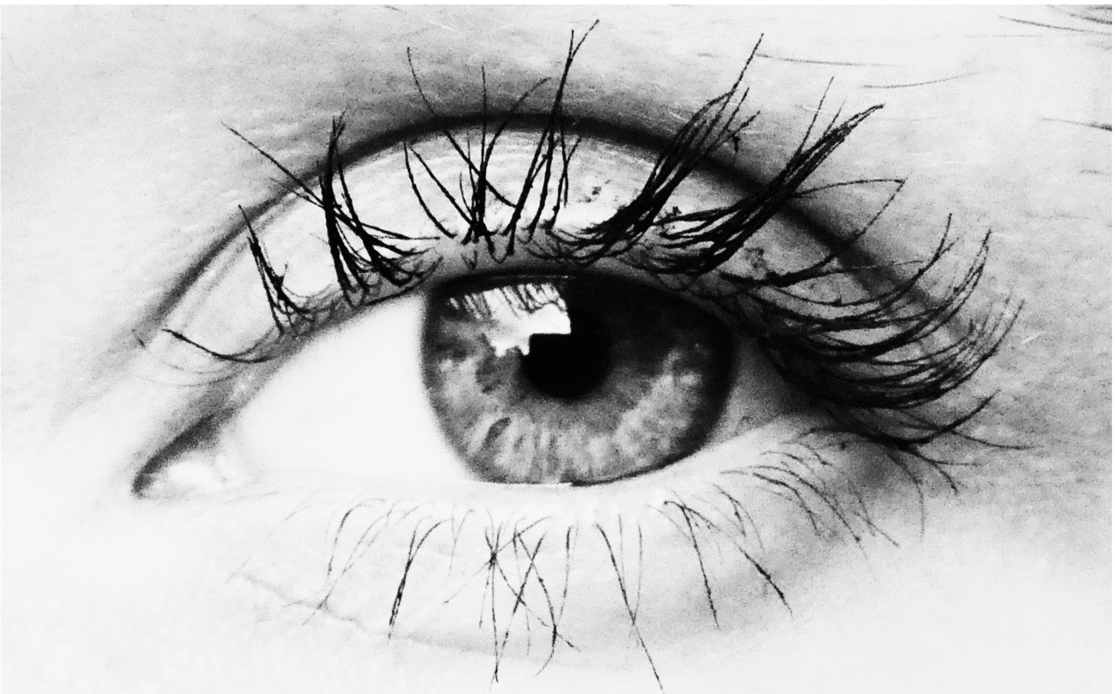

Eye Blinks as an Indicator of Car Drivers' Visual Attention

A statistical analysis of differences in eye blinks between roads of high and low complexity

Master's thesis in Biomedical Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

The majority of all traffic crashes occur due to human error, according to National Highway Traffic Safety Administration. As the development of self-driving vehicles´ progress, the driver's role changes to a more monitoring nature, successively eliminating the effect of human error. However, until fully automated vehicles are achieved, the driver needs to be ready to take control over the vehicle in critical situations. Therefore, visual attention is an important attribute to be a reliable car driver engaged in the traffic environment. The thesis sets out to investigate the usability of human eye blinks as an indicator of car drivers´ visual attention. The investigation is based on electrooculography (EOG) measurements obtained during an on-road experiment performed by Volvo Cars and Research Institutes of Sweden (RISE). The data is used to analyse differences in blink rate and half blink duration between interchange (high demand of attention) and motorway (low demand of attention). Surprisingly, the results indicate that the blink rate increases during interchanges, which contradicts findings from previous studies. The contradiction derives from an increase in blink-saccadic pairs occurring due to the driving behaviour in interchanges.

Additionally, the result implies that half blink duration increases during motorways. From the findings, it is concluded that blinks without large saccadic eye movements are less affected by driving behaviour and could therefore be a potential robust indicator of visual attention. Further, half blink duration is a possible indicator to measure a drivers' visual attention. Therefore, eye blink measurements have the potential to alert vehicle safety systems about the driver´s level of engagement.

Keywords: Eye blinks, Visual attention, Blink rate, Half blink duration, Road complexity

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This thesis is the last project we will perform before graduating from Chalmers University of Technology. Therefore, we would like to take the opportunity to thank everyone at Chalmers that have been involved in our five-year journey.

