Level of significance	0.132	0.132	0.2	0.2	0.2	0.2
Kolmogorov-Smirnov Statistic Level of significance	0.478	0.478	0.406	0.406	0.925	0.925
Normality? (not normal f p<0.05)	YES	YES	YES	YES	YES	YES
Overall assessment of Normality	**YES**	**YES**	**NEAR**	**NEAR**	**YES**	**YES**

Table B. 18. Normality assessment for safety and non-safety categories of section B (Day time trials).

Normality test	**Safety All**	**Non-safety all**	**Safety dual**	**Non-safety dual**	**Safety SCR**	**Non-safety SCR**
Central Tendency						
Mean	0.58	0.41	0.43	0.40	0.57	0.42
Median	0.60	0.39	0.45	0.48	0.61	0.38
Normality ?	YES	YES	YES	YES	YES	YES
Graphical						
Histogram	NO	NO	YES	NO	YES	NO
Box Plot	NO	NO	NO	NO	NO	NO
Q-Q Plot	NO	NO	NO	NO	NO	NO
Normality ?	NO	NO	NO	NO	NO	NO
Measures of dispersion						
Skewness (within +/- 0.5)	0.54	- 0.54	- 0.247	- 0.66	- 0.957	0.955
Kurtosis (within +/-1.0)	0.125	0.125	0.071	- 1.06	1.02	1.04
Normality ?	NO	NO	YES	NO	NO	NO
Statistical tests						
Shapiro-Wilks Statistic Level of significance	0.516	0.516	0.326	0.067	0.47	0.48
Kolmogorov-Smirnov Statistic Level of significance	0.150	0.150	0.2	0.045	0.2	0.2
Normality? (not normal f p<0.05)	YES	YES	YES	NO	YES	YES
Overall assessment of Normality	**NEAR**	**NEAR**	**YES**	**NO**	**NEAR**	**NEAR**

Table B. 19. Normality assessment for safety and non-safety categories of section C (After dark trials).

Normality test	**Safety All**	**Non-safety all**	**Safety dual**	**Non-safety dual**	**Safety SCR**	**Non-safety SCR**
Central Tendency						
Mean	0.75	0.24	0.68	0.31	0.73	0.26
Median	0.77	0.23	0.75	0.24	0.78	0.22
Normality ?	YES	YES	YES	YES	YES	YES
Graphical						
Histogram	YES	NO	NO	NO	NO	NO
Box Plot	NO	NO	NO	NO	YES	YES
Q-Q Plot	NO	NO	NO	NO	NO	NO
Normality ?	NO	NO	NO	NO	NO	NO
Measures of dispersion						
Skewness (within +/- 0.5)	- 1.37	1.37	- 1.21	1.24	- 0.146	0.146
Kurtosis (within +/-1.0)	2.16	2.16	1.46	1.58	- 0.869	- 0.869
Normality ?	NO	NO	NO	NO	YES	YES
Statistical tests						
Shapiro-Wilks Statistic Level of significance	0.117	0.117	0.132	0.121	0.194	0.194
Kolmogorov-Smirnov Statistic Level of significance	0.095	0.095	0.2	0.2	0.2	0.2
Normality? (not normal f p<0.05)	YES	YES	YES	YES	YES	YES
Overall assessment of Normality	**NEAR**	**NEAR**	**NEAR**	**NEAR**	**YES**	**YES**

Table B. 20. Normality assessment for safety and non-safety categories of section C (Day time trials).

