MASTER

Critical visual tasks of cyclists after dark : an exploratory study

a field study on the visual behavior of bicyclists in a complex natural environment

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‘Critical visual tasks of cyclists after dark: an exploratory study’

A field study on the visual behavior of bicyclists in a complex natural environment

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Abstract

The number of cyclists has been widely increased in the world over the years. Meanwhile, current street lighting is mainly designed only on the needs of car drivers. Scientific research about the gaze behavior of cyclists' is needed to improve road lighting for cyclists to increase safety at night. Nonetheless, the number of research on cyclists' gaze behavior is very limited up to now. Besides, the majority of the studies which has been conducted of cyclist eye movements were executed in a controlled indoor environment. Therefore, the work presented in this master thesis investigated the gaze behavior of cyclists in an exploratory field study at night by capturing fixation positions with the aid of an eye-tracker. A secondary auditory task was used to distinguish critical fixations from non-critical fixations. Ten participants cycled a track three times under three conditions (normal speed, high speed, threat) while performing a secondary auditory reaction time task. This study explored an outlier method to identify critical fixations of cyclists using the dual task methodology. A critical eye fixation can be defined as an eye fixation that deduces the performance of a secondary task. Delayed responses to a secondary auditory task indicate cognitive attention to the primary visual task. Different cutoff points (thresholds) of reaction times were used to differentiate critical fixations from non-critical fixations. It was found that different cutoff methods leads to different distributions of the proportions of critical fixations.

Findings of this study suggested that there were small differences in critical fixations when cyclists were cycling at a normal speed, a high speed, and when cyclists felt threatened. Overall results showed that critical fixations were mainly focused on the goal, path, and pedestrians in critical times. It can be concluded that a cyclist's main task at night is to navigate and to steer. Next to this, cyclists need to focus on pedestrians to avoid collision. In addition, cyclists did not often look for or look at salient objects. Instead, cyclists tend to use a combination of visual strategies used by pedestrians (looking at near path) and car drivers (looking at far path). Focusing on obstacles appeared to be less important than scanning the surroundings. From these results one could conclude that top-down processes were of more importance than bottom-up processes while cycling at night. However, one environment feature, namely the sidewalk, appeared to be often fixated on in critical times compared to non-critical times. Furthermore, cyclists tend to focus on pedestrians when they are in a far distance, especially when cyclists feel threatened. Lastly, cyclists mainly fixated on pedestrians' bodies instead of their faces, suggesting that cyclists are more interested in the direction of pedestrians to avoid collision than identifying whether other road users are a possible threat or not. Combining those results, new road lighting guidelines should include lighting that is directed towards the sidewalk parallel to the bicycle path.

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Best, Huyen

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Chapter 1: Introduction

The number of cyclists has been widely increased in the world over the years (Juhra et al., 2012). This activity has extensively been promoted, because of its positive health and environmental aspects. Advantages of cycling are for example, more physical exercise among citizens, less air pollution, and less noise in a city (Juhra et al., 2012). The Netherlands are known to be the leading country of cycling in the world (Schepers et al., 2011). In the Netherlands, cyclists have their own traffic lanes and signs, and there are even bicycle highways. In other words, they are able to drive safely on their own paths next to motorized vehicles (Schepers et al., 2011). However, accidents still occur among cyclists, especially at night (Schepers et al., 2013). Several studies found out that cyclists tend to have a higher risk for an accident at night compared to daytime travels (Johansson, Wanvik & Elvik 2009; Schepers et al., 2013; Wanvik, 2009). An absence of daylight could cause higher risk of accidents. Therefore, street lighting might compensate for the absence of daylight during nights. However, those lights are mainly focused on drivers' needs to see objects on the roads (Schepers et al., 2013). In other words, the need of visibility of pedestrians and cyclists are hardly considered when designing road lighting. Moreover, a study of Westerhuis and De Waard (2016) suggested that the intentions and behavior of cyclists are not always visible for other road users. During daytime and at night the behavior of cyclists are complicated to understand for other road users. Furthermore, scientific evidence about cyclists' behavior is in general limited available. One can argue that it is necessary to understand how cyclists behave in traffic participation to improve road lighting, physical and personal safety for cyclists. Therefore, this study is aimed to study the visual behavior of cyclists.

1.1 Previous work on cyclist's gaze behavior

As stated before, the number of research on cyclists' gaze behavior is very limited up to now. Meanwhile, the majority of these studies of cyclist eye movements was conducted in a controlled indoor environment using videos recordings or simulations (Igari, Shimizu & Fukuda, 2008; Wilkie, Wann & Allison, 2008; Vansteenkiste, 2015; Zeuwts et al., 2016; Frings, Parkin & Ridley, 2014). Laboratory studies with simple tasks might not provide a real representation of complex traffic situations. Therefore, the ecological validity of many of these studies is low. For example, Vlakwerk and colleagues (2015) suggested that in complex traffic situations, the mental workload is higher than in a simple traffic situation. Furthermore, pedestrians rarely follow the active circulation rules in real traffic and they frequently cause disturbance to cyclists according to Bernardi, Krizek and Rupi (2016). Therefore, behavior in a laboratory is likely to be different from behavior in real-life traffic participation. In contrast, Zeuwts et al. (2016) suggested that lab studies provide valuable information for certain tasks. During their experiments, they measured the fixation percentages of cyclists (dwell time) in a laboratory and compared these results with field results. Results demonstrated that on a low-quality bicycle path, eye fixations were predominantly driven towards the road. They found comparable dwell times for the low quality bicycle path in lab and field research. On the contrary, they found different outcomes in dwell time when cycling on a high-quality bicycle path for lab and field research (Zeuwts et al., 2016). In other words, these results suggested that when task complexity increases (low quality bicycle path), the differences in lab and real life might disappear. However, multiple lab applications still included limitations because those experiments were only focused on a single maneuver, such as steering in a curve. In other words, those researches did not consider the whole and more complex traffic situation, such as sharing the space with other road users. So, these implementations might lack of realism during the lab applications. Until now, only a handful of studies were conducted about cyclists' gaze behavior in a natural environment (Mantuano, Bernardi & Rupi, 2017; Vansteenkiste, Zeuwts, Cardon, Philipparts & Lenoir, 2014; Qasem, Uttley & Fotios, 2017). Moreover, even less studies explored the visual behavior of cyclists after dark. Therefore, this study is aimed to explore the visual behavior of cyclists after dark in a field study.

1.2 Visual tasks after dark

Technical solutions, such as street lighting and reflective materials, increase the safety of driving, walking, and cycling at night. Night vision and visual performance is mainly studied regarding physical safety (Van Bommel, 2015). The focus of road lighting research is based on the visibility of the environment, potential hazards, and other road users (Fors & Lundkvist, 2009). Road users should be able to judge distance between road users and speed of other participants, as well as the travel direction. Fors and Lundkvist's literature review (2009) argued that there were no substantial differences in accident risk for car drivers between dark and daylight. In contrast, they argued that pedestrians had a higher risk of having an accident at night. During night driving, the mental workload of a driver increases compared to daytime. A small amount of light at night results in a higher mental workload to detect obstacles and pedestrians. Van Bommel (2015) also mentioned that the ability to do a specific task is based on task size, task luminance and the luminance contrast of the task relative to its background. Caminada and Van Bommel (1984) published a paper with a classification of the requirements for lighting on residential roads, regarding the safety and social aspects of road users. They mentioned four key requirements that road lighting should enable road users to perform or to have at night: obstacle detection, identification of other road users, a need of reassurance, and a need of pleasant view at night. However, these requirements of Caminada and Van Bommel (1984) were never been validated with empirical evidence. These assumptions have been made, and based on that, they decided which light conditions belong to those requirements. Until now, it is not known which task is essential in a complex real-life environment. As human behavior is one of the main cause of accidents, the visual perception of facilities has an important role in bicycle crashes (Schepers et al., 2014). However, road lighting recommendations do not exist for cyclists. In order to develop these recommendations, we first need to know what features in the environment is essential for cyclists to guide them through the world. Therefore, we need to study the critical visual tasks of cyclists specifically. It is important to know which areas should be visible in critical times at night to contribute to a safer environment.

1.3 Research goals

The current study explored the identification of critical visual tasks of cyclists after dark in a complex natural environment. In addition, the study is part of a two larger projects. One specific goal of this project is the improvement of road lighting for cyclists, as part of the project 'outdoor quality of light' at Signify (previously known as Philips Lighting). The project 'outdoor quality of light' aims at improving outdoor road lighting for traffic participants by investigating different aspects of road lighting characteristics and traffic participation behavior. The second goal of this study is the contribution to virtual environment (VE) research. In other words, this current study is part of a validation project of the use of VE in research. Scientists frequently conclude outcomes only based on a VE study without comparing it to a natural environment (Wilson & Soranzo, 2015). Therefore, research should be conducted in a real-life setting as well as in laboratories to validate these results. It should be investigated whether visual behavior is the same in a virtual environment as in a real-life setting before results of a VE and a real-life situation could be generalized (De Kort, IJsselstein, Kooijman & Schuurmans, 2003). This current study examined this field and results might contribute to VE technology usage as a research methodology in the future. So, this study analyzed the visual behavior of cyclists in a real complex environment. The results will be compared with behavior in a virtual environment in a later study. Moreover, study outcomes will be used to improve a virtual environment of the test location, which can be used in further studies. A detailed description of the research aims of current study is provided in the next chapter after the theoretical framework.

Chapter 2: Theoretical framework

The theoretical framework provides background information about visual behavior and previous research about gaze behavior in traffic situations. First, previous research of visual behavior is described in 2.1. This paragraph describes how, where, and, why do we pay attention at specific features in our environment. Basic information about night vision can be found in Appendix I. Second, in 2.2 and 2.3 the deeper understanding of the visual control in locomotion and traffic participation are presented. Third, the dual task methodology to indicate critical eye fixations is further explained in 2.4. Paragraph 2.5 presents the research aims and the research question of this master thesis.

2.1 Visual behavior

2.1.1 Eye movements

Eye vision is the combination of different eye movement types: saccades, fixations, smooth pursuit, and vergence (Duchowski, 2007). The ‘saccade and fixate’ strategy is the main visual strategy used in daily life (Land, Mennie & Rusted, 1999). Saccades are eye movements that relocate approximately three times per second; they describe the voluntary and rapid reflex moments (Duchowski, 2007). A saccade is a rapid change of the eye orientation to a point of attention (Land, 2006). Next to this, there are relative stable periods between two saccades in which the eye is in a fixed position of at least 20 ms till 500 ms. These eye movements are called fixations. It is commonly accepted that the human brain can process a minimal duration of 100ms as a useful fixation (Duchowski, 2007). One fixates on particular places in the environment, because our attention is allocated to that place. Aside from the ‘saccade and fixate’ strategy, smooth pursuit movements aid to stabilize the image on the retina and occur when tracking a small moving object with low velocities. A ‘catch-up saccade’ corrects for the latency of the eyes (100 to 150 ms) when a stationary object starts to move (Land, 2009). At last, vergence eye movements are the eye movements adjusting the angle between the eyes in function of the distance to the object needed for depth perception (Duchowski, 2007). The main focus of this thesis are the eye fixations.

2.1.2 Attention allocation

Human eyes constantly shift the focus of the fovea to enable seeing all relevant parts of the visual environment with high acuity (Land, 2006). A process called overt visual attention is started when making eye, head and body movements. By a continuous sequence of saccades and fixations, one attends to look at something where attention is given to. Bottom-up and top-down stimuli control from overt visual attention. Bottom-up visual attention mainly serves as a filter selecting potentially interesting points in the stimulus. This selection will be further processed under supervision of top-down influences. In that case, both someone’s interests and memory are important while focusing attention on the environment. In contrast, covert visual attention is a process of mentally shifting the attention point on a specific part of the visual field without necessary moving one's eyes. For example, eyes can be focused on the right part of the image, but one has moved the attention (covertly) to the middle part of the image without moving our eyes. Understanding the factors that determine where fixations are placed is a fundamental goal of studying gaze control in scene viewing (Land, 2006). Henderson, Brockmole, Castelhano & Mack (2007) generated two general hypotheses of gaze control: the visual salience hypothesis and the cognitive control hypothesis.

Visual saliency hypothesis

Previously, it has been described that the eyes relocate several times within a second (Duchowski, 2007). This often happens spontaneously and unconsciously, suggesting that saliency provoke eye movements (Desimone & Duncan, 1995). Visual salience is driven by bottom-up processes; a stimulus-driven signal announces that a feature in the environment can be sufficiently distinguished from its surroundings and deserves attention. An item can, for example, pop-out from its surroundings and attract attention (Treisman & Gelade, 1980; Itti & Koch, 2001). For example, in a task-free viewing, the eyes are attracted towards remarkable features or areas of high contrast in the environment. Salience is therefore the consequence of an interaction of a stimulus with other stimuli, as well as with the visual system. According to the contrast saliency model of Itti, Koch & Niebur (1998), built upon the feature-integration theory of Treisman & Gelade (1980), there are three basic features that are known to result in a pop-out: intensity, color, and orientations (Mannan et al., 1996; Tatler, Baddeley and Gilchrist, 2005; Turatto and Galfano, 2001). Moreover, the features motion and shape are additional important features to this theory (Mital, Smith, Hill & Henderson, 2011). Salient features in traffic are for example the motion or the head lights of other road users at night. In addition, changes in colors of traffic lights can predict the fixation in a scene. On one hand, salience can also be seen as an unexpected or surprising visual stimulus (Itti & Baldi, 2006). Bruce & Tsotsos (2009) defined salience as a surprising extent of which a region differs from its neighborhood. For example, an obstacle or another road user pops-out during cycling. While on the other hand, attentional capture by a salient object might occasionally be irrelevant. A salient object might be just a distractor. For example, one might look at an attractive pedestrian while cycling, whereas this fixation does not necessary increase one's performance of reaching his or her destination. Another example is when one looks at a shop window because there are colored LED lights. These pop-out attracted one's eyes but might not be necessary for safe cycling or reaching a destination.

Cognitive control hypothesis

'Top-down' driven eye movements occur when an individual is presented with a task (e.g finding a flower in a grass field; Yarbus, 1967). The goal of the task mainly guided the eyes rather than image properties (Henderson, 2003; Chen & Zelinsky, 2006; Henderson et al., 2007). Internal information that is not present in a stimulus that influences this process are for example the specific task, prior experience, knowledge, and interests of a person (e.g. the cyclist should arrive safe at his/her destination during cycling, so he will search for obstacles or traffic signs). While crossing a road, a cyclist will look at the right and left side of the road, because previous experiences and knowledge suggest that another road user could appear.

2.1.3 Gaze strategy in daily tasks

Eye movements are often investigated with eye-tracking research (Land & Hayhoe, 2001; Land, 2006). Earlier studies of eye-tracking investigated eye movements across a range of daily tasks, such as tea-making (Land, Mennie, Rusted, 1999), sandwich making (Hayhoe, Shrivastava, Mruczek & Pelz, 2003), and hand washing (Pelz and Canosa, 2001). In general, one fixates to retrieve information from a specific location. These fixations occur to retrieve necessary information for an action, while doing a specific task. These studies have demonstrated that fixations provided information needed for future actions and these are directed to task-relevant areas (Rothkoph, Ballard & Hayhoe, 2007). According to the previous mentioned studies, fixations on irrelevant objects were rare and the majority of fixations were focused on task specific objects.

2.2 Traffic participation

2.2.1 Attention in traffic participation

In a traffic participation task, such as driving (Land & Lee, 1994; Land and Horwood, 1995; Salvucci, 2006), walking (Hollands, Patla & Vickers, 2002; Patla and Vickers, 2003), and crossing an intersection (Geruschat, Hassan & Turano, 2003), humans also tend to fixate to task-relevant areas that provide critical information for future actions. These complex tasks consist of multiple actions or objects that require attention and action that needs to be performed. As human behavior is one of the main causes of accidents, the visual perception of facilities plays an important role in bicycle crashes (Schepers et al., 2015). In other words, a wrong or confusing reading of an unstructured path can cause the perception of an unsafe environment. Furthermore, lack of visual information or an inconsistent design can increase unsafe situations (Sener, Eluru & Bhat, 2009). In addition, a high visual workload determines an excessive need of concentration that can lead the user to perceive the path as uncomfortable and to modify his travel choice (Schepers et al., 2015). Investigation of cycling gaze behavior is necessary to understand cyclists travel preferences to improve cycling facilities (Sener, Eluru & Bhat, 2009). To understand the visual behavior in traffic participation, we need to understand how our behavior is influenced by a complex traffic environment (Lim, Sayed & Navin, 2004). A traffic situation is never the same at the same road. Newell (1986) described that motor behavior consist of the link between an individual, a task, and the environment. Fotios, Uttley and Yang (2015) stated that the number of pedestrians on the road influences the gaze behavior of cyclists. It could be argued that all dynamic features in the environment could play a role in the gaze behavior of cyclists. Therefore, the number of cars, pedestrians, and cyclists encountered should be taken into consideration when studying the gaze behavior of road users.

Both internal drives and external stimuli affect our behavior. On one hand, traffic participation is mainly controlled by external stimuli, such as flashing lights of vehicles, or seeing salient obstacles. On the other hand, internal drives and memory will control for traffic behavior. In more complex tasks (e.g. urban driving) the driver must alternate attention between the road, pedestrians, bicyclists, and so on. Working memory is, therefore, an essential component for recollecting information regarding the direction of moving vehicles or the location of traffic lights and traffic signs. Recent evidences suggest that fixation sites are less tied to saliency when meaningful scenes are viewed during active viewing tasks (Land & Hayhoe 2001; Turano, Geruschat & Baker, 2003). Although both bottom-up and top-down factors contribute to gaze control in natural behavior, researchers seem to agree that 'bottom-up' processes are of limited relevance during goal-oriented actions such as road-crossing (Land, 2006; Tatler, Hayhoe, Land & Ballard, 2011). It has been suggested that short-term memory influences the visual search patterns during active tasks instead of salient objects. Furthermore, research suggest that people can avoid fixating on salient points if they are not task-relevant and focus more on task goals (Einhauser, Rutishauser & Koch, 2008; Foulsham & Underwood, 2007). Visual search patterns are directed almost exclusively towards the task-relevant features, which are often temporarily linked to ongoing actions (Hayhoe and Ballard, 2005; Henderson, 2003). However, during free scene exploration, visual behavior is under the control of bottom-up control in the first instances, followed by top-down control for further and more detailed analysis (Helo, Pannasch, Sirri & Rama, 2014). Because a visual stimulus is a driving force, the bottom-up influences are more universal and differ less among individuals. Bottom-up influences can be seen as the result of early visual processes. Salient features are often associated with being important based on prior experiences of a road user. For example, a cyclist knows that he has to wait for a red traffic light. Another example is that we have to wait for road users who are passing by.

2.2.2 Models of traffic participation

Two generally accepted models of traffic participation are the situational awareness model of Endsley (1995) and the SEEV model of Wickens & Horrey (2008). These models are mainly based on the behavior of car drivers and explains how we allocate our attention in traffic.

The four elements of the SEEV-model described by Wickens and Horrey (2008) include: Salience, Effort, Expectancy, and Value. To maximize the benefits and minimize the costs, this model attempts to predict where a person would focus their attention to. *Salience* and *effort* are both bottom-up factors, whereas e*xpectancy* and *value* are top-down processes. Salience is explained before and mainly describes the conspicuity of the environment. Effort refers to the effort needed to shift focal attention from one location to the other location. Expectancy is based on memory, past experiences, and contextual tools. Gaze will be directed to relevant areas where useful information is expected to be found. Value, on the other hand, is the importance of specific information. In addition, Value includes the probability of the occurrence of an event. According to the SEEV-model, we can argue that in terms of night vision, cyclist might detect hazards or other road users by top-down process and bottom-up processes. As stated before, studies with car drivers suggested that a driver's attention is mainly guided by its expectations, experience, knowledge and goals (top-down processes). The road dynamics, on the other hand, drive bottom-up processes. Road dynamics can for example be traffic signs or other road users (Wickens & Horrey, 2008).

The other model by Ensley (1995) states that there are three levels to maintain awareness when navigating through traffic: *perception, comprehension, and projection*. First, we perceive elements of the environment within a volume of time and space. Second, we need to comprehend the meaning of these elements in the current situation. Third, perception and comprehension are employed to project future actions of the elements in the environment. These levels will result into decision making and action guidance (Ensley, 1995).

2.3 Visual control in locomotion

Vision is one of the sensory systems needed for the control of locomotion (Patla, 1998). Determining when, where, what, and how different visual information is acquired is critical to our understanding of visual control of human locomotion (Patla, 1998). Head-and-body movements enables to investigate the relation between gaze and locomotion. (Duchowski, 2002; Patla and Vickers, 2003; Land, 2009; Franchak and Adolph, 2010). As stated before, information from task specific visual search patterns usually guided goal directed locomotion (Hayhoe & Ballard, 2005). These search patterns are normally learned, suggesting that gaze behavior for novice people is different than for experts or people who are known with the situation. The majority of locomotion studies are conducted with car drivers and pedestrians (Gegenfurtner, Lehtinen, Säljo, 2011; Klauer et al., 2014). Cyclists differ in needs compared to pedestrians and car drivers. Speed, balance, and having a restricted or unrestricted visual field are factors that are different among road users. As the research of cyclists is limited, it is useful to understand the gaze behavior of pedestrians and car drivers as well. Gaze behavior in specific situation might be the same for both cyclist and pedestrians, or both cyclist and car drivers. In the end, cyclists, pedestrians, and car drivers have to share road lighting.

2.3.1 Gaze behavior of pedestrians

Gaze behavior research has extensively been conducted on pedestrians walking a simple route and obstacle avoidance during daytime (Marigold et al., 2007; Patla, 1997; Turano, Geruschat & Baker, 2001; Hollands, Patla & Vickers, 2002; Patla and Vickers, 2003; Kitizawa & Fujiyama, 2010). Visual information is essential for navigation, obstacle avoidance, and path selection while walking.

Moving forward

While walking a simple path, gaze does not have to be directed to the path (Turano et al., 2001). On an object-free path, visual attention is directed to heading direction or other objects in the environment (Higuchi & Yoshida, 2013). When pedestrians change direction along a simple travel path, findings suggested that gaze movements anticipate body movement (Hollands et al., 2002). The task is simple that one does not need gaze to something specific. Moreover, Hollands et al. (2002) argued that some fixations are executed because there is nothing necessary to look at. Therefore, in some cases, pedestrians often looked at the pavements.

When one is walking in a more complex environment, one must coordinate the movements over different surfaces and needs to detect the presence of obstacles in addition to heading towards the goal (Patla & Vickers, 2003). People primarily direct their gaze in the direction they are heading to retrieve information for future movements. In a more challenging road, pedestrians fixate on average two steps ahead while stepping forwards and carrying along during walking (Patla & Vickers, 2003). This finding suggested that looking at the path becomes more important when a task is more challenging. Patla and Vickers (2003) argued that this specific type of fixation, called the travel fixation, occurred during walking. Gaze will move to a ‘look ahead’ strategy of approximately one till two seconds o plan changes in walking pattern (Hollands, Marple-Horvat, Henkes & Rowan, 1995; Patla & Vickers, 2003; Pelz & Rothkopf, 2007; Higuchi & Yoshida, 2013). This phenomenon can be called a visual buffer, as gaze is proactive during locomotion. However, Marigold and Patla (2007) found contradictory results. They found that only a small proportion of fixations was directed towards the travel direction. Marigold and Patla (2007) suggested that travel gaze will occur less when there are more interesting features in the environment to look at. In other words, different findings may be due to the available stimuli in environment of the experiment.

Obstacle avoidance

When visual information is needed for obstacle avoidance and accommodation, placement of the feet should be more precisely (Hollands, Patla & Vickers, 2002). Marigold and Patla (2007) suggested that spatial information of the approaching ground area was sampled in small parts. This information will continuously be updated as an individual moves forward, suggesting that one is able to adapt to stability issues and unexpected ground terrain changes. In addition, Marigold, Weerdesteyn, Patla and Duysens (2007) investigated gaze behavior of pedestrians when walking on different ground surfaces. Their findings showed that the fixations were frequently directed to a transition area between different surfaces. These findings suggest that fixations are directed to regions that can maximize the amount of information in order to facilitate safe foot placement. Moreover, Marigold et al. (2007) argued that peripheral vision of unexpected obstacles in the travel path can be sufficient for successful obstacle avoidance. In other words, pedestrians pay much more attention to ground surfaces to detect immediate potential environmental hazards than fixating on obstacles. Kitazawa & Fujiyama (2010) confirmed this finding; they argued that pedestrians mainly pay attention to ground surfaces to detect potential environmental hazards instead of focusing on obstacles.

Social interaction

Fotios, Uttley and Yang (2014) stated that identifying other users is an important task while walking. They argued that it is critical to look at pedestrians at a distance of four meters. In addition, earlier research proposed that face recognition and body gesture are essential for identifying the intent of other road users (Fotios & Raynham, 2011). Fotios and Raynam (2011) argued that facial recognition is important to promote a sense of security and social ease, especially at night when encountering other pedestrians. Facial recognition might increase the reassurance of an individual; when an individual does not feel safe, he or she might not go outside in dark areas (Johannson, Rosén & Küller, 2011). Moreover, visibility of body posture and language also entails the indication of possible threat (Meeren, Van Heijnsbergen & De Gelder, 2005; Davoudian and Raynham, 2012; Fotios and Yang, 2013). Next to that, visibility of body posture might also be fixated on to determine the path of others and prevent collisions. According to Foulsham, Walker and Kingstone (2011), pedestrians mainly focus on the path, objects, and other pedestrians in the distance. This gaze behavior appeared in both lab studies and field studies. Fotios and colleagues (2015) validated that there was a tendency to look at other pedestrians at a distance. One could argue that fixating on pedestrians in the far region is mainly useful for preventing collision. Unfortunately, up to now it is still unclear whether looking at others in the distance is preferred to identify other pedestrians or to prevent collisions with others.

Nighttime studies

The previous described studies were mainly conducted during daytime. Only a handful of studies have investigated the visual behavior of pedestrians at night (Davoudian & Raynham, 2012; Fotios et al., 2015; Fujiyama, Childs, Boampong & Tyler, 2013). Fujiyama et al. (2013) studied the effects of lighting on fixation behavior as participants (elderly) navigated through an obstacle course in a laboratory. Visually obscure objects did not attract the attention of those elderly people. In other words, participants paid more attention to visual information in the environment instead of an actual danger. Davoudian and Raynham (2012) investigated the visual tasks of pedestrians at night on real roads with only limited explicit instructions. Participants looked at the pavement approximately 40-50% of the time. These findings were in line with the study of Patla & Vickers (2003). Davoudian and Raynham (2012) argued that time spent looking at pavements is an effect of leftover time after scanning the environment for potential threats. In addition, they argued that participants, who felt insecure, tended to look less at the pavement and more at the surroundings to search for threats at night. The lack of insecurity of most participants in their study supports the argument that the participants in this study did not pay too much attention to threats in the environment; thus, participants spent more time looking at the path. In addition, the amount of fixations on other pedestrians was also limited in Davoudian and Raynham's experiment. Participants did not encounter many pedestrians, due to the number of pedestrians passing by. When there are no pedestrians to look at, the number of fixations on them simply cannot be high. Alternatively, when a larger number of people appear in the environment, it is impossible to look at them all. It could be argued that it is not necessary to look at all people in the environment.

2.3.2 Gaze behavior of car drivers

Driving is a complex task that involves dealing with different factors, such as steering, speed control, and attention to road characteristics and other road users. Unsurprisingly, driving behavior has been studied for many years (Gegenfurtner, Lehtinen, Säljo, 2011; Klauer et al., 2014). With arrival of new technologies, gaze studies are often conducted in a simulator (Engström, Johansson, Östlund, 2005). Steering and hazard detection are seen as the main tasks of car drivers for reaching their destination and this might also be important for cyclists (Gegenfurtner, Lehtinen, Säljo, 2011). Both road users need to steer and avoid obstacles to reach their destination.

Two-level model of steering

Donges (1978) developed an influential model for the visual control of steering, named the two-level model of steering. The model depicts that steering behavior is dependent on the gaze behavior. In short, the original model states that there are two levels of steering: a guidance level and a stabilization level. The guidance level includes forward view of the road and responses with an anticipatory open-loop control mode. The stabilization level, on the other hand, are feedback signs and compensate for deviations from the current or desired position in a closed-loop control mode. Land and Tatler (2009) modified this model by including the far and near regions. Land (2006) suggested that gaze switches from the far road to the near road and that car drivers mainly fixate on the far road. Therefore, this new model states that steering control uses two visual regions: a distant point (anticipatory open-loop) and near region (closed-loop control). First, efficient steering needs a distant point on the travel path. This point is used for heading. On a straight road, this point is usually a vanishing point or a leading point to which the driver has to steer (Salvucci & Gray, 2004). On a curve, the tangent point is known to be important. This is the inside edge point of the bend (Land & Lee, 1994). Second, the near road region is important while steering. Car drivers look at the near road, including the road and its markings in the immediate proximity of the car for lane keeping. Moreover, hazard detection is necessary for braking and steering in order to avoid collision (Underwood, Phelps, Wright, Van Loon, Galpan, 2005).

Drivers' attention and fixations become more concentrated on specific objects when drivers become more familiar with the route. Another strategy of experienced drivers is that gaze is moved to far down the road in order to gain the maximal lead time to gain information (Shinar, 2008). During this gaze strategy, an attentional capture of obstacles and other hazards are included. Furthermore, Lansdown (2001) demonstrated that attention processing of novice and expert drivers are different. Specifically, he argued that expert drivers relied more on peripheral visual cues compared to novices who relied mainly on foveal fixations. Moreover, Hughes and Cole (1989) suggested that as the number of visual stimuli increases, the visual complexity increases; therefore, car drivers adapt their gaze frequency and fixation during driving and does not always pay attention to everything they saw. In other words, the location of our fixation does not always reveal the target of our attention. The phenomenon of ‘looked but did not see’ is well-known and precedes many crashes (Hughes & Cole, 1989).

Comparison walking and driving behavior

Land (2006) suggested that the near region is rarely fixated by car drivers and that the near region is mainly used by the peripheral visual system for position-in-lane feedback. This statement is in contrast with the gaze behavior of walking; namely, pedestrians frequently gaze at the near path during walking and only a few fixations are made at the distant path. (Foulsham et al., 2011; Pelz & Rothkopf, 2007). This contradiction might be due the fact that path quality is more important for pedestrians to maintain balance in contrast to car drivers. Another possible reason is that pedestrians move at a lower speed, and, therefore, have more time available to anticipate to near hazards. Due to a lack of research on cyclists, we rarely know how cyclists anticipate. As cyclists’ speed and balance are between those of pedestrians and cars, cyclists might use strategies of both pedestrians and car drivers.

2.3.3 Gaze behavior of cyclists

This paragraph describes the small number of earlier research conducted about gaze behavior of cyclists in the laboratory or in the field.

Laboratory studies

Vansteenkiste and colleagues (2015) investigated the visual behavior of cyclists during different steering tasks and under different constraints during day time in different studies. In the two first studies, they investigated visual behavior in an indoor environment on a straight and curved path; cyclists tend to direct their gaze to the future path about one to two seconds ahead (Vansteenkiste et al., 2013; Vansteenkiste et al., 2014). Wilkie, Wann and Allison (2008) investigated active gaze behavior and locomotor control of cyclists in a simulator and found similar results. Participants had to steer through a series of slalom gates and findings showed that participants tended to track the most immediate gate until it was approximately 1-2 seconds away at which point gaze switched to the next slalom gate. A second finding of Vansteenkiste and his colleagues (2014) was that participants mainly looked at the path (41%) and goal (40%), suggesting that both near (path) and far (goal) regions are important for sufficient steering. Frings, Parking and Ridley (2014) investigated risk perception and attention allocation in a variety of contexts for bicyclists in more detail. They explored gaze behavior directed to junctions featuring small and large lanes, vehicles, and different curbs to vehicle distances. Results suggested that cyclists devoted their attention to the nearside of vehicles (60%) and perceived near and offside passing as most risky. A third finding of Vansteenkiste and his colleagues (2013) is the effect of speed and task demand on the visual behavior of a bicyclist. Path fixations were higher on a low-quality bicycle lane than on a high-quality path lane. They argued that less demanding situations (such as a wider path) result in more task-irrelevant fixations. The apparent shift of visual attention turned from distant environmental regions towards more proximate road properties on the low-quality cycling track, because the task is more difficult compared to a high quality bicycle path.