Gothenburg, June 2021

Paula Ek — Felicia Österberg

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Contents

1

Introduction

Today, advanced driving assistance systems (ADAS) are a common attribute in new vehicles, and as the automotive industry evolves, vehicles with an automated driving system (ADS) will enter public roads. This development induces both challenges and advantages, which requires new technology and new types of safety systems. In order to accomplish this, groundbreaking studies need to be executed. This project aims to investigate the usability of eye blinks as an indicator of drivers' visual attention.

1.1 Background

According to the World Health Organization (WHO), 1.35 million people die due to traffic crashes each year. In addition to these fatalities, 20-50 million people also endure severe injuries, that in many cases cause disabilities. Besides causing great personal pain, it also causes an economic loss for the affected persons. In extension, it affects the nation's economy and cost most countries 3% of their gross domestic product (*Road traffic injuries*, 2020).

The National Highway Traffic Safety Administration (NHTSA) states that 94% of traffic crashes occur due to human errors. Driver assistance technologies are already common in today's vehicles and help avoid accidents by intervening in the driving task or warning the driver in hazardous situations. In the near future, it is excepted that vehicles will control the entire driving task and be self-driving (*Automated Vehicles for Safety | NHTSA*, n.d.). This will potentially eliminate human errors and is believed to contribute to safer transportation with fewer fatalities. According to NHTSA, the implementation of automated vehicles has several benefits in addition to the safety aspects. Economic and social aspects are expected to be positively affected since fatalities and injuries caused in crashes hopefully decreases (*Automated Vehicles for Safety | NHTSA*, n.d.). From an environmental perspective, automated vehicles are more sustainable due to fuel efficiency (Bagloee, Tavana, Asadi, & Oliver, 2016). Before self-driving cars enter the public roads, the level of automation will progress successively (*Automated Vehicles for Safety | NHTSA*, n.d.). In step with this progress, the role of the driver changes. As the automation increases, the driver's role will be of a more monitoring nature until a fully automated level is achieved. This will make the role of the driver more passive, which increases the risk of driver disengagement. Lack of engagement endangers safety since it makes the driver less prepared to take control over the driving task when necessary. Therefore, visual attention is an important attribute to be a reliable car driver engaged in the traffic environment (Faure, Lobjois, & Benguigui, 2016). Measuring the degree of drivers´ visual attention could be beneficial for threat assessment in vehicle safety systems. The gaze has been proven to indicate the direction of visual attention, but there is no established method that could specify the degree of visual attention. A driver´s visual inputs are essential in perceiving the surroundings correctly and make the right decisions promoting safe driving (Faure et al., 2016). The eyelids cover the pupil during eye blinks, which causes milliseconds of lost visual input. Researchers believe that this loss of perception causes inhibition of eye blinks during high demands of visual attention (Shultz, Klin, & Jones, 2011). If so, the blink rate (BR) could be a possible measure of visual attention, where a decrease in BR indicates inhibition of blinks. Other researchers have found a correlation between blink duration and visual workload. During high demands of visual workload, the duration of eye blinks has been shown to be shorter (Benedetto et al., 2011).

The demand of the driving task varies with the complexity level of the driving environment. As the complexity level increases, the workload of the driver does too (Faure et al., 2016). It is therefore expected that high complexity road environments necessitate high levels of visual attention. Researchers believe that monotonous driving environments, such as motorways, are less complex (Faure et al., 2016). Roads that require major vehicle control and information processing are believed to be more complex (Faure et al., 2016).

1.2 Aim

The project aims to assess the usability of eye blink pattern as an indicator of car drivers' visual attention on a group level and an individual level.

1.3 Scope and research questions

The usability of eye blinks as a measurement of visual attention will be investigated by analysing data obtained from a previous on-road experiment performed by Volvo Cars and Research Institutes of Sweden (RISE). The experiment included ten test subjects that drove several laps between the interchanges Åbromotet and Fiskebäcksmotet in Gothenburg. During the experiment, the test subjects were video recorded and observed with electrooculography (EOG) measurements that generated observations of the test subjects´ blinking behaviour. This experiment consisted of two road environments, motorway and interchange. Based on previous research, it is believed that the interchange is of a higher complexity level and demands more visual attention compared to the motorway. Therefore, the route of the on-road experiment will be divided into segments of different degree of complexity: motorway and interchanges. Furthermore, previous research has also indicated that visual attention affects the blinking behaviour regarding blink rate and blink duration. Therefore, the hypothesis of this project is that the blink rate and the blink duration decreases during visual attention. These hypotheses will be addressed by answering the following questions:

1. **Are there any differences in blink rate between interchanges and motorways?**

   The BR for each segment and test subject will be calculated and compared against each other to demonstrate differences in BR between interchange and motorway on a group level and an individual level.