Normality test	Safety All	Non-safety all	Safety dual	Non-safety dual	Safety SCR	Non-safety SCR
Central Tendency						
Mean	0.63	0.36	0.68	0.31	0.65	0.35
Median	0.68	0.32	0.73	0.27	0.64	0.35
Normality ?	YES	YES	YES	YES	YES	YES
Graphical						
Histogram	NO	NO	YES	YES	YES	NO
Box Plot	YES	YES	YES	YES	YES	YES
Q-Q Plot	NO	NO	NO	YES	NO	NO
Normality ?	NO	NO	YES	YES	YES	NO
Measures of dispersion						
Skewness (within +/- 0.5)	- 0.495	0.495	- 0.249	0.232	- 0.735	0.720
Kurtosis (within +/-1.0)	0.470	0.470	0.982	0.935	1.73	1.70
Normality ?	YES	YES	YES	YES	NO	NO
Statistical tests						
Shapiro-Wilks Statistic Level of significance	0.451	0.451	0.883	0.873	0.591	0.614
Kolmogorov-Smirnov Statistic Level of significance	0.2	0.2	0.2	0.2	0.2	0.2
Normality? (not normal f p<0.05)	YES	YES	YES	YES	YES	YES
Overall assessment of Normality	**YES**	**YES**	**YES**	**YES**	**YES**	**NEAR**

Appendix C. The post hoc analysis: Normality assessments

Table C. 1. Normality assessment for fixation duration data of safety and non-safety categories for pedestrianised and on-road paths (day time and after dark trials).

Normality test	Safety Pedestrianised After dark	Non-safety Pedestrianised After dark	Safety On-road After dark	Non-safety On-road After dark	Safety Pedestrianised Day	Non-safety Pedestrianised Day	Safety On-road Day	Non-safety On-road Day
Central Tendency								
Mean	285	272	250	241	195	193	200	187
Median	295	245	243	201	202	184	202	147
Normality ?	YES	NO	YES	NO	YES	YES	YES	NO
Graphical								
Histogram	NO	NO	YES	NO	NO	NO	YES	NO
Box Plot	NO	YES	NO	NO	YES	YES	YES	NO
Q-Q Plot	YES	YES	YES	NO	YES	YES	YES	NO
Normality ?	NO	YES	YES	NO	YES	YES	YES	NO
Measures of dispersion								
Skewness (within +/- 0.5)	0.308	0.907	0.574	1.292	- 0.466	0.530	0.208	1.840
Kurtosis (within +/-1.0)	- 0.894	0.112	- 0.487	0.771	- 0.858	- 1.006	- 0.994	4.68
Normality ?	YES	NEAR	NEAR	NEAR	YES	NO	YES	NO
Statistical tests								
Shapiro-Wilks Statistic Level of significance	0.364	0.222	0.484	0.027	0.689	0.300	0.765	0.016
Kolmogorov-Smirnov Statistic Level of significance	0.200	0.200	0.200	0.113	0.200	0.922	0.200	0.121
Normality? (not normal f p<0.05)	YES	YES	NEAR	NEAR	YES	YES	YES	NEAR
Overall assessment of Normality	**YES**	**NEAR**	**YES**	**NO**	**YES**	**YES**	**YES**	**NO**

Table C. 2. Normality assessment for all fixations proportion data of safety and non-safety categories for pedestrianised and on-road paths (day time and after dark trials).

Normality test	**Safety Pedestrianised After dark**	**Non-safety Pedestrianised After dark**	**Safety On-road After dark**	**Non-safety On-road After dark**	**Safety Pedestrianised Day**	**Non-safety Pedestrianised Day**	**Safety On-road Day**	**Non-safety On-road Day**
Central Tendency								
Mean	0.66	0.34	0.89	0.10	0.55	0.44	0.85	0.14
Median	0.63	0.37	0.92	0.07	0.57	0.42	0.83	0.17
Normality ?	YES	YES	YES	YES	YES	YES	YES	YES
Graphical								
Histogram	NO	NO	NO	NO	NO	NO	NO	NO
Box Plot	NO	NO	NO	NO	YES	YES	NO	NO
Q-Q Plot	NO	NO	NO	NO	YES	YES	NO	YES
Normality ?	NO	NO	NO	NO	YES	YES	NO	NO
Measures of dispersion								
Skewness (within +/- 0.5)	1.166	- 1.142	- 2.322	2.322	- 0.501	0.501	0.673	- 0.673
Kurtosis (within +/-1.0)	0.677	0.528	6.368	6.368	0.002	0.002	- 0.951	- 0.951
Normality ?	NEAR	NEAR	NO	NO	YES	YES	NEAR	NEAR
Statistical tests								
Shapiro-Wilks Statistic Level of significance	0.102	0.099	0.002	0.002	0.877	0.877	0.137	0.137
Kolmogorov-Smirnov Statistic Level of significance	0.145	0.180	0.095	0.746	0.200	0.200	0.082	0.082
Normality? (not normal f p<0.05)	YES	YES	NEAR	NEAR	YES	YES	YES	YES
Overall assessment of Normality	**NEAR**	**NEAR**	**NO**	**NEAR**	**YES**	**YES**	**NEAR**	**NEAR**