Gaze constraints model

Vansteenkiste and his colleagues (2014) posed a new model on cycling behavior based on the two-level model of driver steering behavior (Donges, 1978), and two-point visual control model of steering (Salvucci & Gray, 2004). Cycling behavior might be slightly different compared to driving. On a simple road, such as wide lanes, it is reasonable for cyclists to primarily using peripheral vision next to the two-level model of steering. In other words, the two-level models might exist in wide lanes, but when traffic situation becomes more complex, the use of peripheral vision is not sufficient enough (Miura, 1987). Therefore, Vansteenkiste and his colleagues (2003) presented a new gaze constraints model for goal directed locomotion. Both far region for guidance and near region for lane-keeping are still necessary for efficient steering. An addition to this model is that task and environmental constraints predict gaze behavior. The model assumes that 1) reaching a goal requires direct control for stability and vehicle control; 2) there is a need for anticipation for guidance and hazard perception to reach a goal. The close gaze behavior (the near region) characterizes the need for direct control. This need decreases with automatization or mastery of the vehicle. Meanwhile, direct control increases with task complexity. On the other hand, the distant gaze behavior (the far region) controls for the need of anticipation. This behavior will occur more when speed increases or when the environment is less predictable (Vansteenkiste et al., 2014). The environment can be less predictable, when the environment is new. Consequently, one could feel less safe in a less predictable environment. When the need for both direct control and anticipation increases, the attentional demand will also increase. This leads to less irrelevant gaze behavior, due to the increase of mental workload (Vansteenkiste et al., 2014). Vansteenkiste argued that when the need for direct control is the highest, vision will be more similar to the vision of pedestrians on a rough surface (Marigold & Patla, 2007). Gaze will then primarily be directed to the near path with occasionally shifts to distant regions.

Field studies

Vansteenkiste and colleagues conducted their experiments mainly in laboratory studies. As stated before, the ecological validity of laboratory studies are questionable. Meanwhile, only a handful of studies about gaze behavior of cyclists are executed in the field. Vansteenkiste and his colleagues conducted one experiment in a real life situation (Vansteenkiste et al., 2014). They compared the different variables as in their lab studies (such as quality of bicycle lanes, straight paths and curved paths). Results suggested that on a low quality bicycle lane, cyclist looked mainly at the road (60%). In addition, they argued that participants looked at the path to cope with road properties. On a high-quality bicycle path, fixations were almost evenly distributed over the areas of interest. Moreover, participants looked more to other cyclists on a high quality bicycle lane than on a low quality bicycle path, but the dwell times differed highly among the participants. These results suggested that no specific visual strategy is really needed to reach the destination in a safe manner; attention is therefore spread over multiple areas of interest.

Mantuano, Bernardi and Rupi (2016) studied the gaze behavior of cyclists in a more complex environment. The study was conducted in an urban space in Bologna. There were three main outcomes: first, an equilibrium of attention location between the central and lateral parts of the visual scene can be assumed as the optimal cycling visual condition. This especially happens when there is a presence of pedestrians. In other words, cyclists looked at the far region and central region to obtain optimal information to cycle safely. Second, discontinuities of the path, such as intersections and crossroad, and the presence of pedestrians are the elements requiring more attention. Third, absence of physical and visual separation between cyclist and pedestrians seems to lead to a lack of attention to these risk elements. However, there are some limitations of their experiment; first, their sample population included novice and expert cyclers. There might be differences in gaze behavior of novice and expert cyclers (Zeuwts et al., 2016). In addition, participants hardly encountered many other pedestrians or cyclers on their route. Furthermore, only two area of interests were used; namely, fixation focused on the target (central of the field of view) and all fixations out of that target. Lastly, only two parts of the whole route are taken into account in the analysis of that paper. Those roads are both straight roads.

Qasem et al. (2017) investigated cyclists that traveled around 2.4 km on the edge of a park. Participants cycled this route during daytime and nighttime. Results suggested that people tend to fixate mostly at the path ahead, especially after dark. They argued that road lighting should ensure cyclists to see the path, because this might increase the safety of cycling. A limitation of this study was that the trials were executed in a quiet neighborhood near a park. Consequently, participants could not encounter many other road users. To conclude, the number of research about the gaze behavior of cyclists is limited, especially research conducted at night.

2.4 Critical eye fixations

2.4.1 Methods of identifying gaze behavior

Eye fixations guide us through the world, but our attentional resources have limited capacity of cognitive resources (Kahneman, 1973; Lavie, 2005). Selective attention is, therefore, necessary for traffic participations. There are several methods to investigate where our attention is allocated to. Several studies investigated visual tasks of cyclists by asking participants about their opinion on important elements and possible threats in the environment (Schepers & Den Brinker, 2011; Fabriek, De Waard, & Schepers, 2012). This posterior self-report method provides useful insights about what cyclists think it important for them; however, this method is subjective and is only based on the experience and memory of the participants. It is questionable whether this approach provides reliable information; selfreporting of visual behavior requires awareness of what we are looking at. Moreover, a person is not always able to specifically recall or describe where his or her attention was given to in past events (Buswell, 1935). Therefore, a more objective method to measure visual behavior is needed. To measure eye movements more objectively, technology can be used, such as eye-tracking (Holmqvist, Nyström, Andersson, Dewhurst, Jarodzka & Van de Weijer, 2011; Duchowski, 2007).

In a study of Underwood, Chapman, Berger & Crundall (2003) car drivers were sometimes not able to recall details about fixated objects and were sometimes able to recall information about objects that were not fixated at all. In other words, fixations do not necessary indicate that attention is being directed towards the fixated object. The underlying idea is that it is possible for an object to be fixated without it being cognitively processes or entering working memory (Triesch, Ballard, Hayhoe & Sullivan, 2003). Sometimes objects are fixated on and processed, but they are not important and not relevant to the current task. It cannot be assumed that the direction of gaze and the allocation of this attention is also what is of cognitive relevance (Posner, 1980). In other words, what we are looking at might not be important for our cognition. Therefore, one will forget what is looked at. Cyclists do not always focus on what they see while cycling; they do not have conscious attention (Foulsham, Farley, Kingstone, 2013). This is in contrast with the previous mentioned studies mentioned in 2.1.4. These studies argued that we fixate to retrieve information for a specific task and that we hardly focus on task-irrelevant features. However, as stated before, sometimes it is not necessary to fixate on something important. Another possibility is that attention is directed internally and not focused on anything in the visual environment. Davoudian and Raynham (2012) suggested that pedestrians were not performing important visual tasks while walking along the road. Therefore, just indicating visual behavior on eye fixations and subjective experience only might not be a reliable method. Understanding visual behavior requires more than the examination of eye fixations and a posteriori self-report. As a solution, the dual task methodology can be used as a tool to examine what is really important to look at for cyclists.

2.4.2 Dual task methodology

In daily life, we rarely perform one task at a time, but we rather perform different tasks simultaneously. This phenomenon is also referred as dual-tasking (Pashler, Carrier & Hoffman, 1993). The dual task methodology implies that people are able to perform two (or more) activities concurrently, but our attention is of limited capacity. Dividing our attention can result into a decrement in performance in one of the two (or more) tasks compared to performing one of those tasks individually. However, until now it remains unclear how this dual-task interference exactly occurs. Pashler, Carrier and Hoffman (1993) described two major theories why this inference exists. The first theory, the capacity sharing theory, is the most widely accepted and it assumes that we share processing capacities among tasks. When more than one task is performed at a given moment, performance of a task will be impaired. In other words, less capacity is available for each individual task, but they can proceed in parallel. The second theory is the bottleneck (task-switching model) and it assumes that when two tasks need a mechanism at the same time, one or both tasks will be delayed or impaired. In other words, only one process can actually proceed at one time (Pashler, Carrier and Hoffman, 1993).

The dual task methodology is tested in multiple studies and applied in different areas (Strayer & Johnston, 2001; Tombu & Jolicœr, 2003; Plummer & Eskes, 2015; Soangra & Lockhart, 2017). Boot, Brockmole and Simons (2005) argued that a concurrent auditory task affects the allocation of cognitive resources to a visual search task. Fotios, Uttley, and Hara (2013) found that reaction times in a response-t-auditory task, a task which participants had to press a button when they hear an auditory stimulus, were significantly slower when distracting images were presented compared to a black screen. This finding suggests that visual distractions reduce performance in a response-t-auditory task. Fotios et al. (2015) and Qasem et al. (2017) used this auditory task to identify the critical fixations of pedestrians and cyclists. A secondary cognitive task was running concurrently with the task of walking or cycling, requiring that participants responded quickly to an acoustic signal by pressing a button. A delayed response to this task was used to isolate moments where cognitive attention was distracted toward a visual task. In research, task instructions influence the focus attention allocation in a dual task setting (Kelly et al., 2010). As instructing participants to focus on the auditory task, results from this study implied that a secondary task uses up attentional resources and reduces the attention that can be directed towards a primary visual task. These distracted moments can be seen as critical visual tasks. Results of Fotios and his colleagues (2015) showed that there were differences in the dwell percentages of critical eye fixations compared to all eye fixations. Fotios, Uttley, Cheal and Hara (2015) suggested that fixations at critical instances are most frequent at the path and other people during daytime. At night, the path is more likely to be fixated on. Moreover, their participants fixated more at a far distance path compared to near distance when the task is critical. In addition, pedestrians fixated less at other pedestrians after dark compared to daylight. Therefore, it is important to distinguish those eye fixations, because not all fixation are always important. This current study further explored the possibilities of using a dual task for the identification of critical visual tasks of cyclists.

2.5 Current study

The present study was aimed to explore the critical visual tasks of cyclists after dark in a complex natural environment using the dual task methodology. In this study, cyclists cycled three times a route in different circumstances wearing an eye-tracker. Besides cycling as a primary task, they had to perform a secondary task, namely an auditory task, where participants needed to press a button when a sound stimulus occurred.

The theoretical framework summed up several reasons why it was important to conduct the current study about the visual behavior of cyclists. First, the amount of research about cyclists' gaze behavior is limited up to now. Eye movement behavior in traffic is mainly investigated among pedestrians and car drivers. Second, human eye movements are mainly explored in a controlled indoor environment with videos recordings or simulations (Vansteenkiste et al., 2013; Zeuwts et al., 2016). These controlled laboratories and simulations might increase the possibilities of various research, but the ecological validity of many of these studies remains questionable. In other words, laboratory studies with simple tasks might not give a real representation of complex traffic situations. In a real traffic situation, cyclists need to divide their attention to many different things than only one singular maneuver. Furthermore, limited studies of gaze behavior of cyclists were conducted at night (Mantuano et al., 2017; Vansteenkiste et al., 2014, Qasem et al., 2017). Third, only few studies made a distinction between 'important fixations' and 'general fixations' (Fotios et al., 2015, Qasem et al., 2017). Those previous mentioned studies used the dual task methodology to identify critical fixations. Therefore, this study investigated the possibilities using the dual task methodology to indicate critical fixations. Hence, a research question was formulated:

> ***Research question:*** *What are the critical visual tasks of cyclists after dark in a complex natural environment?*

As little is known about the visual behavior of cyclists, this study was explorative. Therefore, no a priori hypotheses about the critical visual tasks of cyclists were formulated. The main point of interest was exploring critical fixations of cyclists using the dual task methodology, as Fotios and colleagues used in their previous studies (2015). The same auditory task was used in current field study.

To answer the research question in more detail, four sub-questions were formulated. In the Netherlands, a bicycle is commonly accepted as transport mode. Many people cycle in normal speed. Therefore, the first sub-question was formulated:

> ***Sub-question 1:*** *What are the critical fixations of cyclists at normal speed?*

However, cyclists can also cycle at a high speed. For example when someone has to hurry to get to work. In that case, cyclists have to cycle faster which frequently occurs during one's everyday life. According to Vansteenkiste and colleagues (2013), an increase of speed means an increase in mental workload. Their model describes an increased need for anticipation when speed increases. This elevation might indicate that hurried cyclists might be more focused on the far region and will look more to the goal area. However, it is unclear whether this is also still the case for critical fixations. In this study, the critical fixations of cyclists who are cycling in normal speed and in high speed were compared. Therefore, the second sub-question was formulated:

> ***Sub-question 2:*** *What are the critical fixations of cyclists at high speed?*

Next to this, the need for anticipation increases when the environment is less predictable (Vansteenkiste et al., 2013). It can be argued that an environment is less predictable when a possible threat is present in the environment. This increases the feeling of being threatened and decreases the feeling of safety (Vansteenkiste et al., 2013). Therefore, the third sub-question was formulated:

Sub-question 3: *What are the critical fixations of cyclists when cyclists feel threatened?*

Sub-question 2 and 3 were answered by letting cyclists cycle in higher speed and increase their mental workload. Furthermore, it is important to know at what distance people are looking at specific objects, such as obstacles and the path. Moreover, it is important to know at what distance cyclists look at other cyclists and pedestrians to create new road lighting guidelines. Therefore, it is chosen to investigate the distance of the critical fixations in this study. Subsequently, the last sub-question was formulated to provide a better understanding of the main question:

Sub-question 4: *At what distance do cyclist look at critical features in the environment?*

Those questions could be answered in an exploratory field study with the aid of an eye-tracker. By re-watching video-recordings made by the eye-tracker one could categorize gaze positions and estimate the distance between eyes and objects.

Chapter 3: Methods

3.1 Participants

The researcher approached the participants to participate in the experiment individually face-to face. Nineteen participants were recruited for the experiment. It was chosen to schedule the experiment during crowded and uncrowded moments in the evening to include different amount of traffic. Therefore, participants participated the weeks before Christmas. Shops were open until late, so there were many people present in the test-set up environment during the evening. However, during this time of the year, the weather is very unpredictable. In case of bad weather circumstances, the scheduled time could be rescheduled. Therefore, participants were all friends or relatives of the researcher. This sample population is chosen, because those participants were more flexible on possible required time changes. In total, twelve participants participated in the experiment. Two participants were excluded in the analysis afterwards, due to technical malfunctions during the experiment and difficulties with calibration. In addition, one participant needed to redo the experiment at another day, due to the weather changes during the experiment itself. In total, six males and four females have finished the experiment and were included in the analysis (M_{age} = 25, *SD* = 2.7, range 23-30 years). It was chosen to use a homogenous sample population, due to the small sample size. All participants are expert cyclists. Participants reported to have normal sight and hearing. Participants participated voluntarily and did not receive any compensation for the experiment.

3.2 Study design

An exploratory eye-tracking field study was conducted to measure critical eye fixations in a naturalistic complex environment after dark using the dual task methodology. The study was executed between 18:00 and 23:00 in December 12th until December 29th 2017. Participants had to cycle the predefined route three times under three conditions (normal speed, high speed, feeling threatened). The order of the three conditions was counterbalanced among the participants to cancel out influences of the order of the conditions. In the normal condition, the participant were asked to cycle the route as they would normally cycle. In the high speed condition, participants were instructed to cycle as they were in a hurry, but they should still cycle safe and follow the traffic rules. In the threat condition, the participants were asked to keep a bag on the luggage carrier safely. In this condition, they could choose their own strategy to keep the bag safely, such as shifting their velocity. Participants were explained that someone could grab the bag while a participant was cycling (appendix A). This was executed to increase the alertness, and presumably mental workload of the participants. The dependent variable was the area of interest of a fixation. A dual task consisting of a secondary auditory task was used to identify critical fixations. A delayed response time of the auditory task indicated attention allocation to the primary visual task.

3.3 Materials

3.3.1 Bicycle

A standard city bike was used for all participants (Figure 1). The saddle and handlebar were adjusted to the length of a participant. The bicycle included a normal front and back lighting, and a luggage carrier in front of the bicycle. A basket was attached to the luggage carrier. The bicycle was equipped with a coaster brake instead of a handbrake, in order to have sufficient place to add the press button of the auditory task to the handlebar.

3.3.2 Eye-tracker

An eye-tracker with a monocular camera and a world view camera (Pupil Labs, 2017) identified eye fixations by capturing the pupil position. The front world camera was directed to the front perspective to capture the video-recordings of the environment. The monocular camera faced the participant's eye capturing the pupil gaze and eye fixations (Figure 2). The eye-tracker included a sensor of 640x480 and a rate of 120 frames per seconds. Pupil Capture and Pupil Player software programs version 0.9.14.07 were used to identify fixations. The software of Pupil Player was based on dispersion-based algorithm (Salvucci & Goldberg, 2000) and specially designed for eye-tracking research. The videos of the front world camera (environment view) and the monocular camera (pupil position) were combined to identify the position of the eye fixation. The infrared filter was taken away from the world view camera to increase night view. During the experiment, the eye-tracker was connected to a laptop. Combining the data of those two cameras resulted to data that could be used for identifying the eye fixations.

Figure 1 & Figure 2: Bicycle with front carrier and helmet with infra-red light + eye-tracker

3.3.3 Helmet with infra-red light

An infra-red light was used to increase night vision for the eye-tracker to record brighter frames without adding light visible for human eyes. The used infra-red light (model EN-IR80A) included three LEDS. The infra-red light turned on automatically while being exposed to light under 10 lux. Dark tape was adhered to the sensor to ensure that the infra-red light was working at any time. In addition, an elliptical E-6010 diffuser was added to the light to increase the angle of the light beam. The infra-red light was added to a mountain bike helmet, which can be seen in Figure 2. An external battery was constructed to the infra-red lamp to supply for power during the test.

3.3.4 Auditory task device

A secondary auditory task was used to indicate a critical eye fixation. A critical eye fixation can be defined as an eye fixation that reduces the performance of a secondary task. Delayed responses to a secondary task indicated cognitive attention to the primary visual task. A sound beep recording was saved on the laptop. The auditory task equipment, including the sound beep, was implemented in a Python script on the laptop and a written script on an Arduino in a button on the handlebar. The button for the auditory task was added to the handle bar, so that participants did not need to take their hands of the handlebar to press. There were two buttons available, so participants could choose their preference to use the button on the left side or right side of the handle bar. All participants preferred the right side of the handle bar. An in-ear ear-plug was used to present the sound beeps. All participants used the same ear-plug and volume was turned on the same level on the laptop. The sounds was loud and clear, without being a disturbance. The auditory task button was connected to the laptop by an USB-port. Figures 3 and 4 shows this device.


Figure 3 & Figure 4: Auditory task device on right handlebar & button secondary task device

3.3.5 Backpack

Participants wore a backpack during the experiment. The backpack included the power supply of the infra-red light, the laptop connected to the eye-tracker and the auditory task device during the experiment.

3.4 Test set-up

The chosen complex environment in the real world was the city center of Eindhoven near the 18-Septemberplein. Figure 6 and 7 shows pictures of the city center of Eindhoven at night. The route of the experiment is shown in Figure 5. This route, with a length of approximately 890 meters, was cycled in approximately four till ten minutes. This differed from person to person due to speed and shortcuts of individuals and other traffic circumstances, such as red traffic lights, as well as the experiment condition. Eye-tracking data obtained on small sections (between two different letters shown in Figure 5) were excluded, because it included small amounts of data points. The route was divided into five separated sections, because those differed in environment characteristics. More information about the route (e.g. length, characteristics) can be found in Table 1. Table 2 includes information about the traffic and weather condition per participant.

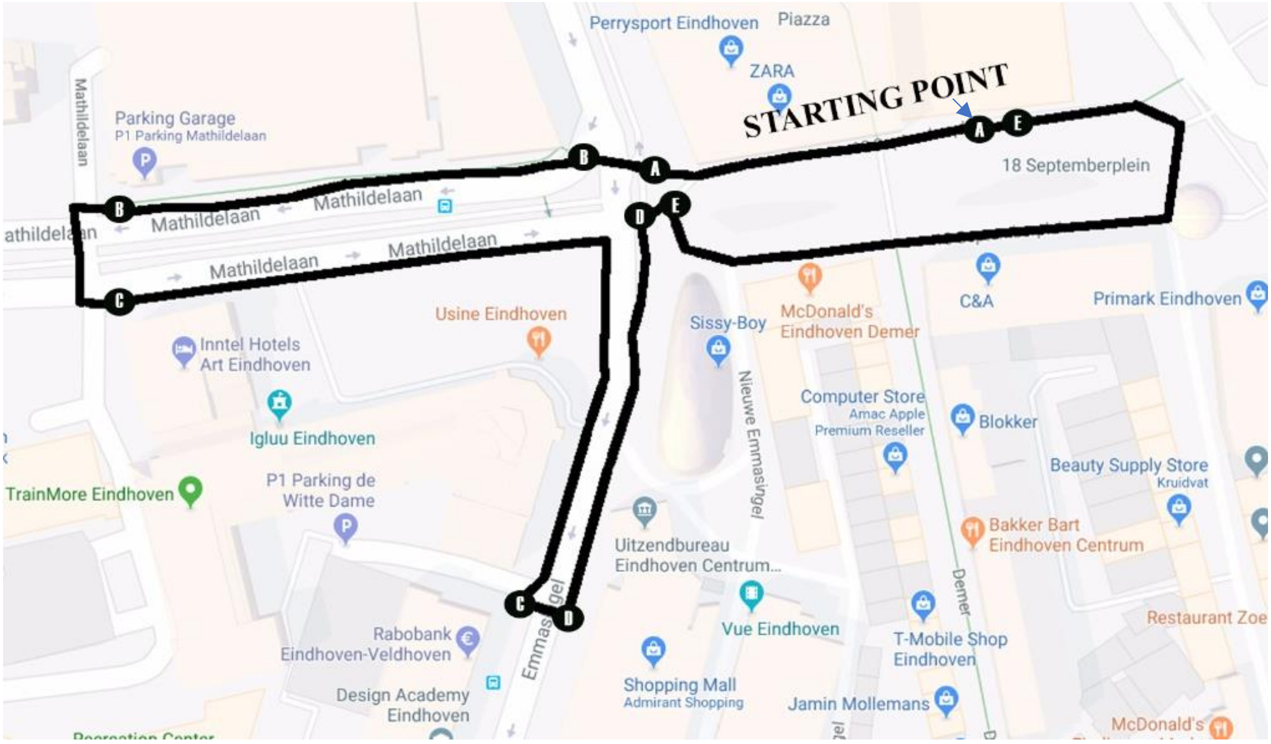


Figure 5: Cycling route divided into sections A, B, C, D, and E.

Figure 6 & Figure 7: Pictures of the city center of Eindhoven

Table 1: Description route

Section	Distance	Description	Interaction possibilities
A	~100m	18-Septemberplein, a piazza with shops/restaurants and underground bicycle racks. No specific route to follow. Generally busy, concrete flat ground, lighting from shops and big light spots on buildings.	Many possibilities to meet other pedestrians, cyclists, and vehicles
B	~140m	Separated flat red bicycle path, with parallel sidewalk and car road. Light mainly from surrounding buildings.	Front cyclists, cyclists who are passing by, pedestrians, and vehicles on parallel roads
C	~250m	Separated flat red bicycle path, with parallel sidewalk, and car road. Light from buildings.	Front cyclists, cyclists who are passing by, pedestrians, and vehicles on parallel roads
D	~115m	Separated flat red bicycle path, with parallel sidewalk and car road. Light from buildings. Road is parallel to 18-septemberplein.	Front cyclists, cyclist who are passing by, pedestrians, and vehicles on parallel roads
E	~235m	18-Septemberplein, a piazza with shops/restaurants and underground bicycle racks. No specific route to follow. Generally busy, concrete flat ground, lighting from shops and big light spots on buildings.	Many possibilities to meet other pedestrians, cyclists, and vehicles

Table 2: Description environment

Participant ID	Date	Start time	Weather condition	Traffic condition
2	Tuesday December 12th	20:00	Dry, snow and ice on the roads	Not crowded
3	Tuesday December 12th	21:00	Dry, snow and ice on the roads	Not crowded
4	Thursday December 14th	18:00	Dry	Crowded, rush hour traffic
5	Friday December 15th	20:30	Dry	Crowded, evening shopping
6	Friday December 15th	21:30	Dry	Crowded, after evening shopping
9	Wednesday December 20th	19:00	Drizzling, reflection on the roads	Not crowded
10	Thursday December 21st	19:00	Drizzling, reflection on the roads	Crowded, evening shopping
11	Thursday December 21st	20:00	Drizzling, reflection on the roads	Crowded, evening shopping
12	Friday December 22nd	21:00	Drizzling, reflection on the roads	Crowded, after evening shopping
13	Thursday December 28th	21:00	Dry	Not crowded

3.5 Procedure

When participants arrived at the place of experiment, they were asked to read the information sheet about the experiment, and they had to fill in the informed consent form if they agreed participating. Subsequently, the researcher explained the set-up of the experiment. The researcher showed the route (Figure 5) that the participant must cycle and explained the auditory task. Participants were told that they had to cycle this route three times. After every round, the participant should stop at the starting point for new information of the researcher. Participants were also able to ask questions if something was unclear.

After the introduction session, participants were asked to wear the eye-tracker. Moreover, the participants had to wear the helmet with the infra-red lamp. The cameras were adjusted and well positioned for a robust eye tracking performance. Calibration was started after positioning. During the calibration session, participants had to look at a calibration circle printed on a carton board from a distance approximately two meters to indicate the pupil position (Pupil Labs, 2017). The calibration process established a mapping from pupil to gaze coordinates. The calibration took around 15 till 30 minutes, depending on the participants' eyes and the compatibility of the eye tracker glasses to the participant's pupil. Examples of other incompatibilities are that the pupil could not be found by the software during calibration or incorrect pupil positions during the calibration.

After calibration, the auditory task was plugged into the laptop and checked for appropriate volume. Then the video recording was started. Recordings of the eye pupil and the world view were made. The necessary devices and tools for data collection were put into the backpack. The auditory task was added to the right side of the handlebar and it was adjusted to the reaching area of the participant. After this, the researcher instructed the participant how he or she should cycle (normal speed, high speed, or threat). Instructions were scripted as to ensure that all participants received the same instructions (Appendix A). After that, participants could start cycling. The researcher cycled approximately five meters behind the participants for safety reasons. During the test, the auditory secondary task occurred continuously with beeps within a random interval between one to two seconds. Participants were asked to press the button on the handlebar as quickly as possible when they heard a beep sound. After every condition, a short break was planned to explain the participant which condition they should cycle next round.

After cycling all three conditions, the recordings were shut down. Participants were asked to fill in the questionnaire. After finishing the questionnaire, the participants were thanked for participation, were debriefed about the third condition, and were able to ask questions. Participants received no compensation for their participation. The experiment has lasted for approximately one hour per participant.

3.6 Measurements

3.6.1 Reaction time

Reaction time of the secondary auditory task was measured to identify the critical eye fixations. For this secondary task, participants responded to an auditory beep (occurring randomly every 1 to 2 seconds) by pressing a button on the handle bar. Reaction time was measured in milliseconds. The reaction time measurement started when the audio file started playing and stopped when the button was pressed on.

3.6.2 Eye fixations

The Pupil Capture software measured the gaze positions during the experiment (Pupil Labs, 2017). In Pupil Capture different plug-ins can be added to visualize different components for eye-tracking data. The fixation number, start timestamp of a fixation, duration, index numbers, and confidence level of fixations were measured and saved by the software. Pupil Player was used to create a video file with the eye fixations points of the participants superimposed on the recordings of the world view camera. A duration of 100 milliseconds and dispersion (maximum distance of all gaze locations during a fixation) of 1.4 degrees were used as a fixation threshold for an eye fixation based. These values were based on software recommendations and literature research (Jacob & Karn, 2003; Blignaut, 2009). With these thresholds, the algorithm can create fixations out of the pupil position video and world view video. Eye fixations were later categorized into areas of interest and divided into non-critical and critical fixations.

3.6.3 Subjective measurements

The participants filled in a short self-formulated questionnaire adapted from Haans & De Kort (2012) after the experiment to obtain a better understanding of the sample population (Appendix B). First, the questionnaire included some general questions about the participants, such as age and gender. In addition, questions about the frequency of cycling, and the familiarity with the route used were asked. Last, some questions about the safety, and light perception of the environment were added to the questionnaire. Those questions were measured on a 5-point Likert-scale. An example of a question is: *'How well or poorly do you think the street lighting in this environment enables you to travel through this environment at night?'* Last, a short validation of the credibility of a latent threat in the threat condition was asked on a 5-point Likert-scale (1=not at all, to, 5=all the time).

Nine of the ten subjects had a car driver's license. Half of the participants were mainly using the bicycle as a transport mode. Others were using a car, public transport or walking more often. However, many mentioned that the times of cycling decreased over years; cycling was especially the main transport when they were younger. Having a car of a public transport card change their way of transportation. All participants have visited the test area several times. All participants has been there as a cyclist or a pedestrian. Overall, participants were positive about the environment. They judged the environment as safe (M = 4.1, SD = 0.88) and comfortable (M =4 .6, SD = 0.70). Moreover, they judged the light as a useful to enable them to travel through this environment at night (M = 4.2, SD = 0.63). However, they perceived the light quality as slightly negative (M = 2.8, SD = 0.63). Nine of the participants believed that there was someone on the road in the threat condition. Two of them were hesitating whether this was really true after a while when cycling this condition. Overall, the participants indicated to have paid more attention to the environment (M = 4.3, SD=0.67) and they did try to find a person who might grab the bag (M = 4.4, SD = 0.70).

3.7 Analysis

Different steps were undertaken to identify the critical fixations in the dataset. This section explains the different analyses. First, eye-tracking data needed to be distracted from the video-recordings (3.7.1). Second, it was necessary to categorize all fixations into an area of interest (3.7.2). Third, it was essential to analyze the reaction time measurements (3.7.3). Fourth, it was required calculating cutoff points to separate critical fixations from non-critical fixations (3.7.4). Next to this, it was desirable to compare data of non-critical and critical fixations. Last, the distance of several categories were estimated to get a better understanding of the areas of interests (3.7.5).

3.7.1 Eye-tracking data

After saving a video-recording, Pupil Player returned an excel file with fixation data points and the number of a fixation consistent with a fixation number in a movie. It was chosen to execute fixation-by-fixation analysis instead of frame-by-frame analysis to analyze the eye-tracking movies. This might result in slightly considerable differences with frame-by-frame analysis, but the fixation-by-fixation approach was very time-saving. Furthermore, Vansteenkiste and his colleagues found a high correlation between those methods of analyses (Vansteenkiste, Cardon, Phillipaerts & Lenoir, 2014).

3.7.2 Analysis fixation categories

Every fixation was categorized into an area of interest. These were made to classify the area of interest of a participant (e.g. looking at the path, pedestrian, or goal). In other words, categories were made to identify where participants were looking at. These categories were based on previous literature review and on preliminary viewing the video recordings before categorizing every fixation. Reviewing the videos beforehand was necessary, due to the complex, unpredictable, and dynamic environment of the experiment. Moreover, the fixation points were checked if they were in the right position after every trial. When fixation points showed distance errors, they were corrected during reviewing the video-recordings, by subjectively moving the fixation point when categorizing the fixation points.

3.7.3 Analysis reaction time

The reaction time of the secondary auditory task was analyzed to identify the critical visual fixations. Repeated measures ANOVAs were executed to determine differences in reaction time per condition and participant. In addition, the reaction times per route were compared to each other with a repeated measured ANOVA.

3.7.4 Analysis critical fixation

Critical eye fixations were derived from reaction time. A Matlab script (Appendix F) divided all fixations into a fixation which occurred inside a stimulus or outside a stimulus. When a sound stimulus occurred, participants had to press the steer button; all fixations that occurred between the start time of the stimulus and the response of a participant were defined as a fixation within a beep. Figure 8 illustrates a visual representation of the responses, fixations and beeps. In this figure, fixation 3, 4, and 5 were included in beep A. Fixation 8,9,10, and 11 were included in beep B. As can be seen in figure 8, fixation 3 and 8 are ongoing fixation that is interrupted by a stimulus. These fixations were included in the fixation within a beep group. For all other observations (outside a beep), one could not determine whether this fixation was critical or not. In figure 8, this is the case for fixation 1, 2, 6, 7, and 12. From the fixations within a beep, one could determine whether it was a critical fixation (included in long reaction time timespan, based on some cut-off method) and which fixation was not a critical fixation (included in small reaction time, based on some cut-off method). When participants missed an occurring beep, all fixations from the start of the beep in a timespan of 2000ms were included as critical fixations. After 2000ms a new beep could started within a random interval of 1-2 seconds.

