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The effects of cycle-crossing visibility aids on driver's reaction time in nighttime traffic
a simulation-based study

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The Effects of Cycle-crossing Visibility Aids on Driver's Reaction Time in Nighttime Traffic: A Simulation-based Study

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Abstract

Cycling at night is particularly dangerous. Implementing visibility aids to improve the detectability on cyclists is essential, especially at intersections. This study aims at investigating the relative effectiveness of different types of cycle-crossing visibility aids on drivers' hazard detection speed in nighttime traffic. The visibility improvements included adopting in-pavement flash lighting (IFL) systems and increased vertical illuminance. Driving simulations were performed by 28 participants between 24 and 45 years old, the driver's brake reaction time (RT) was used as measure of the efficiency of the visibility aids. The results showed that increased vertical illuminance was the most effective way to reduce the brake RT of drivers. The IFL system placed in the road middle also improved the cyclists perception of drivers. However, providing the IFL signal at the roadsides, which appeared in the drivers' peripheral vision, increased driver's average brake RT, particularly for the cycle-crossing with complex environmental cues. In conclusion, this study gave insight into the efficiency of the two types of cycle-crossing visibility aids in low luminance conditions.

Keywords: Night driving, cyclist safety, hazard perception, visibility aids, in-pavement flash lighter

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1. Introduction

Although cyclists represent a relatively small percentage of all road users, they are the most vulnerable group. According to the report of European Commission (2016), in 2014 in the EU countries, 8.1% road accidents fatalities were bicycle fatalities. Particularly, in the Netherlands, Denmark and Hungary the proportion raised up to 25%, 16% and 16% respectively. In the EU countries, with 26% of the cyclist fatalities happened when the light condition was poor (twilight, night), the proportion was even much higher for some countries (e.g., Latvia, 50%, and Croatia, 47%, respectively).

It is well known that the light condition significantly correlates to the safety of cyclists in nighttime traffic. The higher number of cyclist accidents in low luminance conditions is mainly caused by the increased reaction times and it generally reduces the visibility of all the road users (Konstantopoulos, Chapman, & Crundall, 2010). In general, the low-beam headlights on cars do not sufficiently illuminate the road environment to ensure a low-contrast object (e.g. cyclist and pedestrian) can be detected in time (Edwards & Gibbons, 2008). Road visibility aids are essential for night time traffic, especially for the intersections. In the EU countries, 27% of the cyclist fatalities occurred at junctions (EC, 2016). Driving at intersections is believed as the most complex task of drivers, due to the dynamic road conditions and various stimuli (e.g., Werneke & Vollrath, 2012; Werneke & Vollrath, 2013).

To increase the cyclist detectability, different types of road visibility aids can be adopted. Fixed roadway lighting is effective in reducing speed and improving visibility in the low luminance area. Alternatively, placing road signs, reflectors, beacons can alert drivers in advance about the upcoming situations (Campbell et al., 2012). Besides these passive road signs, active warning systems can detect the approaching pedestrian, cyclist, e-bike, or any other vehicle via several types of sensors. Such systems can calculate the time of arrival and generate proper warning signals for drivers or vehicle autonomous systems to perform appropriate operations (Gandhi & Trivedi, 2007).

The purpose of this study was to investigate the relative effectiveness of active warning systems and increased vertical illuminance in guiding driver's attention to the cyclists at intersections in nighttime conditions. In order to study the effect on cyclists perception, additional hazard conditions were introduced as factors, including the cycling speed, and direction. Furthermore, in previous studies (e.g., Makishita & Matsunaga, 2008; Harbluk, Noy, Trbovich & Eizenman, 2007) mental workload was found to be an important factor that influences the driver's visual strategies while driving. Especially at night, driving asks for more effort than daytime (De Waard, 2002). Thus, the present study examined the visual guidance effects of the visibility aids under different mental workload conditions.

The study was simulation-based, and real-world night-driving videos were used for the simulation. The real driving video could provide a higher level of reality and well-controlled stimuli (Underwood, Crundall & Chapman, 2011), meantime, the driving simulator allowed participants to perform vehicle-driver interaction while carrying out the cyclists detection task.

In the following sections, a theory overview (section 2), experimental setup and design (section 3), result and statistically analyze (section 4), discussion (section 5), a short conclusion (section 6) and recommendations will be presented in detail.

2. Theory Background

2.1. Cyclist safety and visibility aids

Cycling at night is particularly dangerous. Generally, the low-beam headlights on cars do not sufficiently illuminate the road environment to ensure a low-contrast object (cyclist) can be detected in time (Edwards & Gibbons, 2008), therefore additional visibility aids are essential. The visibility aids for cyclist, for instance, the reflective vest or bike lights with flash signal are possible to improve the detection and recognition of drivers on cyclist (Boyce, 2008; Kwan & Mapstone, 2004; Wood et al., 2013). However, the effect of such aids is also influenced by many other factors, such as previous experience, visual acuity of drivers, dynamic complexities of road environment (Kwan & Mapstone, 2004). Mayeur, Brémond and Bastien (2010) have found that the complexity of the road spatial context, and the relative motion between the target and its background objects both impair the observers' performance in peripheral target detection. Besides, the visual acuity of the driver has a significant negative relationship with the target detection performance. As Kwan and Mapstone (2004) argued, whether the visibility aids are effective in improving cyclist and pedestrian safety is still a question in real circumstances. Moreover, the usefulness of the visibility aids may be overestimated by cyclists, which may put the cyclists in particular dangerous conditions (e.g., Tyrrell, Wood, Carberry, 2004; Wood et al., 2013).). Hence, additional road visibility aids are necessary for avoiding bicycle-vehicle accidents in a broader range.

2.2. Vechile-cyclist accidents at intersections

For insertions, a main factor that cause accidents is the inappropriate attention allocation of drivers. Most drivers involved in an accident reported that they totally did not notice the other road users (Werneke & Vollrath, 2013). The reasons that lead to such situations are complicated. Werneke and Vollrath (2012) conducted a series of experiments to examine the driving behaviors at intersection. As reviewed by Werneke and Vollrath (2012), the causes generally can be divided into two types of perceptual errors, one is "**failed to look**", that drivers did not look into the hazard coming direction, or looked but too late to apply appropriate operations; the other one is "**looked but failed to see**", that drivers detected the hazard but failed to shift their attention to aware the situations. In particular, the bicycle-car accident highly correlated to the first kind of perception-errors (e.g., Summala, Lamble & Laakso, 1998; Werneke & Vollrath, 2012; Werneke & Vollrath, 2013).

Such perception-errors can be explained by the SEEV model developed by Wickens et al. (2001). This model can be used to describe the attention allocation and visual scanning phenomenon in dynamic human-machine interactions, such like driving and piloting. There are four factors included in the model that affect the visual attention allocation of human operators, Salience, Effort, Expectancy and Value (Figure 2.1). The human visual attention system applies optimal strategies to allocate attention, which is designed to maximize benefits or minimize cost. The expectancy is based on previous experience and contextual cues to reduce the risk of missing important information. Besides, the allocation is driven by the importance of an information, or the probability an event will happen. The expectancy and value together drive the top-down process. Furthermore, visual searching is not effortless, eye movement and head movement sometimes are costly, thus visual scanning or information access might be inhibited spontaneous at some conditions. An additional factor is the salience of the signal, a stronger signal is less possible to be ignored. The effort and salience together lead the bottom-up process.

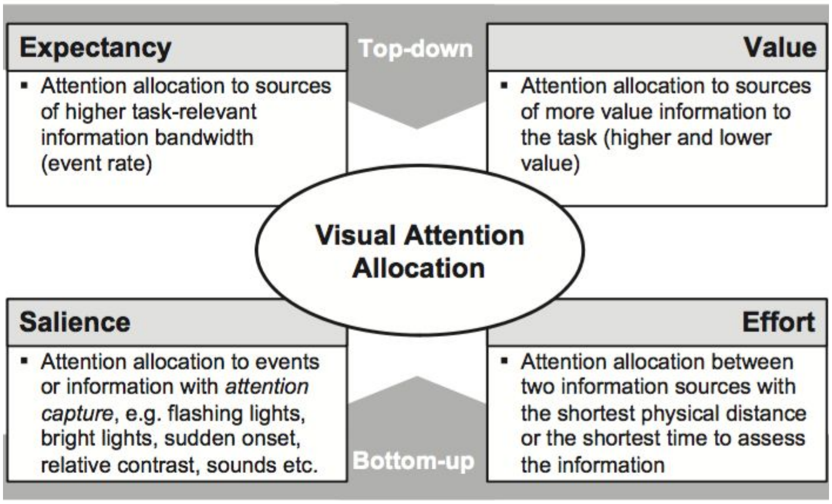

Figure 2.1. The four factors in the SEEV model of Wickens et al. (2001), source: Werneke & Vollrath (2012)

In terms of night driving, the cyclist detection is affected both by the top-down process and the bottom-up process. A driver’s attention is mainly guided by his/ her experience, knowledge, goals and expectation for the present. On the other hand, the road dynamic conditions (e.g., traffic lights, other road users) drive the bottom-up process and lead the allocation of visual attention. In the low visibility conditions, drivers have difficulties to acquire sufficient information about the road situations and potential hazards may be ignored by drivers due to the low salience. Furthermore, driving in low luminance conditions requires a large amount of workload, drivers need to pay more effort to maneuver, observing and making decisions compared with optimal conditions. When performing the demand task, drivers tend to focus on the primary task, and are more likely to neglect other aspects (e.g., Harbluk et al., 2007; Kazazi, Winkler & Vollrath, 2016).

2.3. Intercetion visibility aids

Based on the SEEV model, the solutions to guide the attention and visual searching of drivers can also be divided into two approaches, one is a top-down method, that provide sufficient information about the potential hazards for drivers (e.g., placing road signs, increasing luminance), to enhance the driver’s expectation about the upcoming situation. Another is a bottom-up method, to alert the driver to allocate their attention to the dangerous situations (Werneke & Vollrath, 2012), such like active warning systems (AWS) for cyclist and pedestrians. In fact, the visibility aids are not always disguisable on their effects on the two processes. For example, improving the luminance condition of an intersection can increase the visibility of the cyclist, it may also influence the expectancy of an experienced driver about the hazards occurring and the driver may slow down subsequently when he/she detected an intersection ahead. But still, the visibility aids adopting those two approaches may differ in their efficiency on speed and acuity in terms of hazard perception and situation awareness of drivers at various conditions. Currently, there is a gap in literature about evaluating and comparing the efficiency of different types of road visibility aids from the perspective of driver's hazard perception.

The current study focused on investigating the efficiency of in-pavement flash lighting (IFL). The IFL is one type of AWS. Instead of increasing the visual visibility of hazards, IFL use LEDs mounted on the road in the middle along the crosswalk (Figure 2.2), to alert drivers about the upcoming hazard situations (e.g. approaching cyclists, pedestrians). Campbell et al. (2012) has made a review on the benefits of adopting the treatment of IFL at intersections. After implementing IFL at crosswalks, the number of pedestrian-vehicle crashes reduced (Hakkert et al., 2002; Prevedouros, 2001), the brake gap of drivers increased (Davis et al., 2008; Prevedouros, 2001), the speed of motorists reduced (Van Derlofske et al., 2003, Hakkert et al., 2002), pedestrians waiting time reduced (Prevedouros, 2001) and the rate of driver yield way to pedestrians increased (Davis et al., 2008; Hakkert et al., 2002; Prevedouros, 2001; Van Derlofske et al., 2003) in both nighttime and daytime traffic. All these results came from field observations, whereas few studies are available on evaluating the visual guide effect of such system under well-controlled experimental conditions. Prevedouros (2001) found that the speed yielding effect of such system at different experimental intersections demonstrated different patterns, and the benefits were limited for some particular intersections. Furthermore, Van Derlofske et al. (2003) indicated that the impact of such system seems to show a diminished trend over time. To explain those findings, further examinations are needed, especially to take the lighting and the effect of darkness into consideration (Davis et al., 2008). Therefore, current research aimed at studying to what extent such system can help road users understand the road situations, with road lighting as an additional consideration.

Figure 2.2. An example of in-pavement flash lighting system. Flash lighters are mounted on the road surface at a crossing for both the left and right lanes

2.4. Measures of the efficiency

The efficiency of visibility aids depends on whether they can guide or alert the drivers' attention in time to avoid an accident (Kwan & Mapstone, 2004). The ability of hazard perception has been found to correlate to crash involvement (Horswill & McKenna, 2004). Hazard perception has been studied for decades, in driving it can be comprehended as situation awareness (SA) for critical situations (Sprague, Shibata & Auflick, 2014). In general, there are three levels involved in SA, level 1: perception of elements in the environment, level 2: understanding the meaning of the elements dependent the context, and level 3: prediction related to the status of the elements (Endsley, 1995). Traditionally, signal detection theory (SDT) (Macmillan & Creelman, 2004) has been used to analyze the response bias and sensitivity in detection tasks, whereas it is difficult to apply to traffic hazard perception test. Because in practice, the traffic hazards are complex and infrequent, there is no direct and consistent mapping between the hazards and responses (Horswill & McKenna, 2004). Instead, reaction time (RT), is often used as a measure of the speed of hazard perception. It is the time between the presence of a stimulus and the response of an observer or listener to the stimulus. In the experimental condition, RT is often used as a measure of perceptual speed, it is a hypothetical time that since a stimulus is detected, the information is processed until a manual response is operated (Sprague et al., 2014). Most studies have used filmed traffic sequence to which drivers respond by pressing a button when a traffic hazard has been detected. While such method has been questioned about its validity, one major reason is that people's behavior in the video-based hazard perception test may not be consistent with their real-world driving behavior (Horswill & McKenna, 2004; Underwood et al., 2011).

In recent decades, driving simulators have been widely used in the research of hazard perception. Underwood et al. (2011) have noted that compared to video-based hazard perception test, a driving simulator improves the correspondence between the eye movements evoked within the simulator and the real world, by providing some level of vehicle-driver interaction. Generally, in a simulated driving test, the brake RT is measured. It is the time that human drivers take to perceive, recognize (understand), and decide to apply a brake for roadway hazards. Jurecki and Stańczyk (2014) conducted road simulations to study the relationship between driver's brake RT to hazards and accident risk to selected accident scenarios. The brake RT was found to be a linear function of time to collision (TTC), approximately (see also Jurecki, Stańczyk & Jaśkiewicz, 2017). Thus, brake RT is a fair index to evaluate the efficiency of the visibility aids in a simulation-based study.

2.5. IFL system

As explained earlier, the IFL is expected to provide high conspicuous signals which can alert the driver to allocate their attention to potential hazards. Hence, we hypothesize that drivers' latencies of reaction to hazards reduces by implementing IFL system at intersections. Furthermore, Posner, Snyder and Davidson (1980) have shown that when a cue if offered about the position where the signal will occur in the visual field, the detection latencies of participants are reduced. Posner et al. (1980) explained that the cue reduced the criterion at the expected signal position, hence the detection performance improved. Mahlke et al. (2007) examined the benefits of six in-car night vision enhancement system. Particularly, the system had far infrared sensors with automatic pedestrian recognition, which used an event-based LED display under the windscreen (APR-LED) to alert the driver with position information of the pedestrian (Figure 2.3). The APR-LED system significantly reduced the pedestrians recognition times. Apparently, the driver could easily comprehend the correlation between the signal and the pedestrians presenting on road.

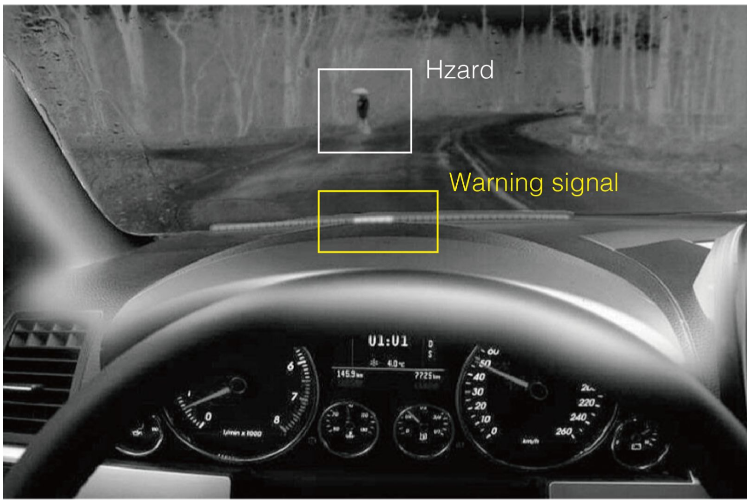

Figure 2.3. Example of APR-LED, source: Mahlke et al. (2007)

Moreover, Ho and Spence (2009) conducted three experiments to examine the spatial warning signals' effect on the participants' speed of fast head-orienting responses. The second experiment was designed to investigate the relative effectiveness of auditory and visual warning signals in guiding driver attention to the appropriate direction or target location. For visual signals, the authors pointed out that the central visual warning signals were less effective than peripheral visual warning signals because they did not provide any spatial information about the target (see also Ho & Spence, 2005). Based on these studies, we expect that the IFL mounted at both roadsides of the intersection, could further improve the hazard detection speed of drivers by peripheral warning signals, that embed cyclist direction information.

2.6. Road Lighting

It is well known that the lighting condition significantly correlates to the cyclist safety at night. Fixed roadway lighting is effective in reducing speed and improving visibility in the low luminance area (Campbell et al., 2012). Jackett and Frith (2013) conducted a field study to examine the relationships between lighting parameters and road safety. They found a statistically significant dose-responses relationship between average luminance and accident risk at night across all road user groups. Specifically, they established the relationships separately for intersections and midblock locations. The intersections were further divided into two sub-groups, Major (with traffic signals or roundabout control) and Minor (all other intersections). As shown in Figure 2.4, the average luminance is negatively correlated to the nighttime/daytime crash ratio for both Major and Minor intersections.

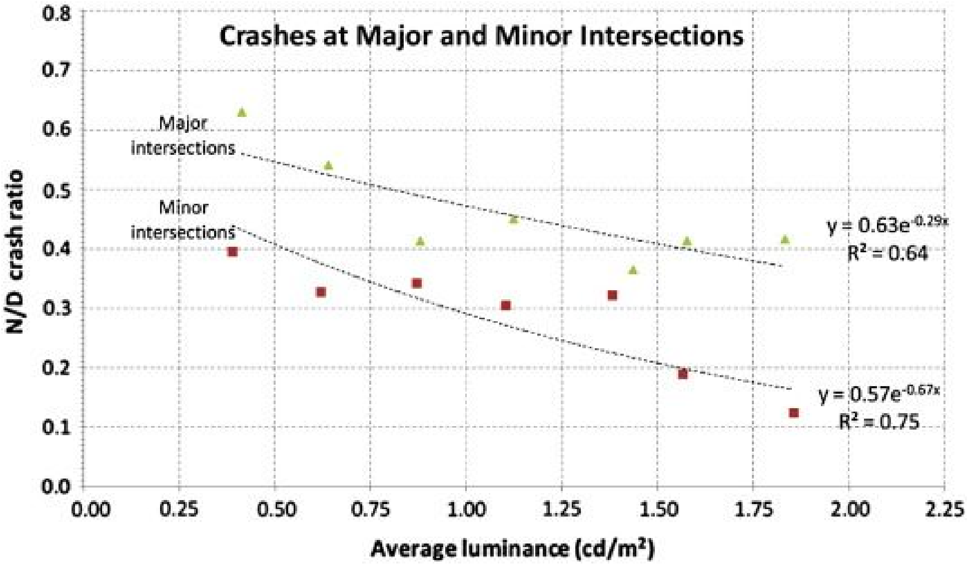

Figure 2.4. The relationships between average luminance and nighttime/ daytime crash ratio for Major and Minor intersections, source: Jackett & Frith (2013)

The higher number of cyclist accidents in low luminance conditions is mainly caused by the increased reaction times and it generally reduces the visibility of all the road users (Konstantopoulos et al., 2010). In terms of road scene, road users are usually detected and recognized from different colors and contrasts. At lower lighting conditions, color vision is poor (Plainis & Murray, 2002) and luminance contrast becomes the major determinant whether the target could be detected by a human observer (Sprague et al., 2014). For an object with constant reflectivity, the luminance contrast which between the luminance of the object and its background decreases with decreasing luminance level, which results in an increase in the inform processing time of the observers (Plainis & Murray, 2002). Hence, increasing the visibility of cyclists is an effective method to enhance cyclist safety at night (Campbell et al., 2012).