Table C. 3. Normality assessment for all fixations proportion towards architectural buildings for pedestrianised and on-road paths (day time and after dark trials).

Normality test	Pedestrianised After dark	On-road After dark	Pedestrianised Day	On-road Day
Central Tendency				
Mean	228	162	156	155
Median	215	141	149	157
Normality ?	YES	NO	YES	YES
Graphical				
Histogram	YES	NO	NO	NO
Box Plot	YES	NO	NO	YES
Q-Q Plot	YES	YES	NO	YES
Normality ?	YES	NO	NO	YES
Measures of dispersion				
Skewness (within +/- 0.5)	0.668	0.808	1.135	- 0.536
Kurtosis (within +/-1.0)	- 0.493	- 0.581	3.602	0.366
Normality ?	NEAR	NEAR	NO	NEAR
Statistical tests				
Shapiro-Wilks Statistic Level of significance	0.422	0.367	0.085	0.865
Kolmogorov-Smirnov Statistic Level of significance	0.200	0.200	0.084	0.200
Normality? (not normal f p<0.05)	YES	YES	YES	YES
Overall assessment of Normality	**YES**	**NO**	**NO**	**YES**

Table C. 4. Normality assessment for fixations duration toward architectural buildings for pedestrianised and on-road paths (day time and after dark trials).

Normality test	**Pedestrianised After dark**	**On-road After dark**	**Pedestrianised Day**	**On-road Day**
Central Tendency				
Mean	0.040	0.008	0.088	0.075
Median	0.025	0.009	0.061	0.066
Normality ?	NO	YES	NO	NO
Graphical				
Histogram	NO	NO	NO	NO
Box Plot	NO	NO	YES	YES
Q-Q Plot	NO	YES	NO	NO
Normality ?	NO	NO	NO	NO
Measures of dispersion				
Skewness (within +/- 0.5)	1.74	0.752	2.377	0.750
Kurtosis (within +/-1.0)	3.46	0.092	6.680	- 0.449
Normality ?	NO	NEAR	NO	NEAR
Statistical tests				
Shapiro-Wilks Statistic Level of significance	0.017	0.043	0.002	0.253
Kolmogorov-Smirnov Statistic Level of significance	0.084	0.044	0.064	0.200
Normality? (not normal f p<0.05)	NEAR	YES	NEAR	YES
Overall assessment of Normality	**NO**	**NEAR**	**NO**	**NO**

Appendix D. Obstacle detection experiment: Normality assessments

Table D. 1. Normality assessment for detected height of the emergent obstacle for road light and bicycle light combinations (Experiment 1).