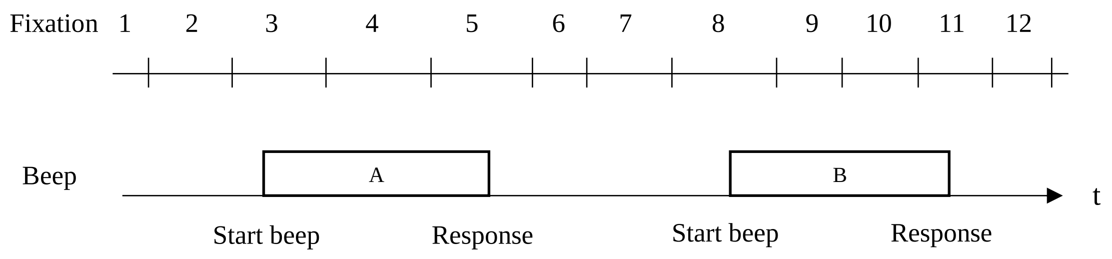


Figure 8: Visual representation measurement fixations

In this experiment, the search for outliers to identify critical fixations was important. In other research, outliers are often the unwanted data in a dataset (Whelan, 2008). These outliers are the slow responses of participants in a reaction time task. According to Ratcliff (1980), there are different methods to find outliers. Ratcliff (1980) mentioned different cutoff thresholds, such as mean + 2 times the standard deviation or trimming a specific percentage of the right tail. It was chosen to calculate the mean + standard deviation, mean + 1,5 standard deviation, mean + 2 standard deviation, median, 5% right tail, 10% right tail, and 25% right tail to find a reasonable reaction time threshold to identify the number of critical fixations. As stated before, repeated measures ANOVA's were executed to indicate differences in reaction time per condition, per route, and per participant. If the analysis showed significant differences for every participant and cycle condition, the cutoff point values per participant per condition were calculated. This regulates the differences in reaction times per participant per condition. The thresholds mentioned before were calculated independently for every participant and cycle condition. All the fixations that occurred in a response that surpassed the threshold can be included as a critical fixation. As comparing all methods is out of scope of this research, two cutoff points were chosen to continue the analysis.

Analysis 1: Highest proportions are the most important critical fixations

Checking the frequencies and proportions of the categories is one method to identify the critical fixations. The category with the highest frequency of critical fixations can be seen as the most important critical visual task. This method was used in multiple earlier studies (Fotios et al., 2015, Qasem et al., 2017).

Analysis 2: Comparison of non-critical and critical fixations

Comparing non-critical with critical fixations per category is a second way to indicate important critical visual tasks. Analysis 1 had been regularly executed in previous research, but a largest proportion of critical fixation might result from the fact that those categories are more available to look at during the experiment. Therefore, a second analysis was executed considering proportion differences between non-critical and critical fixations. If the proportion of a category differed in these two groups, it was suggested that the category might be important for mainly critical tasks or vice versa. In other words, a significant larger proportion of a category in the critical fixation group compared to the non-critical fixation group indicated that that area of interest was of high importance during a critical task. Cross tabulations and chi-square tests were executed to determine differences of proportions between the non-critical and critical group for all categories together. Moreover, standardized residuals were calculated as post hoc test when significant differences were found in the chi-square tests. Post-hoc tests included the examination of standardized and adjusted residuals. An adjusted residual that was more than 1.96 indicated a significantly larger effect than would be expected at the null hypothesis (Agresti, 2007). When a standardized residual value exceeded a value higher than 2 or lower than -2, chi-square tests were executed for a series of bivariate comparisons. Pairwise comparisons were executed using separate cross tabulations and chi-square tests to compare the area of interests of the different conditions.

Analysis 3: Comparison of critical fixations in conditions

The distribution of categories of critical fixations between the different conditions were also compared. Cross tabulations and chi-square tests were executed to investigate the relation of critical fixations in cycling in normal speed compared to cycling in high speed, as well as a comparison between normal cycling and cycling when feeling threatened. In addition, the standardize residuals were calculated to find significant differences in bivariate comparisons if significant differences were found in the chi-square tests.

3.7.5 Analysis distance fixations

Last, the distances of some areas of interests were measured, based on the results of analysis 1, 2 and 3. The analysis included three groups: 0 till 4 meters (near), 4 till 8 meters (middle), and more than 8 meters (far). Chi-square tests of goodness of fit were executed to examine the relation between the different distances and areas of interest.

Chapter 4: Results

4.1 Dataset

The dataset included a total of 23477 obtained fixations. A total of 5662 observations with a confidence lower than 0.6 were excluded. Every fixation with a value below 0.6 can be interpreted as an unreliable data point (Pupil Labs, 2017). Furthermore, it was decided to exclude 5231 fixations, which occurred during crossing roads and waiting at traffic lights. During those events, the pupil position could often not be found due to technical malfunctions. A total of 13232 fixations were included for analysis. Reaction times smaller than 200 milliseconds were dropped in the analysis. These reaction times could not be achieved within the time a stimulus occurred; the button might be pressed randomly and were not pressed after a sound stimulus. A total of 1542 reaction time measurements were included in the analysis.

4.2 Gaze fixation categories

4.2.1 Categorizing fixations

All fixations were categorized within the 28 areas of interest that can be found in Table 3. Categories were based on earlier research and preliminary watching the video-recordings.

Table 3: Categories of fixations

Category	Description	Reason for inclusion
Bicycle	Own bicycle, such as basket and steer	Preliminary reviewing video recordings
Building	All buildings in the environment	Preliminary reviewing video recordings
Bus stop	Stop for buses where people can go out and in	Preliminary reviewing video recordings
Cyclist	People cycling on a bicycle	Fotios et al., 2015; Qasem et al., 2017
Distraction	Salient object, contrast with the environment, could not specifically be defined in other categories	Preliminary reviewing video recordings
Exit	Door or small street where someone can go out	Preliminary reviewing video recordings
Front cyclist	Cyclist cycling in front of the participant	After re-watching video recordings
Goal	Straightforward direction	Vansteenkiste et al, 2013; Turano et al., 2001
Human	Person who is not walking, but the person is standing still	Kingstone, 2009; preliminary reviewing video recordings
Ice	Ice from snow on the ground	Preliminary reviewing video recordings
Intersection	At a crossroad with possible social interaction	Preliminary reviewing video recordings
Kerb	The edge of the pedestrian path / curb	Frings et al., 2014; Qasem et al., 2017

Table continued on next page

Category	Description	Reason for inclusion
Light	Specific light pop-ups, such as Christmas light	Preliminary reviewing video recordings
Object	Large objects in environment	Fotios et al., 2015
Obstacle	Small objects that are uncommon on path that can lead to tripping	Fotios et al., 2015
Other side	Parallel cycle path	Preliminary reviewing video recordings
Path	Bicycle path where participant is cycling on	Fotios et al., 2015; Qasem et al., 2017
Pedestrian	People who are walking	Kingstone, 2009; Fotios et al., 2015
Right	Looking right (changing head direction)	Preliminary reviewing video recordings
Road	Car road	Preliminary reviewing video recordings
Sidewalk	Pedestrian path (mostly parallel), no pedestrian present at moment of fixation	Preliminary reviewing video recordings
Sign	A traffic or advert sign	Preliminary reviewing video recordings
Stop	Place to stop according to traffic rules	Preliminary reviewing video recordings
Traffic light	Looking at the traffic light	Preliminary reviewing video recordings
Unknown	Cannot define category or fixation out of reach	Preliminary reviewing video recordings
Vehicle	Cars, busses and emergency vehicles	Fotios et al., 2015

4.2.2 Measured fixations

Figure 9 shows the distribution of the fixations in all categories inside and outside a beep. A chi-square test of goodness-of-fit was performed to determine whether the proportions of the categories were equally distributed between the fixations that occurred inside and outside a beep.

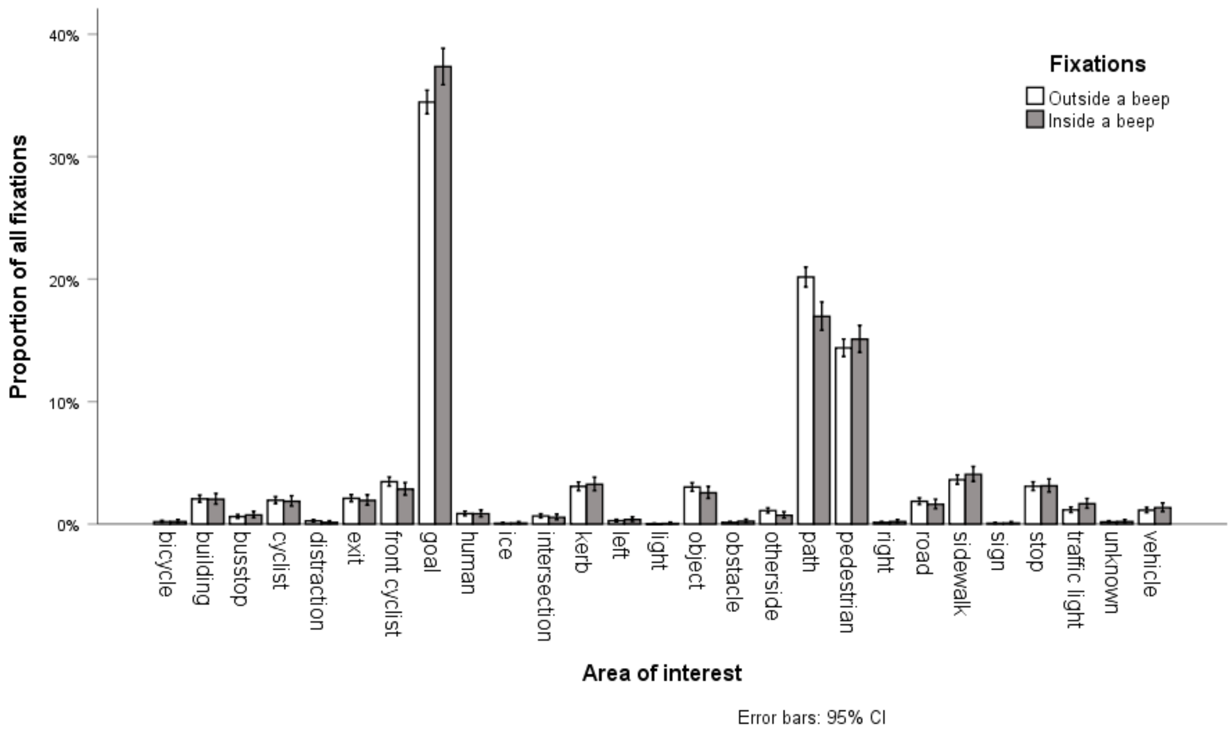


Figure 9: Proportion of fixations inside and outside a beep

Results suggested that the categories were not equally distributed between the two sample populations, X^2 (26, N = 13323) = 49.989, p = 0.003. Post-hoc pairwise comparisons indicated small significant differences in four categories. The proportions of goal (φ_c = 0.028, p = 0.001) and traffic light (φ_c = 0.021, p = 0.018) appeared to be higher in the within beep group compared to the fixations outside a beep. The proportions of looking at the other side (φ_c = -0.018, p = 0.041) and path (φ_c = -0.038, p < 0.001) were smaller in the within beep group compared to the fixations outside beep. Nevertheless, the effect sizes for all comparisons were very small, suggesting that the differences can be neglected. Hence, the proportions of the categories could be seen as overall equally distributed between the fixations occurred inside and outside a beep.

4.3 Deriving critical fixations from dataset

4.3.1 Reaction time

Each response on the auditory task generated a reaction time. The number of responses ranged from 43-62 responses for each participant per each condition. A total of 1542 reaction time measurements with a mean reaction time of 820 milliseconds (SD = 259, range 217-1989) and 120 missing responses were collected.

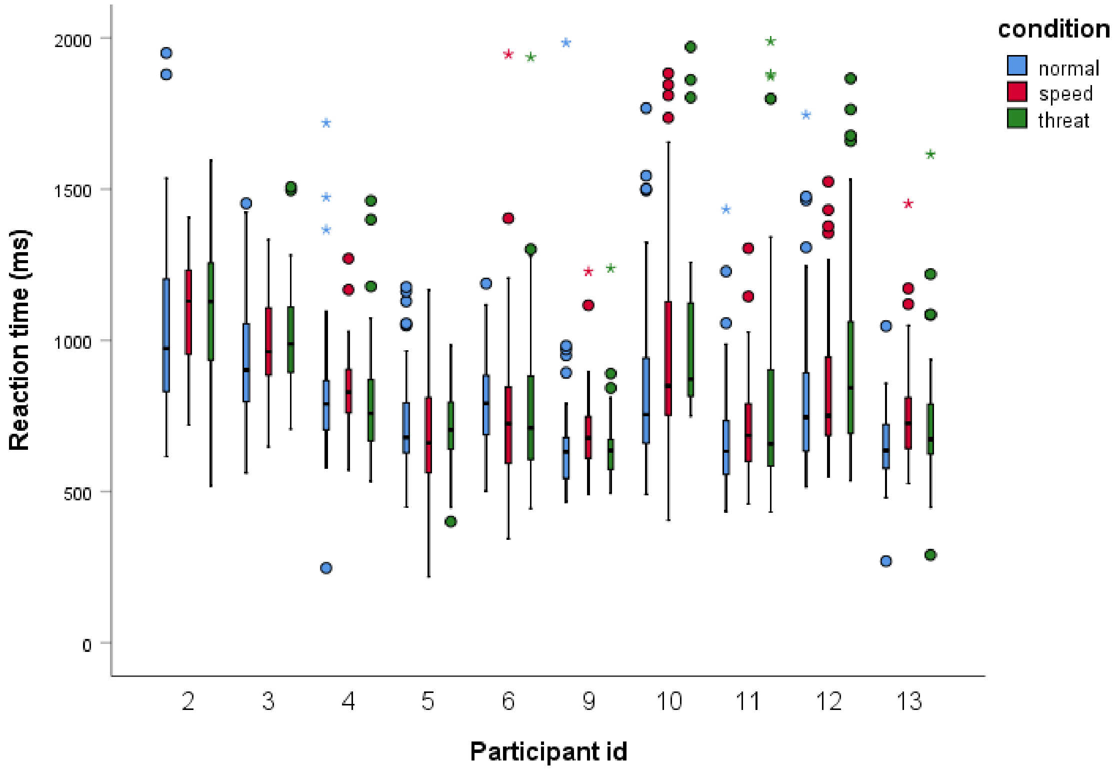


Figure 10: Reaction time auditory task per participant per condition.

As can be seen in Figure 10, differences in reaction time were found between participants and within conditions. Many outliers could be found in the upper part of the graph. Reaction times were therefore transformed into a logarithm to execute repeated measured ANOVA's on a normally distributed dataset. A repeated measures ANOVA was executed and suggested a significant difference between the reaction times of the three conditions, $F(2, 9) = 8.11$, $p < 0.001$. Post-hoc analyses, using the Tukey SD test indicated differences in reaction time between normal speed and high speed ($p = 0.003$). Moreover, a significant difference was found between normal speed and threat ($p = 0.003$), but no differences were found between high speed and threat ($p = 0.999$). As significant differences were found between conditions, it was chosen to use the reaction times per participant per condition for further analysis to identify critical fixations.

A repeated measures ANOVA was also executed to indicate reaction time differences in the route sections. Significant differences were found, $F(4, 9) = 10.38$, $p < .0001$ between the route sections. Post-hoc Tukey SD test indicated significant differences between section A and B ($p = 0.001$), section A and C ($p = 0.009$), section B and D ($p = 0.004$), section B and E ($p = 0.002$), section C and D ($p = 0.024$), and section C and E ($p = 0.013$). Reaction times were generally higher in section B and C compared to A, D and E, suggesting that mental workload is higher in section B and C. Further analyses of the routes are out of scope for this study.

4.3.3 Cutoff methods

A total of 4040 observations measured inside a beep were separated into a non-critical or critical fixation. As the ANOVA analyses in section 4.3.2 validated differences in the mean reaction time (MRT) among the different participants and conditions, it was chosen to calculate the MRT for every participant and condition separately. In addition, the standard deviation, median, 5% of the right tail, 10% of the right tail, and 25% of the right tail were calculated to generate different cutoff methods (Appendix C). Table 4 shows the distribution of non-critical and critical fixations among the fixations measured by the auditory task using different cutoff points.

Table 4: Cutoff point approaches

Cutoff method	Total number of non-critical observations	Total number of critical observations	% of all data critical fixations
5% right tail	3060	980	24.3
Mean + 2 SD	3004	1036	25.6
Mean + 1,5 SD	2872	1168	28.9
10% right tail	2824	1216	30.1
Mean + 1 SD	2635	1405	34.7
1000ms	2480	1560	38.6
75% of the data	2228	1812	44.9
Median	1360	2680	66.3

The mean+2SD and 1000ms cut off points were used in further analysis for two reasons. First, they differed in ratio. In other words, testing with these methods would give different numbers of critical fixations. Using the mean+2SD is more strict and resulted in less critical fixations, whereas the 1000ms cutoff point approach could be seen as less strict. Second, the 1000ms cutoff point was not based on any reaction time of the participants, whereas the mean+2SD was based on the mean reaction time per participant per condition.

4.4 Distribution of critical fixations

4.4.1 Highest frequencies

One way to identify what is a critical fixation is to look at the highest frequencies and proportions of the categories divided in all the critical fixations. Figure 11 illustrates the overall distribution using the mean+2SD cutoff point. Bar plots were computed to provide an improved overview of the fixations distribution over the categories in every condition for every cutoff point (Appendix D). Overall, the order of the areas of interest are similar for the highest frequencies. Without differentiating between conditions, the largest numbers of critical fixations were directed towards the goal, pedestrians, and paths.

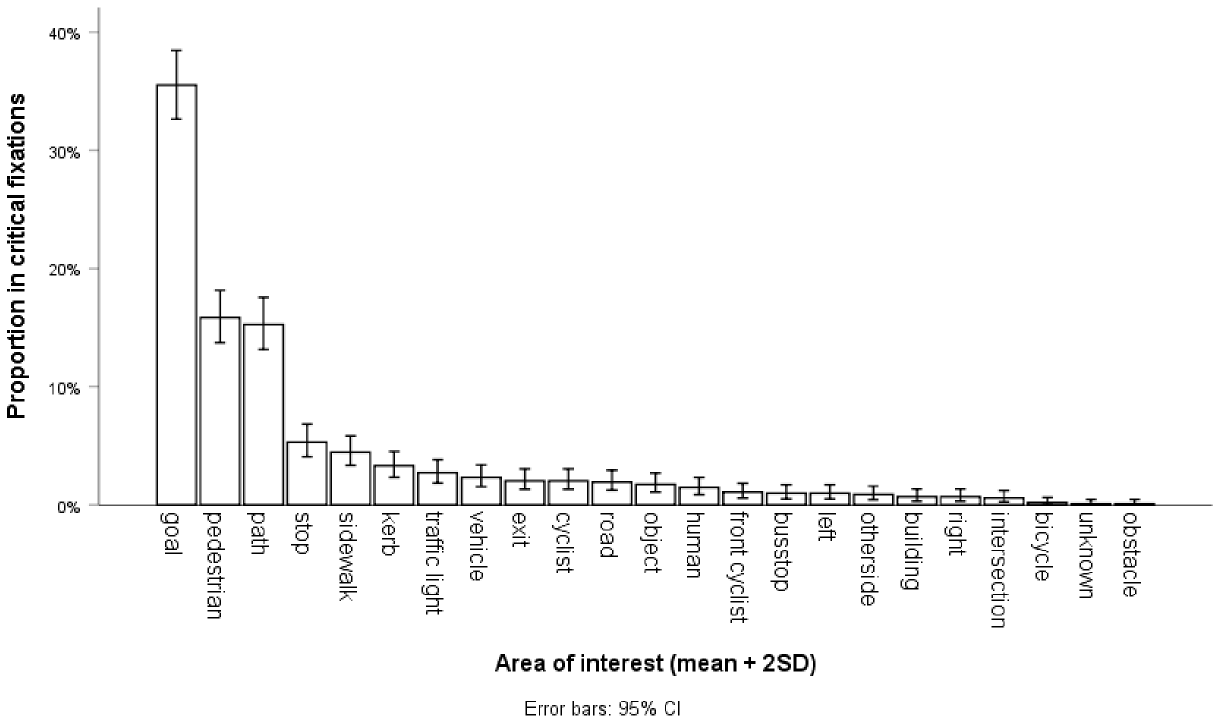


Figure 11: Rank proportion categories in critical fixations. The categories were sorted on the largest amount of observations of a category to the smallest category proportions

Table 5 shows an overview of the top nine highest proportions (all frequencies larger than 50) of the categories of critical fixations. The table includes the order of the proportion of the different conditions for the two cut off point approaches. As can be seen in Table 5, critical fixations were mostly directed towards goal, pedestrians and path for all conditions and the two cut-off methods. In other words, these categories were the three most frequent, and therefore, important critical fixations. After that, stops, sidewalks, and kerbs were the most frequent critical fixations for the majority of the conditions. The last most frequent fixations were on traffic lights, humans, cyclists, objects, vehicles, front cyclists and roads. Objects seem to have a higher proportion when participants felt threatened. Exits seem to be more fixated on when cyclists cycling at normal speed than at higher speed or when they feel threatened.

Table 5: Top 9 most frequent critical fixations

	All		Normal		Speed		Threat	
	M + 2SD	**>1000ms**	**M + 2SD**	**>1000ms**	**M + 2SD**	**>1000ms**	**M + 2SD**	**>1000ms**
1	Goal	Goal	Goal	Goal	Goal	Goal	Goal	Goal
2	Pedestrian	Path	Pedestrian	Path	Path	Path	Pedestrian	Pedestrian
3	Path	Pedestrian	Path	Pedestrian	Pedestrian	Pedestrian	Path	Path
4	Stop	Sidewalk	Stop	Kerb	Stop	Stop	Sidewalk	Sidewalk
5	Sidewalk	Stop	Exit	Stop	Sidewalk	Sidewalk	Kerb	Stop
6	Kerb	Kerb	Kerb	Exit	Vehicle	Kerb	Stop	Kerb
7	Traffic light	Exit	Human	Cyclist	Traffic light	Traffic light	Object	Object
8	Vehicle	Traffic light	Traffic light	Sidewalk	Left	Exit	Cyclist	Front cyclist
9	Exit	Object	Cyclist	Human	Exit	Vehicle	Road	Cyclist

Based on Figure 11, one could conclude that multiple categories had a very small proportion (<5%). It is difficult to indicate what is actually happening with low frequencies and statistical analysis are hard to interpret. Meanwhile, it might be a coincidence that these fixations occurred during the experiment. Therefore, the current categories with less than 50 observations (<5%) were recombined into new categories or were added to an old category.

4.4.2 Categories new dataset

Combining different categories together emerged into a new dataset. Table 6 describes the sixteen new categories. These categories were used in further analyses.

Table 6: New categories of critical fixations

New category	Old categories	Justification
Goal	Goal	
Path	Path, obstacle, ice	All observations were located on the path
Pedestrian	Pedestrian, human	Humans standing still will walk at a certain point
Sidewalk	Sidewalk	
Kerb	Kerb	
Stop	Stop	
Front cyclist	Front cyclist	
Object	Object	
Building	Building, bus stop	Bus stop is a small building
Exit	Exit, intersection	Places where other road users can go in or out
Cyclist	Cyclist	
Traffic light	Traffic light	
Road	Road	
Vehicle	Vehicle	
Environment	Other side, left, right, distraction, sign, light	Looking at the environment others than the most critical ones
Others	Unknown, bicycle	Cannot be placed in other categories

4.5 Critical eye fixations of cyclists

In this paragraph, outcomes of the comparisons between non-critical and critical fixations are described using the two methods (mean + 2SD and 1000ms). Second, the critical and non-critical fixations when cyclists were cycling at normal speed, when cyclists were cycling at high speed, and when they felt threatened were compared separately.

4.5.1 Non-critical fixations and critical fixations

Chi-square tests of independence were performed to determine whether the proportions of the categories were equally distributed between non-critical and critical fixations. A chi-square test was executed for every method (mean+2SD and 1000ms) and for every condition (normal speed, high speed, threat) separately. Table 7 shows the results of the chi-square tests, suggesting significant differences between non-critical and critical fixations for all chi-square tests.

Table 7: Chi-square results of comparison proportion of categories between non-critical and critical fixations

Conditions	Method	X^2	*Df*	*N*	*p*	Φ_c
All conditions	M + 2SD	82.715	15	4040	<0.001	0.143
	>1000ms	85.129	15	4040	<0.001	0.145
Normal	M + 2SD	33.825	15	1607	=0.004	0.145
	>1000ms	47.809	15	1607	<0.001	0.173
Speed	M + 2SD	100.452	15	1120	<0.001	0.300
	>1000ms	52.072	15	1120	<0.001	0.216
Threat	M + 2SD	51.849	15	1313	<0.001	0.199
	>1000ms	52.170	15	1313	<0.001	0.199

Figure 12 shows the proportions of the categories with the mean+2SD cutoff method without differentiating between conditions. There is a significant smaller proportion of critical fixations directed towards buildings (φ_c = -0.041, p = 0.010) and front cyclists (φ_c = -0.063, p < 0.001) compared to non-critical fixations. Moreover, the proportion of critical fixations is significantly larger at the environment (φ_c = 0.047, p = 0.003), stops (φ_c = 0.074, p < 0.001), traffic lights (φ_c = 0.048, p = 0.002) and vehicles (φ_c = 0.050, p = 0.001) categories compared to non-critical fixations. Yet, the effect sizes are all very small.

Figure 13 shows the proportion of the categories with the >1000ms cutoff method without differentiating between conditions. There is a significant smaller proportion of critical fixations directed towards buildings (φ_c = -0.035, p = 0.027), front cyclists (φ_c = -0.075, p < 0.001) and goal (φ_c = -0.066, p < 0.001) compared to non-critical fixations. Moreover, participants looked significantly more at paths (φ_c = 0.050, p = 0.002), stops (φ_c = 0.062, p < 0.001) and traffic lights (φ_c = 0.040, p = 0.010) in critical times compared to non-critical times. In the same way as the mean+2SD cutoff point, the effect sizes are very small.

Comparing Figure 12 with Figure 13, one result pops out from the rest. The direction of path between critical fixations and non-critical fixations is different for the two cut-off points. To clarify, for the mean+2SD, the proportion of critical fixations directed towards path were smaller compared to non-critical fixations. In contrast, for the >1000ms cutoff point, the proportion of critical fixations directed towards path were larger compared to non-critical fixations.

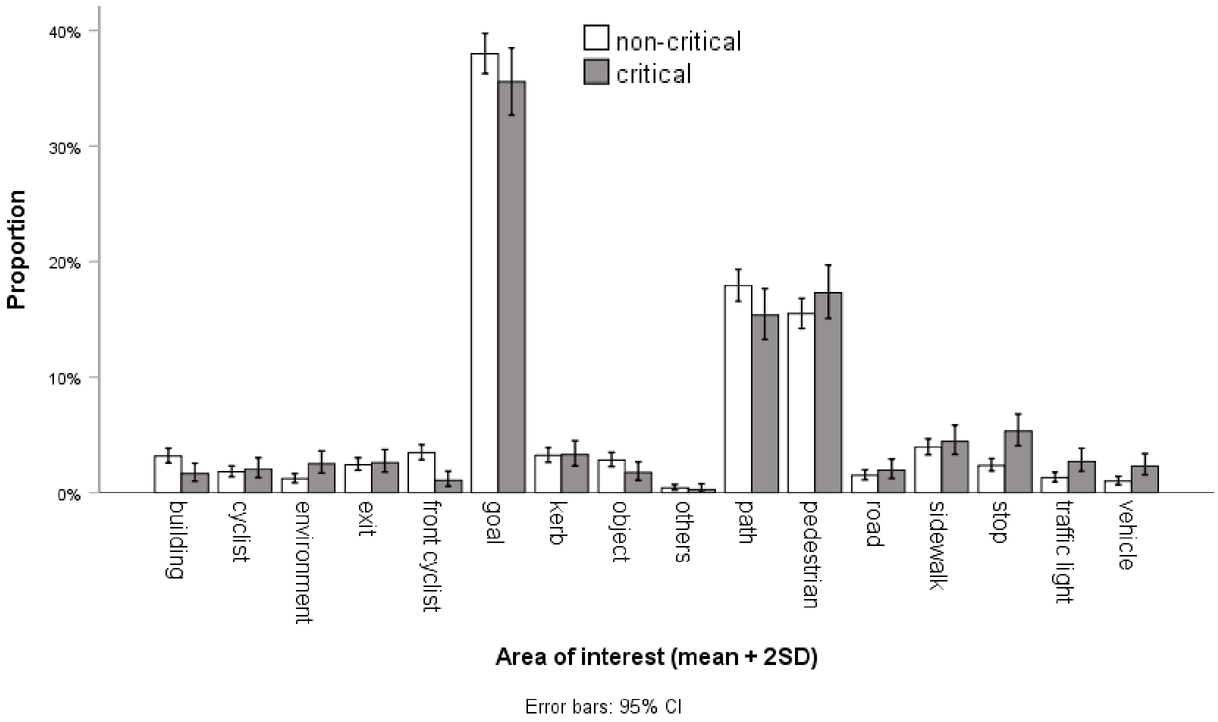


Figure 12: Distribution of proportions critical fixations and non-critical fixations using mean+2SD cutoff point

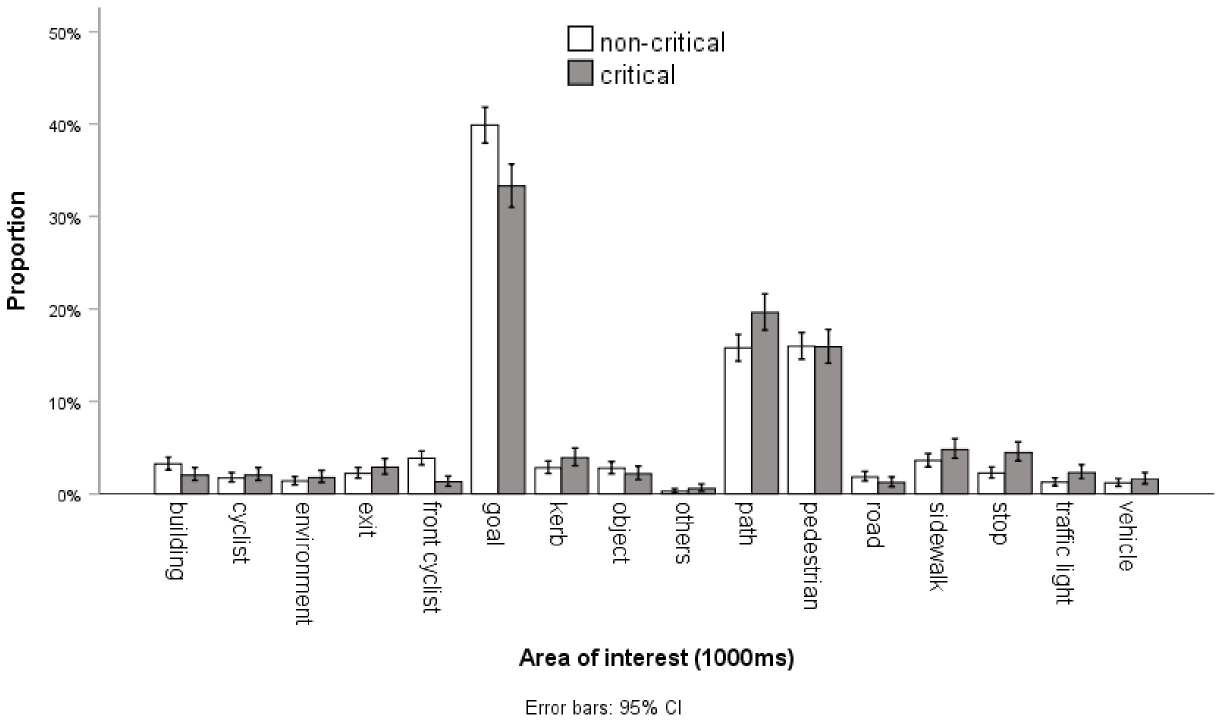


Figure 13: Distribution of proportions critical fixations and non-criticalf fixations using 1000ms cutoff point

Table 8 summarizes the difference in the distribution of proportion percentage between non-critical and critical fixations per category in the three conditions for the different cutoff methods. Post-hoc crosstabulations between non-critical and critical fixations per category were executed when standardized residuals of that category exceeded the value of 2 or -2 in the overall model. All cross tabulations, including bar charts, can be found in Appendix E. Overall results (table 8) suggest that cyclists looked significantly more at stops and less at front cyclists.