Increasing the light levels would make the hazards more visible for drivers at nighttime. For example, the cyclists and pedestrians luminance contrast against the background could be improved by bollard luminaires located at crossing. The bollard luminaires can provide high level vertical illuminance on pedestrians or cyclists, while there is little light on the road surface ahead or behind (Boyce, 2014). Edwards and Gibbons (2008) found that the vertical illuminance to pedestrians (6, 10, 20 and 30 lux), the type of luminance source (high pressure sodium and metal halide) and the color of pedestrians cloth (white, denim, and black) all had an influence on target detection. White cloth pedestrians had a larger detection distance than denim cloth and black cloth. There were interactions between type of luminance source, levels of vertical illuminance and colors of pedestrian cloth, but in general, the detection distance increased with the improving of vertical illuminance level. The authors indicated that the vertical illuminance at 20 lux level likely could provide adequate levels of target detection distance (see also Gibbons & Hankey, 2006). Based on these findings, we expect that increased vertical illuminance at low luminance environment will improve the detection of a cyclist with dark color cloth.

2.7. Additional factors

Amount of literatures have shown that also other factors may influence the RT of drivers. Underwood, Ngai & Underwood (2013) found that in normal daytime lighting conditions, both experienced and inexperienced drivers reacted faster for abrupt-onset events than gradual-onset hazards, presumably because abrupt-onset hazards can capture attention by its sudden presence. The abrupt-onset hazards are completely invisible until the movement begins (Yantis & Jonides, 1984). The perceived abruptness of the hazards onset is influenced by the movement speed of the hazard. At low luminance conditions, the speed perception might be influenced by other factors, including the color, shape, and luminance levels of the hazards (e.g., Alferdinck, 2006; Dougherty, Press & Wandell, 1999; van de Grind, Koenderink & van Doorn, 2000). The visibility of a moving target might vary with the varied backgrounds, luminance conditions. At high speeds that reach the upper limit of motion perception, a target appears to be a blurred to the observer (Morris, 1959), and hence, the detectability of a dark cloth cyclist might be impaired compared to lower speeds.

Second, Jurecki and Stańczyk (2014) found a discrepancy in RT between two entering directions of pedestrians (mock-up). Specifically, drivers reacted faster for the pedestrians entering from the right-hand side than the left-hand side. The authors explained that for a pedestrian entering from the left-hand side, the drivers' visual angle of the pedestrian is much greater than a pedestrian entering from the right-hand side (see Figure 2.5). Therefore, the eye movements takes more time in the first case, subsequently, the RT increased.

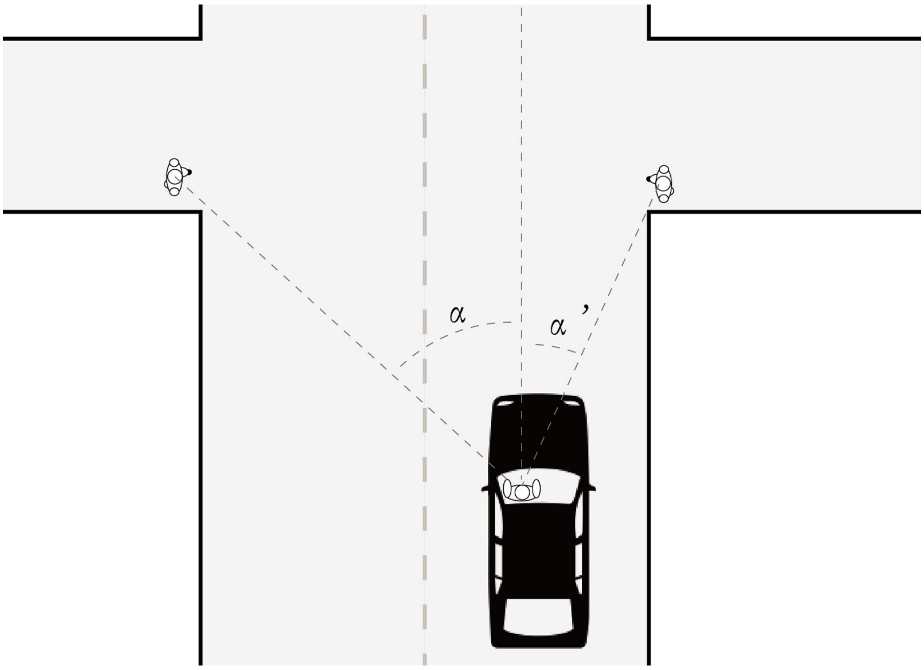

Figure 2.5. An illustration of the view angle of drivers to the pedestrians. α is the left view angle and α' is the right view angle. α is much larger than α'

Werneke and Vollrath (2012) conducted a series of experiments to study drivers' behavior at intersections, particularly where drivers look at and how they allocate their attention. They found that at intersections with high traffic density, drivers glanced more at left-hand side. Whereas, drivers made more gaze at right-hand side when the traffic density was low and both sides had potentially valuable information.

Finally, many previous studies demonstrated that mental workload is an important factor that influences drivers behavior and visual searching strategy. For example, Makishita and Matsunaga (2008) examined the influence of mental workload on the reaction times of drivers across various age groups. They found mental calculations while driving generally increased the average reaction time. Harbluk et al. (2007) pointed out that when the demand of the primary (driving) task was high, drivers tended to look less at their right-hand side. At intersections, drivers significantly reduced the frequency of inspecting glances to traffic lights and to the right side. Driver's mental workload may be impacted by the complexity of the driving context (see Cantin, Lavallière, Simoneau & Teasdale, 2009), the difficulty of steering operation (see Dijkst erhuis, Brookhuis & De Waard, 2011), lighting and weather conditions (see HU, LI & WANG, 2011). Dijksterhuis et al. (2011) examined the relationship between mental effort and steering operations and found that the mental demand of the steering task increased with the decreased of lane width and increased with oncoming traffic density. The peripheral detection task (PDT) can be used to measure the workload of drivers. Generally, the response time to PDT and missed rate to signal both increased with increasing mental demand (Martens & Van Winsum, 2000).

2.8. Hypothesis

This study focused on investigating whether the in-pavement flash lighters of a cycle-crossing improves the speed in hazard perception and recognition of the drivers at nighttime. In addition, we compared the effects of visibility aids including the IFL system with increased vertical illuminance. In this study, the IFL was installed in either the middle of the road or at both roadsides. Furthermore, the cycling speed, approaching direction, and drivers' mental workload were included as additional variables. We propose the following hypotheses for a dark-clothed cyclist in the nighttime, at an uncontrolled cycle-crossing:

[H0a] Compared to standard cycle-crossing conditions, increasing vertical illuminance of the cycle-crossing reduces the RT of drivers to detect a cyclist (Edwards & Gibbons, 2008; Gibbons & Hankey, 2006; Jackett & Frith, 2013).

[H0b] Compared to standard cycle-crossing conditions, in-pavement flash lighters reduce the RT of drivers to detect a cyclist (Campbell et al., 2012).

[H1] The in-pavement flash lighters located on both sides of the cycle-crossing reduces the RT of drivers to detect a cyclist, particularly for the cyclist approaching from the left side of the cycle-crossing (Ho & Spence, 2009; Mahlke et al., 2007; Posner et al.,1980).

[H2] The drivers respond faster for a lower speed of the cyclist than a higher speed (Morris, 1959).

[H3] The drivers respond faster for the cyclist approaching from the right side of the cycle-crossing than the left side when the traffic density is low (Jurecki & Stańczyk, 2014; Werneke & Vollrath, 2012).

[H4] The mental demand of drivers increases with the difficulty of the steering task (Dijkst erhuis et al., 2011).

[H5] A higher level of mental workload leads to an increase in RT of drivers to detect a cyclist (Martens & Van Winsum, 2000).

3. Method

The purpose of this study was to examine the effects of cycle-crossing cyclist visibility aids on driver's brake RT in nighttime traffic, under various conditions. A video-based driving simulator was used to perform the test, the test was a combination of hazard perception and target tracking task. More details will be explained in the following parts.

3.1. Design

The experiment used a full-factorial within-subject design with four independent variables and two dependent variables.

3.1.1 Independent variables

The first independent variable was the *condition of road visibility aid*. Specifically, the control condition (coded as STAN) was a normal cycle-crossing with standard-painted road markings. Compared with the control condition, four conditions were designed to improve the visibility of the cyclist:

Condition 1 (WSM). This condition used an in-pavement warning system to caution the drivers when a cyclist was approaching from one side of the cycle-path. Three active flash lighters were placed on the surface of the road with an interval distance of 87 cm. The largest distance that the system could detect an approaching cyclist was around 25 m. As soon as the cyclist appeared on the screen, the lighters started to flash simultaneously, with a cycle of 1 s (see Figure 3.1).

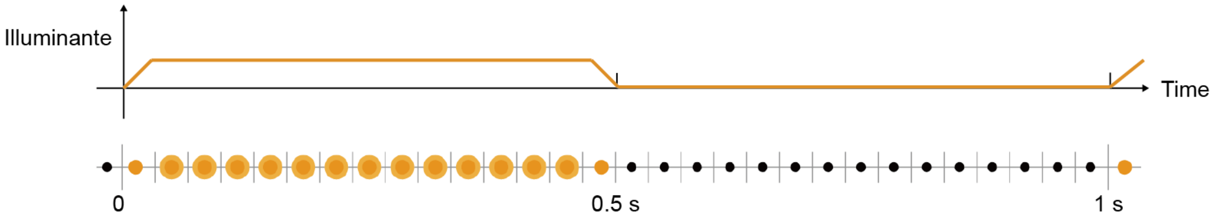

Figure 3.1. An illustration of the in-pavement flash lighting cycle. The lighters illuminante in half a second and go out in half a second.

Condition 2 (WSS). This condition used the same in-pavement warning system as condition 1, the difference was the flashlights were placed on the roadside, with a distance of 7 m from the road middle line. When a cyclist appeared on the screen from the roadside, the flash lighters located at the same side start to flash simultaneously.

Condition 3 (ILM). This condition used the street light along the cycle-path to increase the vertical illuminance. As a result, the luminance of the cyclists was increased. The average illuminance was increased up to 2 times approximately compared to the control condition, referred to as an intermediate level (Appendix C).

Condition 4 (ILH). This condition also used the street light along the cycle-path to increase the vertical illuminance. The average illuminance was increased up to 3 times approximately, compared to the control condition, referred to a high level (Appendix C).

To conclude, there were five conditions of the first independent variable (Figure 3.2): standard cycle-crossing (STAN), warning flash lighters on road middle (WSM), warning flash lighters on roadside (WSS), street light - middle illuminance(ILM) and street light - high illuminance (ILH).

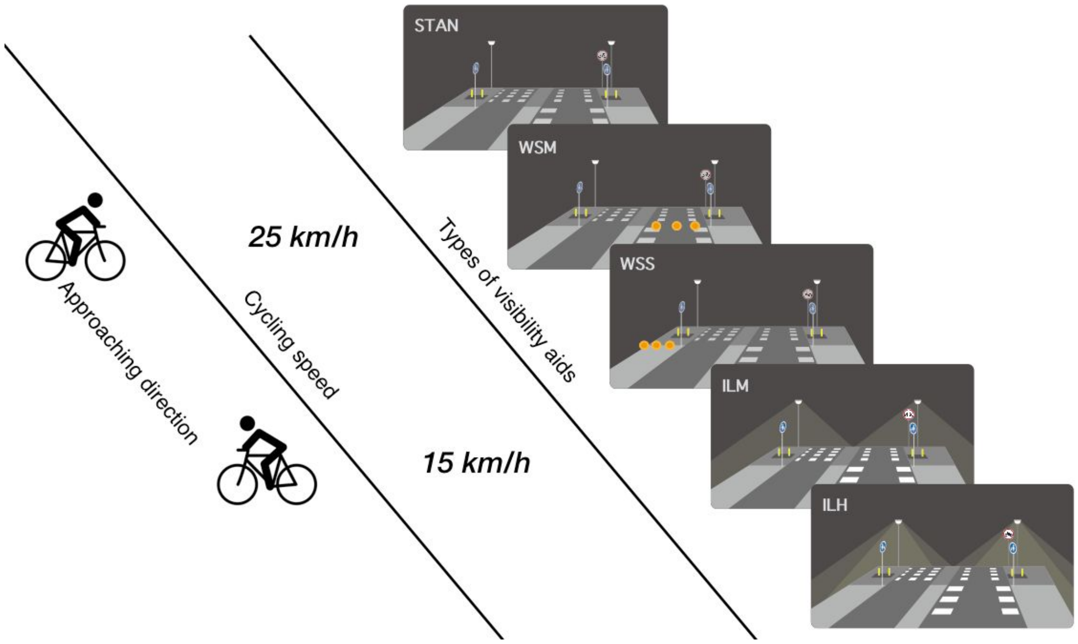

Figure 3.2. Sketch of the conditions of the road visibility aids (STAN: condition 0, the control condition, WSM: condition 1, the in-pavement flash lighters mounted on road middle, WSS: condition 2, the in-pavement flash lighters mounted on roadside, ILM: condition 3, increased vertical illuminance - middle level, ILH: condition 4, increased vertical illuminance- high level). The approaching cyclist with different cycling speeds could be perceived from left or right side of the intersection

The second independent variable was the *cycling speed*: 15 km/h and 25 km/h. The third independent variable was the *approaching direction of the cyclist*: left side and right side. The aim of this variable was to examine whether the effect of the visibility aids was equal for both sides.

The fourth independent variable was the *level of mental workload*: low, middle, and high. To manipulate the demanding of mental workload, and mimic the real driving experience, participants were asked to perform a steering task on a driving simulator. The steering task was a target tracking task (see Figure 3.3). The tracking task was the priority task, the difficulty was varied in three levels: easy, moderate, and difficult, which could be mapped to the three levels of mental workload demanding. A pilot experiment was conducted to examine the manipulation of the steering task (Appendix A).

Figure 3.3. A screenshot when tracking task was performing. Two targets were displayed on the screen (a square target and a plus tracker). The square target randomly moved to left, right, or stranded in place. The direction-change probability, and the moving speed of the target was varied between each difficulty level. The moving range of the square target was yield in the range of the main road. The plus tracker was controlled by participants via the steering wheel. Best tracking was overlaid the plus tracker inside of the square target

Each participant experienced all the three levels of tracking task respectively in three experimental sessions. The order of the difficulty level was randomly assigned. For each experimental session, forty stimuli (*5 conditions x 2 cycling speeds x 2 approaching directions x 2 replicates*) were presented randomly to participants. The participants' task was to detect the cyclist and press down the brake pedal as soon as possible while performing the tracking task.

Besides, sixteen (4 types x 4 replicates) false positives were randomly inserted in the stimuli, accounting for 28% of the total number of stimuli. The approaching cyclist was absent in the false positives. Respectively, the 4 types of false stimulus corresponding to the control condition (STAN), WSM and WSS at left side/ right side. For ILM and ILH, there was no corresponding false stimulus. The intention of adding false positives was to prevent participants overreacting to stimuli.

3.1.2 Dependent variables

For each stimulus, the time when the cyclist appeared on the screen (TCA) was known. The brake onset time (BOT) was chosen to calculate the brake RT. Here, *RT = BOT - TCA*. The pixel distance between the tracker and target was recorded (see Figure 3.3), as a measure of the tracking task performance.

To check the manipulation of mental workload, 20-point likert scale NASA task load index (Hart & Staveland, 1988) (Appendix E) was used after each experimental session. The task load index has 6 items: mental demand, physical demand, temporal demand, performance, effort and frustration. Furthermore, a short demographic questionnaire with 5 questions was used to investigate the gender, age range, eyesight and feelings about the experiment (Appendix F). A driving experience questionnaire (DEQ) with 10 questions was developed (Appendix G), based on a questionnaire about emergency vehicle operations (DQ, n.d.). The questionnaire was used to estimate the driving experience of the participants. In order to perform frame-by-frame analysis of the gaze positions, an eye-tracker was used during the experiment. Around one-third of the participants were randomly chosen to use an eye-tracker.

3.2. Position to appear of cyclists and driving secnarios

The distance from the main road at which the cyclists appeared was fixed. The position was designed according to the stop distance and time to collision (TTC) in the worst scenario: a car was driving on a straight way, and approaching the intersection at a constant speed of 50 (±3) km/h (highest speed limit). A cyclist wearing dark clothes, without using any visibility aids (e.g., bicycle light, reflective belt), was approaching the intersection with a constant cycling speed (see Figure 3.4). Assume the brake reaction time (RT) of the driver was 2 s, the car would stop just in front of the junction. The width of the cycle-path was around 6.5 m, if the driver reacted slower than 2.5 s, a collision might happen.

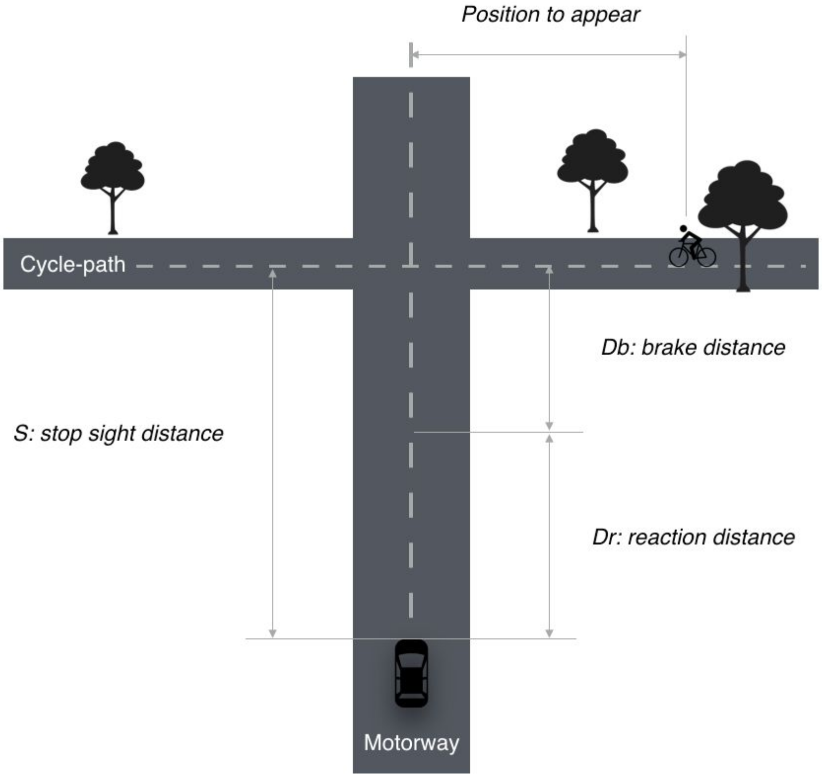

Figure 3.4. A sketch map of the driving scenario

In detail, the vehicle stop distance (SD) could be formed as:

$$SD=Dr + Db = RT*Vcar + Db \tag{1}$$

$$Db = Vcar^2/2ug \tag{2}$$

$$Vs^2 - Vcar^2 = 2 * a * Db \tag{3}$$

$$Vs=Vcar+a*BT \tag{4}$$

$$BT=2Db/Vcar \tag{5}$$

Where:

RT = 2 s: the reaction time of the driver
$Vcar = 50\ (\pm 3)$ km/h, the initial vehicle speed
Dr: the reaction distance
Db: the brake distance
u = 0.8, a normal value of the coefficient of friction between the tires and the road
Vs = 0 km/h, the vehicle speed at the stop point
BT: time interval between brake point and stop point

$$TTC = SD/V_{car} = RT + BT \tag{6}$$

Here, TTC was an assumption time, that after TTC (s) the car might collide with the cyclist if the driver did not operate a brake press or slow down. Particularly, for the cyclists with speed of 15 km/h and 25 km/h, the TTC was 3.4 s and 3.8 s respectively. Therefore, the cyclists should be seen at a distance around 14.2 m (15 km/h) and 26.2 m (25 km/h) from the junction, the higher speed cyclist should be seen 0.4 s earlier than the lower speed cyclist. The cyclists would be presented only when they arrived the criterion distance, in other words, the cyclists were kept out of vision before they reach the criterion distance.