Normality test	R00 C0.1	R00 C0.3	R00 C1.0	R0.2 C00	R0.2 C0.1	R0.2 C0.3	R0.2 C1.0	R2.0 C00	R2.0 C0.1	R2.0 C0.3	R2.0 C1.0	R20 C00	R20 C0.1	R20 C0.3	R20 C1.0
Central Tendency															
Mean	9.7	8.76	5.93	7.60	10.97	9.21	7.09	5.38	7.30	9.58	6.60	5.52	4.09	4.67	4.92
Median	7.1	7.02	5.25	6.65	10.05	7.27	6.52	4.20	6.85	9.80	5.85	4.12	3.67	3.77	4.20
Normality ?	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Graphical															
Histogram	NO	NO	NO	NO	YES	NO	YES	NO	NO	NO	NO	NO	YES	NO	YES
Box Plot	NO	NO	NO	YES	YES	NO	NO	NO	NO	YES	YES	NO	YES	NO	YES
Q-Q Plot	NO	NO	NO	NO	NO	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO
Normality ?	NO	NO	NO	NO	YES	NO	YES	NO	NO	NO	NO	NO	YES	NO	YES
Measures of dispersion															
Skewness (within +/- 0.5)	2.78	1.31	2.58	0.60	0.99	1.11	1.17	2.86	2.29	0.078	0.70	2.45	0.574	2.30	0.57
Kurtosis (within +/-1.0)	8.15	0.62	7.52	- 1.65	0.373	- 0.322	1.52	8.64	6.15	- 1.83	- 0.63	6.62	- 0.397	5.74	- 1.48
Normality ?	NO	NEAR	NO	NO	NEAR	NEAR	NO	NO	NO	NO	NEAR	NO	NEAR	NO	NO
Statistical tests															
Shapiro-Wilks Statistic Level of significance	0.001	0.027	0.001	0.087	0.373	0.015	0.392	0.001	0.003	0.210	0.395	0.001	0.651	0.001	0.123
Kolmogorov-Smirnov Statistic Level of significance	0.009	0.153	0.006	0.191	0.300	0.015	0.200	0.001	0.004	0.213	0.200	0.061	0.200	0.027	0.200
Normality? (not normal f p<0.05)	NO	NEAR	NO	NO	YES	NO	YES	NO	NO	YES	YES	NEAR	YES	NO	YES
Overall assessment of Normality	**NO**	**NO**	**NO**	**NO**	**YES**	**NO**	**YES**	**NO**	**NO**	**NO**	**YES**	**NO**	**YES**	**NO**	**YES**

* R = Road light; C = Bicycle light.

Table D. 2. Normality assessment for detected height of emergent obstacle for road light and variations of cycle lamp mounting position (only 0.32 cd/m^2 bicycle luminance was tested) tested in the obstacle detection (Experiment 2).

Normality test	R00 HLM	R00 HND	R00 HUB	R0.2 HLM	R0.2 HND	R0.2 HUB	R2.0 HLM	R2.0 HND	R2.0 HUB	R20 HLM	R20 HND	R20 HUB
Central Tendency												
Mean	12.77	7.43	3.98	12.69	8.49	4.47	9.43	4.11	6.18	4.56	5.28	5.29
Median	12.50	6.3	3.32	10.10	8.35	3.70	8.97	4.95	5.17	4.12	4.65	4.22
Normality ?	YES	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Graphical												
Histogram	YES	NO	NO	YES	YES	NO	NO	NO	NO	NO	NO	NO
Box Plot	YES	NO	NO	YES	YES	NO	YES	NO	NO	YES	NO	YES
Q-Q Plot	NO	NO	NO	NO	YES	NO	NO	NO	NO	NO	NO	NO
Normality ?	YES	NO	NO	YES	YES	NO	NO	NO	NO	NO	NO	NO
Measures of dispersion												
Skewness	0.13	1.23	1.83	0.86	0.76	1.72	- 0.04	- 2.39	1.10	0.324	1.59	1.19
(within +/- 0.5)												
Kurtosis	-0.001	1.63	4.28	- 0.21	0.82	2.64	- 1.82	6.64	0.198	- 1.58	2.44	0.393
(within +/-1.0)												
Normality ?	YES	NO	NO	NEAR	NEAR	NO	NEAR	NO	NEAR	NEAR	NO	NEAR
Statistical tests												
Shapiro-Wilks	0.921	0.169	0.032	0.276	0.763	0.011	0.157	0.001	0.094	0.209	0.044	0.073
Statistic												
Level of significance												
Kolmogorov-Smirnov	0.159	0.200	0.200	0.193	0.200	0.013	0.142	0.003	0.200	0.082	0.840	0.174
Statistic												
Level of significance												
Normality?	YES	YES	NEAR	YES	YES	NO	YES	NO	YES	YES	NEAR	YES
(not normal If p<0.05)												
Overall assessment of Normality	**YES**	**NO**	**NO**	**YES**	**YES**	**NO**	**YES**	**NO**	**YES**	**YES**	**NO**	**YES**

* R = Road light; C = Bicycle light.