2. **Are there any differences in blink duration between interchange and motorway?**

   The duration of eye blinks in each segment will be compared against each other to demonstrate differences in duration between interchange and motorway on a group level and an individual level.

1.4 Demarcations

The data used for analysis in this project was intended for another study with a different aim. Therefore, the data are not adjusted to answer this project's research questions, which means that other experiments could be a better fit for this project. The observations from the test subjects are assumed to reflect the blinking behaviour of the car driving population of the world. There were only ten test subjects in the on-road experiment, which is too few to draw any definite conclusions for the total driving population. Parts of the video recordings and the EOG-measurements were lost due to problems with the data storage. This resulted in a decrease in data and obstructed the segmentation of the laps.

2
Theory

The Theory chapter is based on information obtained from a literature review of subjects relevant for this thesis. The Theory chapter consists of three main areas: the human eye, mental processes and eye blinks, and driving complexity.

2.1 The human eye

The perception of the environment is mostly based on visual information since the eyes obtain more than half of the sensory receptors of the human body (Tortora & Derrickson, 2015). The eye creates images of the environment by reflecting light on the retina. The fovea centralis is the part of the retina with the highest acuity of the perceived image. The amount of reflected light is adapted by dilation or constriction of the pupil. If the pupil is covered, the intake of light is disrupted, which means that the visual perception of the environment is interrupted during eye blinks. Hence, visual information is lost (Tortora & Derrickson, 2015). An adult human tends to blink around 15 times per minute, and the duration of the blinks are approximately 200-400 ms (Bristow & Rees, 2010). During this time, the pupil is covered by the eyelids for about 100-140 ms. The closure of the eyelids is twice as fast as the reopening (Bristow & Rees, 2010).

2.1.1 Eye movement

Contractions of the extraocular muscles facilitate movements of the eyeball (Duchowski, 2003). Six extraocular muscles enable movement of the eyeball in all directions. The medial and lateral rectus generates horizontal movements, the superior and inferior rectus vertical movements, and the superior and inferior obliques rotational movements. The extraocular muscles give rise to three different eye movements (Duchowski, 2003). Saccades are fast movements that occur when redirecting the fovea centralis between objects, with a duration between 10 to 100 ms. During saccades, the angle of the gaze changes. According to Thomas (1969), small saccades are movements of less than 5 degrees. When observing a stationary object, fixations occur due to the stabilisation of the retina. During fixation, tiny eye movements arise due to attempts to maintain the gaze steady, such as drift, tremor, and microsaccades (saccades approximately smaller than 0.5 degrees (Ko, Poletti, & Rucci, 2010)). The duration of fixations is generally between 150 to 600 ms. The third movement of the eye is smooth pursuits that occur when following an object in motion.

2.1.2 Eye blink

An eye blink is generated by two muscles, the orbicularis oculi (OO) and the levator palpebrae superioris (LP) (Bour, Aramideh, Ongerboer De Visser, & de Visser, 2000). The OO is a flat, broad muscle between the frontal bone, maxilla and lacrimal bone. The muscle lines the opening of the orbit and consists of three portions: palpebral, orbital and lacrimal (Rad, 2021). The LP is a triangular muscle that runs along the top of the orbit, over the eyeball, to the superior eyelid (Sendic, 2021). These two muscles generate eye blinks by reciprocal innervation (Bour et al., 2000). The blinking phase is initiated with the relaxation of the LP muscle, while the OO muscle contracts brief and rapidly, which closes the eyelids. During the reopening of the eyelid, the OO muscle relaxes while the LP muscle returns to tonic activity.