Although the position to appear of the cyclist was fixed, the starting point of each stimulus and false positives were randomized (starting from 0s, 1s, 2s or 3s of the video clip), to prevent participants to have a feeling of the time to appear of the cyclist after presenting some times of stimuli.

3.3. Driving Simulation system

A low-fidelity driving simulator was used (Figure 3.5). Logitech G G29 Driving Force game steering wheel and pedals were used as the input devices. The steering wheel was installed on a 75 cm high, 80 cm wide and adjustable table. The table and pedals were placed on a 20 cm high platform. The platform was placed in front of a 75-inch screen. Participants sat in a chair with a distance of 1.1 m from the screen. The height of the chair could be adjusted. The image resolution of the screen was 1920 X 1080, with a 60Hz refresh rate. Participants could reach a horizontal view angle around 96 degrees. A experimental room around 4 m^2 was seated up with movable walls and opaque curtains. The ambient illumination of the walls were in mesopic level (below 1.5 cd/m^2) in the experimental room .

Figure 3.5. Photos of the driving simulator. The left figure shows the experimental setup, the right figure is a demonstration of the driving simulation. The target and tracker are marked with the yellow frame

A control system of the simulator was developed via MATLAB 2017a. The system was able to randomly play video sequences; randomly adapt the starting point of each video clip; superimpose target and tracker on video images; support the real-time subject-system interaction; and record input data from pedals and steering wheel (see Appendix B). The system recorded the data with a sample rate of 30 samples per second, synchronized with the driving video frame rate (30 FPS). Besides the simulator, a wearable monocular eye-tracker (Pupil Labs) was used to record the participant's gaze positions during the experiment.

3.4. Video materials

Twenty-four driving video clips (20 clips as stimuli and 4 clips as false positives) with the driver's perspective, in length of 11 s, were used. Instead of asking human cyclists to cross the cycle-crossing, post-production techniques via Adobe Creative Suite were used, since recording a night driving video with a real cyclist crossing with high speed would be particularly dangerous. The moving cyclists were added to the driving video clips via post-production (see Appendix C). Furthermore, the flash lighting of the IFL was also created via post-production.

The original driving video was recorded around 10 o'clock on the street of Lage Molenpolderweg, Oosterhout, the Netherlands. In the video, the driver was driving on a straight way, and approaching the intersection with a constant speed. Further information about the intersection can be found in Appendix D. The video was recorded by a GoPro camera with a wide view angle (118.2 degrees). The camera was mounted on the windscreen around the driver's eye height. Other vehicles and cyclists were wiped out from the original video.

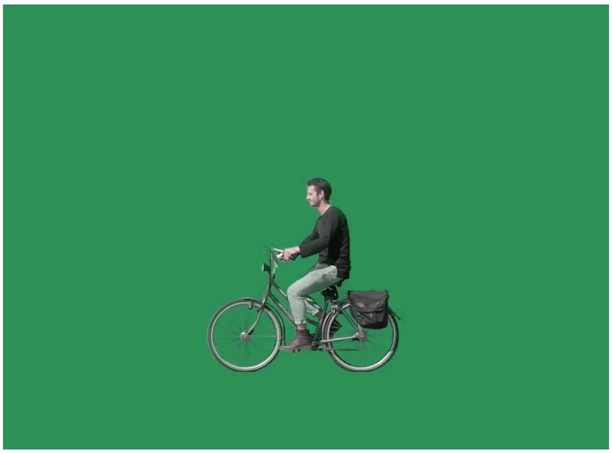

Figure 3.6. A screenshot of the cycling video

Besides, a cycling video with green screen was recorded separately at daytime (Figure 3.6). By motion tracking and composition techniques (see McElwain, 2017), the stimuli video clips were composed by the cycling video and original driving video. The speed, direction and the luminance of the cyclist could be manipulated via post-production software. The size, color, brightness of the cyclist were corrected to match the original video.

3.5. Participants

Twenty-eight adults (12 female and 16 male) between 24 and 44 years old participated in the experiment. All the participants had a driving license with a mean of 10.4 years (SD = 5.7 years). 17 participants reported themselves as experienced drivers, 7 as moderate experienced drivers, and 2 as novice drivers. The participants came from Philips Lightings and Eindhoven University of Technology, all participants volunteered to participate the experiment.

3.6. Procedure

All participants signed a written informed consent before the start of the experiment, then participants were introduced to the purpose of the experiment, including a detailed explanation of the procedure of the experiment.

After participants sat in the chair of the simulator, they were asked to put on the eye-tracker, then the eye-tracking system was calibrated. The participants were asked to press the brake pedal as soon as they detected a cyclist and then to release the pedal. Besides with the cyclist detection task, participants were introduced to steer the tracking marker (a plus marker on the screen) to track the target (a square marker on the screen), which would randomly move to left or right sides continuously. No lever gear was available, and no gas/clutch pedal interaction during the experiment. The participant was instructed to perform the tracking task as accurate as possible.

Each participant had 3-min to practice. In total 7-min were available for each participant to adapt to the dark environment before the start of the formal experiment. The experiment included 3 sessions, each session lasted around 7-min. Participants randomly experienced all the three levels of tracking task. After each session, the participants were asked to fill in the NASA task load index (Hart & Staveland, 1988) by hand. A table lamp was used to illuminate table when the participants filled in the questionnaires. Between each session, participants could take a short break if desired. The eye-tracker would be re-calibrated if participants took off the eye-tracker during the relaxing period. A written demographic questionnaire and DEQ were performed at the end. A box of chocolate was given as a gift to present the gratitude to each participant.

4. Results

Data from 28 adults were collected. Two participants' results were removed from the analysis. The incoming mobile phone call during one participant's experiment, resulted in unstable performance of the participant. Another one failed too many times in responding to the stimuli. All participants reported having normal or correct normal vision.

4.1. Subjective-evaluation on mental workload

An ANOVA with repeated measures was used to test the result of the NASA task load index (Hart & Staveland, 1988). The *subjective mental workload* was the dependent variable. It calculated based on the 6 items of the task load index. The *Cronbach's alpha* for the 6 items was 0.82. The *difficulty of the target tracking task* was the independent variable. The result of *Shapiro-Wilk* test indicated that the normality assumption was fulfilled for each level of mental workload (*p= .095, p= .728, p= .668, respectively*). No Z-score was larger than 3 or smaller than -3.

The difficulty of the target tracking task had a significant influence on the subjective mental workload ($F(2,26)=11.21,\ p < .001,\ \eta_p^2=0.310$) (see Figure 4.1). Specifically, the mental workload increased with increasing task difficulty. The difference between the easy and moderate task, easy and difficult task were both significant (*MD= -1.705, P= .003; MD=-2.096, p< .001, respectively*), whereas, the difference between moderate and difficult tracking task was not significant (*MD=-0.391, p= .386*). On average, participants did not feel a significant increase in mental demand for the difficult compared to the moderate tracking task.

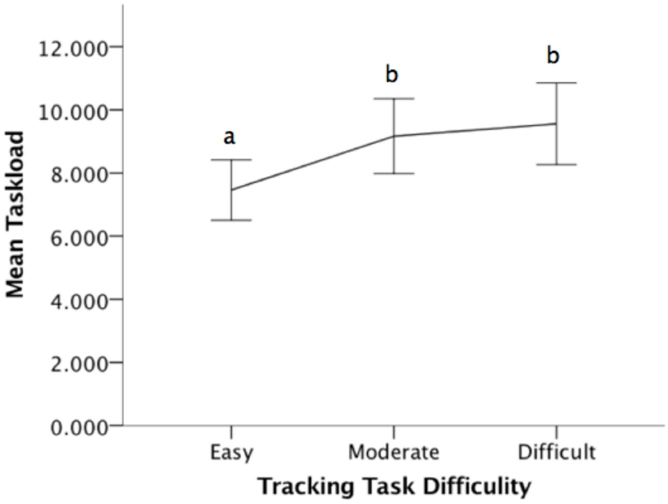

Figure 4.1. Means of the task load index. Easy/ moderate / difficulty represents the levels of the tracking task difficulty

Besides, an ANOVA with repeated measures was also used to test whether there was an order effect. The *order of the session* was used as the independent variable, and the *subjective mental workload* was used as the dependent variable. The order of the tasks did not influence the mental workload ($F(2,26)=0.015, p= .985$).

4.2. Tracking performance

The tracking performance was calculated as the average distance in pixels between the two targets, during the period of one video clip. In particular, a larger distance implied a worse performance. In total 4368 data points were collected (56 video clips x 3 sessions x 26 participants). Z-scores were calculated, and no outlier was found. The independent variable was tracking task difficulty. A generalized linear model (GLM) was used, the dependent variable was the *tracking performance*. To improve the model fit, the *tracking performance* was log transformed. Deviance is a measure of the goodness of the model fit, generally, a higher number indicates a worse fit (David, n.d.). The deviance of the model decreased from 133.584 to 0.120 after the transformation.

The result indicated that the average distance was significantly influenced by the difficulty level of the tracking task ($X^2(2, N=4368)= 2536.733, p< .001, \eta_p^2=0.367$). Pairwise comparisons showed that the performance of easy task was significantly better than the moderate and difficult task (*MD=-11.910 pixels, p<.001; MD= -11.323 pixels, p< .001, respectively)*. The performance of the moderate task and difficult task was also significant different from each other (*MD=0.587 pixels, p= .018*). Figure 4.2 shows the mean value of the logarithmic average distance between the two targets by levels of task difficulty.

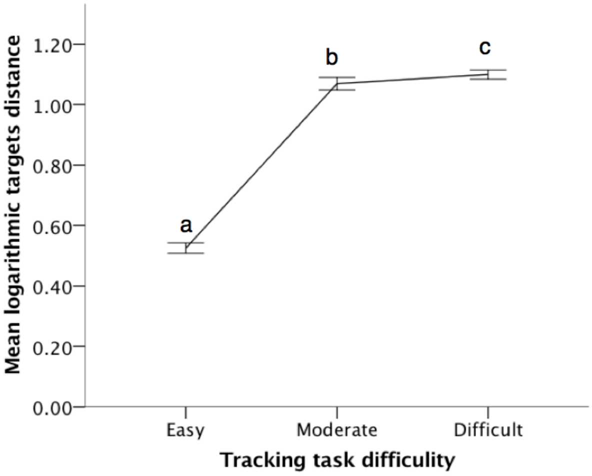

Figure 4.2. Means of the logarithmic distance in pixel between two targets on screen. Easy/ moderate / difficulty represents the levels of the tracking task difficulty

Besides, a GLM analysis was performed which used the *order of the session* as the independent variable. The results showed that the order of the tasks did not influence the tracking performance ($X^2(2, N=4368)= 1.630, p= .443$).

4.3. Response time

In total, 4368 (56 stimulus x 3 sessions x 26 participants) responses were collected, and 3097 data points were used for regression analysis. False alarms (the responses of the false positives) and early responses were excluded. The early response was defined as: the responses before the presence of the stimulus, and the responses faster than 0.2 s. RTs below 0.2 s were excluded because of the high possibility that the responses occurred before the stimulus was perceivable. There was a baseline for the system to establish a brake onset, generally, the time needed for the brake onset was around 0.15 s. For a more robust estimation, the criterion was set to 0.2 s. Therefore, the RT below 0.2 s has a high chance to be an early response.

Furthermore, the late responses were excluded, declared as: the RT above 3.4 s for stimulus with 15 km/h cycling speed, and the RT above 3.8 s for stimulus with 25 km/h cycling speed. This upper bound was set up based on the TTC, as explained in the previous section. The proper responses to stimulus were declared as correct responses. Table 4.1 displays the numbers of each type of responses in detail. The correct responses of RT had a mean of 0.95 s (*SD=0.33 s*, *Median =0.85 s*), and 75% of the RTs were below 1.03 s. Figure 4.3 displays the frequency distribution of RT.

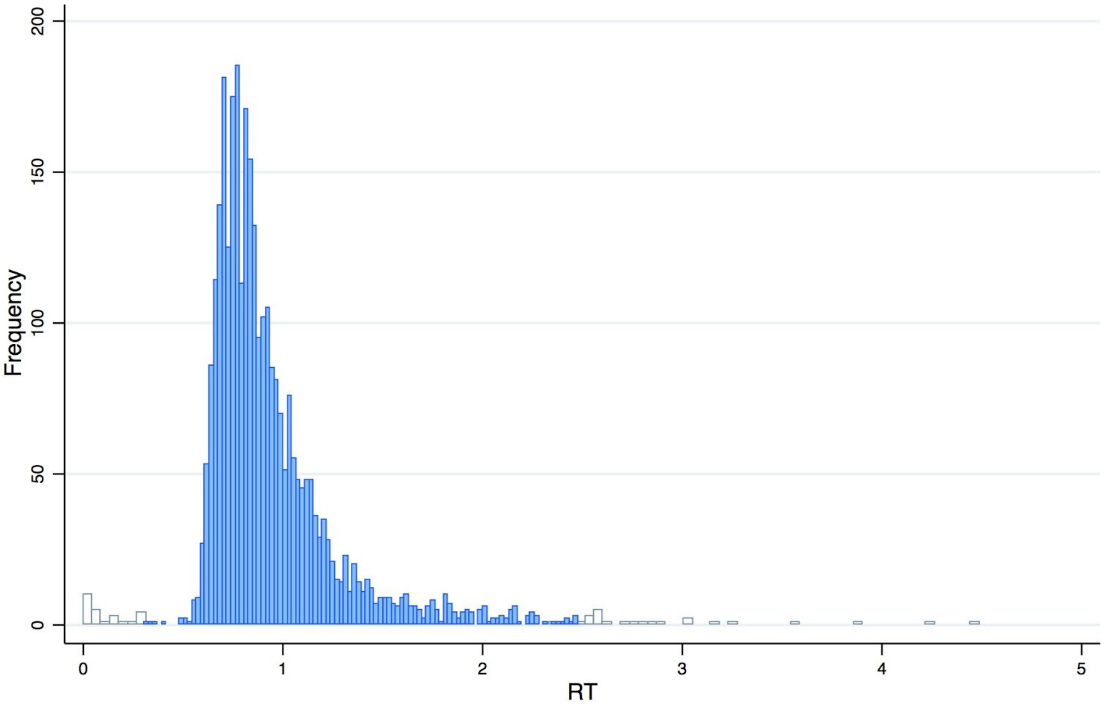

Figure 4.3. A frequency histogram of RT, includes the correct responses (blue bars in middle), early responses (white bars in left tail) and late responses (white bars in right tail)

The histogram revealed that RT was not normally distributed. Extreme values appeared on both sides of the tails. Therefore, the reciprocal of RT was used as the dependent variable in the follow-up analyses. In general, using the reciprocal of such data fits better to a linear model (Wiedermann, 2016).

Table 4.1

The number of responses by types

Conditions of visibility aid	Early response	Correct response	Late response	Failed response
STAN	5	618	1	
WSM	3	621		
WSS	5	619		
ILM	4	619		1
ILH	2	620	1	1
Total	**19**	**3097**	**2**	**2**

Conditions of false positive	False alarms	Correct rejects
STAN	5	307
WSM	7	305
WSS-L	18	294
WSS-R	9	303
Total	**39**	**1209**

4.3.1. Analysis

A GLM was used to estimate the effects of the independent variables. Table 4.2 shows the factor effects on brake 1/RT. The dependent variable was the reciprocal of the RT. The deviance reduced from 0.090 to 0.076 after transformed the RT to 1/RT. The independent within-subjects variables, including: *cycling speed* (coded as Cycle-speed), the *cyclist approaching direction* (coded as Cycle-direction), *level of mental workload* (coded as Workload), and the *condition of the visibility aid* (coded as Condition) were tested. Two-way, three-way and four-way interaction terms of the between-subjects factors were added.

Besides, the *order of the sessions* (coded as Session-order) and *order of the replications* (coded as Rep-order) were added to test the order effects of the experimental sessions and stimulus replications on brake RT. Gender was included as a between-subjects factor, interaction terms between gender and other within factors were also added. Moreover, the *target tracking performance* (coded as TrackP), and *driving experience* (coded as Experience) were included as covariants. Tests to see if the data met the assumption of collinearity indicated that multicollinearity was not a concern (*TrackP, Tolerance=0.994, VIF =1.006; Experience, Tolerance=0.994, VIF=1.006*). For driving experience, the result from 5 questions of the DEQ was used:

question 1: number of years holding a driving license;
question 4: driving times per week/month;
question 5: driving times during rush hours per week/month;
question 6: driving hours per day;
question 7: self-report experience;

The standardized Cronbach's alpha of the 5 items was 0.84, those 5 items were reliable estimators of driving experience.

Table 4.2

Factors' effects on the reciprocal of brake RT of drivers

Effect	The reciprocal of brake RT			
	Df	Wald Chi-Square	P	η_p^2
TrackP**	1	55.651	.000	.018
Cycle-speed**	1	20.962	.000	.007
Cycle-direction**	1	3.967	.046	.001
Condition**	4	167.289	.000	.051
Workload**	2	11.458	.003	.004
Cycle-direction*Cycle-speed**	1	35.312	.000	.011
Cycle-speed*Condition**	4	22.500	.000	.007
Cycle-direction*Cycle-speed*Condition**	4	17.936	.001	.006
Cycle-speed*Gender**	1	4.919	.027	.002
Experience**	1	18.585	.000	.006
Gender**	1	437.255	.000	.124
Session-order**	2	53.992	.000	.017
Rep-order**	1	6.087	.014	.002

**. The mean difference is significant at 0.05 level

4.3.2. Main effects

Tracking performance

The tracking performance had a significant correlation with the brake RT. With the increasing of the average distance between the two targets, the average brake RT also increased. In other words, the cyclist detection performance decreased with decreasing target tracking performance.