Table D. 3. Normality assessment for detected height of the emergent obstacle for road light and bicycle light combinations (Experiment 3)

Normality test	R00 C0.1	R00 C0.3	R00 C1.0	R0.2 C00	R0.2 C0.1	R0.2 C0.3	R0.2 C1.0	R2.0 C00	R2.0 C0.1	R2.0 C0.3	R2.0 C1.0	R20 C00	R20 C0.1	R20 C0.3	R20 C1.0
Central Tendency															
Mean	4.05	3.16	3.79	6.30	3.47	3.31	2.82	4.31	5.78	5.52	4.08	3.32	4.46	3.99	5.15
Median	3.52	3.20	3.30	5.32	3.47	3.32	2.75	3.67	5.70	5.55	3.40	3.15	3.97	4.02	4.65
Normality ?	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Graphical															
Histogram	YES	YES	NO	NO	YES	NO	NO	NO	NO	YES	NO	NO	NO	NO	NO
Box Plot	YES	YES	NO	NO	NO	YES	NO	NO	YES	YES	NO	NO	YES	NO	NO
Q-Q Plot	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES	NO	NO	NO	NO	NO
Normality ?	YES	YES	NO	NO	NO	NO	NO	NO	YES	YES	NO	NO	NO	NO	NO
Measures of dispersion															
Skewness (within +/- 0.5)	0.88	- 0.07	1.98	1.88	0.050	0.96	1.65	1.00	-0.45	- 0.55	1.86	1.77	0.41	1.39	2.19
Kurtosis (within +/-1.0)	- 0.31	- 0.32	4.27	4.18	1.69	1.07	4.59	- 0.127	0.64	1.77	3.70	4.14	- 0.54	2.87	5.78
Normality ?	YES	YES	NO	NO	NEAR	NO	NO	NEAR	YES	NO	NO	NO	YES	NO	NO
Statistical tests															
Shapiro-Wilks Statistic Level of significance	0.141	0.59	0.009	0.023	0.726	0.393	0.032	0.09	0.875	0.637	0.014	0.027	0.824	0.055	0.003
Kolmogorov-Smirnov Statistic Level of significance	0.200	0.94	0.012	0.108	0.200	0.200	0.27	0.86	0.200	0.200	0.020	0.043	0.200	0.076	0.009
Normality? (not normal f $p<0.05$)	YES	YES	NO	NEAR	YES	YES	NO	YES	YES	YES	NO	NO	YES	YES	NO
Overall assessment of Normality	**YES**	**YES**	**NO**	**NO**	**YES**	**NEAR**	**NO**	**YES**	**YES**	**YES**	**NO**	**NO**	**YES**	**NEAR**	**NO**

Appendix E. Contrast measurements: Obstacle detection

Table E. 1. Measurements of luminance at the side/surround of the obstacle with calculated contrast value under each road and bicycle light combinations (experiment1: cycle lamp mounted at handlebar).

Test condition		Obstacle luminance		Contrast
Illuminance (lux)	Bicycle lamp (cd/m2)	Side of obstacle	Surround of obstacle	
0	0	0.001	0.001	0.000
0	0.1	0.078	0.059	0.320
0	0.316	0.248	0.206	0.207
0	1.0	0.800	0.623	0.284
0.2	0	0.013	0.017	-0.220
0.2	0.1	0.087	0.076	0.140
0.2	0.316	0.261	0.219	0.191
0.2	1.0	0.808	0.645	0.253
2.0	0	0.078	0.124	-0.372
2.0	0.1	0.153	0.186	-0.176
2.0	0.316	0.328	0.329	-0.002
2.0	1.0	0.870	0.759	0.146
20	0	0.756	1.228	-0.385
20	0.1	0.850	1.269	-0.330
20	0.316	1.028	1.429	-0.281
20	1.0	1.585	1.840	-0.139

Table E. 2. Measurements of luminance at the side/surround of the obstacle with calculated contrast value under each road and bicycle light combinations (experiment 2: cycle lamp mounted at three positions).