Two other main results can be derived from Table 8. First, there were differences in outcomes between the two cutoff points. To clarify, the directions (- or +) of some categories differed between the two cutoff points. For example, in the high speed condition the proportion of path is significantly lower for critical fixations than for non-critical fixations in the mean+2SD cutoff point. In contrast, for the >1000ms cutoff point approach, results confirmed that the proportion of critical fixations directed towards the path was significantly higher compared to non-critical fixation. Second, there were differences in the direction (- or +) of the proportions for the different conditions. For example, when cycling at a high speed, a significantly smaller proportion of critical fixations is directed towards kerbs compared to non-critical fixations. In contrast, when cyclists felt threatened, a significantly larger proportion of critical fixations was directed towards kerbs compared to non-critical fixations.

Table 8: Difference between proportions of categories (%) in non-critical and critical fixations.

	Normal		**Speed**		**Threat**	
	m + 2 SD	>1000ms	m + 2 SD	>1000ms	m + 2 SD	>1000ms
Building	-1.5	-1.9	+0.2	+0.3	-2.6**	-1.3
Cyclist	+0.1	+0.7	-1.2	-0.4	+1.5*	+0.7
Environment	+2.3**	+1.4	+2.2***	+1.2	-0.5	-1.0
Exit	+1.3	+1.1	-0.4	+0.7	-0.3	+0.2
Front cyclist	-1.8*	-1.9**	-3.3*	-3.9**	-2.6*	-2.6**
Goal	-5.5	-7.2**	+0.4	-5.6	-2.3	-6.7*
Kerb	+0.1	+1.2	-3.9*	-0.8	+2.9**	+2.7**
Object	-1.2	-1.7*	-2.3*	-0.3	-0.7	-0.1
Others	-0.3	-0.3	+0.5*	+0.2	-0.4	+1.0**
Path	-0.3	+5.6**	-9.4**	+3.9	+2.2	+3.6*
Pedestrian	+4.9*	+3.6	-0.5	-3.9	-2.1	-2.2
Road	-0.7	-1.5*	+0.1	-0.6	+1.8**	+0.5
Sidewalk	+0.1	+0.9	+2.1	+0.9	-1.2	+0.6
Stop	+2.4*	+0.5	+6.4***	+3.2**	+1.6	+3.5***
Traffic light	+0.8	+0.3	+3.3**	+2.8**	+1.3*	+0.7
Vehicle	-0.5	-0.9	+4.6***	+2.3**	+1.2	+0.4

*Note: Significance at the .05 level, * = p<0.05, ** = p<0.01, ***=p<0.00. A plus (+) means that the proportion of critical fixations is larger than the proportion of non-critical fixations for that category. A minus (-) indicates that the proportion of critical fixations is smaller than the proportion of the non-critical fixations for that category.*

4.5.2 Comparison critical fixations in normal speed, high speed and threat

A chi-square test of independence was performed to examine the relation of the distribution of proportion of areas of interest between cycling at normal speed and cycling at high speed. Next to this, a chi-square test of independence was performed to examine the relation of the distribution of proportion of areas of interest between normal cycling and cycling when feeling threatened.

A significant difference was found between the distribution of gazes over categories normal speed and high speed when using the mean+2SD approach (X^2 (15, N = 583) = 34.748, p = 0.003), as well for using the 1000ms approach (X^2 (15, N = 957) = 42.250, p < 0.001). Moreover, a significant difference was found between the proportions of critical fixations between normal cycling and feeling threatened when using the mean+2SD approach (X^2 (15, N = 825) = 34.784, p = 0.003), as well as using the 1000ms approach (X^2 (15, N = 1141) = 48.876, p < 0.001). A representation of the proportions of categories in different conditions can be found in Figure 14 and Figure 15.

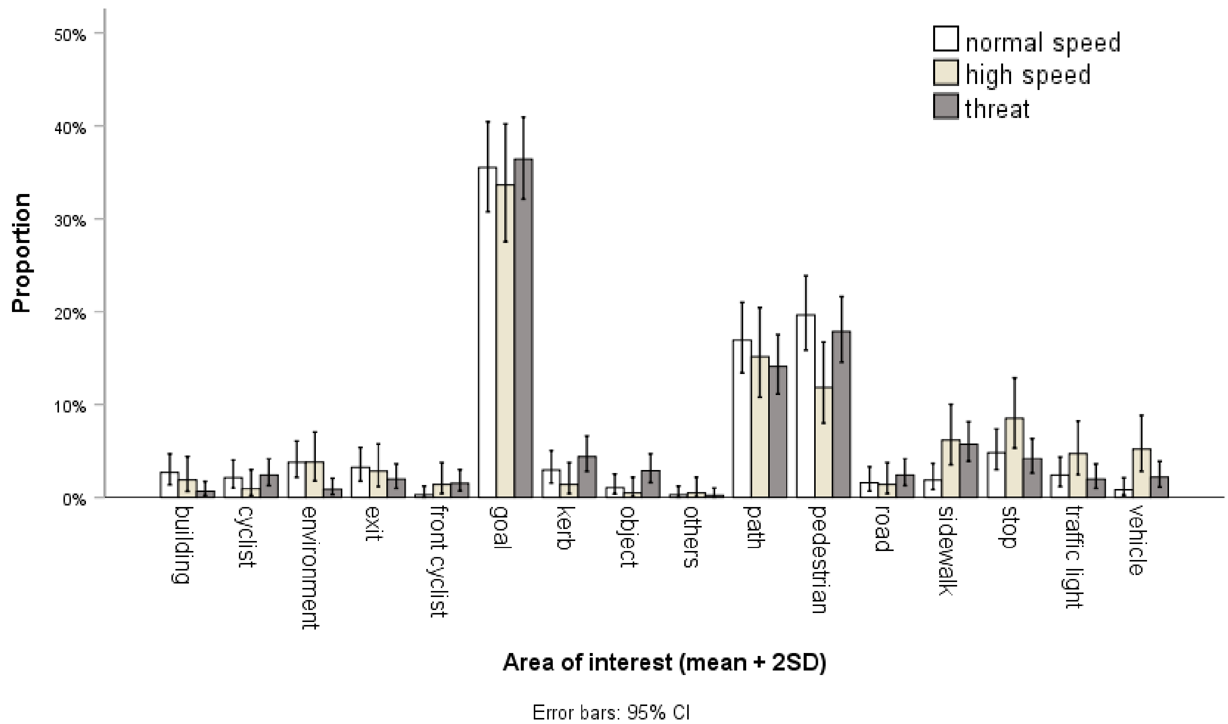


Figure 14: Comparison of critical fixations between three conditions for mean+2SD

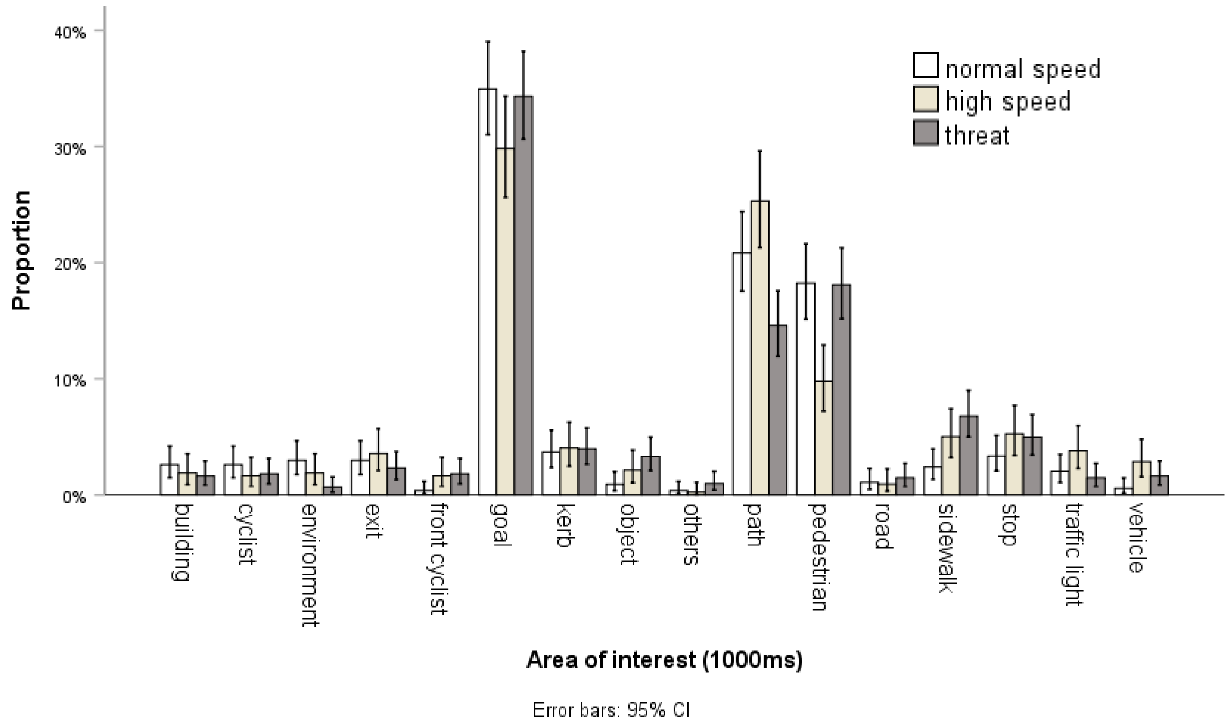


Figure 15: Comparison of critical fixations between three conditions for 1000ms

Table 9: Difference between proportions of critical fixations (%) in normal vs high speed and normal vs threat.

	Normal speed – high speed		Normal speed – threat	
	m + 2 SD	>1000ms	m + 2 SD	>1000ms
Building	-0.8	-0.7	-2.0*	-0.9
Cyclist	-1.3	-0.9	+0.2	-0.8
Environment	+0.0	-1.1	-2.9**	-2.3**
Exit	-0.4	+0.6	-1.2	-0.7
Front cyclist	+0.9	+1.3*	+1.2	+1.4
Goal	-1.9	-5.1	+0.9	-0.6
Kerb	-1.6	+0.4	+1.4	+0.3
Object	-1.4	+1.2	+1.8	+2.4**
Others	+0.2	-0.2	-0.1	+0.6
Path	-1.7	+4.5	-2.8	-6.2**
Pedestrian	-7.8*	-9.4***	-1.7	-0.1
Road	-0.2	-0.1	+0.8	+0.4
Sidewalk	+4.3**	+2.6*	+3.8**	+4.4**
Stop	+3.7	+2.0	-0.6	+1.7
Traffic light	+2.3	+1.8	-0.4	-0.5
Vehicle	+4.4**	+2.3**	+1.4	+1.1

*Note: Significance at the .05 level, * = p<0.05, ** = p<0.01, ***=p<0.00. A plus (+) means that the proportion of critical fixations was larger than the proportion of non-critical fixations for that category. A minus (-) indicates that the proportion of critical was smaller than the proportion of the non-critical fixations for that category.*

Table 9 includes the significant differences between proportions of the critical fixations for the different categories. Post-hoc tests consisted of examining the standardized residuals. When those residuals exceeded the >2 or <-2, an independent chi-square was executed for that specific category.

A significant difference was found between normal speed and high speed for the categories pedestrians, sidewalk and vehicle when using the mean+2SD cutoff point. When cyclists were cycling at high speed they looked significantly less at pedestrians. In contrast, they looked significantly more at sidewalks and vehicles when they were cycling in high speed. The cutoff point 1000ms also suggested significant differences in all previous mentioned categories, including one extra category; proportion of fixations directed towards other cyclists is significantly higher when cyclists were cycling in high speed.

A significant difference was found between the distributions of gaze fixations at the normal speed and when cyclists felt threatened for buildings, the environment and the sidewalk using the mean+2SD cut off point (see Table 9). When cyclists felt threatened, they looked significantly less at buildings and the environment and more at the sidewalk compared to normal cycling. For the 1000ms cutoff point, significant differences were found between normal cycling and feeling threatened for critical fixations directed towards environment, object, path, and sidewalk. Cyclists looked significantly less at the environment and path when they felt threatened compared when they were cycling normally. They looked more at front cyclists, objects and sidewalks when they felt threatened compared to when they did not feel threatened.

Figure 14 and Figure 15, as well as in Table 9, presents different results occur between the two cutoff methods. In other words, for those categories participants looked more (+) at a specific category in one condition compared to the other condition for one cutoff point method; though, they looked less (-) at that specific category for the other cutoff point method. There were differences in direction for the critical fixations towards exit, kerb, object, others, and path between normal speed and high speed. This is also the case for cyclist, goal, others, and stops in the comparison between normal speed and feeling threatened.

4.6 Distance

The distance of important areas of interest were estimated to identify at what distance cyclists focused on these critical features. The highest overall proportions of critical fixations were goal, path, and pedestrians. The category goal describes the heading direction of the cyclist; therefore, no distance could be estimated for this category, as it would be infinity. Therefore, only path and pedestrian were included in further analyses. In addition, vehicles and stops showed a significantly higher proportion in critical fixations compared to non-critical fixation; therefore, they were also included in further analysis. Moreover, compared to normal cycling, a higher proportion of critical fixations seemed to be directed towards sidewalks when cyclists were cycling at high speed and when they felt threatened. Therefore, sidewalk was included in further analysis too. The distance of pedestrians encountered by the participants were distinguished between three categories: near (0-4m), middle (4-8m) and far (>8m). Next to this, it was analyzed whether pedestrians were walking alone or in groups and whether the participants looked at the face or body of a pedestrian. For the other areas of interest, the fixations were divided into two group: near (0-4m) and far (>4m).

4.6.1 Distance of static objects

Path, sidewalk, and stop are static objects. Table 10 shows the distribution of far and near fixations of the three static objects. Cyclists mainly looked at the sidewalk from a far distance. Fixations of path and stops were somewhat evenly distributed between far and near region. Figure 16 shows the results of the critical fixations with the >1000ms cutoff point, including all static objects. As results of mean+2SD and 1000ms showed comparable results, all other bar charts of static objects could be found in Appendix H. The errors bars (Figure 16) illustrate that the fixations on static objects seems equally distributed among far and near regions when cycling in higher speed. When cycling at normal speed, the error bars suggest that cyclists tend to look more at the near region than the far region. When cyclists feel threatened, they looked more at the far region than the near region.

Table 10: Distribution of critical fixations per category (%) on static objects

	Mean+2SD		1000ms	
	Near	Far	Near	Far
Path	48.4%	51.6%	52.0%	48.0%
Sidewalk	13.0%	87.0%	20.0%	80.0%
Stop	46.7%	53.3%	52.9%	47.1%

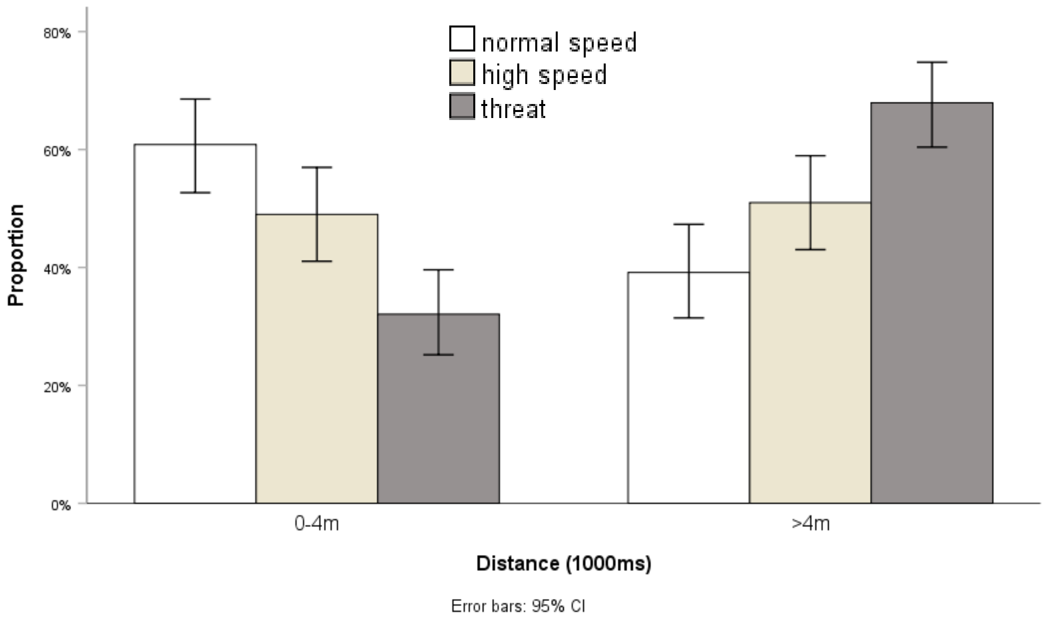


Figure 16: Distribution of fixation distance of static objects in the three conditions (1000ms cutoff point)

4.6.2 Distance of dynamic objects

When critical fixations were directed towards vehicles, they were only fixated when those vehicles were far away (>8m). This is different for fixations at pedestrians. Table 11 shows that many critical fixations were directed towards pedestrians that are positioned far away. The number of fixations between 4-8m is smaller than >8m, but is larger than near fixations, suggesting that pedestrians were mainly fixated on when they were far located from a participant.

Table 11: Distribution of critical fixations per category (%) on dynamic objects

	Mean + 2SD			1000ms		
	Near	Middle	Far	Near	Middle	Far
Pedestrian	12.3%	19.6%	68.1%	10.9%	26.2%	62.9%
Vehicle			100%			100%

As can be seen in Figure 17, the errors bars suggest that cyclists mainly gazed at pedestrians in the far region when cyclists were cycling at normal speed and when they felt threatened. For high speed, cyclists focused mainly at pedestrians in the middle region. As results of using the mean+2SD and 1000ms are comparable, more bar charts can be found in appendix G.

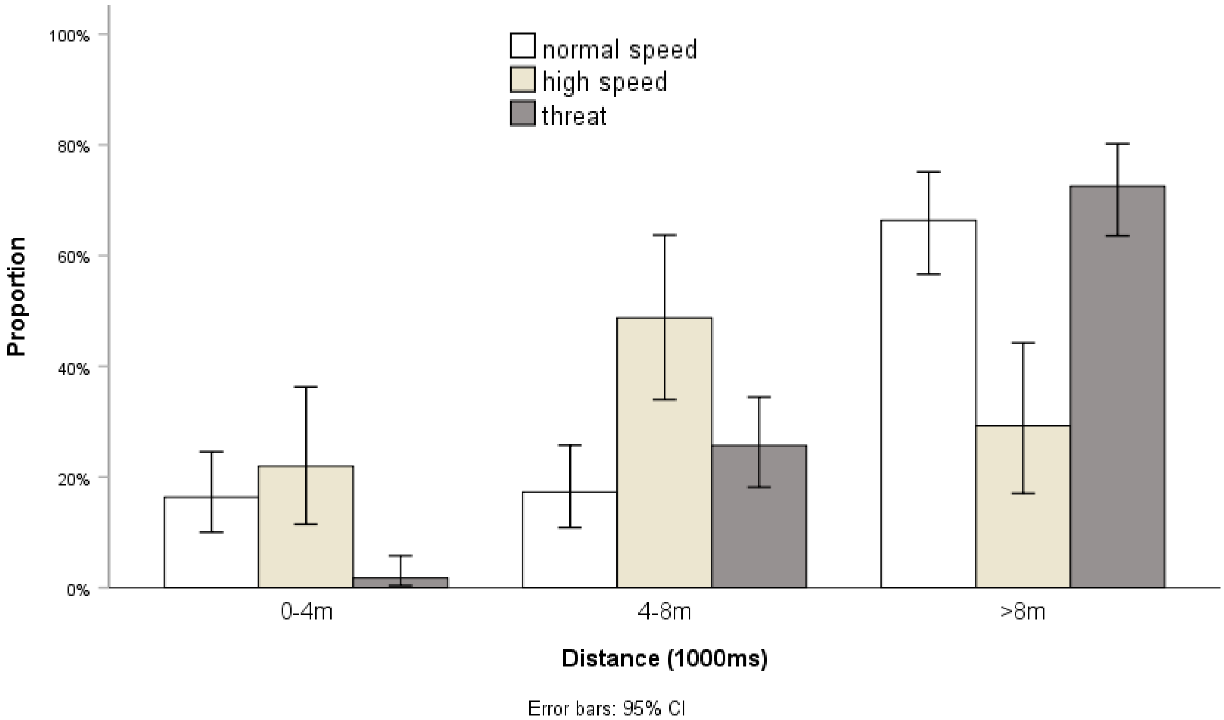


Figure 17: Distribution of fixation distance of pedestrians in three conditions (1000ms cutoff point)

Fixations directed towards pedestrians were further analyzed. Fixations on pedestrians were categorized into fixations to the face or body of a pedestrians. Moreover, a separation was made between pedestrians who were walking alone or who were walking with other people. Chi-square tests of independence were executed to determine the relation between distance and amount of people. The distance and fixations directed towards face or body were also tested with a chi-square test of independence. In addition a chi-square test of independence was executed to examine the relation between fixations directed towards body or face and whether pedestrians were walking alone or in a group. The contingency tables can be found in Appendix G.

Using the mean+2SD cutoff point, a significant difference was found between fixating on body or face and the number of persons walking, X^2 (1, N = 170) = 4.548, p = 0.033. Results suggest that fixations were mainly directed towards body,for both when pedestrians were walking alone (33.5%) or in a group (29%). In contrast, 26.5% of the fixations were directed towards the face when pedestrians were walking alone and 11% when pedestrians were walking in a group. For the >1000ms cut off point method, a more clear deviation is visible, X^2 (1, N = 239) = 6.440, p = 0.011. Results suggest that fixations were mainly directed towards the body for both when pedestrians were walking alone (36%) or in a group (31%). A small number of fixations was directed towards the face when pedestrians were walking alone (23.4%) or in a group (9.6%).

Lastly, the percentage of looking at face or body significantly differed between distance using the 1000ms cutoff point, X^2 (1, N = 246) = 14,278, p = 0.001. Table 12 shows that participants looked more at bodies and pedestrians far away than at faces and pedestrians nearby.

Table 12: Fixations on body/face and distance

	1000ms	
	Body	Face
0-4m	7.7%	3.3%
4-8m	22.4%	4.1%
>8m	36.5%	26%

Chapter 5: Discussion

5.1 General discussion

5.1.1 Critical visual tasks of cyclists

The aim of this study was to investigate critical visual tasks of cyclists in a complex natural environment after dark in an exploratory study. For this purpose, ten participants cycled a track three times under three conditions (normal speed, high speed, threat) while performing a secondary auditory reaction time task. The main findings suggested that the goal is the most frequent critical fixation category for cyclists. The goal can be described at the heading direction of a cyclist. Hayhoe and Ballard (2005) explained the same results by illustrating that visual search patterns for car drivers are mainly guided for goal directed locomotion. This phenomenon is also described in the Wilkie and Wann model of steering (2003). The model of steering suggests that gaze is fixated onto the point in the world that you currently wish to travel toward. This point can supply all the information you need to successfully reach the target. Moreover, this finding implies that cyclists use visual information mainly for navigation and efficient steering like car drivers do. This is conforming the two-level model of steering (Donges, 1978; Salvucci & Gray, 2004). Shinar (2008) suggest that gaze is, therefore, displaced towards the distant region to retrieve maximal amount of information. In addition, looking at the heading direction is also found in gaze behavior of pedestrians walking a simple route (Higuchi & Yoshida, 2013).

Furthermore, path and other pedestrians walking in the environment were the second and third most frequently fixated on areas of interest in this study. Our findings suggest that scanning the path is of high importance, for example to detect surface obstacles and other hazards. At night the ability to see small objects is more difficult than in daylight. This results into fixations towards the path, but also at the sidewalks, and kerbs, which were also found in the nine most frequently fixated categories. In the current study, participants did not often look at obstacles. These findings are comparable with the results of Kitazawa and Fujiyama (2010). They argued that pedestrians mainly paid attention to ground surfaces to detect potential threats on the ground, instead of focusing on those obstacles. This might explain why cyclists look at those places mentioned before.

Fotios et al. (2015) found partly comparable results in the gaze behavior of pedestrians. In their study, pedestrians mainly gazed to the path. Next to it, the goal, pedestrians, and general environment were most frequent focused on. In other words, there is a small difference in order of the three most frequent categories. Our results suggest fixations mainly on the goal, path, and pedestrians. This result reflects that the gaze strategies of pedestrians and cyclists are slightly different. In addition, our findings are partly consistent with the findings of Qasem et al. (2017). They found many fixations towards the path. However, the number of fixations on pedestrians was lower in their study. These differences might be explained due the fact that participants in that study encountered a small number of cyclists and pedestrians. Fotios and colleagues (2015) stated that the number of people encountered in a study will affect the proportion of fixations on people and the probability of fixating on people. Moreover, Qasem and his colleagues argued that the observation of the path and scanning surfaces for hazards are of importance. In contrast, our findings suggest that goal is overall the most fixed gaze direction and our participants passed by obstacles without fixating on them. It is unclear why this difference occurred. Vansteenkiste and colleagues (2014) also found partly similar results. Participants in their study mainly looked at the path (41%) and the goal (40%). However, they did not find many fixations on pedestrians in their study, due to the low number of pedestrians passing by.

Moreover, findings from the current study show that cyclists mainly look at bodies of pedestrians instead of faces. Fotios and Raynham (2011) argued that facial recognition is important to promote a sense of security and social ease. Consequently, one could argue that gazes at faces should have occurred many times in our experiment. Instead, our findings suggest that body posture might be more important than face recognition for cyclists at night. That body posture is important for pedestrians was mentioned in other studies for pedestrians (Meeren et al. 2005; Davoudian & Raynham, 2012; Fotios & Yang, 2013). This finding also contributes to the statement that collision avoidance might be more important than identifying faces or findings threats. However, faces could become more important when pedestrians are nearby, because faces should be recognized in some cases (Fotios & Raynham, 2011). Results of current study also suggest that fixations on the face became larger at a near distance, but that human bodies are still more often fixated on. On could also argue that it is hard to identify faces at night. Consequently, cyclists might focus on bodies to identify the direction a pedestrian is going to, because that is easier to interpret. Next to this, it could be argued that understanding body gesture might take more time than face recognition. Therefore, more fixations are directed towards bodies, because it takes more movements of a pedestrian and fixations of a participant to understand the intention of a pedestrian. Nevertheless, one should keep in mind that our participants might looked at the hands of pedestrians avoiding stealing the bag in the threat condition. This can have increased the number of fixations on body. Moreover, the category exits was also included in the top nine of critical fixations, suggesting it is important for cyclists to look at places where they can encounter other road users, such as pedestrians.

While comparing critical with non-critical fixations, one should keep in mind that all comparisons for all results had very small effect sizes. In other words, even when a significant difference was found, the size of the difference between two groups is very small. Comparing critical fixations with non-critical fixations in current study, cyclists gazed more at the environment in critical times compared to non-critical times using the mean+2SD cutoff point approach. No evidence or related research can be found for this phenomenon in the published literature. Therefore, this finding might be a coincidence. Another reason might be that participants looked more at the environment because they were searching for something. Moreover, Foulsham and colleagues (2013) argued that participants could be daydreaming during an experiment. Consequently, performance of the auditory task decreases due to distraction in our study. Subsequently, those fixations are included as a critical fixation in the long reaction time. In other words, a decreased performance on the secondary task does not always mean that attention is allocated to the primary task. It could reflect the attention to a task that is irrelevant to cycling. Next to this**,** pedestrians and places to stop revealed to be important as well in critical times compared to non-critical times. An explanation might be that cyclists should stop at that point, because they need to follow the traffic rules. As it was instructed to follow the traffic rules, this task became important. However, it is unclear why reaction times would increase when looking at stops. When participants looked at pedestrians, they might want to predict the intentions of the pedestrians. This might lead to a slower reaction time. More research needs to be executed to gain a better understanding of these outcomes. Using the 1000ms cutoff point, the proportion of looking at the path is significantly higher in critical times than in non-critical times. It can be that cyclists searched for hazards on the path. Consequently, a decrement in performance of the auditory task occurred. These fixations are at cost of fixations towards goal, cyclists in front of the participants and roads. People sometimes looked at the cyclist in front of them, but much less in critical times. This suggests that cyclists looking at cyclists in front of them is not seen as very important. It could be that the front cyclist was blocking the view to the goal destination.

5.1.2 Critical visual tasks of cyclist at high speed

Cyclists in the current study mainly gazed towards goal, path and pedestrians when they were cycling at a higher speed in critical times. One could conclude that cyclists at a higher speed used the same visual strategy as when they are cycling with normal speed. Their main goal is to navigate and steer to the destination.

Comparing the proportions of critical fixations between cycling in normal speed and cycling when in higher speed, high speed cyclists looked significantly more at sidewalks and vehicles for both cutoff points. In addition, they looked significantly less at pedestrians. One could argue that vehicles are important to look at, because the intention of the driver of a vehicle is not always be known. A collision with a vehicle might be very dangerous; especially at high speeds. When cyclists are cycling in high speed, sidewalks appeared to be more important. It could be that participants were searching for possible threats, such as pedestrians that might occur in their collision course. Because searching for threats is more important than focusing on threats (Kitazawa and Fujiyama, 2010), the proportion of looking at pedestrians decreases. Using the 1000ms cutoff point, participants also appeared to look more at cyclists in front of the participant. One could argue that when one is cycling at higher speed, one has to look at cyclists cycling in front of them to avoid collision.

The fixations into the environment, places to stop, traffic lights and vehicles were significantly higher in critical times compared to non-critical times using the mean+2D cutoff point. While using the 1000ms cutoff point, only a significant increase of fixations for places to stop, traffic lights, and vehicles was found in critical times All these fixations are at the expense of fixations towards front cyclists while using the 1000 ms. While using the mean+2SD, less fixations were directed towards front cyclists, kerb, object and path. Following the traffic rules is an aspect that cyclists might keep considering; it was told that participants had to follow traffic rules. Therefore, they had to wait for stops and red traffic lights. Consequently, reaction times increases, because those tasks were important to finish the experiment. Cycling fast remains their main task, so participants might only look at features that contributed to the task explanation. Vehicles might be important because they need to be avoided and surpassed; otherwise a collision could occur.

Moreover, it could be argued that those previous mentioned categories (traffic light, vehicles and the environment) can be seen as salient objects that popped out in different ways. Those salient objects captured the attention of the cyclists. Mital et al. (2017) confirmed this. They stated that salience can be described in means of motion (vehicles), shape, and color (traffic lights). Moreover, Itti & Bald (2006) argued that salience can be seen as an unexpected stimulus (vehicles and traffic light). Besides navigation to the destination, cyclists might focus on salient objects. Those objects might interfere with reaching their destination (Bruce & Tsotsos, 2009). From these results one can argue that saliency plays a more important role when cyclists cycle at higher speed. In contrary, if this would really be the case, one would not only expect significant differences in the comparison between critical and non-critical fixations, but also between normal speed and high speed. However, these differences were not found. It remains questionable whether saliency plays a more important role when cycling in higher speed than in normal speed. Therefore, the intention behind many fixations in those categories remains unclear.

5.1.3 Critical visual tasks of cyclists when feeling threatened

When cyclists felt threatened, they mostly fixated on goal, path, and pedestrians in critical times. This suggests that cyclists that felt threatened used the same gaze strategies as in normal cycling. Therefore, the main task remained navigating and steering to the destination by looking at the goal direction.

Different outcomes were found in the comparison between cyclists cycling at normal speed and when feeling threatened between the two cutoff points. For the mean+2SD cutoff point, cyclists looked significantly more at sidewalks, suggesting that they might looked for threats on the sidewalk, such as walking pedestrians that might steal the bag located at the front carrier. This is at the expense of looking at buildings, and the environment. Searching for pedestrians appeared to be more important than fixating on pedestrians. One could argue that this finding is in line with the findings of Kitazawa and Fujiyama (2010), and Marigold and colleagues (2007). Both studies argued that pedestrians mainly pay attention to ground surfaces to detect potential environmental (static) hazards, instead of focusing on obstacles. This also might exist for searching dynamic objects in the environment; they were looking to avoid possible collision, but they did not focus on them. For the 1000ms cutoff point, cyclists are significantly more focused on the sidewalk and objects compared to normal cycling. This is at the expense of looking at the environment, and the path. It is unclear why objects are more fixated on when cyclists are feeling threatened than when they are cycling normally. More research needs to be executed to gain a better understanding of these occurrences.