Condition of visibiliy aid

The effect of visibility aid was highly significant. Compared to the control condition (STAN), the mean brake RT decreased by 0.03 s in the condition of WSM ($p= .018$), 0.10 s in ILM ($p< .001$), and 0.07 s in ILH ($p< .001$). Particularly, the decrement in mean RT in ILM and IMH, were significantly larger than WSM ($p< .001$). The mean difference in RT between ILM and ILH, was not significant ($p= .420$). Note that, in WSS, the mean RT significantly increased by 0.07 s compared to the control condition ($p< .001$). In conclusion, when contrasted to the STAN, WSM, ILM and ILH both significantly reduced the average brake RT of drivers, whereas the WSS increased the brake RT (see Figure 4.6).

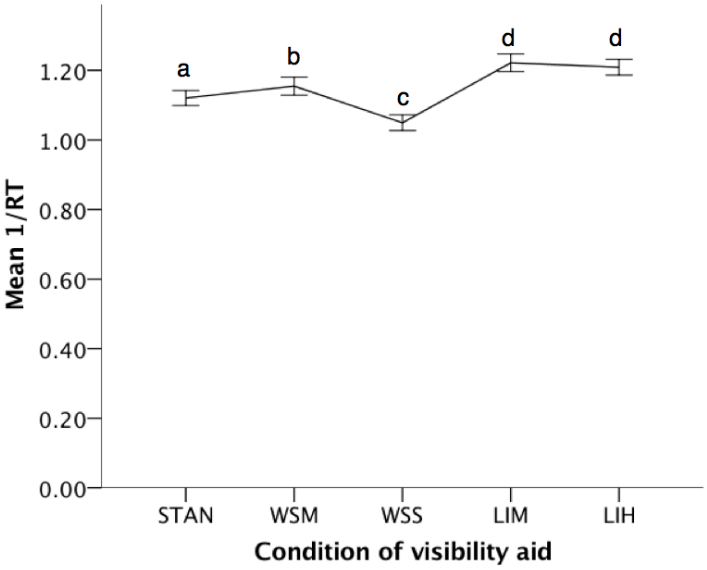

Figure 4.6. The means of brake 1/RT by types of road visibility aid: STAN, the control condition; WSM, active warning lighters mounted on road middle; WSS, active warning lighters mounted on roadside; ILM, street light - middle illuminance; ILH, street light - high illuminance

Cycling speed

For the condition of higher cycling-speed, the average brake RT increased by 0.05 s, compared to the lower speed condition ($p< .001$) (see Figure 4.5). In general, participants reacted slower for the higher speed cyclists than the lower speed cyclists.

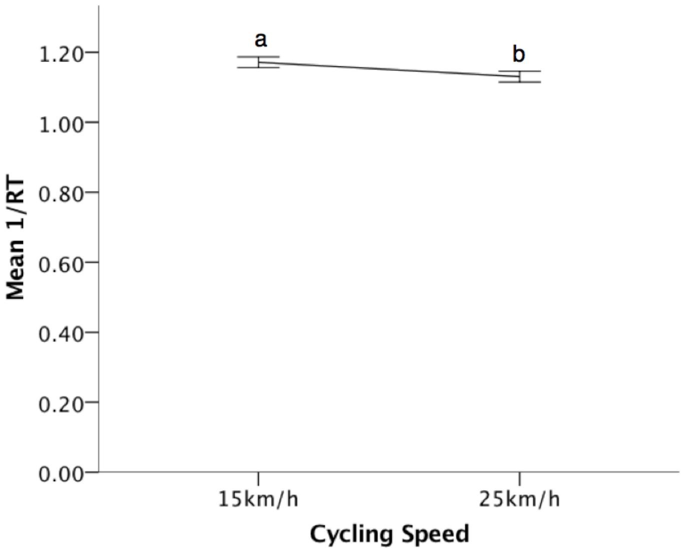

Figure 4.5. The means of 1/RT by cycling speed (right) and approaching direction (left)

Approaching direction

The a*pproaching direction* of the cyclist demonstrated a significant effect on the brake RT *(Figure 4.4).* The average brake RT of participants was shorter for the cyclists approaching from the right side than the left side.

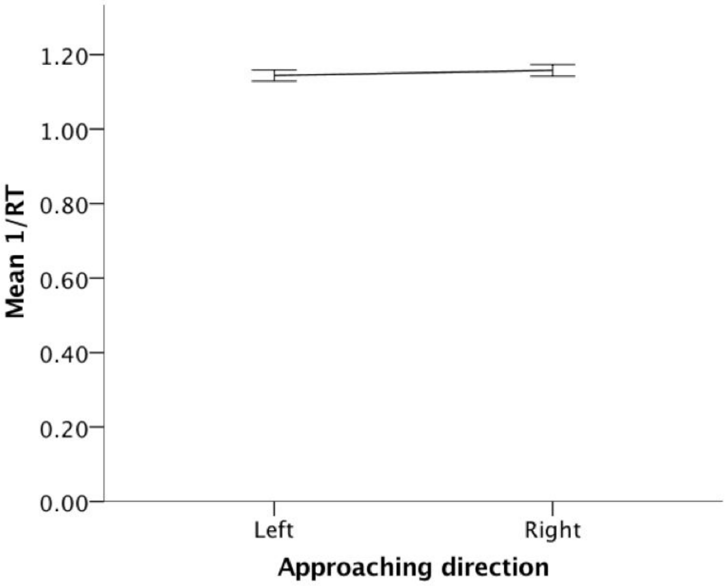

Figure 4.4. A plot of mean difference on 1/RT by approaching direction

Mental workload

Mental workload had a significant effect on brake RT. The mean difference in brake RT between the middle and high level of mental workload, was not statistically significant (*p= .387*). Significant differences were found in brake RT between the low and middle (*p= .014*), low and high (*p*= *.001*) level of mental workload, the average brake RT reduced by 0.03 s, when compared the high level, to the low and middle level (see Figure 4.7).

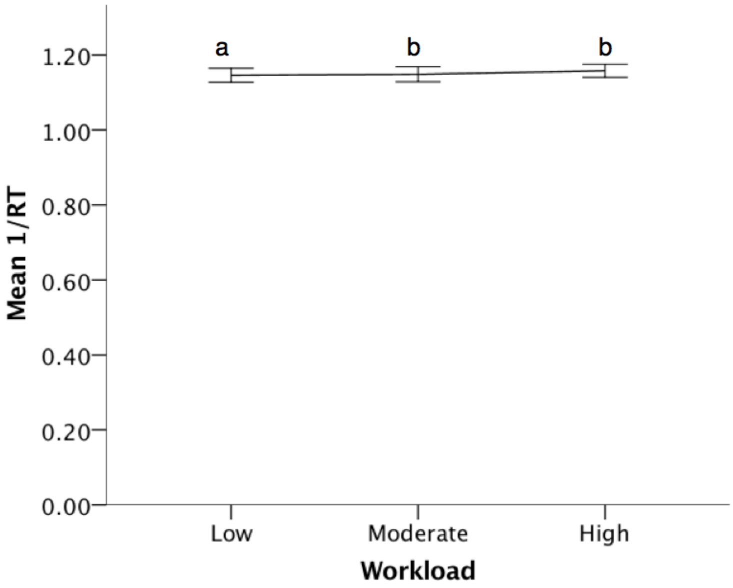

Figure 4.7. Means of 1/RT by levels of mental workload

4.3.3. Interaction effects

Only the significant interaction effects will be reported below.

Approaching direction * Cycling-speed

Pairwise comparisons indicated that for the left side approaching, the mean difference of brake RT between the two speed conditions was not significant at *0.05* level (*p*= *.067*), while for the right side approaching, the speed demonstrated a significant effect (*p*< *.001*). Comparing the two speed levels, for the lower cycling speed, the mean brake RT of left side approaching cyclist significantly longer than the right side approaching (*p*< *.001*), whereas, for the higher cycling speed, the effect of direction shown an opposite trend (*p*= *.005*) (Figure 4.8).

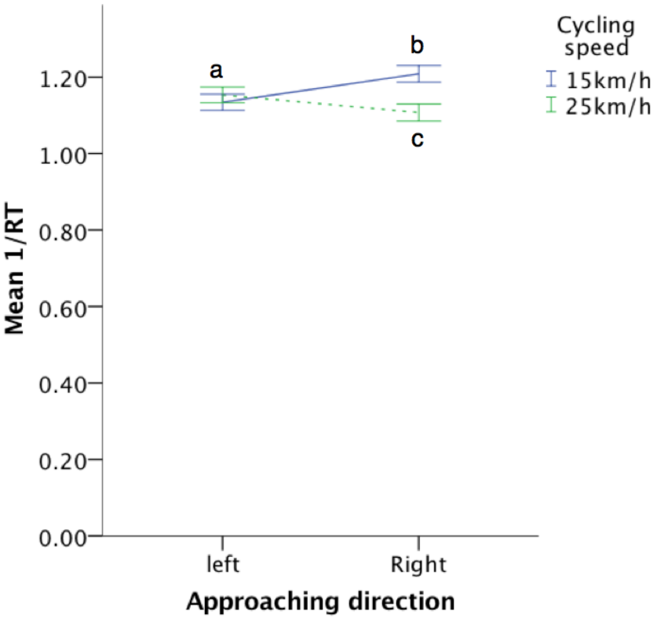

Figure 4.8. A plot of interaction effect between approaching direction and cycling speed

Conditions of visibility aid * Cycling-speed

As shown in Figure 4.9, there was a significant interaction between *cycling speed* and *condition of visibility aid*. For all conditions the brake RT significantly decreased for low speeds except for WSS.

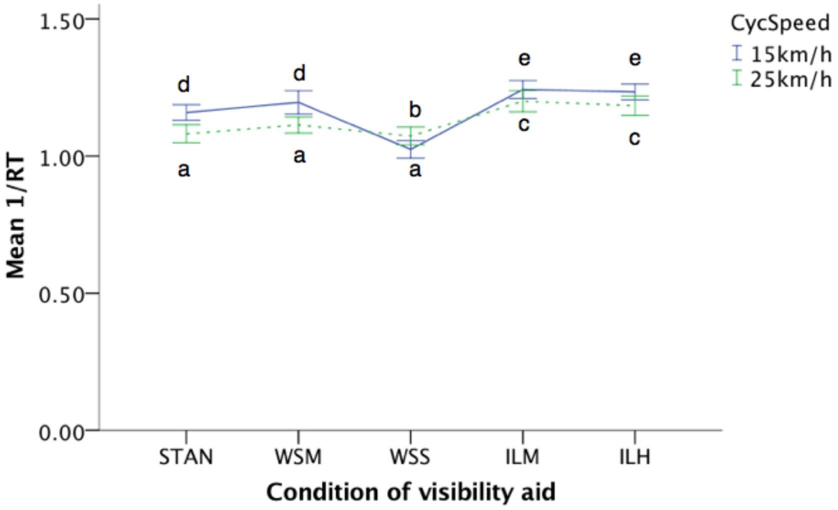

Figure 4.9. A plot of interaction effect between cycling speed and conditions of visibility aid

Conditions of visibility aid * Cycling-speed * Approaching direction

The interaction between *cycling speed* and *condition of visibility aid* was different across approaching direction (Figure 4.10). Particularly, in condition of WSS, for lower speed cyclists which approaching from the left, drivers' average brake RT was significantly higher compared to all other conditions.

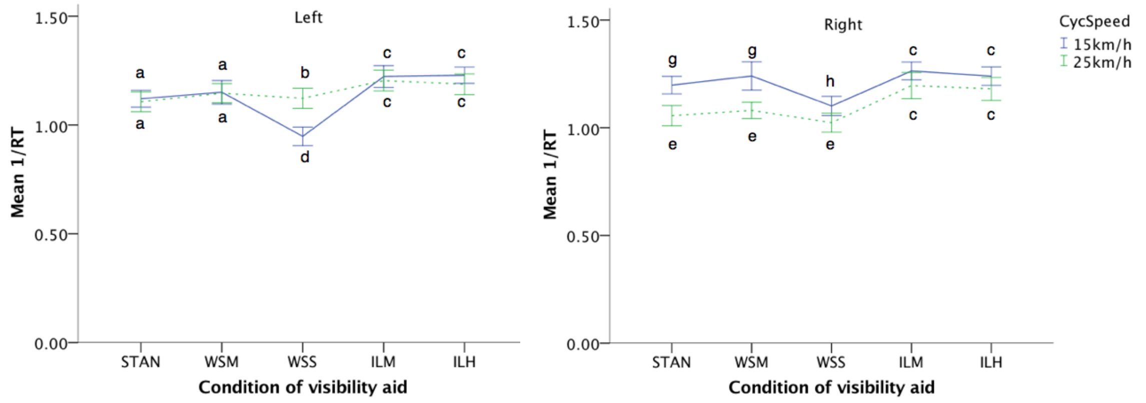

Figure 4.10. A plot of three-way interaction effect between approaching direction, cycling speed and conditions of visibility aids

4.3.4. Effects of gender and driving experience

A significant difference in brae RT between gender was found, as shown in Figure 4.11. The mean RT of the male participants was 0.23 s smaller than the RT of female participants.

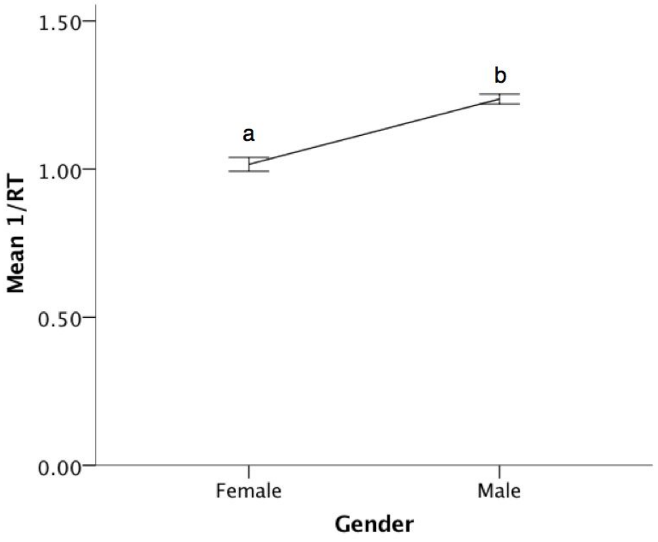

Figure 4.11. Mean brake 1/RT of the female and male participants

A significant interaction between *gender* and *cycling speed* was found. In specific, for the female participants, the average RT was significantly smaller for the low speed compared to the high speed (Figure 4.12), with a mean difference of 0.23 s (*p*< *.001*). However, for male participants, the two levels of cyclist speed did not differ in the average brake RT (*p*= *.069*).

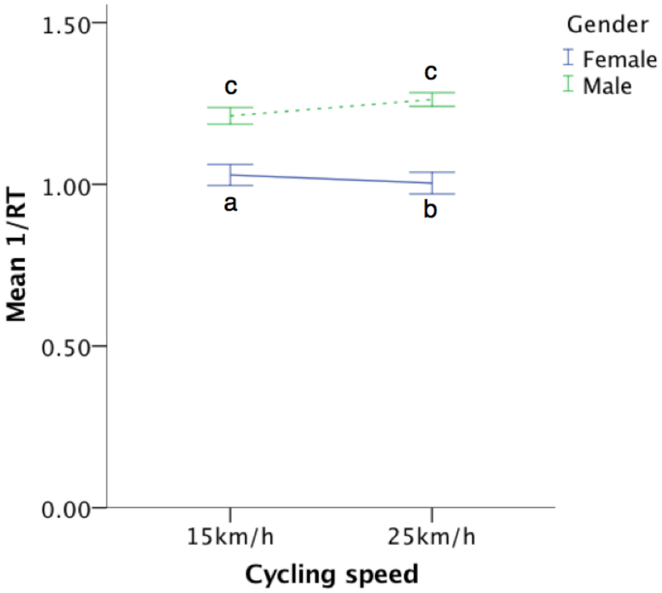

Figure 4.12. A plot of interaction effect between speed of hazard and gender

Besides, the driving experience of participants negatively correlated with the mean brake RT, the correlation was statistically significant. Thus, as the driving experience increased, the average brake RT decreased.

4.3.5. Order effects

The order of the three sessions had a significant influence on brake RT. *Post hoc* analysis showed that the average RT of the first session was longer than the second session (*p< .001*). The difference in brake RT between the third session and the second session did not statistically significant (*p= .079*) (see Figure 4.13).

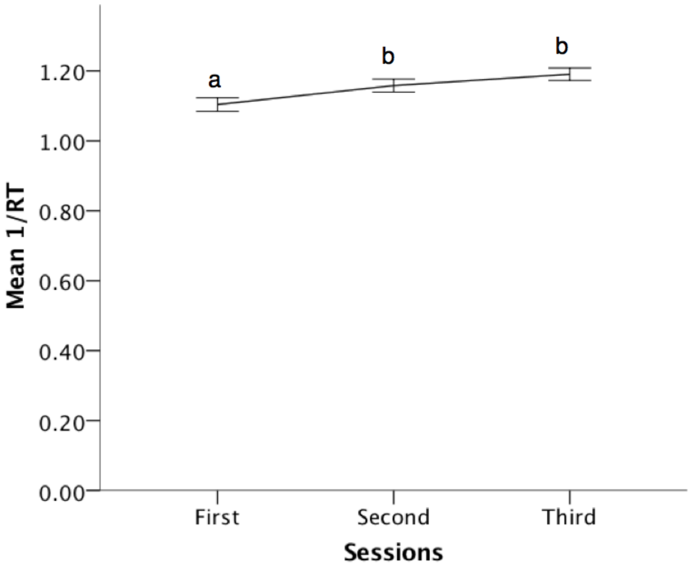

Figure 4.13. The mean 1/RT of the three experimental sessions

The order of the two replications also showed a significant influence on brake RT. Each stimulus was replicated for two times, the average brake RT decreased subtly for the secondly presented stimulus (see Figure 4.14).

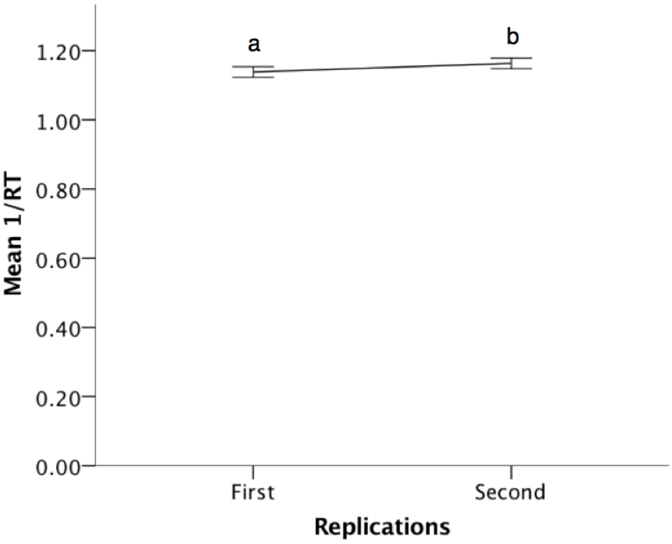

Figure 4.14. The mean 1/RT of the two replications

4.4. Discriminability

Based on Signal Detection Theory (SDT) (Macmillan & Creelman, 2004), the response can be declared as a correct response if the hazard was correctly detected, and declared as a false response if the hazard was missed on detection. Besides, the response of false positives (hazard absent) can be declared as false alarms, and correctly reject if no response was performed. However, in the current study, the correct responses and false alarms were not able to be firmly distinguished, due to they were overlapping distributed. Underwood et al. (2013) have argued that the false alarm rate is distinct only when the number of false alarms is known for each stimulus. For a driving hazard perception test, there are always degrees of dangerous presenting, therefore false alarms may occur at any period. With regards to the current study, though only one response exists for each stimulus, it is difficult to assign the response to either a correct response or a false alarm. For example, participants might press the brake pedal just at the moment when the cyclist was visible in a stimulus video clip. Indeed, the brake onset might occur after the presentation of the cyclist, whereas such response had a high probability to be an early response (a kind of false alarms) in the situation. Especially, the road signs in the video might offer extra cues about the time to perform the brake, participants were possible to brake just on time without really seeing the cyclist.