Test condition		Obstacle luminance		Contrast
Illuminance (lux)	Bicycle lamp (cd/m2)	Side of obstacle	Surround of obstacle	
0	Helmet	0.167	0.172	-0.027
0	Handlebar	0.248	0.206	0.207
0	Hub	0.208	0.118	0.758
0.2	Helmet	0.177	0.182	-0.029
0.2	Handlebar	0.261	0.219	0.191
0.2	Hub	0.208	0.128	0.629
2.0	Helmet	0.255	0.285	-0.106
2.0	Handlebar	0.328	0.329	-0.002

2.0	Hub	0.262	0.240	0.090
20	Helmet	1.088	1.337	-0.186
20	Handlebar	1.028	1.429	-0.281
20	Hub	1.075	1.273	-0.156

Table E. 3. Measurements of luminance at the side/surround of the obstacle with calculated contrast value under each road and bicycle light combinations (experiment3: cycle lamp mounted at the hub).

Test condition		**Obstacle luminance**		**Contrast**
Illuminance (lux)	Bicycle lamp (cd/m2)	Side of obstacle	Surround of obstacle	
0	0	0.001	0.001	0.000
0	0.1	0.066	0.039	0.716
0	0.316	0.208	0.118	0.758
0	1.0	0.637	0.401	0.586
0.2	0	0.014	0.015	-0.109
0.2	0.1	0.068	0.050	0.367
0.2	0.316	0.208	0.128	0.629
0.2	1.0	0.621	0.360	0.728
2.0	0	0.093	0.123	-0.244
2.0	0.1	0.144	0.156	-0.079
2.0	0.316	0.262	0.240	0.090
2.0	1.0	0.632	0.521	0.212
20	0	0.918	1.207	-0.239
20	0.1	0.960	1.194	-0.196
20	0.316	1.075	1.273	-0.156
20	1.0	1.439	1.609	-0.106

Published research arising from the thesis

Journal paper

Fotios, S., **Qasem, H.**, Cheal, C., & Uttley, J. (2017). A pilot study of road lighting, cycle lighting and obstacle detection. *Lighting Research & Technology, 49(5),* 586-602.

Book chapter

Uttley, J., Simpson, J., & **Qasem, H**. (2018). Eye-Tracking in the Real World: Insights About the Urban Environment *Handbook of Research on Perception-Driven Approaches to Urban Assessment and Design* (pp. 368-396): IGI Global.

Conference proceedings papers

Castleton, H., Fotios, S., **Qasem, H**. (2015). *Lighting for cycling: detecting road surface hazards.* Paper presented at the 28th Session of the CIE, Manchester, UK.

Uttley, J., **Qasem, H.**, Fotios, S. (2016). *Using skin conductance to indicate attention to environmental features – a pilot test.* Paper presented at the IAPS 2016, The human being at home work and leisure, Lund.

Uttley, J., Fotios, S., **Qasem, H**. (2016). *Characteristics of salient trip hazards based on eye-tracking data.* Paper presented at the IAPS 2016, The human being at home work and leisure, Lund.

Qasem H., Uttley. J., Fotios S. (2017). *Lighting for cyclists: an Eye Tracking Study in Natural Settings to Investigate Where They Look.* Paper presented at the Lux Europa 2017, Ljubljana, Slovenia.

Fotios, S., Uttley, J., Fox, S., **Qasem, H.** (2017). *A Novel Method For Demonstrating That Light Encourages Pedestrian Activity.* Paper presented at the Lux Europa 2017, Ljubljana, Slovenia.

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