Comparisons between non-critical and critical fixations using the mean+2SD cutoff point suggest that cyclists are looking more for other cyclists that might steal the bag, as well as roads, traffic lights and kerbs in critical times compared to non-critical times. This is at the cost of looking at front cyclists. One suggestion for these findings is that there is a possibility that a threat or obstacle might be present at roads and kerbs. Moreover, even when feeling threatened cyclists had to wait for traffic lights. However, this might not be the case in real life. When cyclists feel threatened, they will not always wait for a traffic light, as their own feeling of safety might be more important than traffic rules. Using the 1000ms cutoff point, cyclists looked more at kerbs, paths, and stops in critical times compared to non-critical times. This is at the cost of looking at front cyclists and the goal. As kerbs and path are near each other, cyclists might looked at those areas to avoid tripping. Even when they feel threatened, they need to avoid tripping. In addition, as stated before, they need to stop at the stops in order to follow the traffic rules.

5.1.4 Distance of critical features

The distance of three static objects was measured: the path, the sidewalks and stops. Results of current study showed that critical fixations towards stops and path are evenly distributed among the near and far region, suggesting that both regions are important for cyclists. Mantuano, Bernardi and Rupi (2016) found similar results. They argued that far and central regions are needed to obtain optimal information to cycle safely. Moreover, in previous research, car drivers mainly fixated on the far path, whereas pedestrians looked at the near path (Foulsham et al, 2001; Pelz & Rothkopf, 2007). Combining those results, one could argue that cyclists use a combination of strategies used by car drivers and pedestrians. Cyclists, as do pedestrians, need to keep balance (Marigold & Patla, 2007). In contrast, cyclists move with higher speed than pedestrians; consequently, they are necessary, as with car drivers, to look ahead at the path (Land, 2006). In addition, the sidewalk is mainly looked at from a far distance. The reason behind this gaze behavior can be explained as before. Cyclists tend to look at sidewalks to identify possible threats when it is dark. It can be argued that it is safer to look for possible threats in the far region than near region, because one has more time to take action if necessary.

Results of current study are somewhat contradictory with the gaze constrains model of Vansteenkiste and his colleagues (2013). The model states that distance gaze behavior increases when speed or mental workload increases. On one hand, the proportion of distant fixations in the current study is lower than the proportion of near fixations in the categories measured for the higher speed. In higher speed, the number of fixations are equally directed towards the near path and at the far path. This is in contrast with the constraint model of Vansteenkiste and colleagues (2013). The need for direct control should be higher when speed increases. Therefore, it was expected that the far region would be fixated on when cycling at a high speed. Our findings contradicts this statement by showing an equal number of fixations directed to the near and far region. On the other hand, there are more fixations in the far region when cyclists feel threatened, suggesting that when cyclists feel threatened, their gaze behavior is consistent with the model. One can therefore argue that when a cyclist feels threatened, the environment is less predictable. Cyclists will look at the far region to anticipate to the environment.

When cyclists are cycling at a higher speed, it can be argued that they tend to look far away to keep the 1-2 second view. This can be explained by the look ahead strategy. This strategy explains that car drivers are fixating their gazes to the road about 1 or 2 seconds ahead (Wilkie & Wann, 2003). Moreover, Wilkie, Wann and Allison (2008) argued that gazes of cyclists were about 1.5 seconds away from next slalom gates. If one compensated velocity with distance of fixations in the current study, then the results might support the look ahead strategy. Therefore, the distance of looking at features will become larger with increasing speed. However, specific velocities of cyclists were not measured in this study. Consequently, the velocity could not be calculated per fixation. An overall velocity could be calculated, but these values are not be useful for estimating the speed at a specific moment.

In addition to the static objects, the distance of vehicles and pedestrians was measured. Results of current study suggest that cyclists only fixated on vehicles in the far region (>8m). A reason for this might be that cyclists have to estimate the intentions and direction of car drivers at a far distance to avoid collision. Furthermore, vehicles have a higher speed compared to pedestrians. Therefore, the time to impact, in case of collision course, is smaller. Moreover, in general there was a gap of at least 2 meters between a bicycle path and a car road. Consequently, it is not needed to look at vehicles at a distance smaller than 4 meters.

Moreover, cyclists fixated more at pedestrians who are walking far away than those walking nearby. It is possible that the tendency to look at the far distance is more appropriate to avoid collision. In other words, cyclists do not start looking at pedestrians to identify their faces or to find threats in the near region, but they need to detect whether they are on a collision course from a distance. Only when our participants were cycling at a higher speed, they tend to look mostly at pedestrians in the middle range (4-8m). This might indicate that they want to execute both tasks, collision avoidance and face recognition. Therefore, one can conclude that collision avoidance might still be more important than face recognition for cyclists cycling in high speed, but that face recognitions remains important if needed. These results are partly consistent with a study by Fotios and his colleagues (2015) for gaze behavior of pedestrians. They found a tendency to look at other pedestrians when they are far away, but this was mainly found during daytime observations and not at night. It is unclear why this difference occurred.

Last, results of the current study showed that the proportion of far fixations on pedestrians is largest when cyclists feel threatened. Perhaps, when a participants was looking for an individual who could steal the bag, he/she was more interested in where pedestrians were located and which direction they were moving to so that they can depart from their path. In other words, they were already planning ahead what to do when pedestrians would move to a specific location. To conclude, overall findings suggest that it really depends on the mental workload, the task, and the speed of a cyclist which area they look at and from which distance.

5.2 Reflection on method to identify critical fixations

This study aimed at examining a reliable method to identify critical fixations. Discriminating critical fixations from the non-critical fixations is hardly investigated in past studies (Fotios, Uttley & Hara, 2013; Fotios et al., 2015; Qasem et al., 2017). As using self-reported measurements is subjective, but executed in many previous studies (Fabriek et al., 2012; Schepers & Den Brinker 2011), the dual-task approach was embraced to identify where the gazes of a cyclist were directed to. This is done by imposing that attention was allocated to the concurrent secondary auditory task (Pashler et al., 1993). Delayed responses to this auditory task indicated that participants were distracted and attention was allocated to the environment instead of the auditory task (Boot et al., 2005). An advantage of this method was that we could distinguish the critical from the non-critical fixations with a handy device. However, it should be mentioned that many fixations did not occur within those beeps. These could therefore not be identified whether those fixations are critical or not. Hence, the dual task methodology is a start of developing objective methods to identify critical fixations and outliers.

An important finding of this research is that different cutoff point methods identified dissimilar distribution of proportions of the categories in critical fixations. Therefore, it is important to think about what cutoff point to use when discriminating critical fixations from non-critical, as well as for finding outliers in general. Ratcliff (1980) mentioned this aspect as well for identifying outliers in reaction time research. Especially in this application, different cutoff points leaded to different significant results in comparisons. In current study, eight different cutoff points derived 4040 measured fixations within the beeps to 980 till 2680 possible critical fixations. The current study only included analyses with two cutoff points (mean+2D and 1000ms) to find reasonable cutoff points to compare with each other. Differences in distribution of proportions of categories between the mean+2SD and the 1000ms cutoff point were found. Moreover, sometimes the direction of interaction was changed due to the different cutoff points. Future research should aim at investigating more cutoff points to identify which cutoff is the most convenient to use. Moreover, mean reaction time calculations per participant per condition for each cutoff points were useful in this study. Results suggested that the mean reaction time was in general higher when cyclists were in a hurry or felt threatened compared to the mean reaction time when cyclists were cycling normally. When only calculating the mean reaction time per participant, all critical fixations would be found when cyclists were cycling at high speed or when they felt threatened.

Comparing non-critical with critical fixations had never been executed in previous research. Qasem et al. (2017) and Fotios et al. (2015) only included analyses of the most frequent categories captured within the dual task. In this study, it was further investigated by looking at differences between non-critical and critical fixations. Some areas of interest might only appear in critical times, suggesting that this area of interest is of importance, even if the overall frequency is low. Nonetheless, it remains questionable whether it was really necessary, in our study, to make a distinction between non-critical and critical fixations. On the one hand, as stated before, results showed small significant differences between non-critical and critical fixations in some categories. Based on this, the separation of critical fixations from non-critical fixations seems useful. On the other hand, one could argue that the overall order of the distribution of the categories remains the same for both the non-critical and critical fixations (see Figure 12 and Figure 13). Differences in order of the categories occurred in categories that contained less than 5% of the overall fixations. In addition, the effect sizes were small, suggesting that there is hardly any difference. Next to this, one could argue that the dual task method did perhaps not work as intended, but this requires future research.

Furthermore, all measured fixations were assumed to be equally important in the analysis. In current study, every fixations that occurred within the start of a stimuli and the response of a participant is coded as critical or non-critical. As a longer reaction time has a longer range, it included more fixations than shorter reaction times. Fotios et al. (2015) and Qasem et al. (2017) took another approach. They decided that only one fixation that appeared within a two second timespan from the start time of the auditory stimuli was the most important. However, this approach is subjective, because the researcher can decide which of the multiple gazes in the most important one. Moreover, a combination of several fixations might result to a sequence of critical fixations. In other words, a visual task can consist of a series of fixations. Therefore, it was chosen to include all fixations above the reaction time cutoff point without prioritizing, adding weights or transforming ‘more important’ fixations within a beep. On the other hand, not all fixations that are included at a slow performance and long reaction time could be a critical fixation. For this reason, our approach is not entirely robust. Including subjective reports of participants after cycling could be a solution for more robustness. By asking people reflecting on what they were doing at critical times during the video, one could get a better understanding of the reason behind a critical fixation.

Last, it should be mentioned that the areas of interest were categorized subjectively in this study. The researcher manually identified every fixation in the video-recording. Even when a fixation point could be seen clearly in the video, it could still be unclear where a participant was really looking at. In that case, it could be that a researcher categorized the fixation in the wrong category. This problem is extensively explained in the work of Holmqvist et al. (2011). To check for inter coder reliability and validity, future studies should include a second coder. Contradictory, defining a category of a fixation will never be completely objective, as what a human being is seeing or interpreting can be different. As algorithms of computers are still not able to recognize and define every fixation exactly, subjectively categorizing with two independent coders might still be a useful solution for now.

Chapter 6: Limitations and future research

6.1 Limitations of study

There are some noteworthy limitations of this study that are not mentioned yet. First, executing an experiment in a real environment with different road users leads to unexpected and uncontrollable variables. A disadvantage of a field study within this topic is that the frequency of all possible fixation areas cannot be known. One cannot estimate how many obstacles and other objects are possible to fixate on in the real world, or even to keep these number the same across trials and participants. Furthermore, it was not possible to control for the environmental conditions, such as weather circumstances and the behavior of other road users. Moreover, the dwell time of fixations are still dependent on the number of stimuli that are available in the environment. Fotios and colleagues (2015) stated that the number of pedestrians encountered in a study affected the proportion of fixations on people and the probability of fixating on people. Next to this, some categories did not occur often in the trials; analyses are hard to interpret for small frequencies. Therefore, categories with a small frequency were added together. Though, it should be considered that these categories can still be critical. Moreover, path and goal were the two most frequent measured categories. Consequently, everyone is able to look at the goal or at the path at any time. Yet, this study is more realistic and represents the real world better than a laboratory study. It provides a more objective representation of the real world. This is an advantage compared to many previous research in laboratories (Zeuwts, 2016; Vansteenkiste, 2015). Participants in this study were cycling in a complex environment where conditions and variables were not controlled to create a high ecological validity. One other large inconvenience what should be mentioned, was the behavior of other road users during this field study. Those people often looked at the participants, because they wore an eye-tracker and a helmet with a big infra-red light. This might influence the visual behavior of the participants as well, but this could not be taken into account in the analysis.

Second, the number of critical fixations was not normally distributed among participants. The range differed from 1 till 338 fixations per participant per condition. This might be due to the fact that some participants missed many beeps in a trial. Therefore, many critical fixations were included in their fixation dataset. One should keep in mind that most of the critical fixations are part of the visual behavior of only several participants. Moreover, the cutoff points were very strict for some participants, whereas for others they were less strict. For example, participants with a mean reaction time lower than 1000 milliseconds had very low numbers of critical fixations when using the 1000 milliseconds cutoff point. In addition, participants with a small distribution of response time, also included a low number of critical fixations while using the mean+2SD cutoff point. However, due to the low sample size, it was chosen to include all participants. Results should be more robust when more participants had more critical eye fixations and that the eye fixations were more normally distributed among participants.

Third, the pupil position could not always be identified due to technical malfunctions of the eye-tracker. Consequently, some eye fixations were missing within a beep. The eye-tracker is an objective method to indicate fixations, but it was not stable while cycling. Road surfaces were not always flat and smooth. Any disturbance can lead to a movement of the eye-tracker on the participants' heads. Moreover, the videos-recordings were very dark. It was therefore hard to indicate the areas of interest at times. An infrared light was used to get a brighter view without adding light visible for the human eye, but still, there was not always enough light to see small objects on the ground or sidewalk. Next to this, it should be mentioned that it was a challenge to estimate the exact distances due to the darkness; therefore, the critical fixations were divided into two or three distance groups. This approach is useful, but future research is recommended to use more advanced technology that can really measure the distance. Beside, this field study was weather dependent. The eye-tracker could not be used during rainy weather (Pupil Labs, 2017). It was drizzling in several trials. Results showed small significant differences between non-critical and critical fixations for some categories, but the overall differences were generally small. However, future studies should try to keep the weather conditions constant.

Furthermore, hardly any obstacle detection (e.g., objects on the track) occurred in this study. It might be that obstacles were absent in this study. Cyclists are therefore looking at other areas. The key visual needs of Camanida and Van Bommel (1984) were partly found in this experiment. Participants did indeed try to identify other road users. The participants also felt comfortable and reassured while cycling the route. However, it is unclear what other studies included in the fixation category 'obstacle', as it seems that participants of other studies did focus more on obstacles. Another reason might be that cyclists mainly used their peripheral visual system to identify obstacles on the path (Marigold, Weerdesteyn, Patla & Duysens 2007). Our participants were all expert cyclists. Lansdown (2001) argued that expert drivers relied more on peripheral visual cues compared to novice drivers. Unfortunately, the current study was not able to study the peripheral visual system, so did many other studies. Therefore, the differences in results remain unclear.

Moreover, in the threat condition, the majority of the participants believed that there was someone stealing the bag. They did feel more stressed or scared about it. However, this scenario is not likely to appear in real-life. It could be assumed that people are more worried about their own safety when they cycle at night instead of losing their belongings. Consequently, cyclists will not follow the traffic rules when they feel an increase of fear or crime. However, recreating a unsafe feeling of real threat is unethical in research. Therefore an alternative was chosen to increase the mental workload and stress levels. In the future, other methods to induce stress should be tested. Last, smooth pursuits and vergence were out of scope in this. Hence, those eye movements are also very important during locomotion. Future research should take those eye movements into account when investigating the gaze behavior of cyclists at night. Despite these limitations, the current study contributed to the understanding of visual behavior of cyclists after dark.

6.2 Virtual environment recommendations

For many of the limitations mentioned earlier, virtual reality might be a solution. One disadvantage of this current research was the weather dependency. Exact weather circumstances could not be replicated. Virtual reality is a useful tool to keep constant weather circumstances and crowdedness (Fox, Arena & Bailenson, 2009; Kuliga, Thrask, Dalton & Hölscher, 2015). Using VR, different participants could receive the exact same scenario; therefore, the comparisons of fixations are more appropriate and easier to interpret (Witmer & Singer, 1998). Moreover, the number of dynamic objects in this research was also varied among the trials. Consequently, it was hard to compare the exact amount of objects available in those trials. A virtual environment should include representable dynamic objects to represent the real world. Without any dynamic objects, such as pedestrians, cyclists, and vehicles, the situation is less complex. Moreover, faces and body details are hard to recognize at night; cyclists tend to look more at bodies than faces. Therefore, body language should be clear in a virtual environment. As proxemics are different between a natural and virtual environment, it should be taken into account that the proportions of the sizes of different features should not be inconsistent with each other (Witmer & Kline, 1998; Bailenson, Blascovich, Beall & Loomis, 2003; Sanz, Olivier, Bruder, Pettré & Lécuyer, 2015). Unnatural proportions of sizes of objects can lead to misunderstanding and a lower feeling of presence. The most representative results will be found when a natural environment can be replicated in a virtual environment with the exact same traffic conditions. The current study contributes to VE technology usage as a research methodology. In the future, one can validate VE research by comparing real life gaze behavior with VE gaze behavior.

6.3 Future research

As discussed before, this study has attempted to identify critical fixations in traffic participation for cyclists. In order to gain a better understanding of the methods and approaches we have used, more research needs to be executed within this topic. Findings of this study suggested several recommendations for future studies that are not mentioned yet. First, one has to investigate the motives behind eye fixations. It was out of scope of this study to investigate why cyclists looked at specific areas. Most importantly, the factors that forced cyclists to look at a specific object are still unknown. It might be for example that cyclists looked at pedestrians, because pedestrians did not follow the traffic rules (Bernardi, Krizek & Rupi, 2016). However, those questions still remained unanswered. Moreover, the differences across cyclists should also need to be taken into consideration. Every individual cyclist might have different visual strategies that lead to the same goal (Vansteenkiste et al., 2014). Next to this, a more detailed analysis of curves, slaloms, and straight lanes should be taken into account. Vansteenkiste et al. (2014) argued that gaze behavior is different for different road properties. We found differences in reaction time between different route sections, but it was not possible to test the different parts of the model proposed by Vansteenkiste and his colleagues, due to low frequency of gazes in curves and slaloms in this study. Future research should examine whether these models apply to a complex natural environment. Finally, it is important to use an eye-tracker that can capture the human pupil during nighttime. During this experiment, the eye-tracker could move, which leaded to wrong measurements of the pupil position. It would be a wise choice to spend enough time and resources on a valuable eye-tracker system that keeps pupil tracking constant while moving. This will lead to better measurements of pupil positions in the video-recordings.

6.4 Conclusion

This study contributed to the research of gaze behavior by executing a field study. The work presented in this master thesis explored possible methods to identify critical visual tasks of cyclists at night. The dual task methodology was used to investigate the visual tasks of cyclists and distinguish critical fixations from non-critical fixations. When using this methodology, results showed that choosing the right cutoff point is important. This study found that different cutoff methods leads to different outcomes. Despite the limitations of this study, one could conclude that this study contributes to the understanding of gaze behavior of cyclists. New interesting insights were found in this study. First, the goal, path, and pedestrians are the most important areas of interest for cyclists. Therefore, cyclists's main tasks at night are to navigate and steer through the environment; they tend to use a combination of visual strategies used by pedestrians (looking at near path) and car drivers (looking at far path). Focusing on obstacles seems to be less important than scanning the surroundings. Based on these results, one could conclude that top-down processes are of more importance than bottom-up processes while cycling at night. This study did not focus on peripheral vision, but it could be argued that obstacles are mainly processed by the peripheral visual system. However, one environmental feature appeared to be important and often fixated on in critical times compared to non-critical times; namely, the sidewalk. Therefore, it is recommended that road lighting should not only be directed towards the path, but also directed to the sidewalk parallel to the bicycle path. In this experiment, many sidewalks were dark. This might be the reason why cyclists looked at the sidewalk; they need to consider whether there were any threats approaching them. Moreover, cyclists mainly fixated on pedestrians' bodies instead of faces. It is not face recognition for safety judgement why people look at pedestrians, but for example to avoid collisions. Last, cyclists mainly looked at pedestrians when they are in a far distance, especially when they felt threatened. Combining these results, one could argue that road lighting at sidewalks are important to identify the directions of pedestrians. To conclude, new interesting insights were found in the current exploratory study. This study contributed to the understanding of gaze behavior of cyclists and differences of gaze behavior between cycling at normal speed, at high speed and when cyclists felt threatened. More research is needed both in situ as field studies and in virtual reality to understand the intents behind many fixations. If road lighting guidelines would include the recommendations from the knowledge gained in this study, cyclists could feel safer at night. So in the end, more people will cycle, and less accidents will occur.

References

Agresti, A. (2003). *An introduction to categorical data analysis*. Florida: John Wiley & Sons.

Bailenson, J. N., Blascovich, J., Beall, A. C., & Loomis, J. M. (2003). Interpersonal distance in immersive virtual environments. *Personality and Social Psychology Bulletin*, *29*(7), 819-833.

Ballard, D. H., & Hayhoe, M. M. (2009). Modelling the role of task in the control of gaze. *Visual cognition*, *17*(6-7), 1185-1204.

Bernardi, S., Krizek, K. J., & Rupi, F. (2016). Quantifying the role of disturbances and speeds on separated bicycle facilities. *Journal of Transport and Land Use*, *9*(2), 105-119.

Blignaut, P. (2009). Fixation identification: The optimum threshold for a dispersion algorithm. *Attention, Perception, & Psychophysics*, *71*(4), 881-895.

Bommel, W. V. (2014). *Road lighting: fundamentals, technology and application*. New York: Springer

Boot, W. R., Brockmole, J. R., & Simons, D. J. (2005). Attention capture is modulated in dual-task situations. *Psychonomic Bulletin & Review*, *12*(4), 662-668.

Boyce, P. R. (2014). *Human factors in lighting*. Crc Press.

Bruce, N. D., & Tsotsos, J. K. (2009). Saliency, attention, and visual search: An information theoretic approach. *Journal of vision*, *9*(3), 5-5.

Buswell, G. T. (1935). How people look at pictures: a study of the psychology and perception in art. Oxford, England: Univ. Chicago Press.

Caminada, J. F., & Van Bommel, W. J. M. (1984). New lighting criteria for residential areas. *Journal of the Illuminating Engineering Society*, *13*(4), 350-358.

Castelhano, M. S., Mack, M. L., & Henderson, J. M. (2009). Viewing task influences eye movement control during active scene perception. *Journal of vision*, *9*(3), 6-6.

Chen, X., & Zelinsky, G. J. (2006). Real-world visual search is dominated by top-down guidance. *Vision research*, *46*(24), 4118-4133.

Davoudian, N., & Raynham, P. (2012). What do pedestrians look at at night?. *Lighting Research & Technology*, *44*(4), 438-448.

De Kort, Y. A., IJsselsteijn, W. A., Kooijman, J., & Schuurmans, Y. (2003). Virtual laboratories: Comparability of real and virtual environments for environmental psychology. *Presence: Teleoperators and virtual environments*, *12*(4), 360-373.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual review of neuroscience*, *18*(1), 193-222.

Donges, E. (1978). A two-level model of driver steering behavior. *Human factors*, *20*(6), 691-707.

Duchowski, A. T. (2002). A breadth-first survey of eye-tracking applications. *Behavior Research Methods, Instruments, & Computers*, *34*(4), 455-470.

Duchowski, A. T. (2007). *Eye tracking methodology.* Springer.

Einhauser, W., Rutishauser, U., & Koch, C. (2008). Task-demands can immediately reverse the effects of sensory-driven saliency in complex visual stimuli. *Journal of vision*, *8*(2), 2-2.

Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. *Human factors*, *37*(1), 32-64.

Engström, J., Johansson, E., & Östlund, J. (2005). Effects of visual and cognitive load in real and simulated motorway driving. *Transportation research part F: traffic psychology and behaviour*, *8*(2), 97-120.

Fabriek, E., de Waard, D., & Schepers, J. P. (2012). Improving the visibility of bicycle infrastructure. *International journal of human factors and ergonomics*, *1*(1), 98-115.

Fajen, B. R., & Warren, W. H. (2003). Behavioral dynamics of steering, obstable avoidance, and route selection. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(2), 343.

Fors, C., & Lundkvist, S. O. (2009). Night-time traffic in urban areas: A literature review on road user aspects. *VTI rapport 650A.*

Fotios, S., & Raynham, P. (2011). Correspondence: Lighting for pedestrians: Is facial recognition what matters?. *Lighting Research and Technology*, *43*(1), 129-130.

Fotios, S., & Yang, B. (2013). Measuring the impact of lighting on interpersonal judgements of pedestrians at night-time. *Proceedings of the CIE Centenary Conference "Towards a New Century of Light"*, 990-998.

Fotios, S., Uttley, J., & Hara, N. (2013). Critical pedestrian tasks: Using eye-tracking within a dual task paradigm. *Proceedings of the CIE Centenary Conference "Towards a New Century of Light"*, 234-240.

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

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

Fotios, S., Yang, B., & Edwards, P. (2014). Empirical evidence towards appropriate lighting characteristics for pedestrians. *Proceedings of CIE 2014 Lighting Quality & Energy Efficiency*, 833-842.

Foulsham, T., & Underwood, G. (2007). How does the purpose of inspection influence the potency of visual salience in scene perception?. *Perception*, *36*(8), 1123-1138.

Foulsham, T., Walker, E., & Kingstone, A. (2011). The where, what and when of gaze allocation in the lab and the natural environment. *Vision research*, *51*(17), 1920-1931.

Fox, J., Arena, D., & Bailenson, J. N. (2009). Virtual reality: A survival guide for the social scientist. *Journal of Media Psychology*, *21*(3), 95-113.

Franchak, J. M., & Adolph, K. E. (2010). Visually guided navigation: Head-mounted eye-tracking of natural locomotion in children and adults. *Vision research*, *50*(24), 2766-2774.

Frings, D., Parkin, J., & Ridley, A. M. (2014). The effects of cycle lanes, vehicle to kerb distance and vehicle type on cyclists' attention allocation during junction negotiation. *Accident Analysis & Prevention*, *72*, 411-421.

Fujiyama, T., Childs, C., Boampong, D., & Tyler, N. (2007). How do elderly pedestrians perceive hazards in the street? An initial investigation towards development of a pedestrian simulation that incorporates reaction of various pedestrians to environments.

Gegenfurtner, A., Lehtinen, E., & Säljö, R. (2011). Expertise differences in the comprehension of visualizations: A meta-analysis of eye-tracking research in professional domains. *Educational Psychology Review*, *23*(4), 523-552.

Geruschat, D. R., Hassan, S. E., & Turano, K. A. (2003). Gaze behavior while crossing complex intersections. *Optometry and Vision Science*, *80*(7), 515-528.

Hall, E (1969). *The Hidden Dimension*. New York: Anchor Books.

Hayhoe, M., Shrivastava, A., Mruczek, R., & Pelz, J. B. (2003). Visual memory and motor planning in a natural task. *Journal of vision*, *3*(1), 6-6.

Hayhoe, M., & Ballard, D. (2005). Eye movements in natural behavior. *Trends in cognitive sciences*, *9*(4), 188-194.

Helo, A., Pannasch, S., Sirri, L., & Rämä, P. (2014). The maturation of eye movement behavior: Scene viewing characteristics in children and adults. *Vision research*, *103*, 83-91.

Henderson, J. M. (2003). Human gaze control during real-world scene perception. *Trends in cognitive sciences*, *7*(11), 498-504.

Henderson, J. M., Brockmole, J. R., Castelhano, M. S., & Mack, M. (2007). Visual saliency does not account for eye movements during visual search in real-world scenes. *Eye movements,* 537-562.

Higuchi, T., & Yoshida, H. (2013). Gaze behavior during adaptive locomotion. *Eye movement—developmental perspectives, dysfunctions and disorders in humans. Nova Science, New York*, 111-127.

Hollands, M. A., Marple-Horvat, D. E., Henkes, S., & Rowan, A. K. (1995). Human eye movements during visually guided stepping. *Journal of motor behavior*, *27*(2), 155-163.

Hollands, M. A., Patla, A. E., & Vickers, J. N. (2002). "Look where you're going!": gaze behaviour associated with maintaining and changing the direction of locomotion. *Experimental brain research*, *143*(2), 221-230.

Holmqvist, K., Nyström, M., Andersson, R., Dewhurst, R., Jarodzka, H., & Van de Weijer, J. (2011). *Eye tracking: A comprehensive guide to methods and measures*. OUP Oxford.

Hughes, P. K., & Cole, B. L. (1986). What attracts attention when driving?. *Ergonomics*, *29*(3), 377-391.

Igari, D., Shimizu, M., & Fukuda, R. (2008). Eye movements of elderly people while riding bicycles. *Proceedings of the 6th International Conference of the International Society for Gerontechnology.*

Itti, L., & Baldi, P. F. (2006). Bayesian surprise attracts human attention. *Advances in neural information processing systems*, 547-554.

Itti, L., & Koch, C. (2001). Computational modelling of visual attention. *Nature reviews neuroscience*, *2*(3), 194.

Itti, L., & Koch, C. (2001). Feature combination strategies for saliency-based visual attention systems. *Journal of Electronic imaging*, *10*(1), 161-170.

Itti, L., Koch, C., & Niebur, E. (1998). A model of saliency-based visual attention for rapid scene analysis. *IEEE Transactions on pattern analysis and machine intelligence*, *20*(11), 1254-1259.

Jacob, R. J., & Karn, K. S. (2003). Eye tracking in human-computer interaction and usability research: Ready to deliver the promises. *The mind's eye*, 573-605.

Johansson, M., Rosén, M., & Küller, R. (2011). Individual factors influencing the assessment of the outdoor lighting of an urban footpath. *Lighting Research & Technology*, *43*(1), 31-43.

Johansson, Ö., Wanvik, P. O., & Elvik, R. (2009). A new method for assessing the risk of accident associated with darkness. *Accident Analysis & Prevention*, *41*(4), 809-815.

Juhra, C., Wieskoetter, B., Chu, K., Trost, L., Weiss, U., Messerschmidt, M., Malczyk, A., Heckwolf, M., & Raschke, M. (2012). Bicycle accidents–Do we only see the tip of the iceberg?: A prospective multi-centre study in a large German city combining medical and police data. *Injury*, *43*(12), 2026-2034.

Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice-Hall.

Kelly, V. E., Janke, A. A., & Shumway-Cook, A. (2010). Effects of instructed focus and task difficulty on concurrent walking and cognitive task performance in healthy young adults. *Experimental brain research*, *207*(1-2), 65-73.

Kitazawa, K., & Fujiyama, T. (2010). Pedestrian vision and collision avoidance behavior: Investigation of the information process space of pedestrians using an eye tracker. *Pedestrian and evacuation dynamics 2008*, 95-108.

Klauer, S. G., Guo, F., Simons-Morton, B. G., Ouimet, M. C., Lee, S. E., & Dingus, T. A. (2014). Distracted driving and risk of road crashes among novice and experienced drivers. *New England journal of medicine*, *370*(1), 54-59.

Kuliga, S. F., Thrash, T., Dalton, R. C., & Hölscher, C. (2015). Virtual reality as an empirical research tool - Exploring user experience in a real building and a corresponding virtual model. *Computers, Environment and Urban Systems*, *54*, 363-375.

Land, M. F. (2006). Eye movements and the control of actions in everyday life. *Progress in retinal and eye research*, *25*(3), 296-324.

Land, M. F. (2009). Vision, eye movements, and natural behavior. *Visual neuroscience*, *26*(1), 51-62.

Land, M. F., & Hayhoe, M. (2001). In what ways do eye movements contribute to everyday activities?. *Vision research*, *41*(25-26), 3559-3565.

Land, M. F., & Lee, D. N. (1994). Where we look when we steer. *Nature*, *369*(6483), 742.

Land, M. F., & Horwood, J. (1995). Which parts of the road guide steering?. *Nature*, *377*(6547), 339-340.

Land, M. F., & Tatler, B. (2009). *Looking and acting: vision and eye movements in natural behaviour*. Oxford: Oxford University Press.

Land, M. F., Mennie, N., & Rusted, J. (1999). The roles of vision and eye movements in the control of activities of daily living. *Perception*, *28*(11), 1311-1328.

Lansdown, T. C. (2001). Causes, measures and effects of driver visual workload. *Stress, workload and fatigue*, 351-369.

Lavie, N. (2005). Distracted and confused?: Selective attention under load. *Trends in cognitive sciences*, *9*(2), 75-82.

Lim, C., Sayed, T., & Navin, F. (2004). A driver visual attention model. Part 1. Conceptual framework. *Canadian Journal of Civil Engineering*, *31*(3), 463-472.

Mannan, S. K., Ruddock, K. H., & Wooding, D. S. (1996). The relationship between the locations of spatial features and those of fixations made during visual examination of briefly presented images. *Spatial vision*, *10*(3), 165-188.

Mantuano, A., Bernardi, S., & Rupi, F. (2017). Cyclist gaze behavior in urban space: An eye-tracking experiment on the bicycle network of Bologna. *Case studies on transport policy*, *5*(2), 408-416.