Therefore, as Underwood et al. (2013) proposed, the measures provided by SDT (Macmillan & Creelman, 2004) were not applicable for the current study. Instead, the method provided by Underwood et al. (2013) was adopted. Specifically, the discriminability of participants was represented by the ratio of correct responses relative to the number of false alarms and early responses. In the experimental scenarios, if the RT of a driver was larger than 2.5 s, a collision might happen with a high probability. Therefore, RTs above 2.5 s were excluded from the correct responses. Therefore, different from the correct responses in previous sections (see section 4.3), the correct responses were re-defined as the RT between 0.2 and 2.5 s. Here, the discriminability (sensitivity) is formed as:

$$\frac{Correct\ Responses - (False\ Alarms + Early\ responses)}{Correct\ Responses + (False\ Alarms + Early\ responses)} = D \qquad (7)$$

For a participant with a high sensitivity, D would be close to +1. If the majority of responses were false alarms, D would be close to -1. The sensitivity of each participant was calculated for each level of mental workload. Explicitly, the lowest sensitivity was 0.76, and the highest sensitivity reached +1. Furthermore, a GLM was performed which used D as a dependent variable, *level of mental workload* as an independent variable. The result indicated that the sensitivity was significantly different between the levels of mental workload ($X^2(2, N=4368)=$ 70.211, $p< .001$, $\eta_p^2=0.012$). For the high level, the discriminability was significantly higher than both the middle and low level ($p< .001$). For the low and middle level, there was no significant difference in discriminability ($p= .240$). However, as can be seen from Figure 4.15, the differences were subtle.

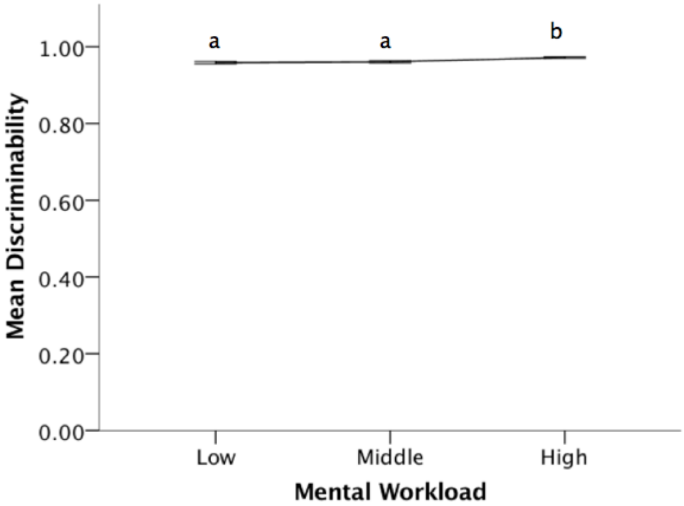

Figure 4.15. A plot of discriminability for three levels of workload

To test the sensitivity across hazard conditions was less meaningful at the current circumstance. First, the number of false positives was not equal for each condition of the visibility aids. For example, for the ILM and ILH, there were no corresponding false positives, whereas for the WSS, there were two types of false positives (false signals on the left or right roadside). Thus, WSS had a higher chance to get false alarms, ILM and ILH had a much lower chance. Second, for hazard speed and direction, though the number of false positives was equal for each condition, consider the relatively low false alarm rate in our data, the result would be less reliable.

4.5. Result of eye-tracking recordings

In total eleven participants' gaze positions during the experiment were recorded, and participants' data were used for the analysis. Because of a technical failure, one participant result was removed. The data were processed before being analyzed. The eye-tracking video had a framerate of 30FPS. For each frame, there were three two-dimension coordinates of the gaze position were recorded. Each coordinate had a confidence level which was indicating the reliability of the value. For each frame, only one coordinate among the three with the highest confidence level was used. Besides, the coordinates with a confidence level lower than 0.8 were removed.

4.5.1. Overview of the gaze-shifting

In the current study, we were most interested in the horizontal shifting of the gaze-position. Figure 4.16 displays an example frequency histogram of the x-axis values of the gaze position (i.e. in horizontal direction) of one experimental session of a participant. All histograms can be found in Appendix H. Most of the time, participants were gazing at the front area of the driving road (the x-axis value was around 0.5, generally). Due to the re-calibration of the eye-tracker for each participant, the coordinate systems might have little difference in the original location between the participants.

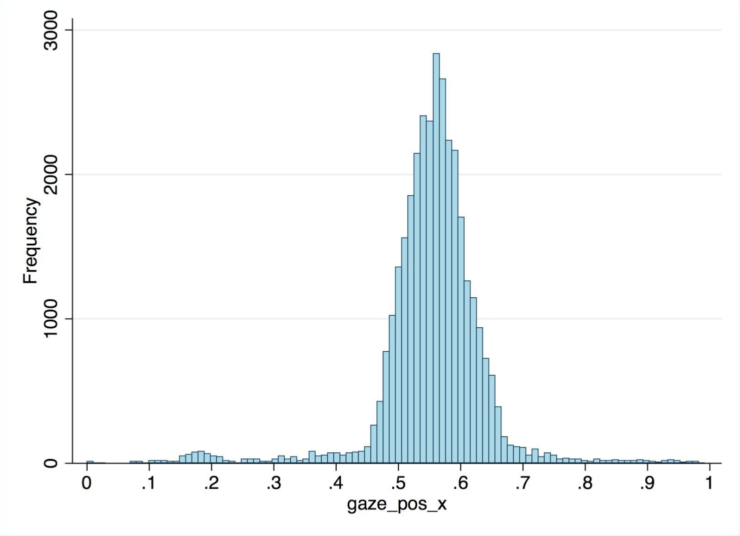

Figure 4.16. An example frequency histogram of the x-axis values of gaze position of one experimental session of a participant

Figure 4.17 displays an example scatter plot of the x-axis values of the gaze-position by frame index of one experimental session of a participant. All plots can be found in Appendix G. As can be seen from the plots, some participants frequently swept over both sides of the road, whereas other participants only occasionally looked at the roadside. The frame-by-frame analysis showed that when getting close to the cycle-crossing, the frequency of roadside inspections was increased. Because the coordinate systems of the eye-tracker were slightly different for each participant, and the head position of participants might change during the experiment, the inspection frequency of the left and right side of the cycle-crossing was hardly possible to distinguish in the current data set.

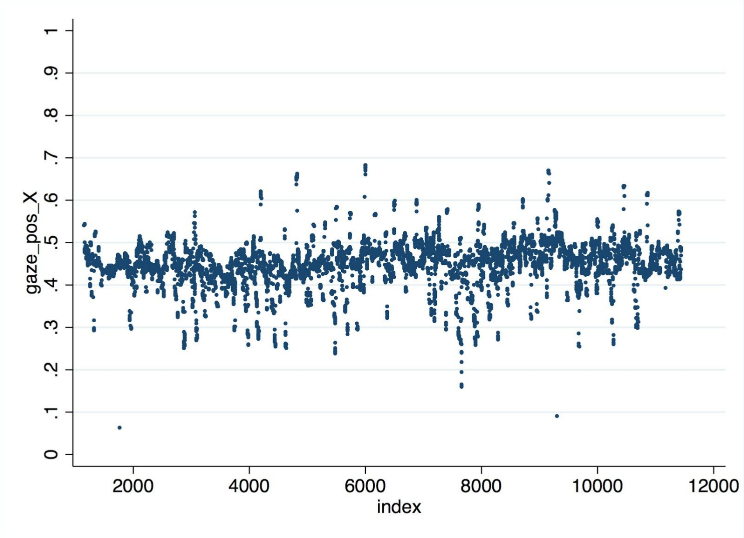

Figure 4.17. An example scatter plot of x-axis values of gaze-position by frame index of one experimental session of a participant

Gaze-shifting and brake RT

The brake RT was found to be significantly related to the frequency of the inspections to the relatively distant positions of the roadside. The inspection range (IR) represented the level of frequency that participants inspected to farther positions away from the road middle. The IR was larger if the participants inspected to the farther positions more frequently. The IR of 10 participants' eye-tracking data were calculated, more details about the calculation can be found from the Appendix H. A *Spearman's rank-order correlation* was run to determine the relationship between IR and brake RT. There was a moderate, positive correlation between IR and brake RT, which was statistically significant ($r_s(1190)=0.630,\ p< .001$). Thus, for a participant with larger IR, the brake RT was also longer. No statistically significant relationship was found between IR and gender, or IR and driving experience.

4.5.2. The cyclists perception time

The cyclist perception time (PT) is defined as the time between the moment the the cyclist emerged on the screen and the moment the participants firstly glanced at the approaching cyclist. The PT could be represented by the number of frames between the two time points in the eye-tracking videos. In order to calculate the number of frames, 30 (10 participants x 3 sessions) eye-tracking videos were checked frame-by-frame. In total 590 observations of PT were identified (*M=0.75 s, SD=0.41 s*). As indicated in previous studies (e.g. Posner et al., 1980; Yantis & Jonides, 1984) participants could have detected the cyclist by using peripheral vision sometimes, and did not necessarily have to shift their gaze at the cyclists. In this situation, the PT could not be identified.

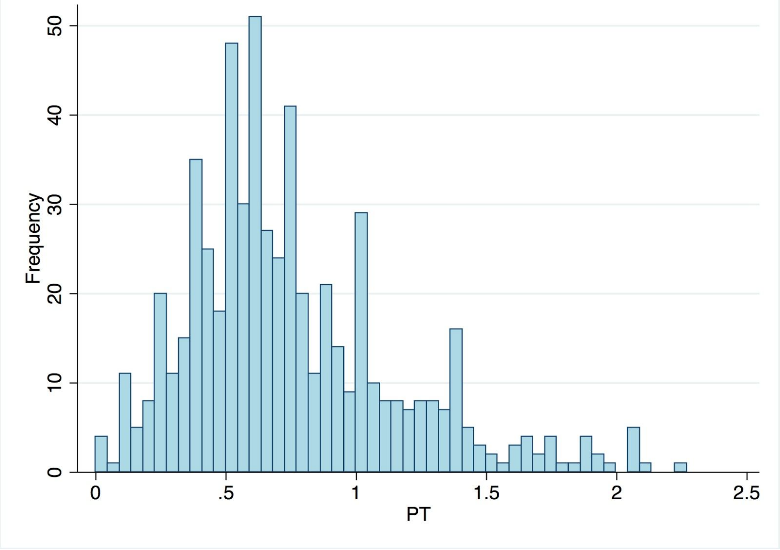

Figure 4.18. A frequency histogram of the PT

Figure 4.18 displays a frequency histogram of those identified PT observations. A *spearman's rank-order correlation* analysis showed that the PT had a moderate, positive correlation with the participants' mean brake RT, which was statistically significant ($r_s(598) = 0.391, p < .001$). Furthermore, GLM was used to examine the effects of the independent variables, including the *level of mental workload*, *cycling speed*, *approaching direction*, *condition of visibility aid*, *gender* and *driving experience.* The reciprocal of the PT was used as the dependent variable. The *target tracking performance* was included as a covariant.

Table 4.3

Factors' effects on the reciprocal of PT of drivers

Effect	The reciprocal of PT			
	Df	Wald Chi-Square	P	η_p^2
Cycle-speed**	1	10.368	.001	.023
Experience**	1	16.597	.000	.027
Gender**	1	19.640	.000	.035
Workload	2	.651	.722	.000
Cycle-direction	1	.730	.393	.001
Condition	4	5.558	.235	.012
TrackP	1	2.545	.111	.004

**. The mean difference is significant at 0.05 level

As shown in table 4.3, the *cycling speed* significantly influenced the average PT. Participants noticed the cyclists with a higher speed later than the cyclists with lower speed. Besides, there was a significant difference in mean PT between the male participants and female participants. Male participants noticed the cyclists earlier than the female participants. Moreover, driving experience negatively correlated with PT, the correlation was statistically significant. When the driving experience increased, the average PT decreased. In other words, experienced drivers generally perceived the cyclists earlier. No other significant effect or correlation was found.

5. Discussion

The present study focused on examining the relative effects of two different types of cycle-crossing visibility aids (the street lights and IFL systems) on driver's brake RT, for various hazard conditions. The hazards in the present study were cyclists with various speeds and moving directions. Simulation-based experiments were performed. The participants' mental workload was manipulated via simulated steering task. The following parts will discuss the findings in detail.

5.1. efficiency of cycle-crossing visibility aids

5.1.1. Increased vertical illuminance

The increased vertical illuminance (ILM and ILH) of the cycle-crossing significantly reduced the driver's brake RT, the hypothesis **[H0a]** was supported, and it was found to be the most effective way to reduce the RT. In mesopic vision, the luminance contrast is the main determinant whether a hazard can be detected by other road users (Sprague et al., 2014). With regards to the current study, the increase in vertical illuminance directly led to an increase in the luminance contrast between the cyclist and its background. Therefore, drivers could perceive the cyclists earlier when the vertical illuminance was increased. The luminance of the cyclists were increased by two different levels in this study, no significant difference was found between these two levels. In order to get a better understanding of the relationship between the increased vertical illuminance and driver's brake RT, more luminance levels could be tested in the future.

5.1.2. IFL systems

The hypothesis **[H0b]** was supported. For the IFL mounted in the road middle, driver's brake RT was significantly reduced compared to the standard-painted road markings (STAN), whereas the effect was smaller than the ILM and ILH. In terms of visual guiding, the efficiency of IFL in the road middle was limited in poor lighting conditions (cf. Hakkert et al., 2002; Prevedouros, 2001). In field tests, drivers can react to the flash lighting (e.g., yielded the right-of-way) even if they failed in detecting the cyclist or pedestrian. The benefits of IFL systems were smaller in our study, since around 28% false positives were added, to prevent drivers from overreacting (react to the flash signals without perceiving any hazard). But in the real world implementation, as Hakker et al. (2002) suggested, the false alarm and miss detection rate of AWS should be restricted to an acceptable level.

Moreover, the hypothesis **[H1]** was not supported by the result. Placing the IFL system at roadside did not get the anticipated results, contrarily, drivers' brake RT increased across all hazard conditions. Particularly, for the left side of the cycle-crossing and low speed cyclists, the brake RT had a notable increase (see Figure 4.9). Though previous studies (e.g., Ho &

Spence, 2009; Posner et al.,1980) have suggested that providing direction and position information can further improve the visual guiding performance of a warning system, it is not necessarily so in the current study. On the left roadside, the cyclists with lower speed presented closer to the road middle area. The background was more complex in that area. As a result, the cyclists became less conspicuous. Thus, when the conspicuity of the hazard is low, proving direction or position information by the peripheral visual signal may introduce more distraction.

Controversially, participants demonstrated different attitudes towards the IFL system mounted on roadsides. Someone indicated such alert systems could help them notice the cyclists coming from the roadsides, whereas some participants commented that the signal at the roadside distracted them. It would be interesting to further investigate the correlation between drivers' acceptance and the effect of the IFL systems. Future studies could also explore the effects of combining both of the IFL systems and the increased vertical illuminance, especially for the intersections having frequent accidents. Combining different types of road facilities may further improve the road safety (Campbell et al., 2012).

5.2. Influence of cycling-speed

The result supported the hypothesis **[H2]**, that drivers reacted faster for the lower speed cyclists than the higher speed cyclists. Particularly, the cycling speed demonstrated an effect only when the cyclists were approaching from the right side of the cycle-crossing. One must notice that, the higher speed cyclists appeared earlier 0.4 s than the lower speed cyclists in the scenarios, and the driver-cyclist distance was larger for the higher speed cyclists at the beginning of the presence. The cyclists with lower speed might be perceived as more abrupt hazards than the higher speed cyclists. Because the cyclists with lower speed presented on the screen with a shorter time, and they presented more close to the cycle-crossing, which might be perceived more dangerous and abrupt compared to the higher speed cyclists. Generally, drivers react faster for abrupt onset hazards than gradual onset hazards (see Olson & Sivak, 1986; Underwood et al., 2013). Moreover, Jurecki and Stańczyk (2014) have indicated that the distance between the vehicle and hazard have a positive correlation with the RT, for distant objects, drivers react slower. Thus, one may conclude that the difference in RT between the two speed levels might not completely be caused by the difference in speed. Further testing is needed to explain whether such a difference was caused by either the driver-cyclist distance or the cycling speed. Future test could vary both the speed and position to appear of the cyclist. For example, to alternate the cyclists between visible and invisible when they are approaching the cycle-crossing. Other road users (e.g. pedestrians, motorcyclist) could be added as different types of hazard with different speeds.

Besides the hazard, there was a second stimulus (the warning signal) in the test videos. If the cyclist was not blocked out from the driver's vision before the presence of the second stimuli (e.g. the cyclist emerged from the edge of the screen), participants might perceive the cyclist much earlier than the presence of the warning signal. This may lead to a large variation in the brake RT. If the cyclist is still far away, the situation will not be perceived urgent enough, participants may be hesitated to press the brake pedal (Summala, 2000). Similar to the research conducted by Jurecki and Stańczyk (2014), the current study aimed at estimating the brake RT which is correlated to TTC, rather than measuring the gap-acceptance. Thus, in our circumstance, blocking hazards out of vision could allow a more accurate estimation on RT.

The difference in the effect of speed between approaching directions might be caused by the complexity of the environmental background of the cycle-crossing. Mayeur et al. (2010) found that the complexity of video background negatively influenced the hazard perception and reaction speed. In our experimental videos, the background of the right side cycle-path was relatively uniform, whereas, for the left side, the background was more complicated, especially the area which was near to the cycle-crossing. Thus, the effects of the cycling speed might be concealed by the disturbances in the background.

5.3. Influence of approcing direction

The effect of approaching direction on brake RT was significant. The result supported the hypothesis **[H3]**, that participants' average brake RT for the cyclists approached from the right side was shorter compared to the left side. But the difference was subtle. As indicated by Werneke and Vollrath (2013), where the driver's attention is allocated is mainly influenced by the value (the goal), expectation about the hazard occurring, and salience of the stimulus. When the traffic density is low and both sides had potentially valuable information, drivers inspect the right-hand side more frequently. In our scenario, participants clearly knew that the cyclists could approach from both sides of the road, and there was no other road users. Therefore participants might pay more attention at the right side of the cycle-crossing. But in the experiment, participants did not need to make a real turn, the goal was absent in the simulation context. Moreover, the road simulation study conducted by Jurecki and Stańczyk (2014) used a left hand drive car and was at daytime. They found that the longer RT for left side mock-up pedestrians was mainly caused by the limited angle of view of the drivers for the left side approaching pedestrians. Comparatively, the current study conducted the experiment by using a driving simulator at mesopic light level. Participants approximately sat aligned with the road middle line, and, therefore, the difference in viewing angle between the left side and right side was smaller than in the field test. Therefore, the effect of the direction in the current study was smaller than previous studies (cf. Werneke & Vollrath, 2012; Werneke & Vollrath, 2013).

5.4. Steering task difficulity and mental workload

The hypothesis **[H4]** was statistically supported. The result of the NASA questionnaire (Hart & Staveland, 1988) indicated that the mental demand of the moderated tracking task was higher than the easy tracking task, but the difficult tracking task did not further increase the mental demand. Particularly, participants responded faster to the cyclists when they had a higher level of mental workload, which was against our hypothesis **[H5]**. Presumably the overall task demand was relatively low, causing participants a lack of concentration. Apparently, the moderate and difficult tracking task forced participants to be more alert and concentrated. Subsequently, the sensitivity of participants increased (see Figure 4.13), the average brake RT reduced, and the tracking performance increased. The mimic steering task was limited in increasing the mental workload, probably because the tracking task was relatively simple, and the experiment was conducted in a simulation context. Adding such a simulated steering task would be a reasonable method to increase the reality of the driving simulations, only when the degree of tracking difficulty, and the movement of the targets are carefully designed.

5.5. Gender and driving experience

Gender demonstrated a strong effect on driver's brake RT. The result was consistent with previous studies (e.g., Konstantopoulos et al., 2010; Sagberg & Bjørnskau, 2006). Generally, males reacted faster than females on pressing the brake pedal. The the cycling speed showed a significant effect only for female participants, but did not influence male participants. Male participants might be more engaged at the tasks. Moreover, experienced drivers reacted faster than moderate and novice drivers. Experienced drivers might be better at optimizing their visual searching strategies for typical road conditions (see Konstantopoulos et al., 2010; Underwood, 2007). Besides gender and driving experience, Campbell et al. (2012) suggested that the most vulnerable road users should be considered as important participants when evaluating the efficiency of road infrastructures. Future studies could focus on evaluating the effects of visibility aids on drivers in different age groups.

5.6. Order effects

A significant order effect of the experimental sessions was found. The average brake RT reduced in order of session. Besides, the brake RT reduced for the second replication of the stimulus compared to the first one. But the effect of the replication order was subtle. In general, participants reacted faster when they had more practice. Especially, they might notice the time when the cyclist should appear, because in the testing videos, there were some conspicuous road signs which appeared a few seconds before the presentation of the cyclists. These signs might offer cues for participants to anticipate the time of the presentation of the cyclists.

5.7. The cyclists perception time

Recarte and Nunes (2003) divided the target detection into three stages, (a) the first stage is the perception time (PT), starting from the moment that the stimulus is presented until the moment that it is glanced at; (b) the second stage is the inspection time, that is the time when the stimulus is being gazed at, more information can be extraction and elaboration in this stage; (c) the third stage is the decision time, since the gaze shifts away from the target, until the manual operation is given.

The brake RT in the present study consisted of all the three stages. Beside of the brake RT, the study examined the PT, with the purpose of achieving a better understanding of the perception stage. Limited numbers of PT were identified. For those observations, the effects of *cyclists speed, gender,* and *driving experience* were consistent with the effects founded on brake RT. Explicitly, male participants, and experienced drivers were faster at both perception and reaction stages. Moreover, participants perceived the higher speed cyclists later than the lower speed cyclists, subsequently, the brake RT was longer for the cyclists with higher speed. In terms of the steering task, no significant difference was found between the difficulty levels. The target tracking performance was not significantly correlated with the PT. These findings implied that the difficulty of the steering task affected more the later stages rather than the perception stage.

Moreover, participants demonstrated different gaze-shifting patterns. Participant that frequently glanced at the distant positions which were far away from the road middle, generally reacted slower. The diffused gaze-shifting might be caused by the lack of concentration, which resulted in the slower reactions.

5.8. Simulation sickness

6 out of 28 participants reported feeling a little bit uncomfortable during the simulation. The major uncomfortable feeling was dizzy, and followed by eye pain. Presumably, the dizzy feelings mainly caused by the frame-to-frame coherence problem, such like “freezing effect” or “jump moving” of the video. To do real-time video-based interaction via MATLAB system could be a huge challenge, and the capacity of the computer was limited when running the simulation. Sluggish running might occur occasionally, which led to the impairment in the video playback quality. In order to moderate simulation sickness, the playback quality should be further improved.

6. Conclusion

This study aimed at investigating the relative efficiency of IFL systems and increased vertical illuminance on the speed of drivers' cyclists perception and reaction at a cycle-crossing. A low-fidelity driving simulator was developed. Video-based hazard perception test and simulator-based driving test were combined in the experiment. In terms of the dark-clothed cyclists in nighttime traffic, the main findings include:

- Drivers reacted faster for lower speed cyclists than the higher speed cyclists.
- The increased vertical illuminance of the cycle-crossing was the most effective way to reduce the the brake RT of drivers.
- IFL placed in the road middle reduced the brake RT of drivers. But placing the IFL signal at the roadside which was located at the peripheral vision of drivers, led to an increase in drivers' brake RT, especially when the contextual condition of the cycle-crossing was complex.

The study gave insight into the efficiency of cycle-crossing visibility aids and cyclist safety in nighttime traffic. Based on the current study, future research ideas were generated. First, future studies should investigate the effect of the visibility aids on vulnerable drivers, such like elder drivers and inexperienced drivers. Second, it would be interesting to duplicate the experiment for different cycle-crossings, to examine whether the contextual cues (e.g. traffic density and road environment) could influence the result. Third, well-designed tests are needed to examine the effect of moving speed of hazards. For the visibility aids, the influence of different levels of vertical illuminance should be further studied. At last, the relationship between the driver's acceptance and the effect of the AWSs is worthwhile to explore.

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Appendix A

The Pilot Study

1. Design

To check the manipulation of the mental workload and the performance of the simulation system, a pilot study was conducted. In total 11 adults participated the pilot test, one participant braked off before finishing the experiment. Thus result from 10 participants between 23 to 64 years old was used for the analysis. 5 participants are female and 5 participants are male. All the participants were recruited at Philips Lighting.

The independent variable was *tracking task difficulty*, including three levels: easy, moderate and difficult. A repeated measures design was used in which each participant experienced all levels of tracking task. The dependent variable was the *subjective task load*, and *tracking task performance*. Similarly, the pilot test included all the hazard conditions which were tested in the main experiment, but each condition was only replicated for one time. No false positive was included, because measuring the RT was not the main purpose of the pilot study, and adding false positives would require much more time for each session. As a scaled version of the main experiment, the procedure and measures of the pilot study were treated in the same way, except that eye-tracker was not used in the pilot study.

2. Result

2.1 Subjective-evaluated task load

A one-way repeated measured ANOVA was used to test the effect of task difficulty on participants' mental workload. The 6 items of the task load index (Appendix E) were used to calculate the subjective mental workload, the *Cronbach's alpha* for the 6 items was 0.83. The tests of normality indicated the normality assumption was fulfilled (*p= .164, p= .200, p= .200 respectively for each difficulty level*). As can be seen from Figure a.1, the difficulty of the tracking task had a significant effect on the mental demand (F*(2,10)=11.394, p= .001).* The pairwise comparison indicated, the mean workload of the moderate and difficult task both significantly higher than the easy task (*MD=3.94, p= .004; MD=4.92, p= .001*, respectively), but there was no significant difference between the two levels (*p= .743*).

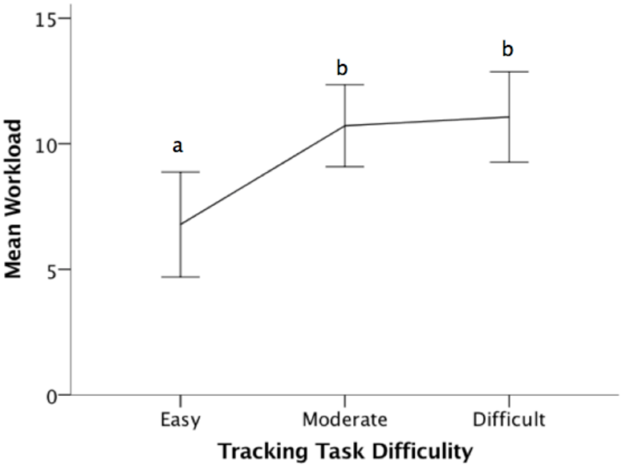


Figure a.1. A plot of mean workload cross three levels of tracking task difficulity

2.2 Tracking performance

A GLM was used to analyze the variance of the tracking task performance between each level of task difficulty. The *tracking performance* was calculated based on the average targets distance in pixel during one session. Larger distance implied a worse performance. Z-scores were calculated, and no outlier was found. The logarithm of the tracking performance was used a the dependent variable. The *task difficulty* was the independent variable. The average task performance significantly decreased with the task difficulty ($X^2(2, N=1200)= 791.981, p< .001$), with the increasing of the task difficulty, the tracking task performance decreased (Figure a.2). Moreover, the performance of the easy task, moderate task, and difficult task significantly different from each other ($MD_{(2-1)}=10.53$ pixel, $p=< .001$, $MD_{(3-1)}=14.43$ pixel, $p< .001$, $MD_{(3-2)}=3.9$ pixel, $p< .001$).

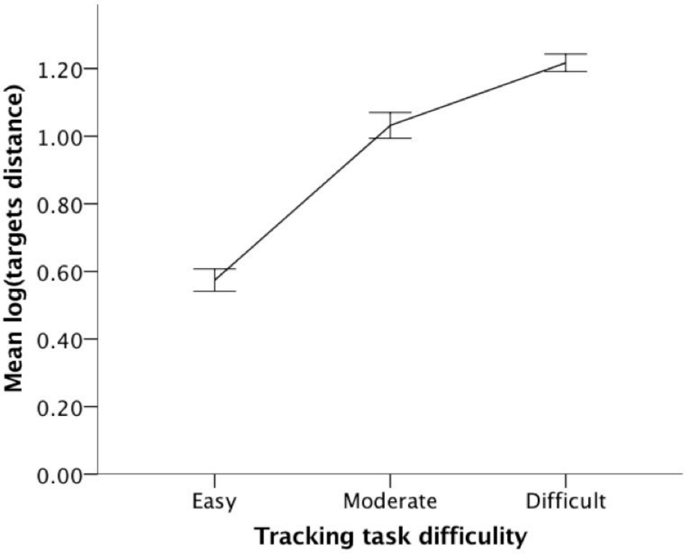


Figure a.2. A pilot of average logarithm targets distance across three levels of task difficulty

2.3 Exploretive analysis

In total 1320 (101 missing) responses were collected. An explorative analysis of the factors was performed by using GLM. The dependent variable was the reciprocal of brake RT, the independent variables including the *approaching direction*, *cycling speed*, *level of workload* and *condition of visibility aid*. All two-way interaction terms, three-way interaction terms were added. Moreover, the *tracking performance* was used as a conviranent in the model. The t*racking performance* had a significant correlation with the RT, $X^2(1, N=1152)=5.292, p = .021$. Moreover, a significant effect of cycling speed was found, $X^2(1, N=1152)=6.744, p = .009$. Participants reacted slower for the high speed hazards than the low speed hazards with 0.28 s ($p= .009$). No other effect was found to be significant.

3. Discussion

First, the steering tracking task could increase the participants' mental workload, whereas the most difficult steering task could not make a difference on the mental workload compared with the moderate task. Presumably, for the difficult task, the target moving speed was much higher than the tracker, participants could hardly make the tracker keep pace with the target. As a result, they might just perform the task with limited effort. Based on this finding, the difficulty of the highest level tracking task was adjusted. Specifically, the probability of direction changing of the target, and the moving speed of the tracker were increased.

Moreover, the mean RT demonstrated a decreasing trend with the increase of the tracking task difficulty (Figure a.3), though the decrease was not significant. One possible explanation was the mental demand of the primary task was not high enough to influence the target detection performance. A few participants commented that they felt bored and distracted during the tests, this suggested the mental demand of the experiment was relatively low. However, consider the difficulty of the moderate and difficult tracking task were already on an average- higher level, further increment on the difficulty may impair the practical meaning of the current study, therefore the difficulties were not adjusted once again.

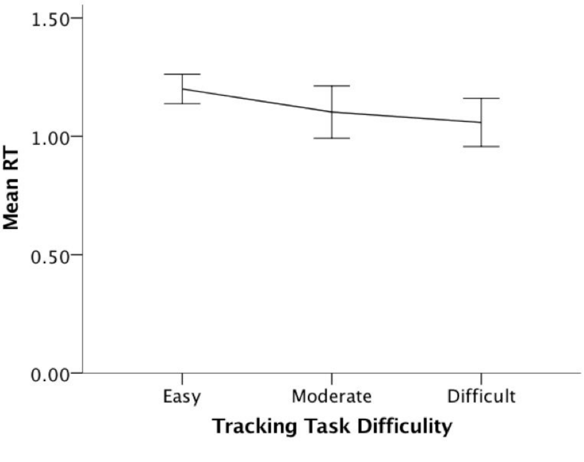


Figure a.3. A plot of mean RT across three levels of tracking task difficulity

Second, 4 participants had reported the brake interaction was not natural. Participants were told to release the brake pedal after they had pressed down it, while the video was continuously playing with normal speed during the brake until the pedal was released. Such system was designed to offer a smooth experience when the video clips were cutting. After each brake operation finished, the next video clip immediately started to play, the whole experience would feel like driving on a straight way continuously without any abrupt. However, such design did not offer real time feedbacks to participants, which led to confusion and frustration. Participants might immediately apply another brake if they did not detect any change in the video, the system counted the brake as a response to the current video clip, and automatically cut to the next one. Consequently, many false responses were generated. To address this problem, the system was improved by offering feedbacks for the brake operations. When the system detected a brake onset, the video playback speed would gradually slow down, until a brake offset was detected, the system started to play the next video clip.

Last, 3 participants reported had a little bit uncomfortable feelings during the experiment, included dizzy, and eye pain. No one reported had extremely uncomfortable or tired feelings. Thus, we were confident with the system to perform the following experiments.

Appendix B

Simulation system flowchart

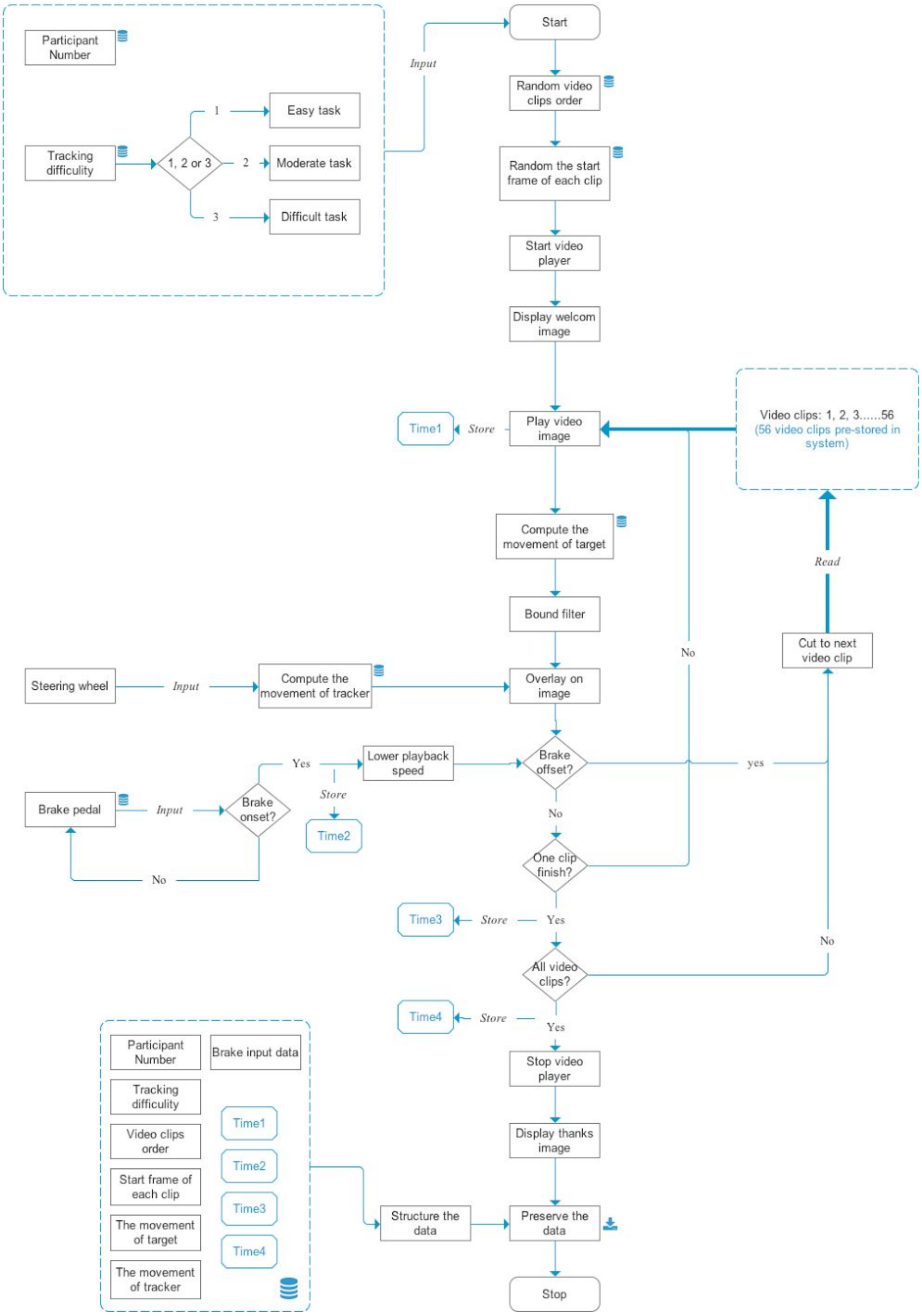


Figure b.1. The functional flow chart of the simulation system. The system was developed with MATLAB 2017a, was able to randomly display video sequences; randomly adapt the starting point of each video clip; superimpose target and tracker on video images; support real-time interaction; and record input data from pedals and steering wheel.