Marigold, D. S., & Patla, A. E. (2007). Gaze fixation patterns for negotiating complex ground terrain. *Neuroscience*, *144*(1), 302-313.

Marigold, D. S., Weerdesteyn, V., Patla, A. E., & Duysens, J. (2007). Keep looking ahead? Re-direction of visual fixation does not always occur during an unpredictable obstacle avoidance task. *Experimental brain research*, *176*(1), 32-42.

Meeren, H. K., van Heijnsbergen, C. C., & de Gelder, B. (2005). Rapid perceptual integration of facial expression and emotional body language. *Proceedings of the National Academy of Sciences*, *102*(45), 16518-16523.

Mital, P. K., Smith, T. J., Hill, R. L., & Henderson, J. M. (2011). Clustering of gaze during dynamic scene viewing is predicted by motion. *Cognitive Computation*, *3*(1), 5-24.

Miura, T. (1987). Behavior oriented vision: functional field of view and processing resources. In *Eye movements from physiology to cognition* (pp. 563-572).

Pashler, H., Carrier, M., & Hoffman, J. (1993). Saccadic eye movements and dual-task interference. *The Quarterly journal of experimental psychology*, *46*(1), 51-82.

Patla, A. E. (1997). Understanding the roles of vision in the control of human locomotion. *Gait & Posture*, *5*(1), 54-69.

Patla, A. E. (1998). How is human gait controlled by vision. *Ecological Psychology*, *10*(3-4), 287-302.

Patla, A. E., & Vickers, J. N. (2003). How far ahead do we look when required to step on specific locations in the travel path during locomotion?. *Experimental brain research*, *148*(1), 133-138.

Pelz, J. B., & Canosa, R. (2001). Oculomotor behavior and perceptual strategies in complex tasks. *Vision research*, *41*(25-26), 3587-3596.

Pelz, J. B., & Rothkopf, C. (2007). Oculomotor behavior in natural and man-made environments. In *Eye Movements* (pp. 661-676).

Plummer, P., & Eskes, G. (2015). Measuring treatment effects on dual-task performance: a framework for research and clinical practice. *Frontiers in human neuroscience*, *9*, 225.

Posner, M. I. (1980). Orienting of attention. *Quarterly journal of experimental psychology*, *32*(1), 3-25.

Qasem, H., Uttley, J., & Fotios, S. (2017). Lighting for cyclists: an eye tracking study in natural settings to investigate where they look. *Proceedings of the LUX Europa 2017 European Lighting Conference*, 599-603

Renge, K. (1980). The effect of driving experience on driver's visual attention: an analysis of objects looked at, using the verbal report method. *IATSS research*, *4*(1), 95-106.

Rothkopf, C. A., Ballard, D. H., & Hayhoe, M. M. (2007). Task and context determine where you look. *Journal of vision*, *7*(14), 16-16.

Salvucci, D. D. (2006). Modeling driver behavior in a cognitive architecture. *Human factors*, *48*(2), 362-380.

Salvucci, D. D., & Goldberg, J. H. (2000) Identifying fixations and saccades in eye-tracking protocols. *Proceedings of the 2000 symposium on Eye tracking research & applications*, 71-78.

Salvucci, D. D., & Gray, R. (2004). A two-point visual control model of steering. *Perception*, *33*(10), 1233-1248.

Sanz, F. A., Olivier, A. H., Bruder, G., Pettré, J., & Lécuyer, A. (2015, March). Virtual proxemics: Locomotion in the presence of obstacles in large immersive projection environments. *Virtual Reality (VR)*, 75-80.

Schepers, P., Den Brinker, B., De Waard, D., Twisk, D., Schwab, A., & Smeets, J. (2013). Studying the role of vision in cycling: Critique on restricting research to fixation behaviour. *Accident Analysis & Prevention*, *59*, 466-468.

Schepers, P., & den Brinker, B. (2011). What do cyclists need to see to avoid single-bicycle crashes?. *Ergonomics*, *54*(4), 315-327.

Schepers, P., & Wolt, K. K. (2012). Single-bicycle crash types and characteristics. *Cycling Research International*, *2*(1), 119-135.

Schepers, P., Agerholm, N., Amoros, E., Benington, R., Bjørnskau, T., Dhondt, S., De Geus, B., Hagemeister, C., Loo, B. & Niska, A. (2015). An international review of the frequency of single-bicycle crashes (SBCs) and their relation to bicycle modal share. *Injury prevention*, *21*(1), 138-143.

Sener, I. N., Eluru, N., & Bhat, C. R. (2009). An analysis of bicycle route choice preferences in Texas, US. *Transportation*, *36*(5), 511-539.

Shinar, D. (2008). Looks are (almost) everything: where drivers look to get information. *Human Factors*, *50*(3), 380-384.

Shinoda, H., Hayhoe, M., & Shrivastava, A. (2001). What controls attention in natural environments?. *Vision research*, *41*(25-26), 3535-3545.

Soangra, R., & Lockhart, T. E. (2017). Dual-task does not increase slip and fall risk in healthy young and older adults during walking. *Applied bionics and biomechanics*, *2017*.

Staal, M. A. (2004). Stress, cognition, and human performance: A literature review and conceptual framework.

Strayer, D. L., & Johnston, W. A. (2001). Driven to distraction: Dual-task studies of simulated driving and conversing on a cellular telephone. *Psychological science*, *12*(6), 462-466.

Suzuki, T., Nakamura, Y., & Ogasawara, T. (1966). Intrinsic properties of driver attentiveness. *The Expressway and the Automobile*, *9*, 24-29.

Tatler, B. W., Baddeley, R. J., & Gilchrist, I. D. (2005). Visual correlates of fixation selection: Effects of scale and time. *Vision research*, *45*(5), 643-659.

Tatler, B. W., Hayhoe, M. M., Land, M. F., & Ballard, D. H. (2011). Eye guidance in natural vision: Reinterpreting salience. *Journal of vision*, *11*(5), 5-5.

Tombu, M., & Jolicœur, P. (2003). A central capacity sharing model of dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(1), 3-3.

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive psychology*, *12*(1), 97-136.

Triesch, J., Ballard, D. H., Hayhoe, M. M., & Sullivan, B. T. (2003). What you see is what you need. *Journal of vision*, *3*(1), 9-9.

Turano, K. A., Geruschat, D. R., & Baker, F. H. (2003). Oculomotor strategies for the direction of gaze tested with a real-world activity. *Vision research*, *43*(3), 333-346.

Turano, K. A., Geruschat, D. R., Baker, F. H., Stahl, J. W., & Shapiro, M. D. (2001). Direction of gaze while walking a simple route: persons with normal vision and persons with retinitis pigmentosa. *Optometry and Vision Science*, *78*(9), 667-675.

Turatto, M., & Galfano, G. (2001). Attentional capture by color without any relevant attentional set. *Perception & Psychophysics*, *63*(2), 286-297.

Underwood, G., Chapman, P., Berger, Z., & Crundall, D. (2003). Driving experience, attentional focusing, and the recall of recently inspected events. *Transportation Research Part F: Traffic Psychology and Behaviour*, *6*(4), 289-304.

Underwood, G., Chapman, P., Bowden, K., & Crundall, D. (2002). Visual search while driving: skill and awareness during inspection of the scene. *Transportation Research Part F: Traffic Psychology and Behaviour*, *5*(2), 87-97.

Underwood, G., Phelps, N., Wright, C., Van Loon, E., & Galpin, A. (2005). Eye fixation scanpaths of younger and older drivers in a hazard perception task. *Ophthalmic and Physiological Optics*, *25*(4), 346-356.

Vansteenkiste, P. (2015). The role of visual information in the steering behaviour of young and adult bicyclists. *Ghent University*.

Vansteenkiste, P., Cardon, G., D'Hondt, E., Philippaerts, R., & Lenoir, M. (2013). The visual control of bicycle steering: The effects of speed and path width. *Accident Analysis & Prevention*, *51*, 222-227.

Vansteenkiste, P., Cardon, G., Philippaerts, R., & Lenoir, M. (2015). Measuring dwell time percentage from head-mounted eye-tracking data–comparison of a frame-by-frame and a fixation-by-fixation analysis. *Ergonomics*, *58*(5), 712-721.

Vansteenkiste, P., Van Hamme, D., Veelaert, P., Philippaerts, R., Cardon, G., & Lenoir, M. (2014). Cycling around a curve: the effect of cycling speed on steering and gaze behavior. *PloS one*, *9*(7), 102792.

Vansteenkiste, P., Zeuwts, L., Cardon, G., Philippaerts, R., & Lenoir, M. (2014). The implications of low quality bicycle paths on gaze behavior of cyclists: A field test. *Transportation research part F: traffic psychology and behaviour*, *23*, 81-87.

Vlakveld, W. P., Twisk, D., Christoph, M., Boele, M., Sikkema, R., Remy, R., & Schwab, A. L. (2015). Speed choice and mental workload of elderly cyclists on e-bikes in simple and complex traffic situations: A field experiment. *Accident Analysis & Prevention*, *74*, 97-106.

Wanvik, P. O. (2009). Effects of road lighting: an analysis based on Dutch accident statistics 1987–2006. *Accident Analysis & Prevention*, *41*(1), 123-128.

Westerhuis, F., & De Waard, D. (2017). Reading cyclist intentions: Can a lead cyclist's behaviour be predicted?. *Accident Analysis & Prevention*, *105*, 146-155.

Wickens, C. D., & Horrey, W. J. (2008). Models of attention, distraction, and highway hazard avoidance. *Driver distraction. Theory, effects and mitigation*, 249-279.

Wilkie, R. M., & Wann, J. P. (2003). Eye-movements aid the control of locomotion. Journal of vision, *3*(11), 3-3.

Wilkie, R. M., Wann, J. P., & Allison, R. S. (2008). Active gaze, visual look-ahead, and locomotor control. *Journal of experimental psychology: Human perception and performance*, *34*(5), 1150.

Wilson, C. J., & Soranzo, A. (2015). The use of virtual reality in psychology: a case study in visual perception. *Computational and mathematical methods in medicine*, *2015*.

Witmer, B. G., & Kline, P. B. (1998). Judging perceived and traversed distance in virtual environments. *Presence*, *7*(2), 144-167.

Witmer, B. G., & Singer, M. J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence*, *7*(3), 225-240.

Yarbus, A. L. (1967). Eye movements during perception of complex objects. *Eye movements and vision*, 171-211.

Zeuwts, L., Vansteenkiste, P., Deconinck, F., van Maarseveen, M., Savelsbergh, G., Cardon, G., & Lenoir, M. (2016). Is gaze behaviour in a laboratory context similar to that in real-life? A study in bicyclists. *Transportation research part F: traffic psychology and behaviour*, *43*, 131-140.

List of Appendix

Appendix A: Scripts during experiment

These scripts are told to the participants during the experiment. The scripts could be told in Dutch or English.

Intro

This is the route you must cycle (shows maps). During this test you are asked to cycle this route three times. I will cycle behind you (approximately 5 meters behind). After every round, please stop at the starting point, so here (points at map), so I will check whether the eye-tracker is still working properly and if the video recording went well. While you are cycling, please follow the normal traffic rules. Do you have any questions?

Condition 1: Normal cycling

During this round you are asked to cycle the route with normal speed, just cycle as you normal cycle to a friend without any hurry.

Condition 2: Cycling in a hurry

Please cycle the route as you are in a hurry, but you are still following the traffic rules and you have to cycle safely. Your task is not to win a race, but try to cycle faster than normal, like you need to be on time for lecture (but being 5 minutes late is still fine, but we prefer to be in time).

Condition 3: Cycling when feeling threatened

Please cycle the route again, but be aware that there is someone on the road that can grab your bag from your luggage carrier. That person will stand/cycle/walk somewhere randomly, and tries to grab the bag from your bicycle. But he/she is not going to push you off the bicycle, so don't be scared of that. His or her task is to touch the bag, and if possible, even better grab the bag. Your task is to cycle safely according to the traffic rules, but just try not to lose your bag. If the person reaches for the bag, please brake and stop.

Questions of that most of the participants asked:

What's in for them? Answer: They get a small reward for their participation and a little bit more if they are possible to touch the bag or even more if they can grab the bag.

I feel a little bit scared, what if I collide with that person? Answer: The person is trained to do his task as safely as possible. You will not collide with that person.

Do I know this person? Answer: No, you don't.

Appendix B: Questionnaire

Dear participant,

Thank you for participating in the experiment. The last part of the experiment consists of some general questions about yourself and your experience of cycling. Please indicate what answer fits you and your experience. Please don't think too long before answering, because there is no wrong answer.

1. What is your age? ____

2. What is your gender? F / M

3. Do you own a driving license? YES / NO

4. What mode of transport do you use most? Please indicate (1=most, 5=least)

    a. Vehicle (driver) ____
    b. Vehicle (passenger) ____
    c. Bicycle ____
    d. Walking ____
    e. Public transport ____

5. How often do you cycle?

    a. Almost everyday
    b. Several times a week
    c. Once a week
    d. Once in two weeks
    e. Once a month
    f. Less than once a month

6. Have you ever visited the area you have cycled? More answers are possible.

    a. Yes, I have been here by car
    b. Yes, I have been here as a pedestrian
    c. Yes, I have been here as a cyclist
    d. Yes, I have been there as a passenger in a car or public transport

7. How often did you visit this area in the last year?

    a. Almost everyday
    b. At least several times a week
    c. At least once a week
    d. At least once in two weeks
    e. At least once a month
    f. At least once in 2-3 months
    g. Around two times a year
    h. Around once a year

8. Do you see yourself as a vulnerable person? YES / NO

9. How crowded do you judge the overall environment at the moment you were cycling?

    Quiet 1 2 3 4 5 Very crowded

10. How safe or unsafe do you judge this environment?

Unsafe	1	2	3	4	5	Safe

11. How uneasy or comfortable do you feel with the idea of cycling in this environment at night?

Uneasy	1	2	3	4	5	Comfortable

12. How well or poorly do you think the street lighting in this environment enables you to travel through this environment at night?

Poorly	1	2	3	4	5	Well

13. Is there too little or too much light in this environment?

Too little	1	2	3	4	5	Too much

14. Did you pay more attention to the environment when it was told that there might be someone who might grab your bag?

Not at all	1	2	3	4	5	All the time

15. Did you try to find the person who might grab your bag while cycling?

Not at all	1	2	3	4	5	All the time

16. Did you believe that someone might grab your bag on the road? YES / NO

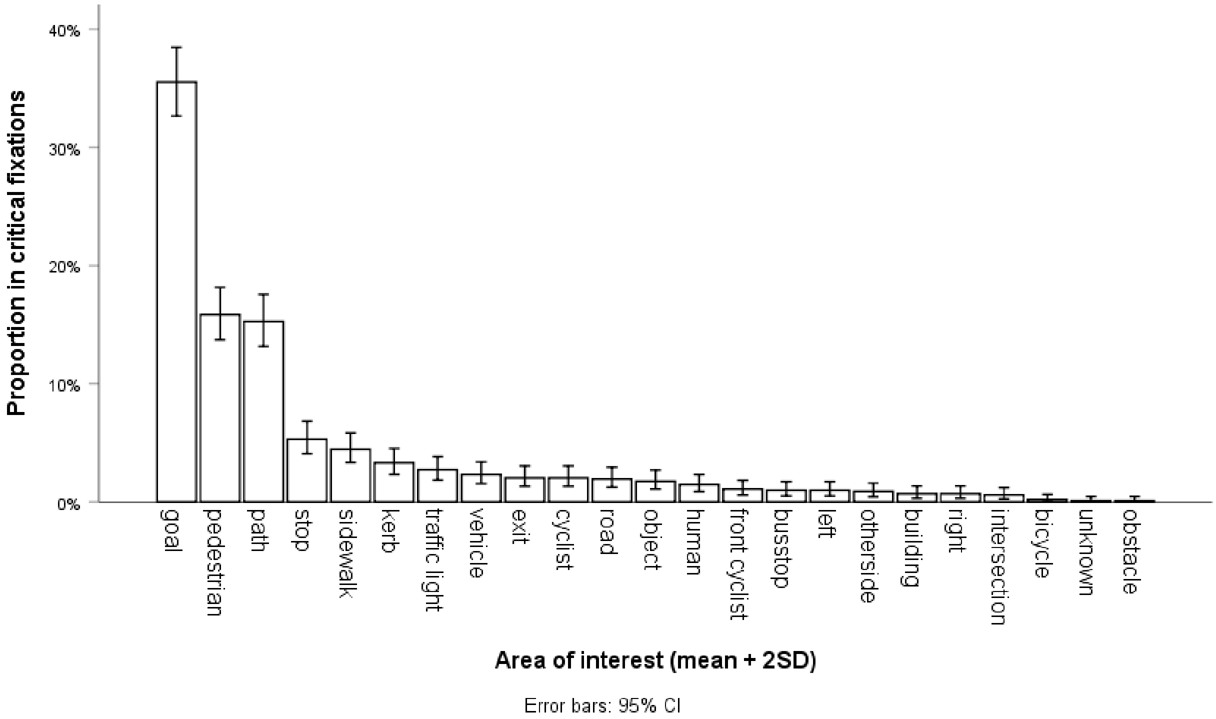
Participant ID: ___

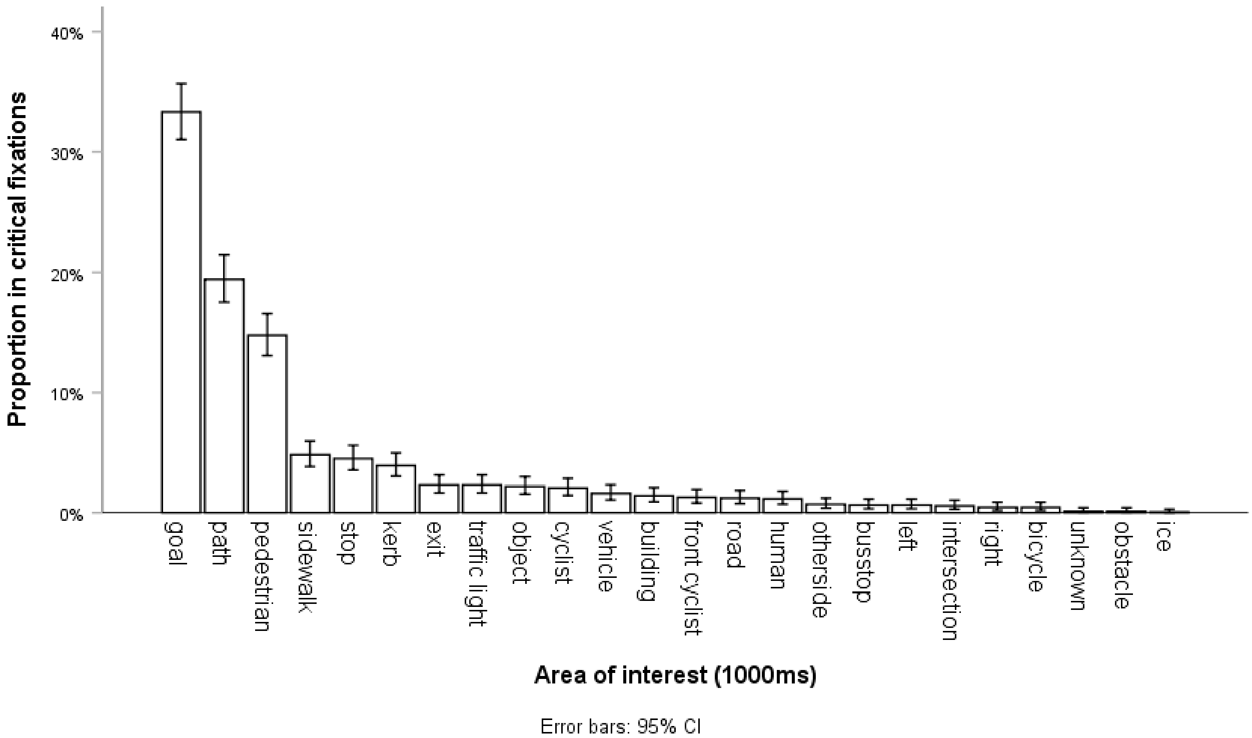
Appendix C: Mean reaction time per participant per condition

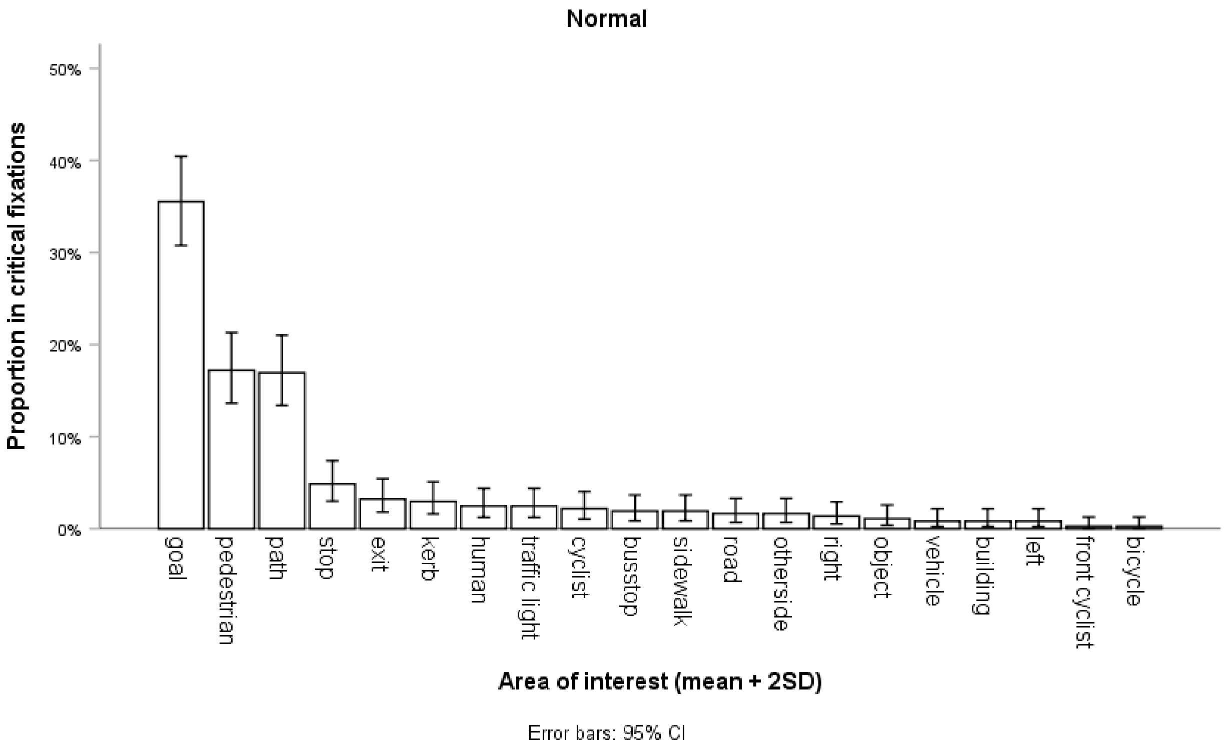
The table below shows the different values per participant per condition

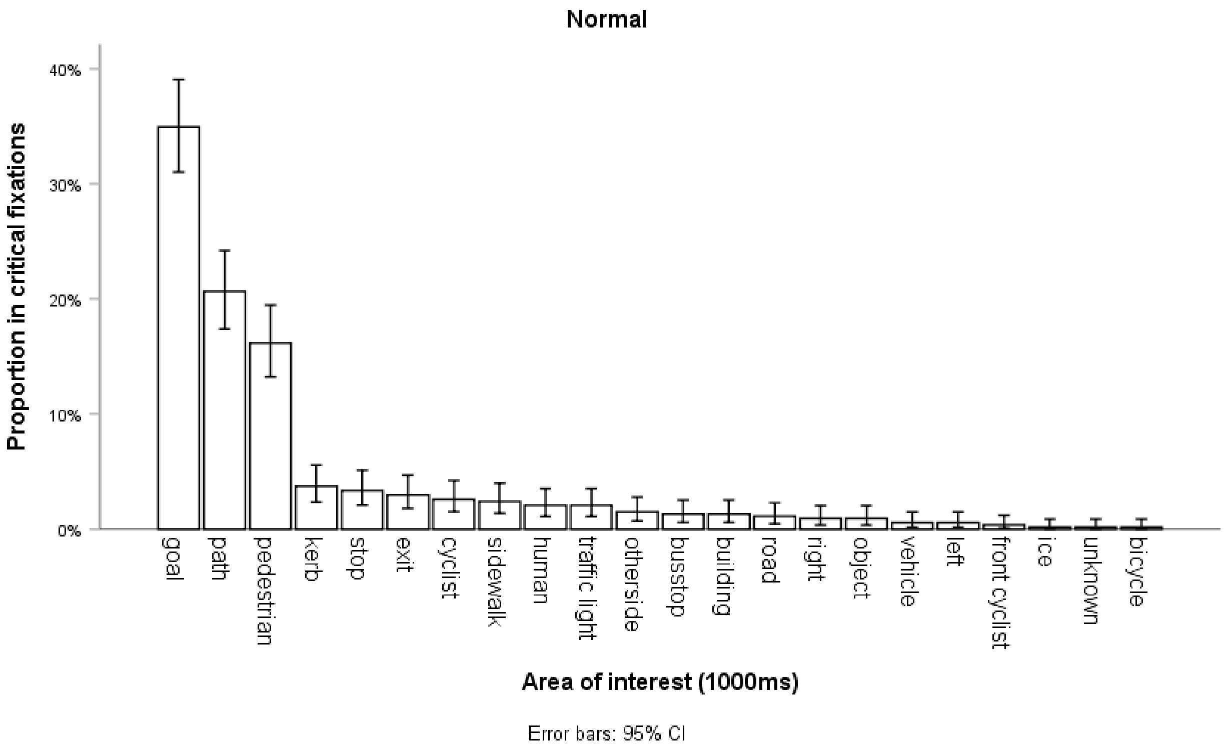
id	condition	mean	SD	1,5 SD	2SD	mean+1SD	mean+1,5SD	mean+2SD	median	75%	90%	95%
2	1	1.038	284,5038	426,7557	569,0076	1.322	1.465	1606,972	973	1203	1369	1536
2	2	1100	174,3034	261,4551	348,6068	1.274	1.361	1448,607	1129	1232	1333	1337
2	3	1092,841	246,5399	369,8099	493,0798	1.339	1.463	1585,921	1128	1255	1359	1491
3	1	946,8033	186,471	279,7065	372,942	1.133	1.227	1319,745	902	1054	1220	1278
3	2	994,1818	161,0267	241,5401	322,0534	1.155	1.236	1316,235	962	1108	1235	1280
3	3	1014,731	179,577	269,3655	359,154	1.194	1.284	1373,885	987,5	1110,5	1254	1281
4	1	817,0508	216,0023	324,0035	432,0046	1.033	1.141	1249,055	789	869	1053	1366
4	2	826,4528	135,8689	203,8034	271,7378	962	1.030	1098,191	828	904	944	1029
4	3	793,32	194,9192	292,3788	389,8384	988	1.086	1183,158	757,5	870	1022,5	1178
5	1	731,1091	168,4315	252,6473	336,863	900	984	1067,972	679	795	1049	1129
5	2	680,0909	182,7756	274,1634	365,5512	863	954	1045,642	660,5	810,5	935	963
5	3	708,2931	112,9291	169,3937	225,8582	821	878	934,1513	704,5	795	843	895
6	1	798,0371	154,4887	231,7331	308,9774	953	1.030	1107,014	791	884	1043	1108
6	2	762,0851	263,7794	395,6691	527,5588	1.026	1.158	1289,644	724	850	933	1206
6	3	778,6604	260,9286	391,3929	521,8572	1.040	1.170	1300,518	710	882	1095	1277
9	1	650,6451	207,819	311,7285	415,638	858	962	1066,283	631	678	776	950
9	2	692,8298	135,6683	203,5025	271,3366	828	896	964,1664	677	756	802	896
9	3	649,1395	124,7085	187,0628	249,417	774	836	898,5565	636	673	757	842
10	1	855,5919	301,1919	451,7879	602,3838	1.157	1.307	1457,976	754	941	1496	1501
10	2	989,1731	365,1604	547,7406	730,3208	1.354	1.537	1719,494	849,5	1127,5	1607	1810
10	3	1083,267	430,3231	645,4847	860,6462	1.514	1.729	1943,913	872	1257	1862	1970
11	1	672,1091	188,5783	282,8675	377,1566	861	955	1049,266	633	743	932	1057
11	2	707,1132	167,6142	251,4213	335,2284	875	959	1042,342	685	790	882	1027
11	3	807,2045	394,943	592,4145	789,886	1.202	1.400	1597,091	657	903	1342	1872
12	1	808,8167	247,7811	371,6717	495,5622	1.057	1.180	1304,379	745,5	892	1130,5	1385,5
12	2	841,8637	243,6886	365,5329	487,3772	1.086	1.207	1329,241	750,5	944,5	1267	1377
12	3	934,55	323,1344	484,7016	646,2688	1.258	1.419	1580,819	842,5	1061,5	1411	1668
13	1	650,5968	116,4061	174,6092	232,8122	767	825	883,409	635,5	721	782	814
13	2	757,4737	171,6525	257,4788	343,305	929	1.015	1100,779	725	811	970	1120
13	3	722,1905	187,5689	281,3534	375,1378	910	1.004	1097,328	672	789	888	1084

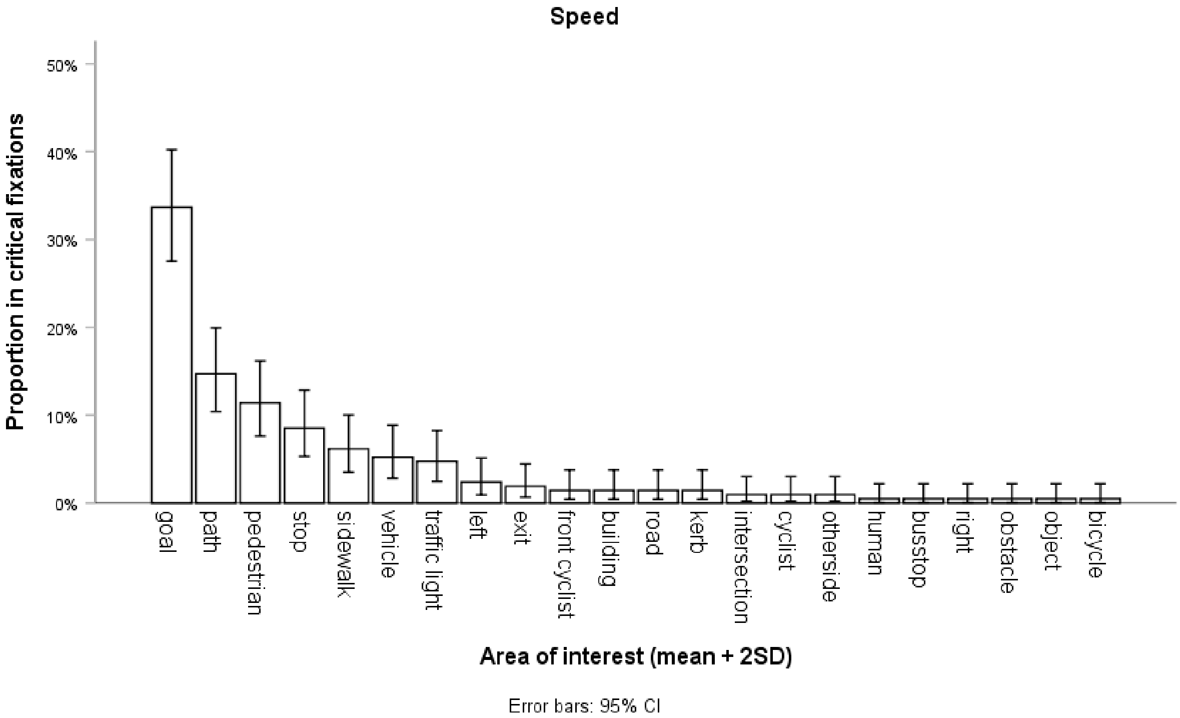
Appendix D: Bar charts of most frequent critical fixations