Appendix C

Hazards and luminance level

1. Hazard Conditions

In total 20 hazard conditions were tested in the experiment (5 visibility aids x 2 approaching directions x 2 cycling speeds). Figure b.1 displays the screenshots of 10 example conditions (5 visibility aids x 2 approaching direction) that were sniped from the lower cycling speed videos

15 km/h-ILH-Left

15 km/h-ILH-Right

15 km/h-ILM-Left

15 km/h-ILM-Right

15 km/h-WSS-Left

15 km/h-WSS-Right

15 km/h-WSM-Left 15 km/h-WSM-Right

15 km/h-STAN-Left 15 km/h-STAN-Right

Figure b.1. The screenshots of 10 example conditions

2. Luminance level of cyclists and background

The luminance was measured in three time spots of the stimulus videos; (1) at 0.5 s; (2) at 1.5 s; (3) at 2.5 s. For each time spot, three regions of the hazard (cyclist) were measured, including the head, shirt, and trousers regions. Besides, six background regions around the cyclist (one above, one below, two left, and two right regions) were measured. Table 1, 2, and table 3 display the average luminance of the measured regions of hazards in detail. In the tables, the approaching directions were coded as L and R (left and right); the cycling-speeds were coded as 25 and 15 (25 km/h and 15 km/h).

luminance cd/m^2 - 0.5 s									
Condition	Head	Shirt	Trousers	Above	Below	Left 1	Left 2	Right 1	Right 2
L-25-STAN	3.64	1.96	3.53	1.25	0.99	1.51	1.34	0.73	1.2
L-25-WSM									
L-25-WSS									
L-25-ILM	6.98	2.18	4.77	1.23	0.82	1.02	0.95	1	0.96
L-25-ILH	8.92	2.14	4.43	1	1.17	0.99	1	0.85	1.14
L-15-STAN	6.7	2.21	4.06	1.54	1.76	2.3	2.47	1.91	1.78
L-15-WSM									
L-15-WSS									
L-15-ILM	14.03	4.49	7.81	2.03	1.8	1.89	2.4	1.3	2
L-15-ILH	17.22	3.57	7.68	1.88	2	2.09	2.22	1.35	1.5
Condition	Head	Shirt	Trousers	Above	Below	Right 1	Right 2	Left 1	Left 2
R-25-STAN	3.43	1.82	2.88	1.33	0.75	0.68	1.24	1.12	1.05
R-25-WSM									
R-25-WSS									
R-25-ILM	7.13	2.2	5.13	1.06	0.88	0.83	1.13	1.05	0.9
R-25-ILH	8.68	2.07	5.09	0.82	0.79	0.96	1.45	0.93	1.1
R-15-STAN	7.33	2.17	4.67	1.93	2.64	1.33	3.07	1.52	1.9
R-15-WSM									
R-15-WSS									

R-15-ILM	13.23	4.05	8.72	1.83	2.73	2.35	2.48	1.64	1.95
R-15-ILH	17.9	3.77	8.23	2.06	2.62	1.65	2.6	1.86	2.16

luminance cd/m^2 - 1.5 s									
Condition	Head	Shirt	Trousers	Above	Below	Left 1	Left 2	Right 1	Right 2
L-25-STAN	6.39	2.25	3.66	1.11	1.17	0.93	0.98	0.88	0.96
L-25-WSM									
L-25-WSS									
L-25-ILM	15.47	4.02	7.58	1.09	0.89	1.16	1.12	1.02	1.12
L-25-ILH	22.27	2.9	6.74	1.01	1.11	1.18	1.26	1.08	1.79
L-15-STAN	12.07	2.83	6.33	2.03	3.63	1.9	2.7	1.6	2
L-15-WSM									
L-15-WSS									
L-15-ILM	24.33	6.21	12.06	2.34	3.68	2.08	3.89	1.76	1.86
L-15-ILH	39.21	5.37	14.18	2.57	3.52	2.43	3.63	1.53	1.38
Condition	Head	Shirt	Trousers	Above	Below	Right 1	Right 2	Left 1	Left 2
R-25-STAN	6.7	1.75	4.2	0.98	1.08	0.86	1.05	0.98	1.04
R-25-WSM									
R-25-WSS									
R-25-ILM	17.6	3.93	8.51	1.17	1.71	1.47	1.7	1.08	1.36
R-25-ILH	22.75	3.32	8.79	1.24	0.94	1.07	1.11	0.85	1.02
R-15-STAN	12.07	3.61	7.05	1.77	3.5	1.98	3.86	1.6	1.75
R-15-WSM									
R-15-WSS									
R-15-ILM	25.44	6.48	14	2.22	3.89	2.5	2.81	1.7	2.7
R-15-ILH	39.01	5.65	15.27	2.07	3.54	1.77	3.94	2.12	2.49

luminance cd/m^2 - 2.5 s									
Condition	Head	Shirt	Trousers	Above	Below	Left 1	Left 2	Right 1	Right 2
L-25-STAN	13.82	3,73	7.24	2.62	3.45	1.78	3.74	1.54	2.01
L-25-WSM									
L-25-WSS									
L-25-ILM	32.53	7.55	15.23	1.97	3.96	2.33	3.89	1.89	3.18
L-25-ILH	60.76	6.7	21.21	1.84	4.59	1.86	3.82	1.12	2.53
L-15-STAN	20.67	5.1	10.68	1.57	4.87	1.75	7.42	1.7	3.89
L-15-WSM									
L-15-WSS									
L-15-ILM	32.33	7.09	14.6	1.32	2.54	1.6	2.4	1	1.68
L-15-ILH	55.2	6.68	19.72	0.97	2.82	1.98	2.37	0.93	1.43
Condition	Head	Shirt	Trousers	Above	Below	Right 1	Right 2	Left 1	Left 2
R-25-STAN	15.19	3.69	7.02	1.39	2.57	1.62	2.33	1.26	1.4
R-25-WSM									
R-25-WSS									
R-25-ILM	53.31	9.96	23.24	2.55	4.67	1.57	8.03	1.87	3.9
R-25-ILH	84.87	9.49	28.93	2.79	5.28	2.63	5.8	1.33	2.78
R-15-STAN	21.32	5.12	10.05	2.69	5.79	2.35	5.31	2.15	2.68
R-15-WSM									
R-15-WSS									
R-15-ILM	50.99	10.06	23.16	2.3	5.74	2.74	5.42	1.8	2.6
R-15-ILH	83.78	8.5	32.17	1.87	5.13	2.16	7.75	1.85	3.68

Appendix D

The Tested Road and Cycle-crossing

A cycle-crossing located at Oosterhout, the Netherlands was chosen as the testing intersection. Figure c.1 illustrates the road and cycle-crossing on Google Map. The cycle-crossing is an uncontrol, right turning intersection. The cycle-path is perpendicular to the motorway. As can be seen from Figure c.2, the cycle-path is not straight, and the vision of drivers will be blocked by trees and shrubbery along the roadside. For the experiment, the cyclist should be visible at least 25 m away from the cycle-crossing. Therefore, in the test videos, some trees and shrubbery were wiped out through post-production method.

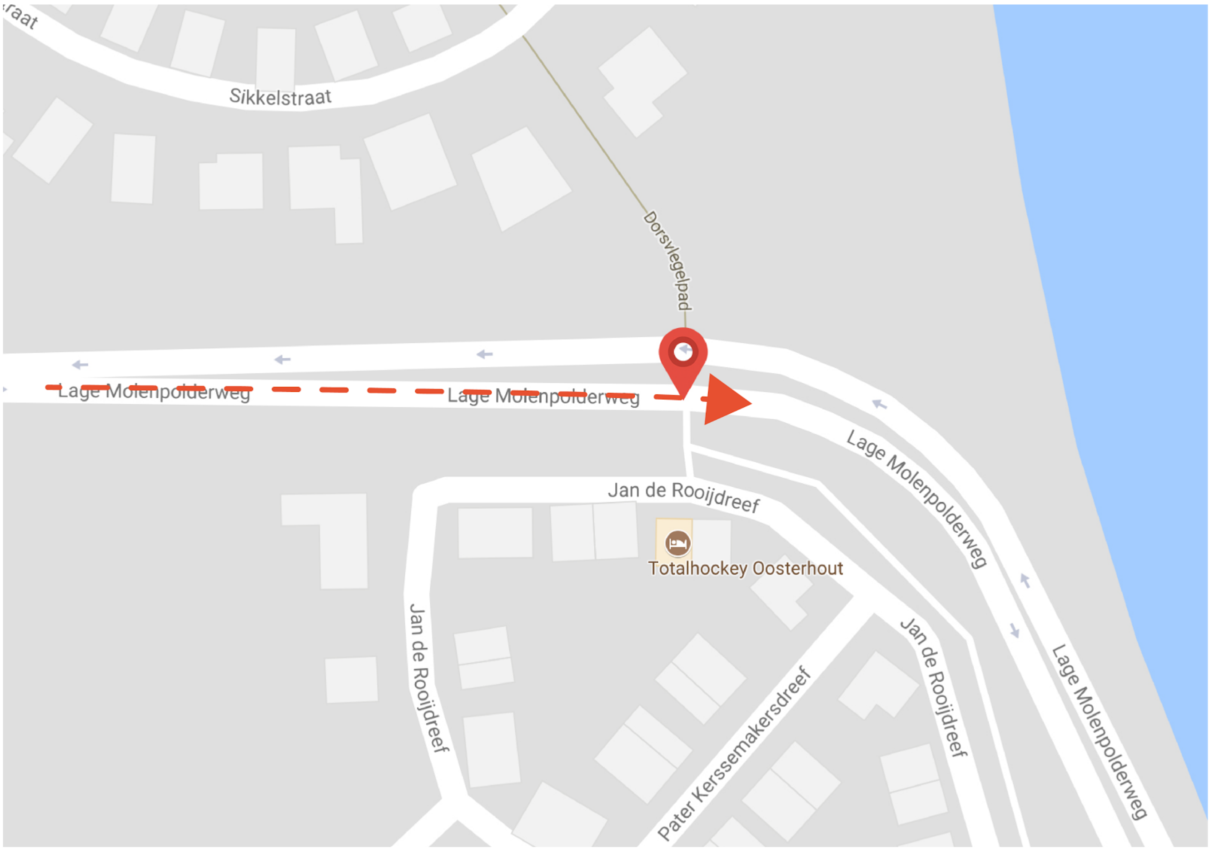


Figure c.1. The location of the testing road. The red marker indicates the location of the intersection, and the red arrow indicates the driving direction in the experimental scenario (source: Google Map)

Figure c.2. The testing cycle-crossing at day time (source: Google Map)

Appendix E

NASA task load index

Task	Date

Mental Demand How mentally demanding was the task?

Very Low Very High

Physical Demand How physically demanding was the task?

Very Low Very High

Temporal Demand How hurried or rushed was the pace of the task?

Very Low Very High

Performance How successfully were you in accomplishing what your level of performance?

Poor **Good**

Effort How hard did you have to work to accomplish your level of performance?

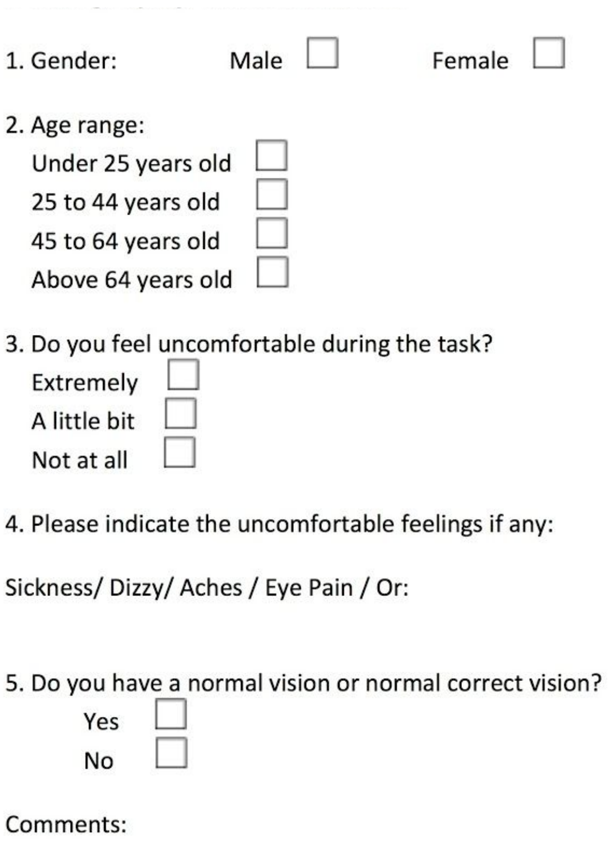
Very Low Very High

Frustration How insecure, discouraged, irritated, stressed, and annoyed were you?

Very Low Very High

Appendix F

Demography Questionnaire



1. Gender: Male ☐ Female ☐

2. Age range:
  Under 25 years old ☐
  25 to 44 years old ☐
  45 to 64 years old ☐
  Above 64 years old ☐

3. Do you feel uncomfortable during the task?
  Extremely ☐
  A little bit ☐
  Not at all ☐

4. Please indicate the uncomfortable feelings if any:

Sickness/ Dizzy/ Aches / Eye Pain / Or:

5. Do you have a normal vision or normal correct vision?
  Yes ☐
  No ☐

Comments:

Appendix G

Driving Questionnaire

The following questions are designed to help assess your current level of driving experience.

1. The number of years with your current driving license _____

2. What mode of transportation do you most commonly use?

Motor Vehicle (Driver) ☐ Motor Vehicle (Passenger) ☐

Walk ☐ Bicycle ☐ Transit ☐

3. Do you own or lease a motor vehicle? Yes ☐ No ☐

If No: Do you have the use of a motor vehicle? Yes ☐ No ☐

4. How often do you drive? (Check one box in both columns.)

Per Week – never	☐	**Per Month –** never	☐
1-5 times	☐	1-4 times	☐
6-10 times	☐	5-9 times	☐
>10	☐	>10	☐

5. How often do you drive during rush hour?

Per Week – never	☐	**Per Month –** never	☐
1-5 times	☐	1-4 times	☐
6-10 times	☐	5-9 times	☐
10 or more	☐	10 or more	☐

6. How many hours do you normally drive per day?

Up to 1⁄2 ☐
1⁄2 to 1 ☐
1 to 2 ☐
More than 2 ☐

7. Do you consider yourself to be an experienced driver?

Experienced ☐ Moderately ☐ Novice ☐

8. How **do others** rate your driving skills? (*You may check more than one box*)

Cautious ☐
Overly cautious ☐
Confident ☐
Very confident ☐
Routine ☐
Assertive ☐
Somewhat aggressive ☐
Aggressive ☐
Considerate ☐

9. Using the scale, indicate your driving experience on the following roadways.

	Never		Seldom		Often
Country/Rural	1	2	3	4	5
City – Suburbs	1	2	3	4	5
City – Downtown	1	2	3	4	5
City –Freeways	1	2	3	4	5

10. Indicate your level of comfort driving in the following hazardous conditions.

	Very Comfortable	Comfortable	Uncomfortable
Night	☐	☐	☐
Rain	☐	☐	☐
Snow	☐	☐	☐
Ice	☐	☐	☐
Fog	☐	☐	☐

Appendix H

IR and plots of eye-tracking data

1. IR

The IR was calculated based on the frequency and the range of X-axis values of gaze positions. A higher IR of a participant implied that he/she inspected to the farther positions away from the road middle more frequently. Take a participant as an example, 5% to 95% of the gaze positions located in the *range1* in the easy tracking session, *range2* in the moderate session, and *range3* in the difficult session. 25% to 75% of the gaze positions located in *range4*, *range5*, and *range6* respectively for each session. Then the average inspection range of this participant was formed as:

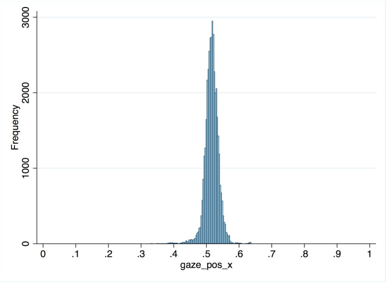
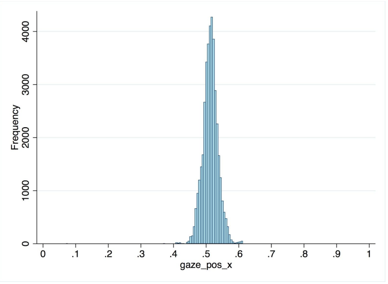
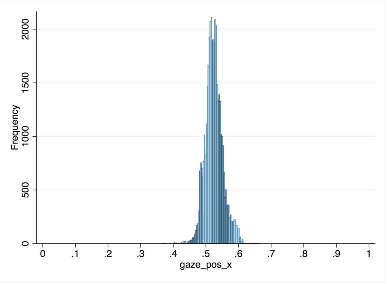
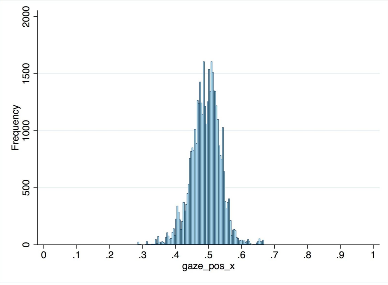
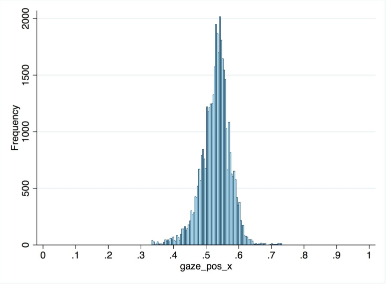
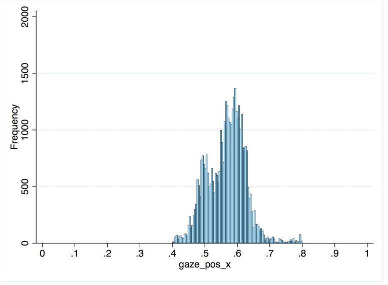
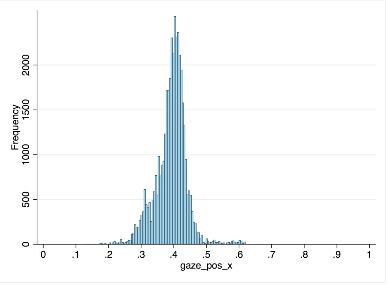
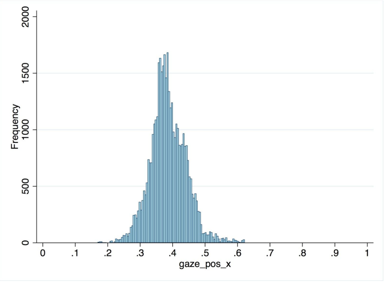
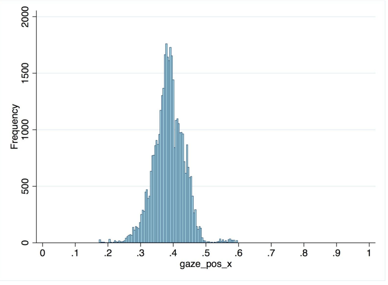
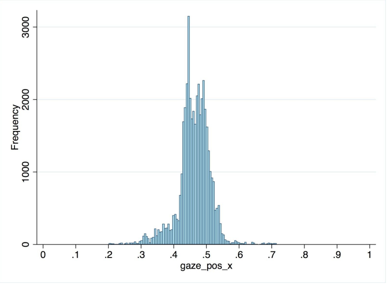
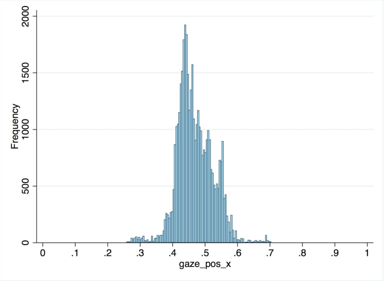
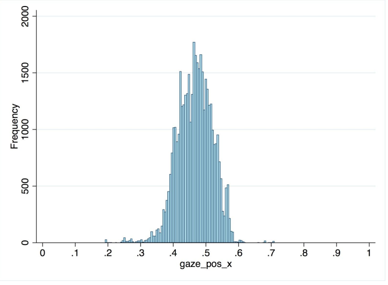
$$IR = \frac{range1+range2+range3+range4+range5+range6}{6} \tag{8}$$