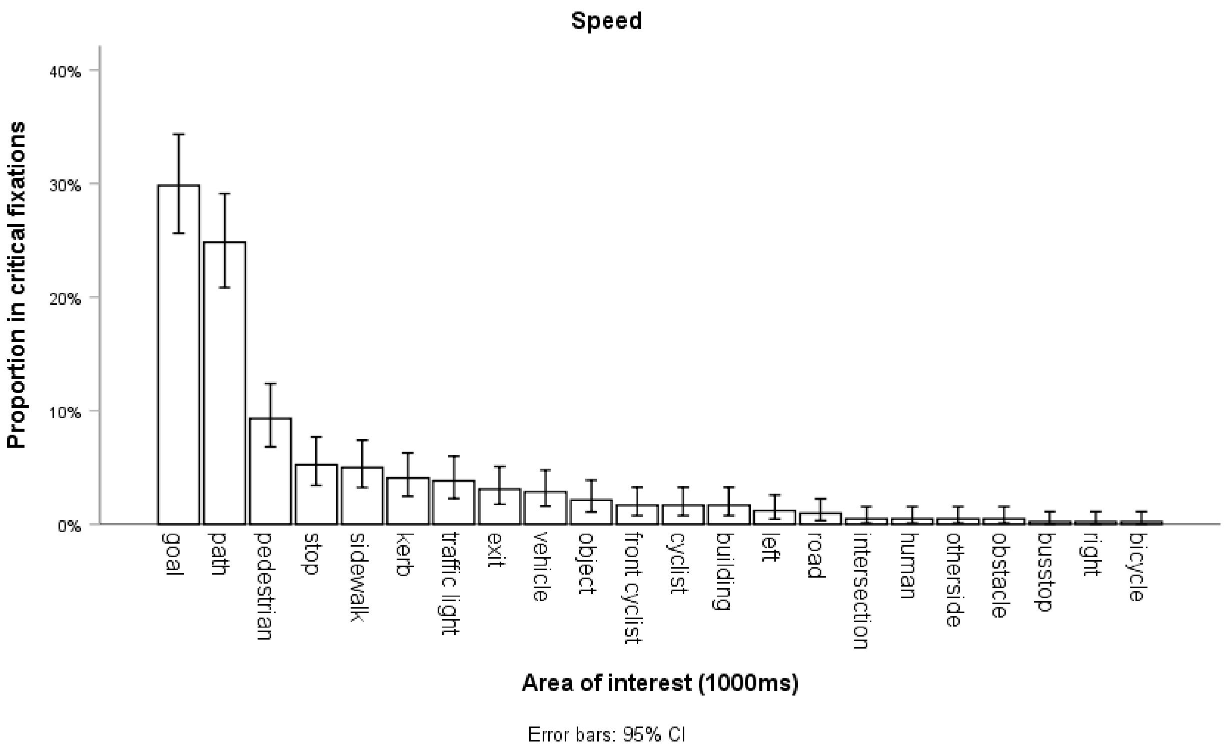


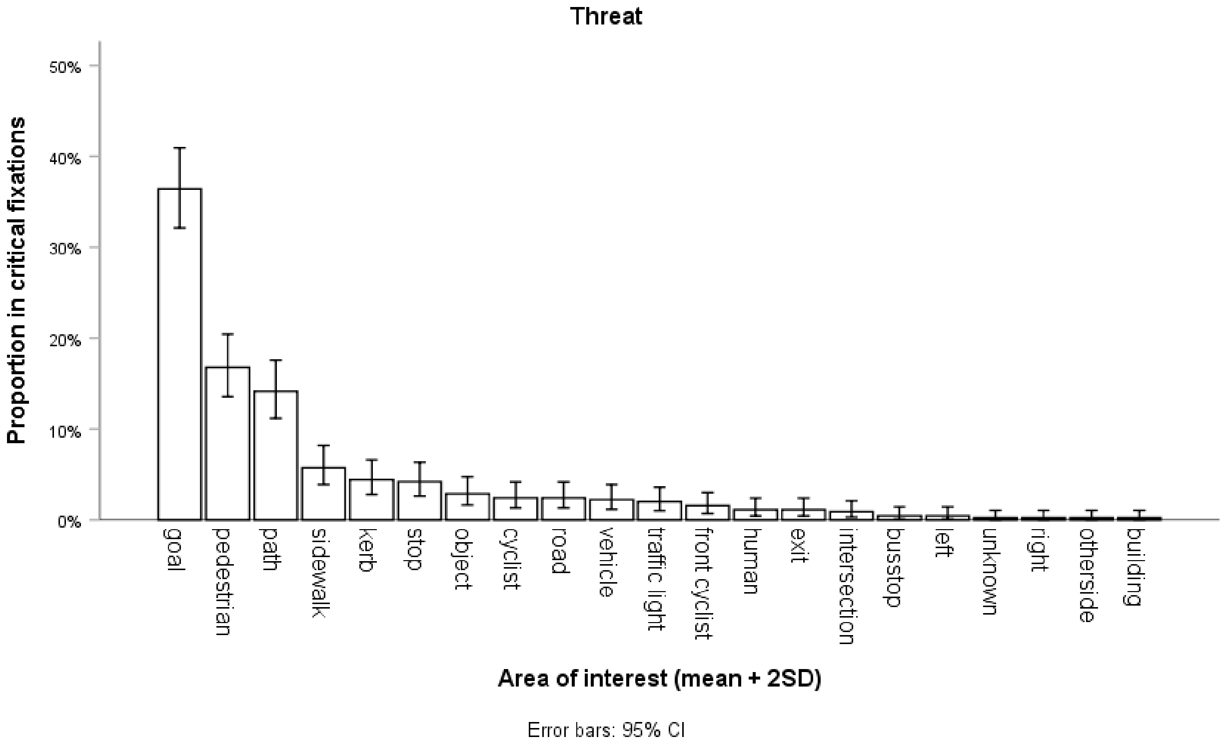


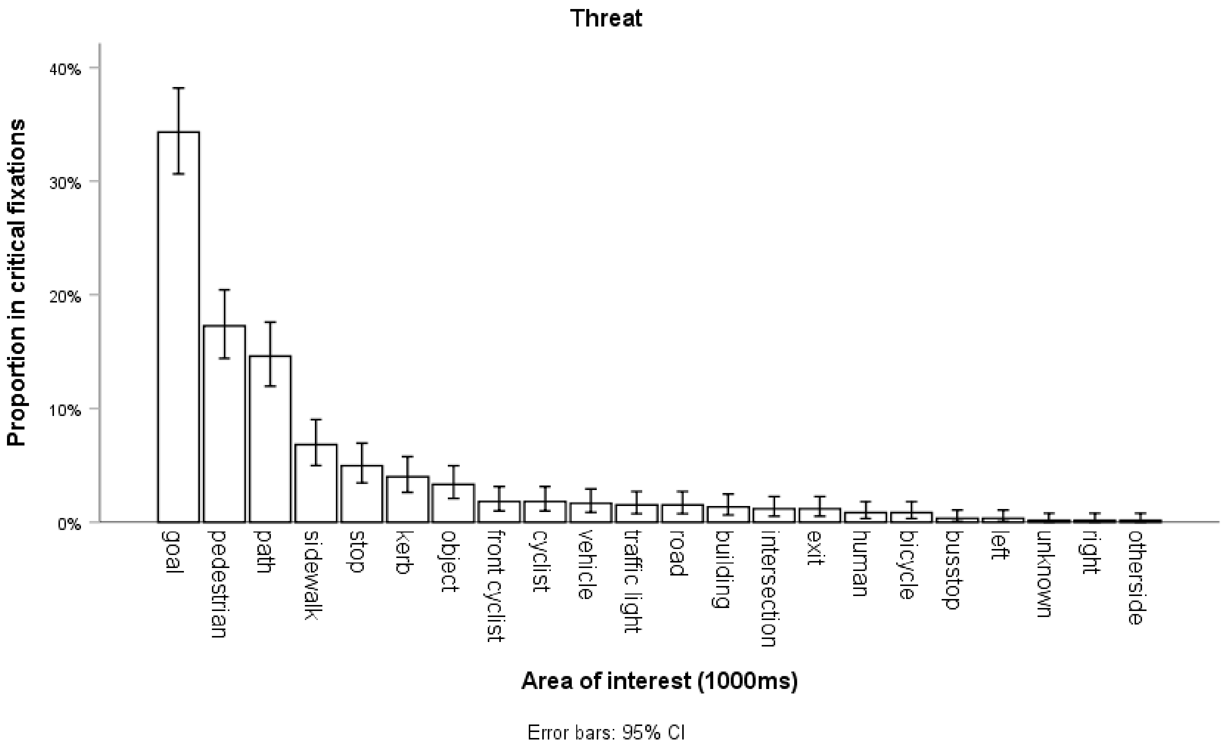

Normal
50%
40%
30%
20%
10%
0%
Proportion in critical fixations
goal
pedestrian
path
stop
exit
kerb
human
traffic light
cyclist
busstop
sidewalk
road
otherside
right
object
vehicle
building
left
front cyclist
bicycle
Area of interest (mean + 2SD)
Error bars: 95% CI


Normal
40%
30%
20%
10%
0%
Proportion in critical fixations
goal
path
pedestrian
kerb
stop
exit
cyclist
sidewalk
human
traffic light
otherside
busstop
building
road
right
object
vehicle
left
front cyclist
ice
unknown
bicycle
Area of interest (1000ms)
Error bars: 95% CI


Speed
Proportion in critical fixations
50%
40%
30%
20%
10%
0%
goal
path
pedestrian
stop
sidewalk
vehicle
traffic light
left
exit
front cyclist
building
road
kerb
intersection
cyclist
otherside
human
busstop
right
obstacle
object
bicycle
Area of interest (mean + 2SD)
Error bars: 95% CI


Speed
Proportion in critical fixations
40%
30%
20%
10%
0%
goal
path
pedestrian
stop
sidewalk
kerb
traffic light
exit
vehicle
object
front cyclist
cyclist
building
left
road
intersection
human
otherside
obstacle
busstop
right
bicycle
Area of interest (1000ms)
Error bars: 95% CI

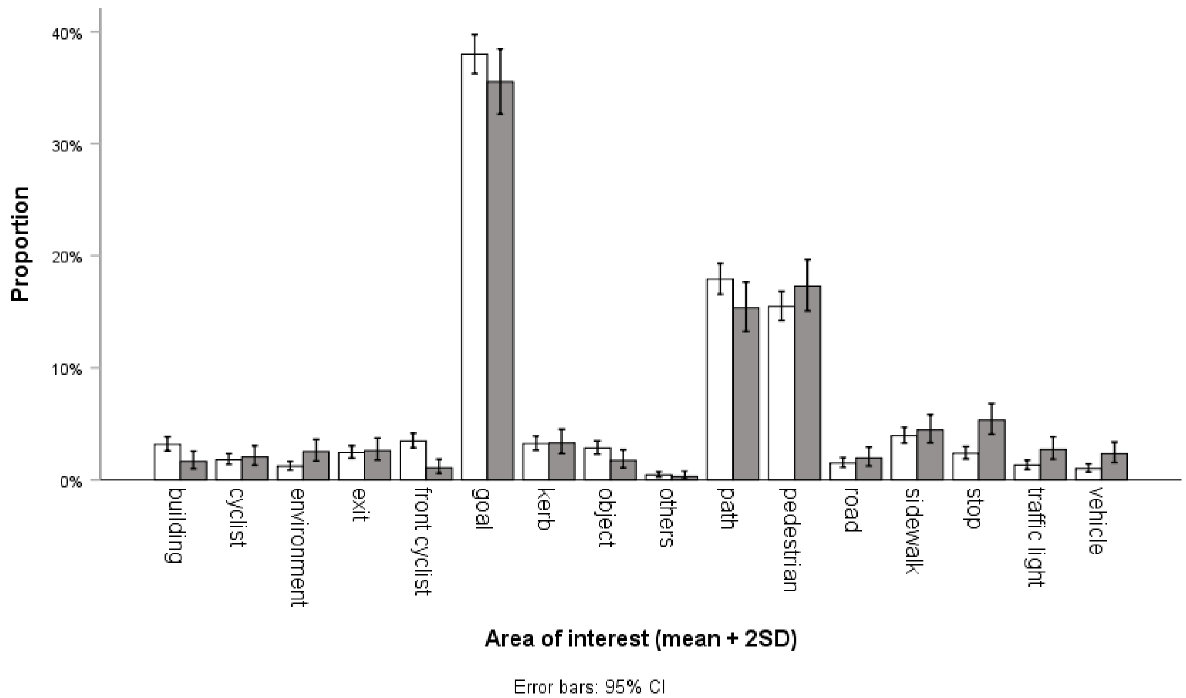

Threat
50%
40%
30%
20%
10%
0%
Proportion in critical fixations
goal
pedestrian
path
sidewalk
kerb
stop
object
cyclist
road
vehicle
traffic light
front cyclist
human
exit
intersection
busstop
left
unknown
right
otherside
building
Area of interest (mean + 2SD)
Error bars: 95% CI


Threat
40%
30%
20%
10%
0%
Proportion in critical fixations
goal
pedestrian
path
sidewalk
stop
kerb
object
front cyclist
cyclist
vehicle
traffic light
road
building
intersection
exit
human
bicycle
busstop
left
unknown
right
otherside
Area of interest (1000ms)
Error bars: 95% CI

Appendix E: Bar charts and contingency tables comparison non-critical and critical fixations

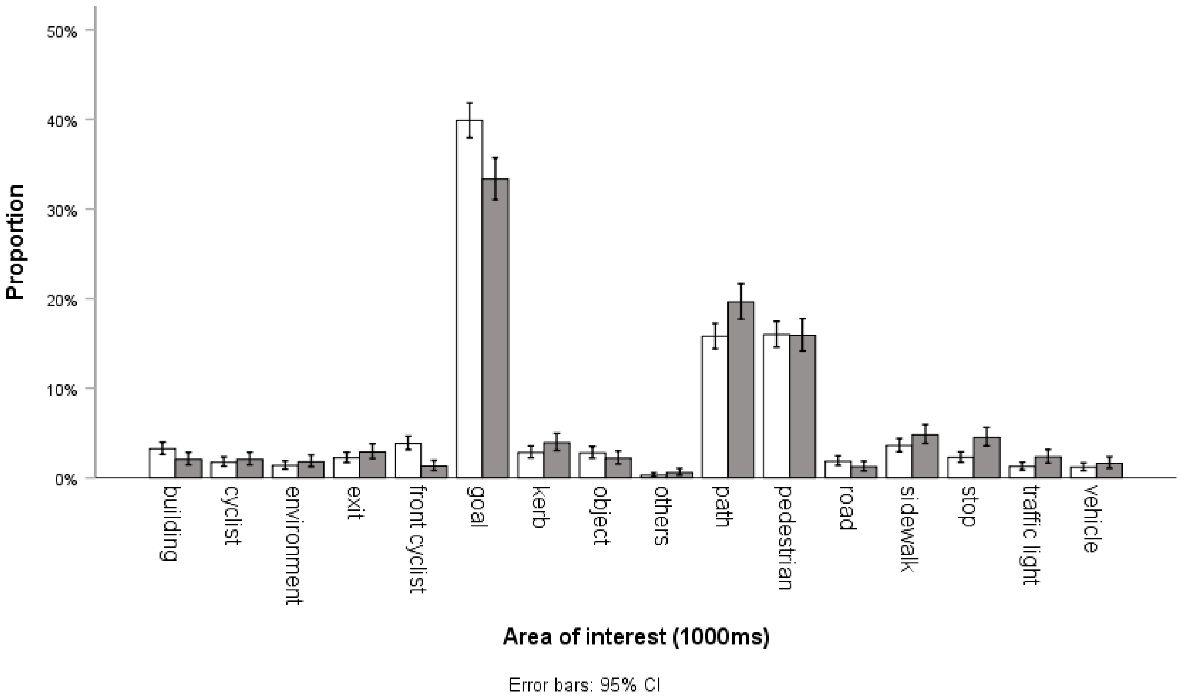
All conditions together, mean +2SD

newcat	fixations: 0=non,1=critical 0	1	Total
building	95	17	112
cyclist	54	21	75
environment	36	26	62
exit	73	27	100
front cyclist	104	11	115
goal	1,141	368	1,509
kerb	97	34	131
object	85	18	103
others	13	3	16
path	538	159	697
pedestrian	465	179	644
road	45	20	65
sidewalk	118	46	164
stop	71	55	126
traffic light	39	28	67
vehicle	30	24	54
Total	3,004	1,036	4,040



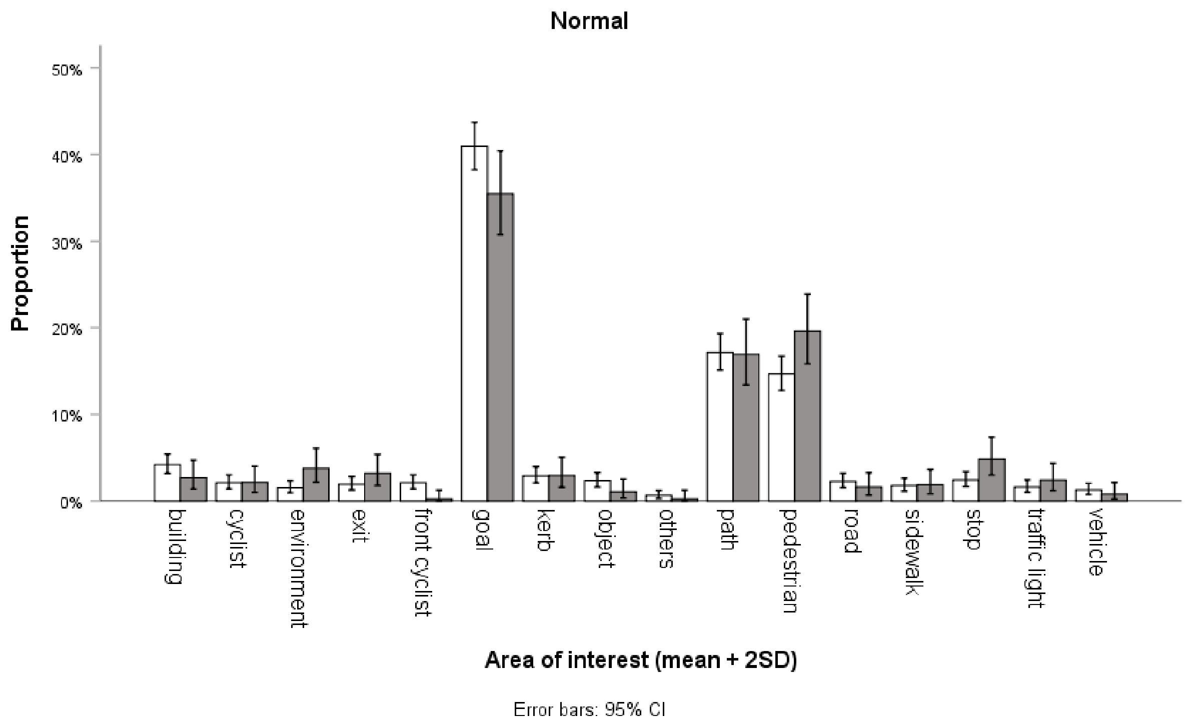
All conditions together, 1000ms

newcat	fixations: 0=non,1=critical 0	1	Total
building	80	32	112
cyclist	43	32	75
environment	34	28	62
exit	55	45	100
front cyclist	95	20	115
goal	989	520	1,509
kerb	70	61	131
object	69	34	103
others	7	9	16
path	391	306	697
pedestrian	396	248	644
road	46	19	65
sidewalk	89	75	164
stop	56	70	126
traffic light	31	36	67
vehicle	29	25	54
Total	2,480	1,560	4,040



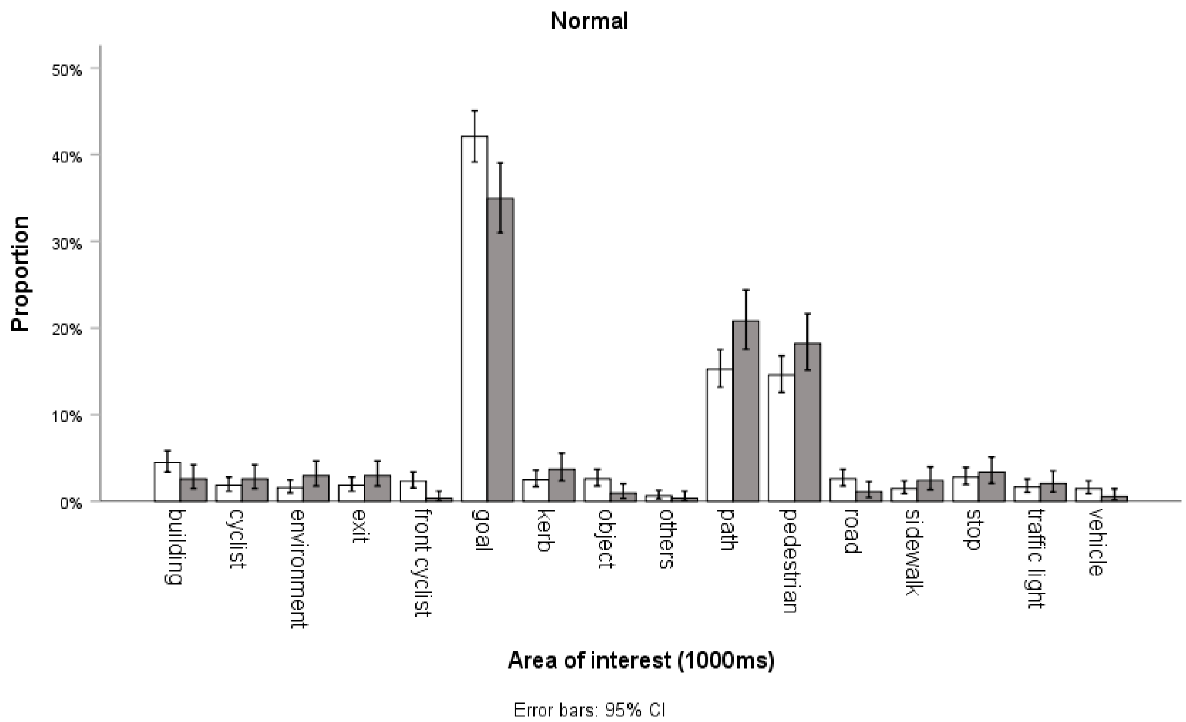
Normal speed, mean +2SD

newcat	fixations: 0=non,1=critical 0	1	Total
building	52	10	62
cyclist	26	8	34
environment	19	14	33
exit	24	12	36
front cyclist	26	1	27
goal	506	132	638
kerb	36	11	47
object	29	4	33
others	8	1	9
path	212	63	275
pedestrian	181	73	254
road	28	6	34
sidewalk	22	7	29
stop	30	18	48
traffic light	20	9	29
vehicle	16	3	19
Total	1,235	372	1,607



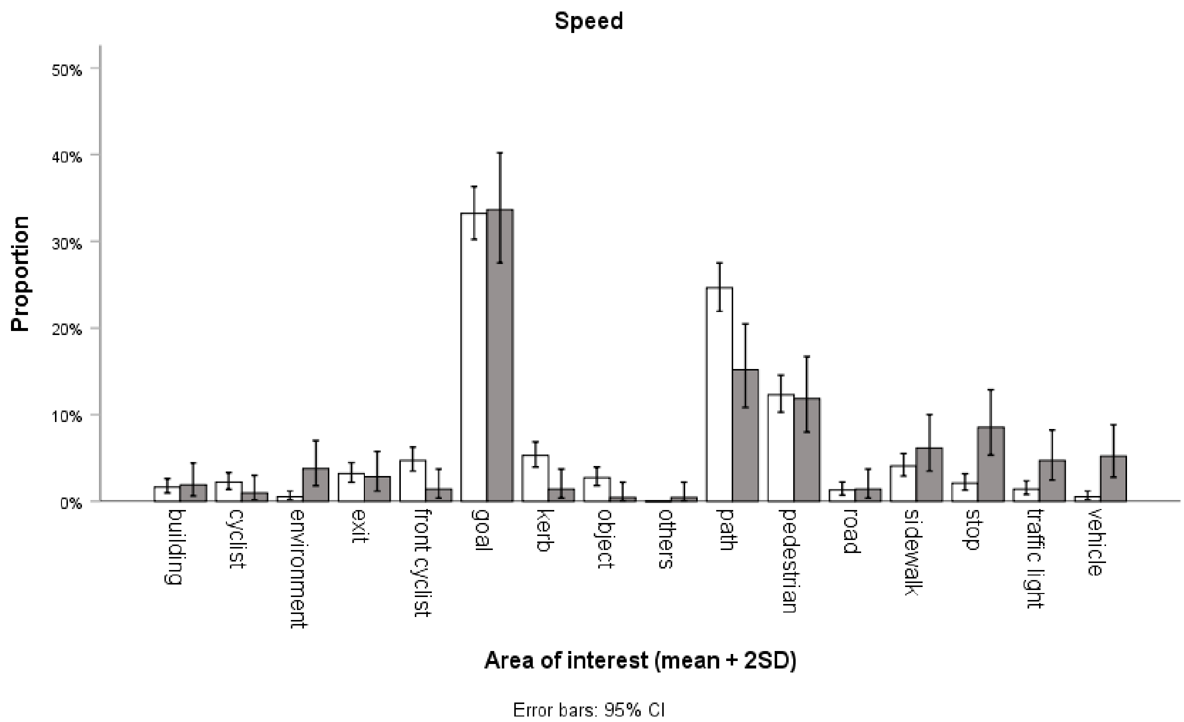
Normal speed, 1000ms

newcat	fixations: 0=non,1=critical 0	1	Total
building	48	14	62
cyclist	20	14	34
environment	17	16	33
exit	20	16	36
front cyclist	25	2	27
goal	450	188	638
kerb	27	20	47
object	28	5	33
others	7	2	9
path	163	112	275
pedestrian	156	98	254
road	28	6	34
sidewalk	16	13	29
stop	30	18	48
traffic light	18	11	29
vehicle	16	3	19
Total	1,069	538	1,607



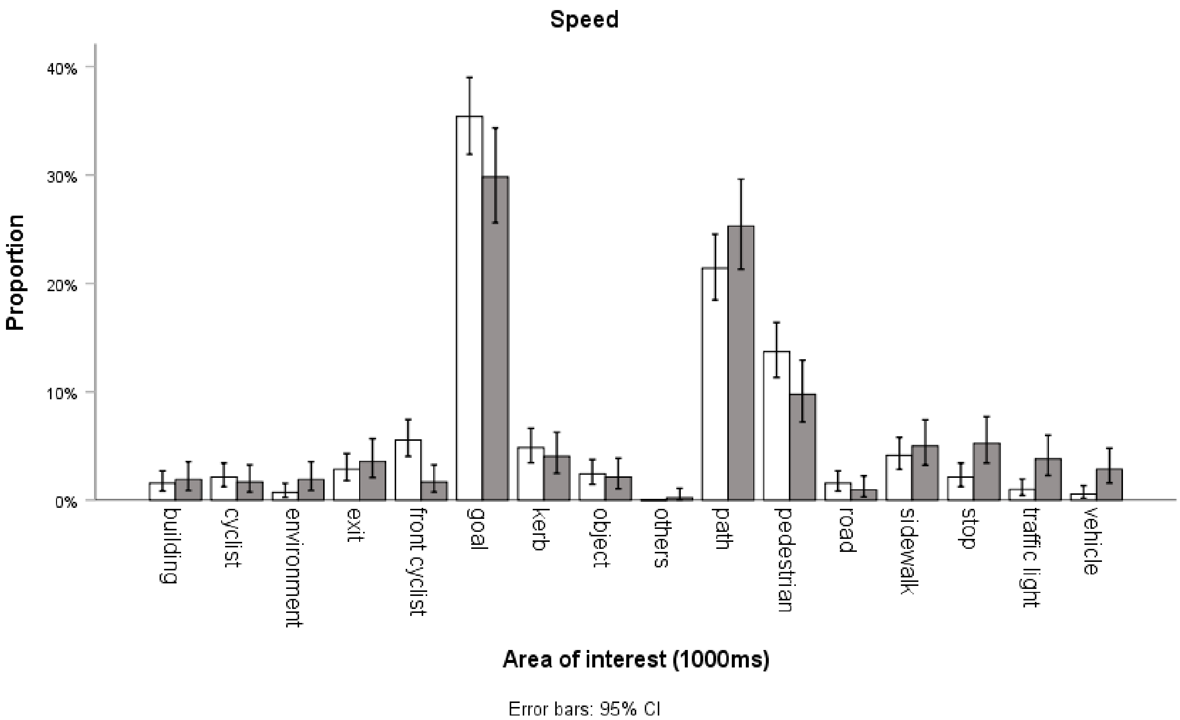
High speed, mean+2SD

newcat	fixations: 0=non,1=critical 0	1	Total
building	15	4	19
cyclist	20	2	22
environment	5	8	13
exit	29	6	35
front cyclist	43	3	46
goal	302	71	373
kerb	48	3	51
object	25	1	26
others	0	1	1
path	224	32	256
pedestrian	112	25	137
road	12	3	15
sidewalk	37	13	50
stop	19	18	37
traffic light	13	10	23
vehicle	5	11	16
Total	909	211	1,120



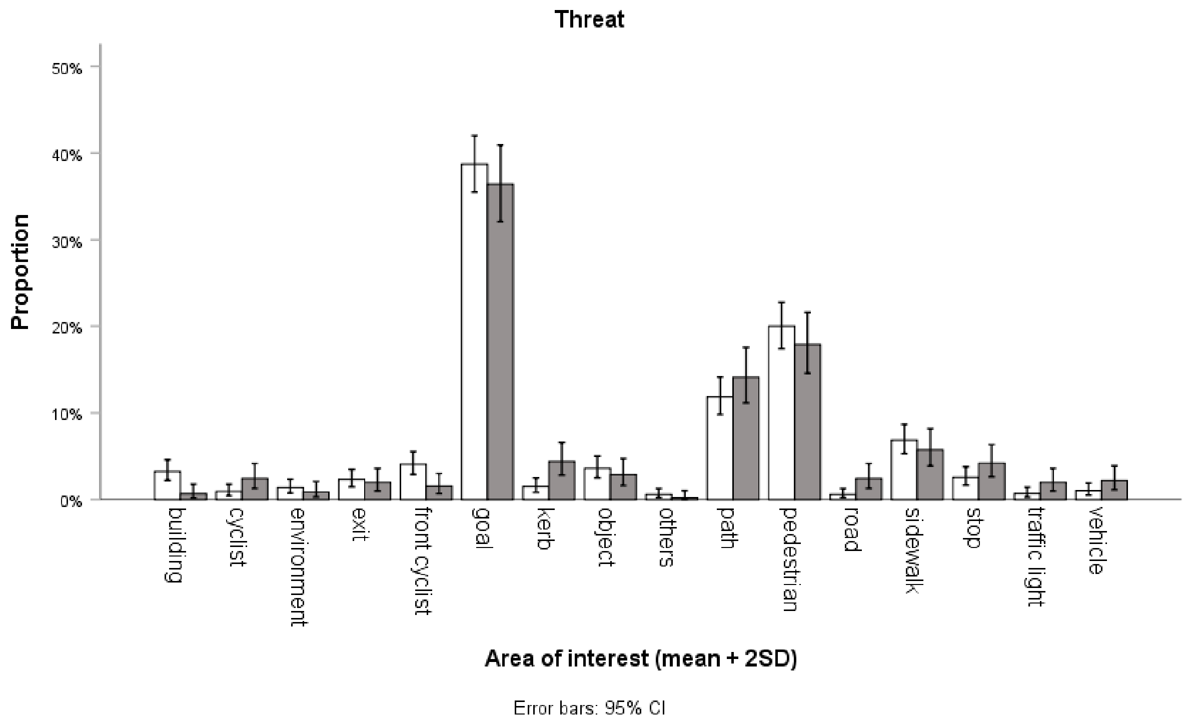
High speed, 1000ms

newcat	fixations: 0=non,1=critical 0	1	Total
building	11	8	19
cyclist	15	7	22
environment	5	8	13
exit	20	15	35
front cyclist	39	7	46
goal	248	125	373
kerb	34	17	51
object	17	9	26
others	0	1	1
path	150	106	256
pedestrian	96	41	137
road	11	4	15
sidewalk	29	21	50
stop	15	22	37
traffic light	7	16	23
vehicle	4	12	16
Total	701	419	1,120