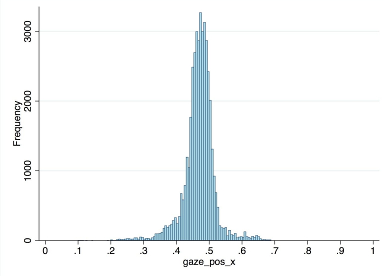
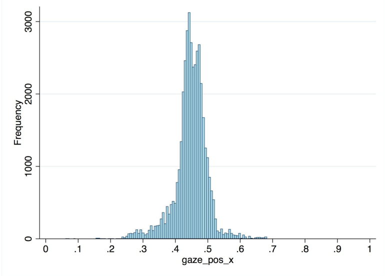
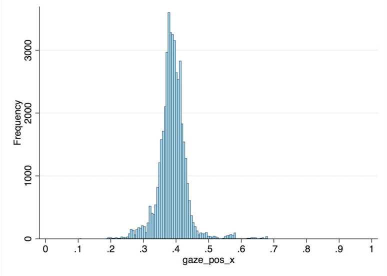
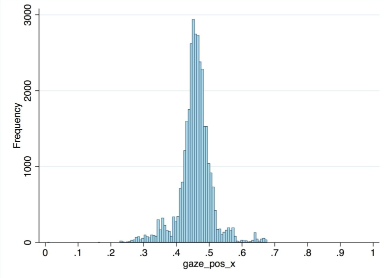
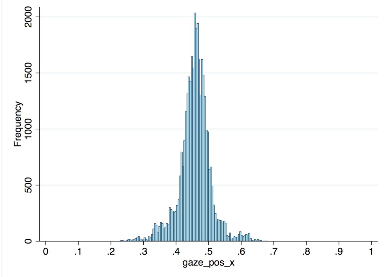
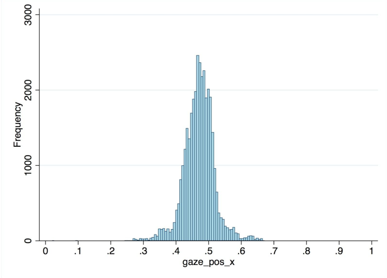
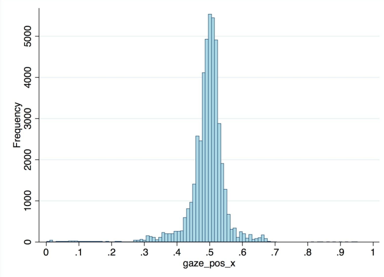
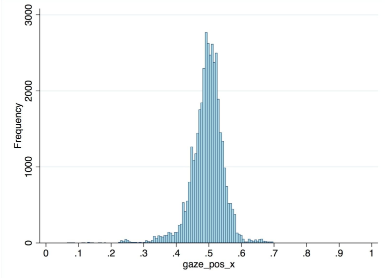
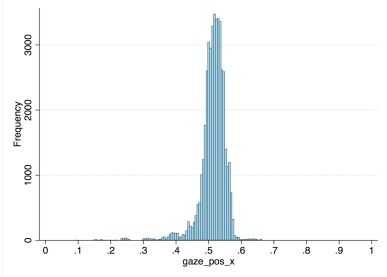
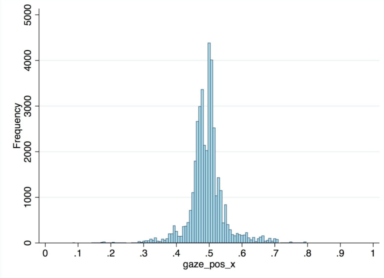
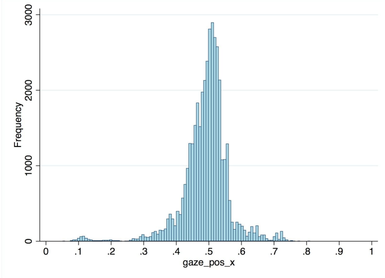
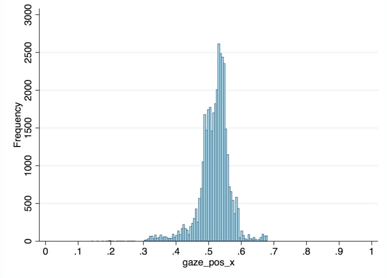
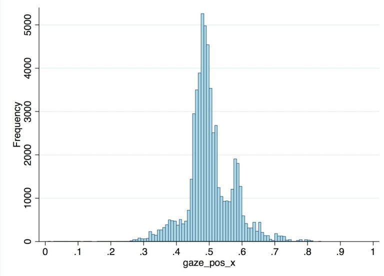
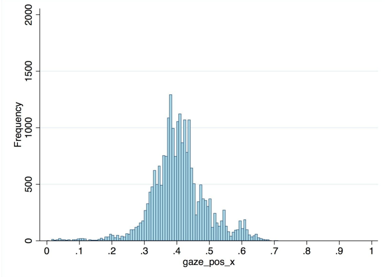
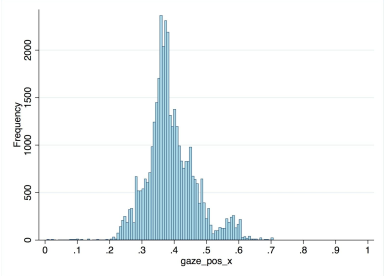
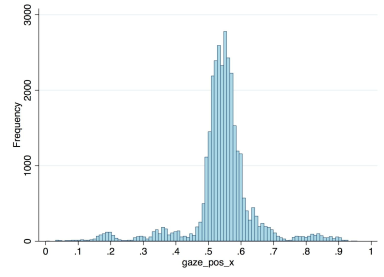
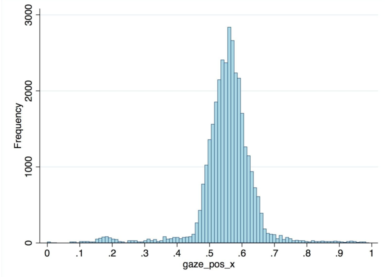
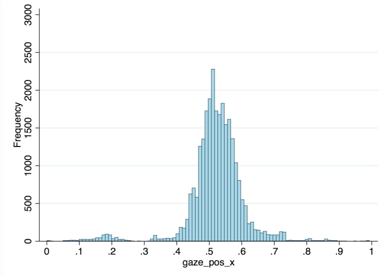
Participant	5%-95% X-axis value of gaze position			25%-75% X-axis value of gaze position		
	Easy	Moderate	Difficult	Easy	Moderate	Difficult
bb	0.35 - 0.64	0.37 - 0.61	0.38 - 0.66	0.36-0.64	0.41-0.61	0.39-0.64
cc	0.29 - 0.67	0.33 - 0.73	0.40 - 0.80	0.29-0.67	0.34-0.73	0.40-0.80
ca	0.13-0.62	0.17-0.62	0.17-0.60	0.16-0.62	0.18-0.62	0.18-0.60
ba	0.20-0.71	0.26-0.70	0.19-0.71	0.21-0.71	0.27-0.70	0.19-0.68
bd	-0.22 - 0.68	-0.02 - 0.68	-0.01- 0.68	-0.16-0.68	0.09-0.68	0.20-0.68
aa	-0.09-0.67	-0.22-0.68	-0.11-0.66	0.00-0.67	-0.47-0.66	0.09-0.66
bc	-0.64 - 0.95	-0.72-0.69	-0.09 - 0.67	-0.42-0.82	-0.72-0.69	0.15-0.65
be	-0.69 - 0.79	-0.84 - 0.78	-0.62 - 0.68	-0.66-0.79	-0.77-0.76	-0.61-0.68
cb	-0.01 - 2.65	-0.65 - 3.82	-0.55 - 1.27	0.03-2.07	-0.38-3.77	-0.52-1.18
cd	0.32-0.96	-0.00-13.59	0.00-0.99	0.04-0.92	0.00-0.98	0.01-0.95

Participant	Average value of the gaze position range (IR)	Mean brake RT
bb	0.26	0.758
cc	0.39	0.774
ca	0.45	0.822
ba	0.48	0.779
bd	0.81	0.807
aa	0.83	0.863
bc	1.20	1.038

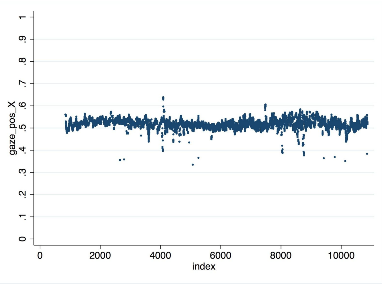
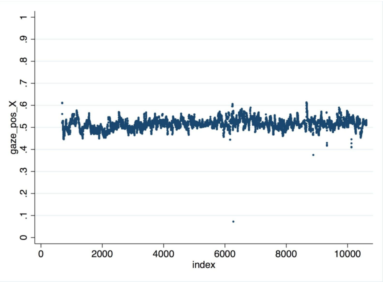
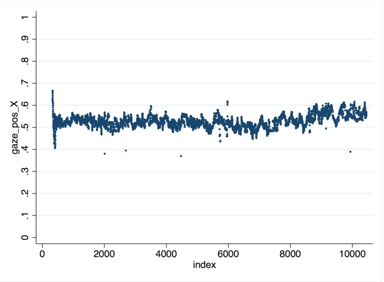
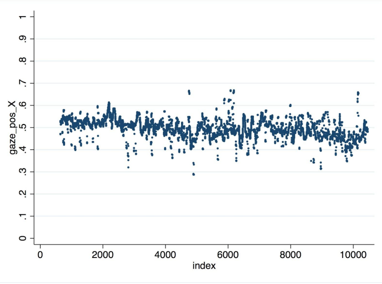
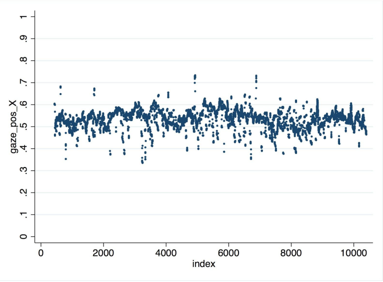
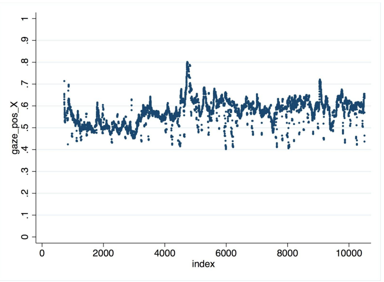
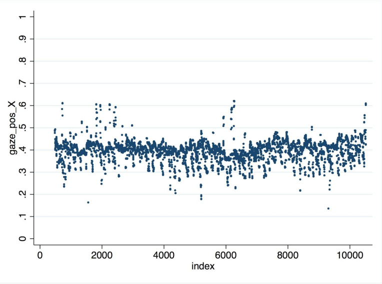
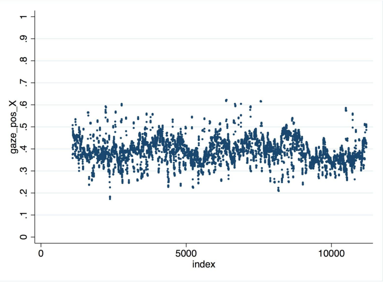
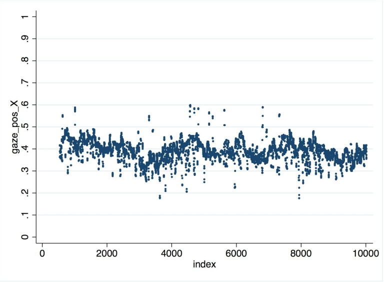
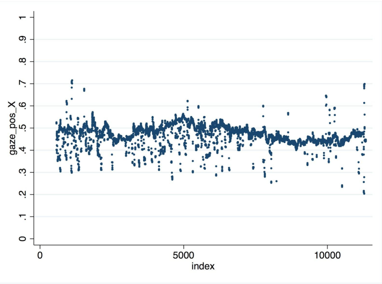
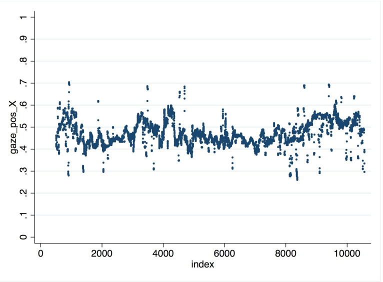
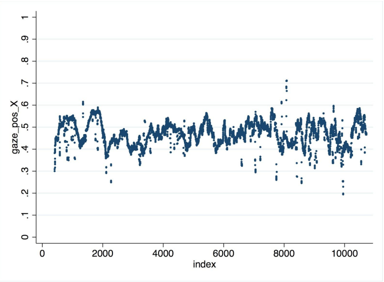
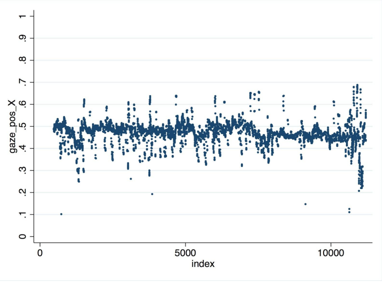
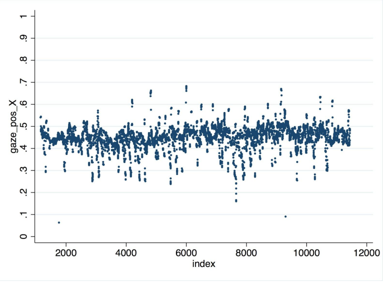
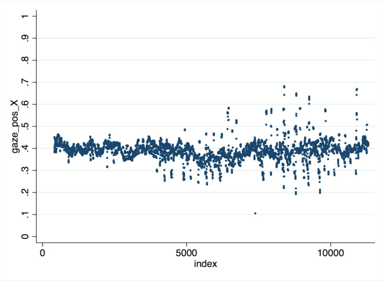
be	1.45	0.933
cb	2.21	1.115
cd	3.13	1.554

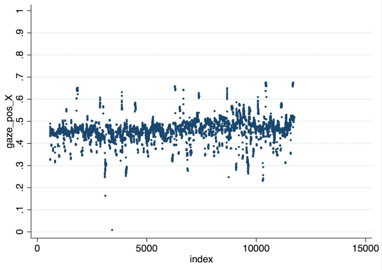
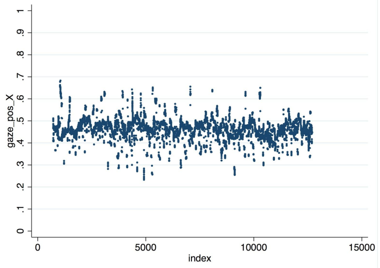
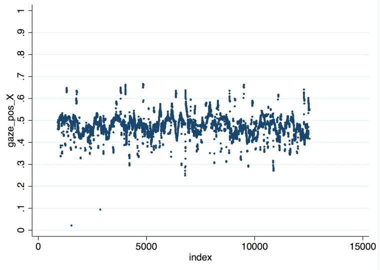
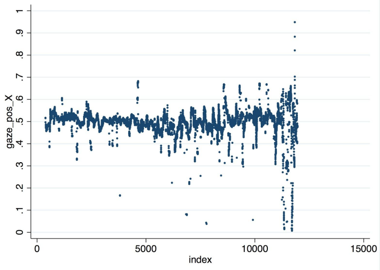
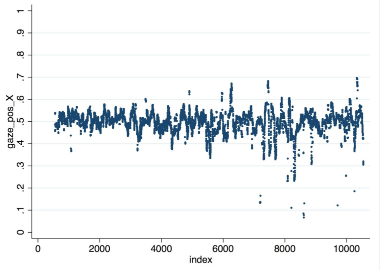
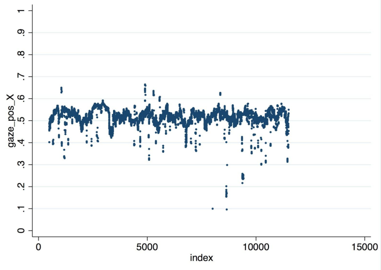
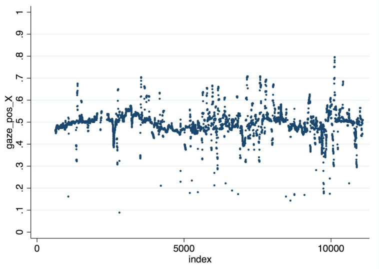
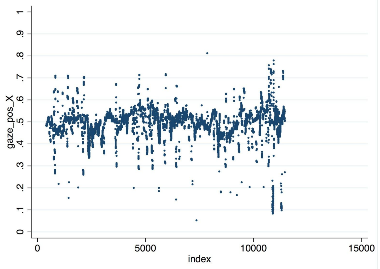
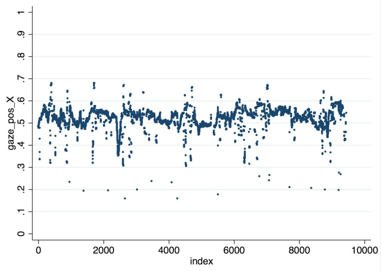
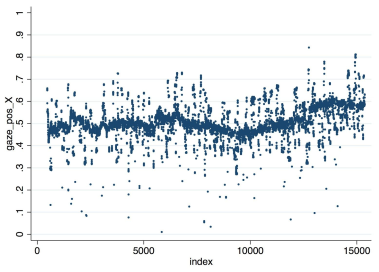
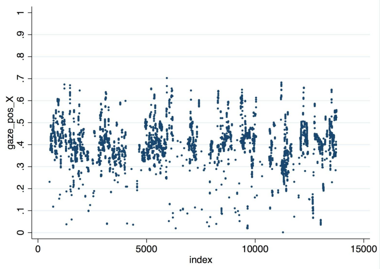
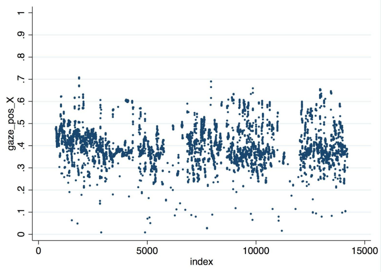
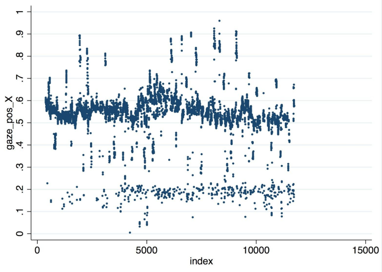
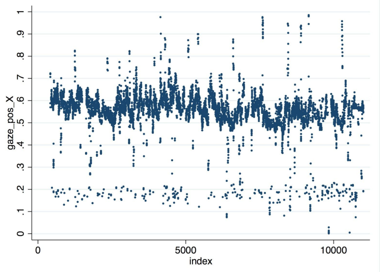
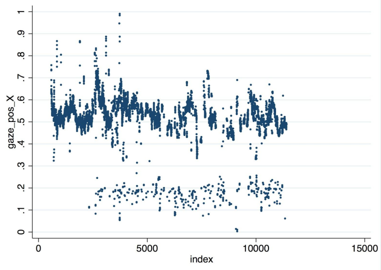
2. Frequency histograms of the x-axis values of the gaze position

	Target tracking difficulity		
	Easy session	Moderate session	Difficult session
bb			
cc			
ca			
ba			

bd			
aa			
bc			
be			
cb			
cd			

3. Scatter plots of x-axis value of the gaze-position by frame index

	Target tracking difficulty		
	Easy session	Moderate session	Difficult session
bb			
cc			
ca			
ba			
bd			

aa	gaze_pos_X 0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1 0 5000 10000 15000 index	gaze_pos_X 0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1 0 5000 10000 15000 index	gaze_pos_X 0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1 0 5000 10000 15000 index
bc	gaze_pos_X 0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1 0 5000 10000 15000 index	gaze_pos_X 0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1 0 2000 4000 6000 8000 10000 index	gaze_pos_X 0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1 0 5000 10000 15000 index
be	gaze_pos_X 0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1 0 5000 10000 index	gaze_pos_X 0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1 0 5000 10000 15000 index	gaze_pos_X 0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1 0 2000 4000 6000 8000 10000 index
cb	gaze_pos_X 0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1 0 5000 10000 15000 index	gaze_pos_X 0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1 0 5000 10000 15000 index	gaze_pos_X 0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1 0 5000 10000 15000 index
cd	gaze_pos_X 0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1 0 5000 10000 15000 index	gaze_pos_X 0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1 0 5000 10000 index	gaze_pos_X 0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1 0 5000 10000 15000 index