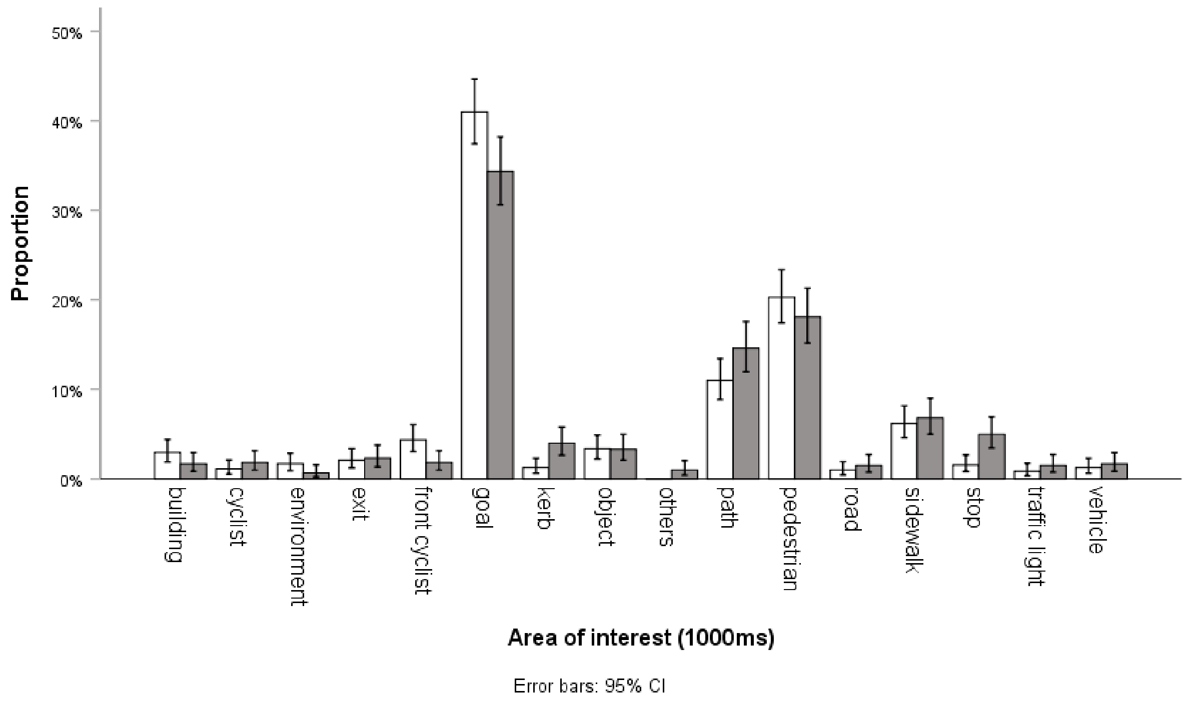
Threat, mean+2SD

newcat	fixations: 0=non,1=critical 0	1	Total
building	28	3	31
cyclist	8	11	19
environment	12	4	16
exit	20	9	29
front cyclist	35	7	42
goal	333	165	498
kerb	13	20	33
object	31	13	44
others	5	1	6
path	102	64	166
pedestrian	172	81	253
road	5	11	16
sidewalk	59	26	85
stop	22	19	41
traffic light	6	9	15
vehicle	9	10	19
Total	860	453	1,313



Threat, 1000ms

newcat	fixations: 0=non,1=critical 0	1	Total
building	21	10	31
cyclist	8	11	19
environment	12	4	16
exit	15	14	29
front cyclist	31	11	42
goal	291	207	498
kerb	9	24	33
object	24	20	44
others	0	6	6
path	78	88	166
pedestrian	144	109	253
road	7	9	16
sidewalk	44	41	85
stop	11	30	41
traffic light	6	9	15
vehicle	9	10	19
Total	710	603	1,313



Appendix F: Matlab script critical fixations

```
clear all
close all

%loading data
[Data,TextData] = xlsread('inmatlabfixationdata.xlsx');
%creating empty arrays to add data
beep_fixation = zeros(length(Data),1);
part = zeros(length(Data),1);
%one array for text (names of values)
Strings = TextData(1,:);

%finding variables by name of the index
indRT = find(contains(TextData','reactiontime'));
indstamp = find(contains(TextData','start_timestamp'));
indRTMS = find(contains(TextData','RT_ms'));
indEnd = find(contains(TextData','end_timestamp'));


for i = 1:length(Data)
   %no NaN, no value of RT
   if ~isnan(Data(i,indRT))
       %looks at dataset to include value when there is no RT
       for j = 1:(length(Data)-i)
          %timestamp + RT > other timestamp
          if Data(i,indstamp)+Data(i,indRTMS) > Data(i+j,indstamp)
              beep_fixation(i+j) = 1;
              part(i+j) = Data(i,indRT);
          end
       end

       %looking at previous fixation
       if Data(i,indEnd) < Data(i-1,indEnd)
              beep_fixation(i-1) = 1;
              part(i-1) = Data(i,indRT);
       end
   end
end


newStrings = [Strings(1,1:indstamp-1) 'beep_fixation'
Strings(:,indstamp:indstamp+1) 'part' Strings(:,indRT:size(Strings,2))];
newData1 = [Data(:,1:3)];
newData2 = [TextData(2:length(TextData),4:indstamp-1)];
newData3 = [beep_fixation Data(:,indstamp:indstamp+1) part
Data(:,indRT:size(Data,2))];

filename = 'test.xls';
xlswrite(filename, newStrings,1,'A1')
xlswrite(filename, newData1,1, 'A2')
xlswrite(filename, newData2,1,'D2')
xlswrite(filename, newData3,1,'G2')
```

Appendix G: Contingency tables distances

Contingency tables of distance of static objects

```
. tab newcat distance if critSD==1, chi V
```

newcat	distance 1	2	Total
path	77	82	159
sidewalk	6	40	46
stop	35	20	55
Total	118	142	260

```
Pearson chi2(2) =  27.3966   Pr = 0.000
     Cramér's V =   0.3246
```

```
. tab newcat distance if critthousand==1, chi V
```

newcat	distance 1	2	Total
path	159	147	306
sidewalk	15	60	75
stop	37	33	70
Total	211	240	451

```
Pearson chi2(2) =  25.9417   Pr = 0.000
     Cramér's V =   0.2398
```

Contingency tables of distance of pedestrians (perdis = distance)

```
. tab newcat perdis if critSD==1 & pedestrian==1, chi V
```

newcat	perdis 1	2	3	Total
pedestrian	22	35	122	179
Total	22	35	122	179

```
. tab newcat perdis if critthousand==1 & pedestrian==1, chi V
```

newcat	perdis 1	2	3	Total
pedestrian	27	65	156	248
Total	27	65	156	248

```
. tab perdis bodyface if critSD==1, chi V
```

perdis	bodyface 1	2	Total
1	14	8	22
2	26	9	35
3	70	50	120
Total	110	67	177

```
Pearson chi2(2) =   2.9549   Pr = 0.228
     Cramér's V =   0.1292
```

```
. tab perdis group if critSD==1, chi V
```

perdis	group 1	2	Total
1	12	10	22
2	20	8	28
3	70	50	120
Total	102	68	170

```
Pearson chi2(2) =   1.9354   Pr = 0.380
     Cramér's V =   0.1067
```

```
. tab bodyface group if critSD==1, chi V
```

bodyface	group 1	2	Total
1	57	49	106
2	45	19	64
Total	102	68	170

```
Pearson chi2(1) =   4.5482   Pr = 0.033
     Cramér's V =  -0.1636
```

```
. tab perdis bodyface if critthousand==1, chi V
```

perdis	bodyface 1	2	Total
1	19	8	27
2	55	10	65
3	90	64	154
Total	164	82	246

```
Pearson chi2(2) =  14.2781   Pr = 0.001
     Cramér's V =   0.2409
```

```
. tab perdis group if critthousand==1, chi V
```

perdis	group 1	2	Total
1	16	11	27
2	33	25	58
3	93	61	154
Total	142	97	239

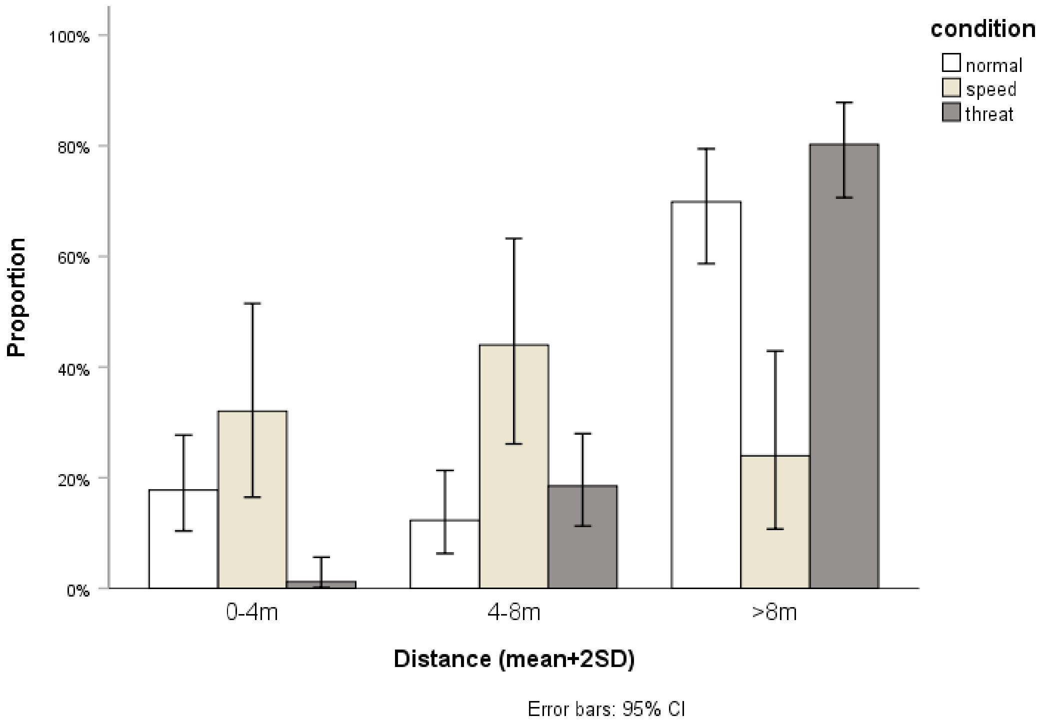
```
Pearson chi2(2) =   0.2135   Pr = 0.899
     Cramér's V =   0.0299
```

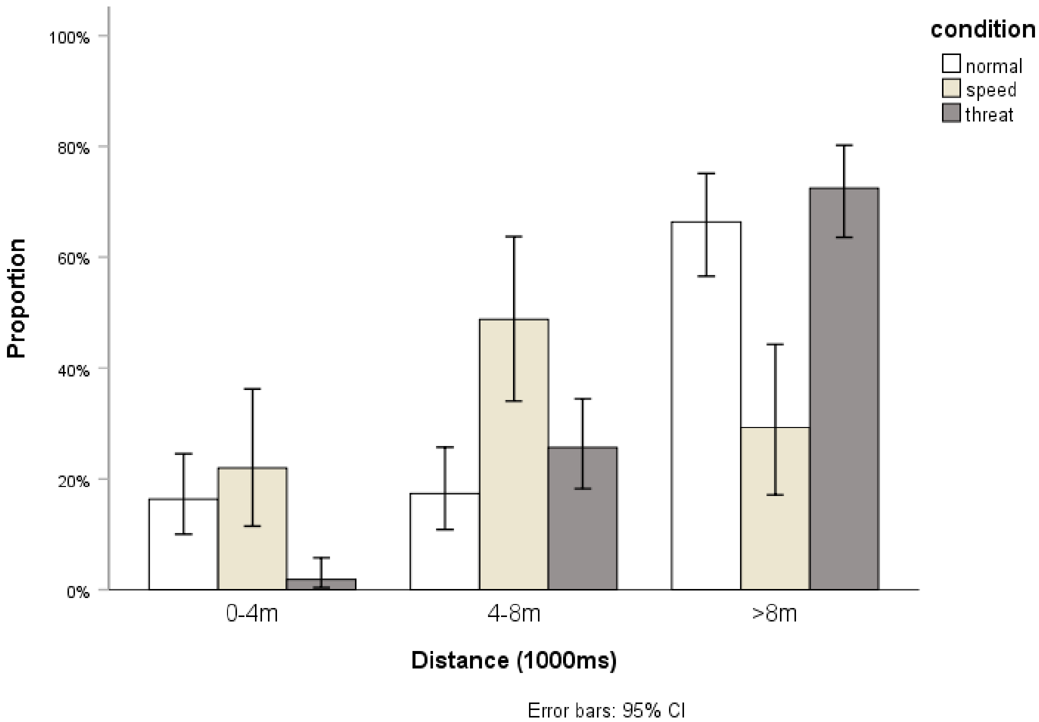
```
. tab bodyface group if critthousand==1, chi V
```

bodyface	group 1	2	Total
1	86	74	160
2	56	23	79
Total	142	97	239

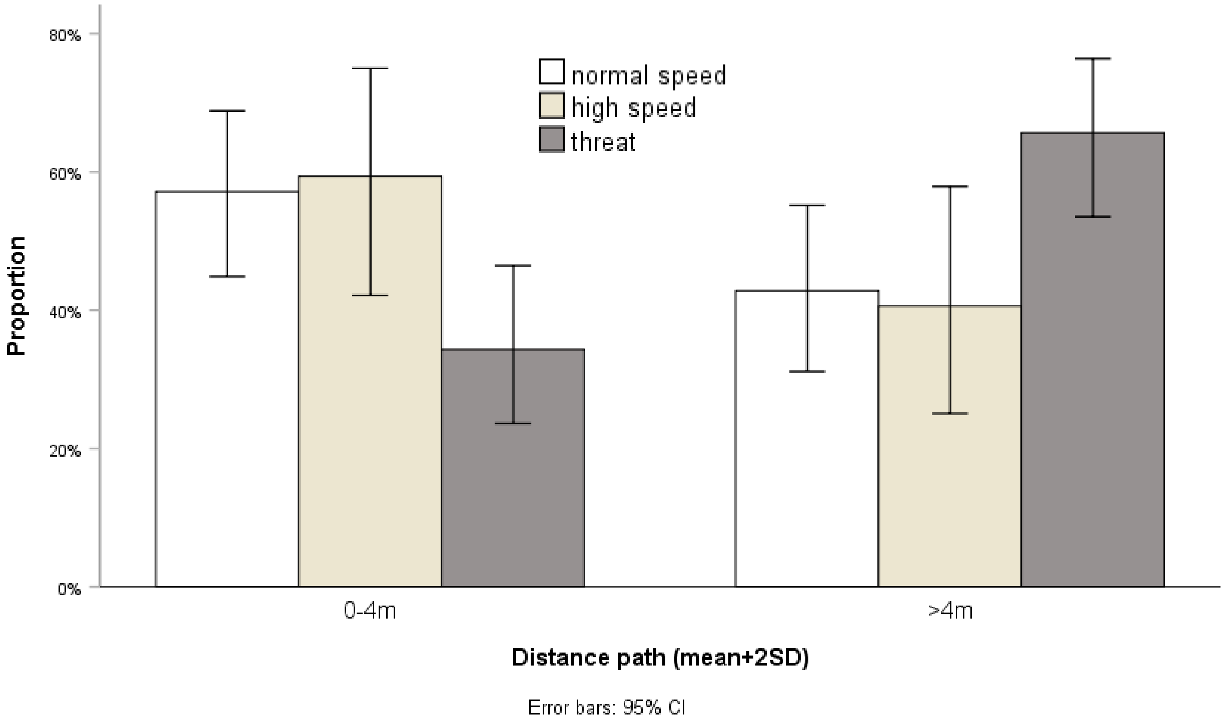
```
Pearson chi2(1) =   6.4403   Pr = 0.011
     Cramér's V =  -0.1642
```

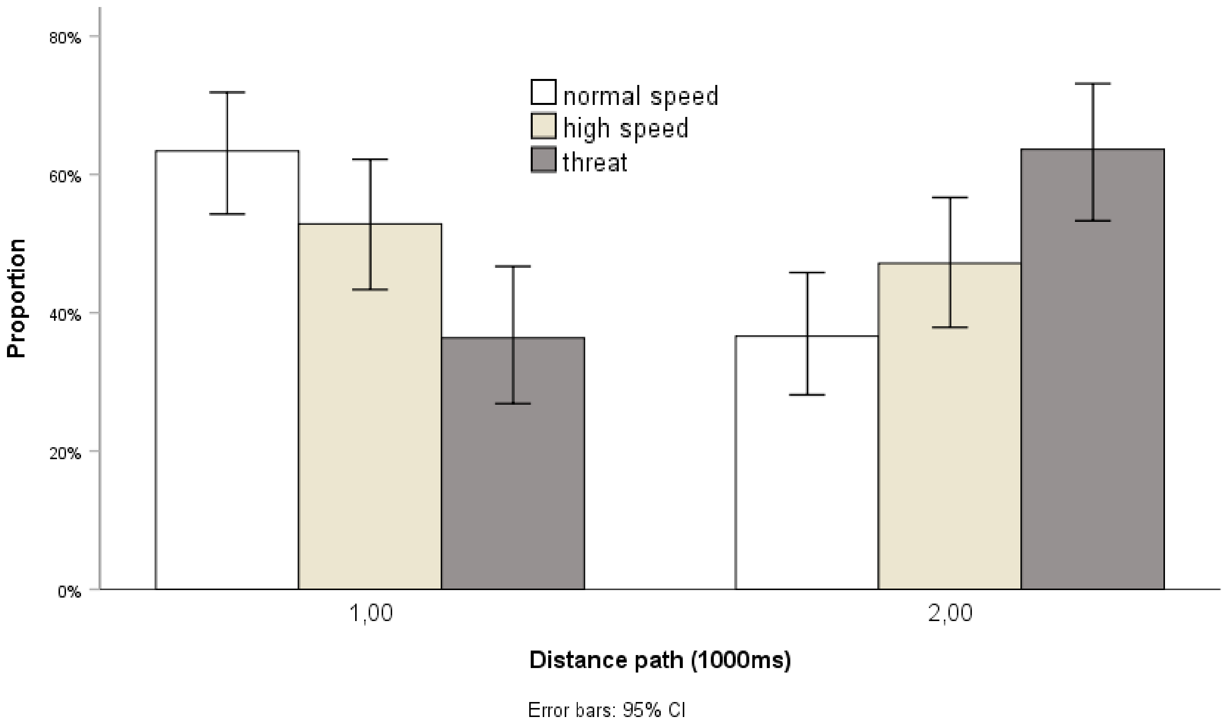
Distance of pedestrians per condition

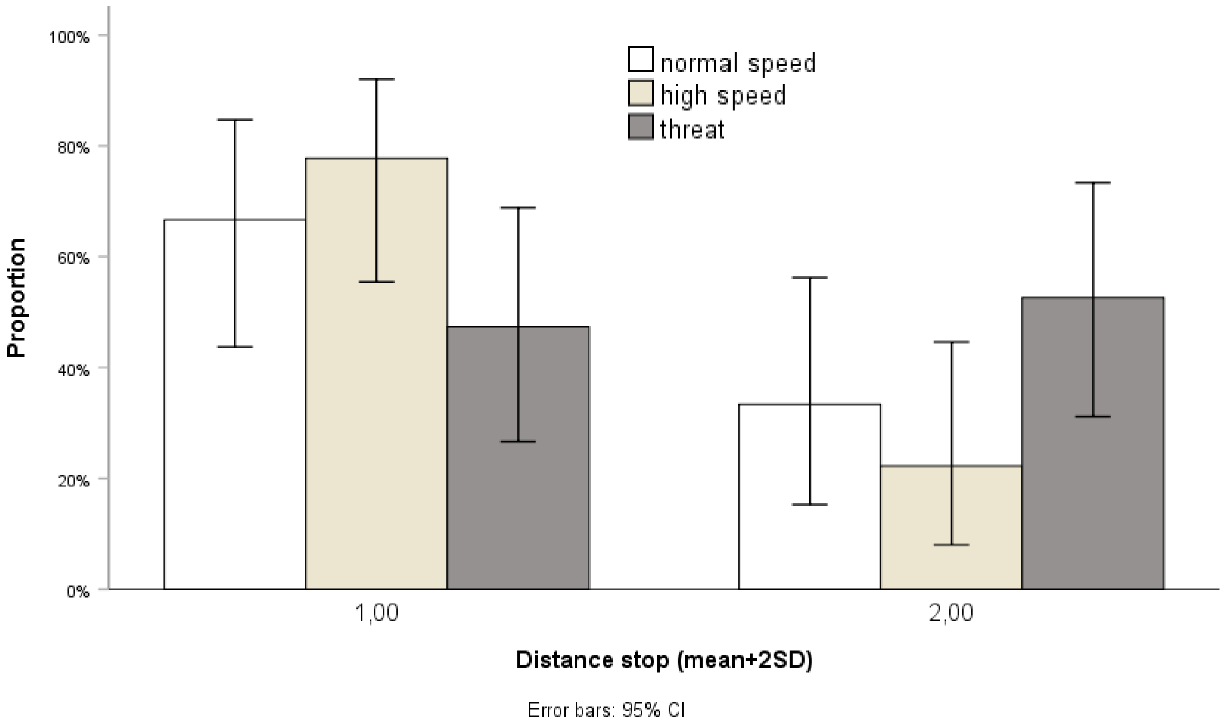


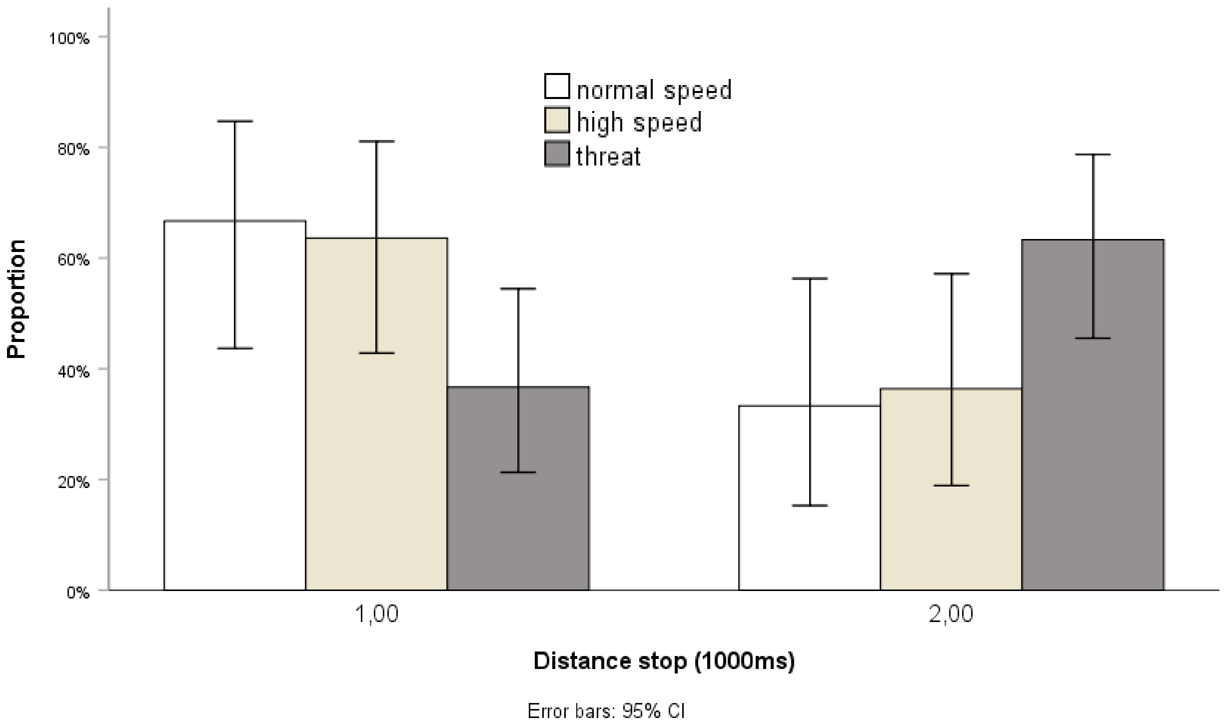


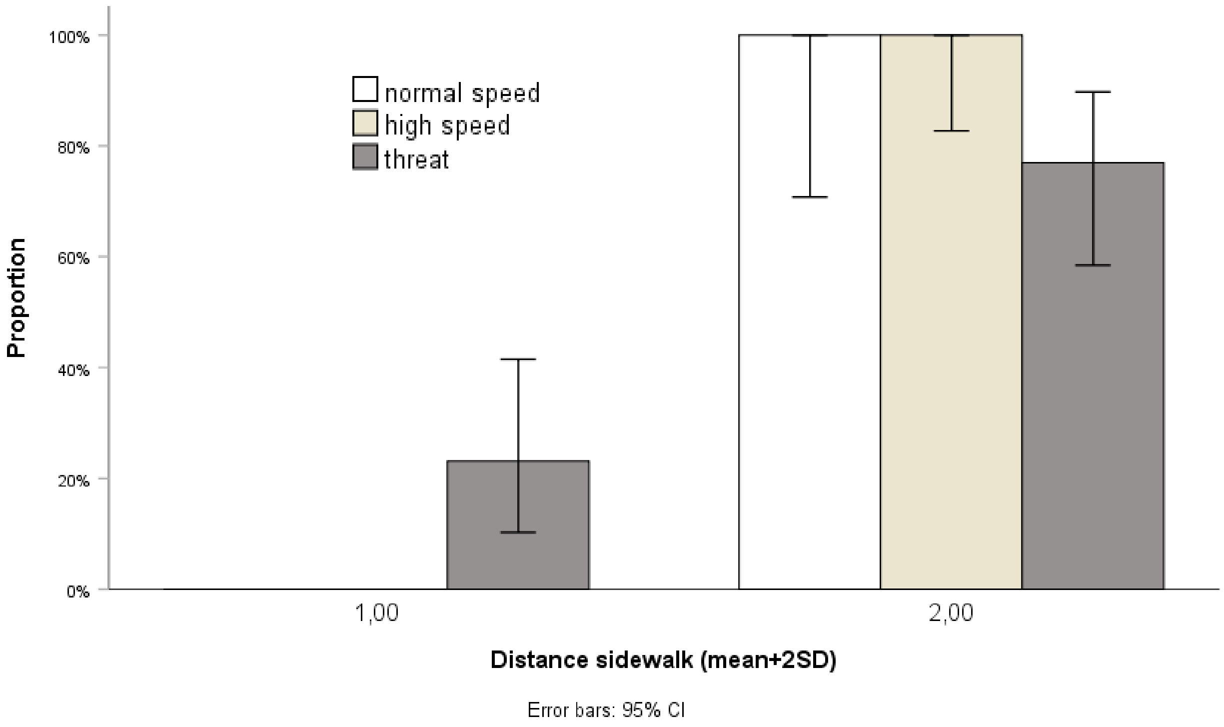
Appendix H: Distance of static objects

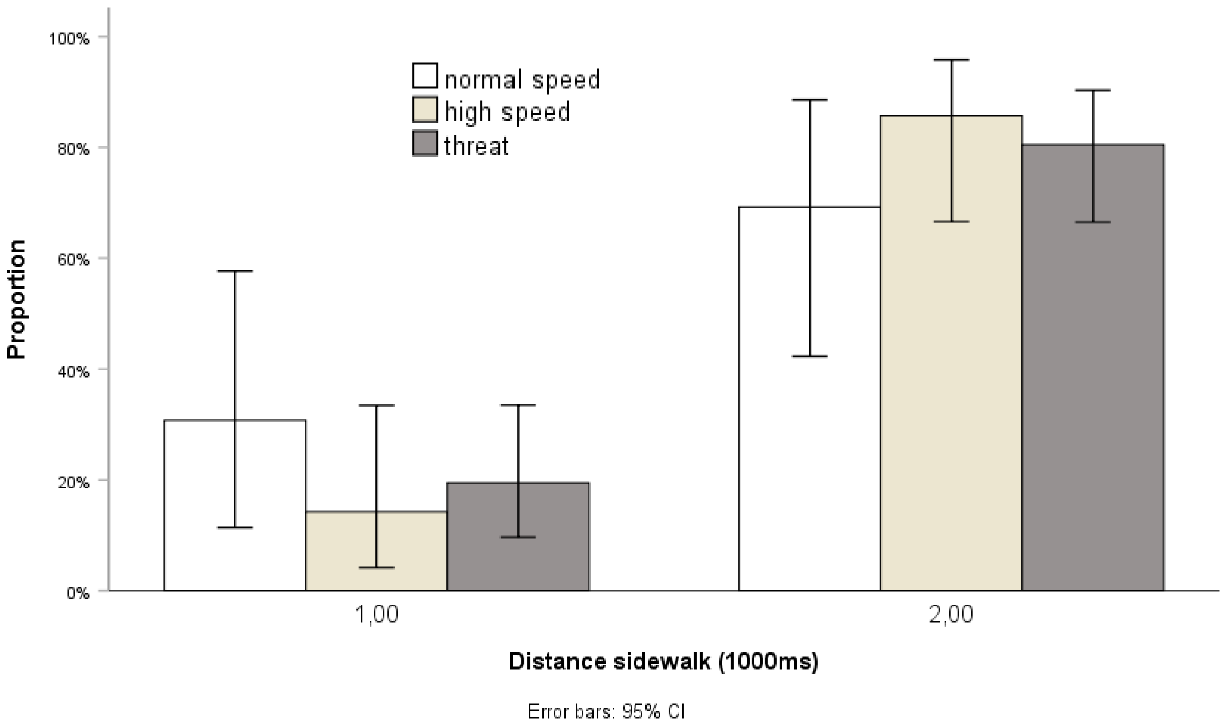





100%
80%
60%
40%
20%
0%
Proportion
normal speed
high speed
threat
1,00
2,00
Distance stop (mean+2SD)
Error bars: 95% CI


100%
80%
60%
40%
20%
0%
Proportion
normal speed
high speed
threat
1,00
2,00
Distance stop (1000ms)
Error bars: 95% CI


100%
80%
60%
40%
20%
0%
Proportion
normal speed
high speed
threat
1,00
2,00
Distance sidewalk (mean+2SD)
Error bars: 95% CI


100%
80%
60%
40%
20%
0%
Proportion
normal speed
high speed
threat
1,00
2,00
Distance sidewalk (1000ms)
Error bars: 95% CI

Appendix I: Extra literature

Night vision

The human eye retrieves visual information from our surroundings. Not only during daytime, but our vision is also able adapting night-time conditions. Photopic vision (luminance levels > 3 cd/m^2) mainly regulates the vision during the day (Boyce, 2014). On the other hand, scotopic vision regulates night vision and occurs at low luminance levels (<0.003 cd/m^2). The transitional range between scotopic and photopic vision is known as mesopic vision. The amount of light that enters the eye, which is automatically regulated by the intensity of the surrounding lights, determines the size of the pupil. The pupil will grow larger in a dimmed situation. Moreover, rods and cones are photoreceptor cells that contribute to form a representation of the visual world (Boyce, 2014). There are more rods than cones in our retina. Rods are more sensitive to light and rods are more sensitive to shorter wavelengths compared to cones. In addition, rods cannot discriminate color, because those photoreceptors contain one type of pigment. On the other hand, cones have a high density in the fovea. There are three types of cones that are sensitive to different parts of the light spectrum. In other words, one cone type is sensitive to short wavelengths, the other is sensitive to medium wavelengths, while the last is sensitive to long wavelengths. The fovea provides the possibility for high visual acuity. This current study focusses on the gaze behavior in the evening and should not be confused with complete darkness in the environment. For example, light (e.g. shops, road, and vehicles) is always available in urban areas (Van Bommel, 2015). In other words, outdoor environments are hardly completely dark. A human is unable to see anything without any light, but we can detect objects and explore the environment with a small amount of light. In addition, acuity, color sensitivity, and gaze control are important factors to perceive complex real-world scenes (Boyce, 2014).

When creating road lighting guidelines, it is important to retain several human vision disadvantages in mind (Fors & Lundkvist, 2009; Van Bommel, 2015). Without proper road lighting, more accidents will occur. First, human vision deteriorates in low light conditions. Night-time driving involves a wide range of light conditions, where the deterioration in human vision varies with the light condition. For example, visual acuity and contrast sensitivity are different in different light conditions; they decrease in low light conditions. Second, glare and dark adaptation are also of importance for night-time vision. High illuminance levels might induce glare which is not desirable for night vision at all. Glare causes a temporary visual impairment due to the presence of bright light. Furthermore, dark adaptation needs to be considered when creating guidelines because it is a relatively slow process. Third, different road users have different needs at night; thus, the needs of all users should be considered in road lighting design. One should adapt existing technology that facilitates nigh-time traffic to the needs of all users (Van Bommel, 2015) while taken light pollution and energy waste into account.