Closing the eyelids have many necessary functions, such as regulate the amount of light, protect the eye from extraneous objects and distribute lacrimal fluids that lubricate the eye (Tortora & Derrickson, 2015). Eye blinks could be categorised into three groups: spontaneous, voluntary, and reflex (Smit, 2008). Spontaneous blinks maintain the eye moist by spreading tears over the cornea, and these blinks are periodic and instinctively. Voluntary blinks occur purposely and could be made to communicate and enforce spoken words or emotions. Reflex blinks are induced by external stimuli, such as tactile, acoustic and optic impressions. Depending on the character of the blink, different portions of the OO muscle is involved (Smit, 2008). The short muscle fibres of the palpebral portion of the OO muscle enables a rapidly accurate movement of the eyelid, which is necessary during spontaneous and reflex blinks. During voluntary eye blinks, such as winking and determined eye blinks, the orbital portion of the OO muscle is involved due to its large muscle fibres that permit vigorous and lingering contractions. The kinematics of an eye blink depends on the type of the blink (Smit, 2008). A reflex blink is characterised by a quick and distinct down-phase due to strong initial activation of the muscles, with a longer duration of the up-phase. Movement of the eyelid during voluntary blinking is slower since the contraction of the OO muscle is weaker and more persistent. The muscle activity is the lowest during spontaneous eye blinks, resulting in longer duration and less eyelid movement. According to a study, the duration of a reflex blink is short with low variability, while the duration of spontaneous blinks was long with high variability (VanderWerf, Brassinga, Reits, Aramideh, & de Visser, 2003).

During eye blinks, the eyeball moves due to contractions of the extraocular muscles and the eyes are pressed about 1-2 mm into the orbit (Smit, 2008). All of the extraocular muscles, except the superior oblique, are involved during blinking. Blinking is accompanied by rotation of the eyeball directed nasally downward and back. After a blink, the eye rotates back to the initial position (Smit, 2008).

2.1.3 Eye potential

In the epithelial tissue of the cornea and retina, there is a constant flow of ions in and out of the cells through pumps and ion channels. Due to this phenomena, different electrical fields arise in parts of the eye (Zhao et al., 2012). The eye could therefore be described as an electrical dipole, where the cornea is positively charged, and the retina negatively charged (Malmivuo & Plonsey, 2012). This is called the corneoretinal dipole (CRD), and it has a magnitude of 0.4-1 mV.

2.1.4 Electrooculography (EOG)

EOG is a technique that measures the changing potential of the CRD that arise due to movements of the eyeball and can therefore be used to measure eye blinks (Barea, Boquete, Mazo, & López, 2002). The potential can be recorded by sensing induced voltage (μV) between electrodes located in the area of the eyes. Besides the recorded CRD potential, several factors are influencing the obtained signal (Barea et al., 2002). These are movements of the eyelid and various artefacts arising from the placement of electrodes, movements of the head and impact from the lighting. Usually, five electrodes are positioned around the eyes to measure movement in vertical and horizontal direction (Barea et al., 2002). Signals from the vertical movement are obtained by electrodes placed above and below the eye, while signals from the horizontal movement are obtained by electrodes placed beside the lateral canthi of the eyes. The fifth electrode is used as a reference and placed on the forehead. EOG measurements provide accurate data of the eye movement, thus, detailed information of an eye blink. However, it is an invasive technique and therefore difficult to apply outside laboratory set-ups (Benedetto et al., 2011).

When the gaze is directed straight forward, the gaze angle is zero degrees (Ryu, Lee, & Kim, 2019). From this, a baseline can be obtained, which generally is zero volts (Ryu et al., 2019). Eye movements create non-zero gaze angles, which results in negative or positive EOG values. In the horizontal and vertical components, positive values represent one direction, while a negative value represents the opposite direction (Ryu et al., 2019). The EOG values have a linear behaviour for gaze angles of ± 30, which generally is the maximum angle of eye movements (Ryu et al., 2019). The EOG value increases or decrease with approximately 20 μV for every degree the gaze angle changes (López, Ferrero, Villar, & Postolache, 2020). The eyeball moves nasally downward during a blink, and EOG recordings in the vertical direction can therefore be used to evaluate blinking behaviour (Ryu et al., 2019). Figure 2.1 illustrate the changes in amplitude of the EOG signal for different eye movements. Figure 2.1 shows the EOG signal from an eye blink (1), fixation (2), and different degrees of saccadic eye movements (3-5), where 3 represents a lower gaze angle than 5. As seen in the image, an eye blink generate a distinguished signal that starts and ends at the baseline and have a large amplitude relative to saccadic eye movements (Ryu et al., 2019). A higher gaze angle generates a larger change in amplitude relative to the baseline.

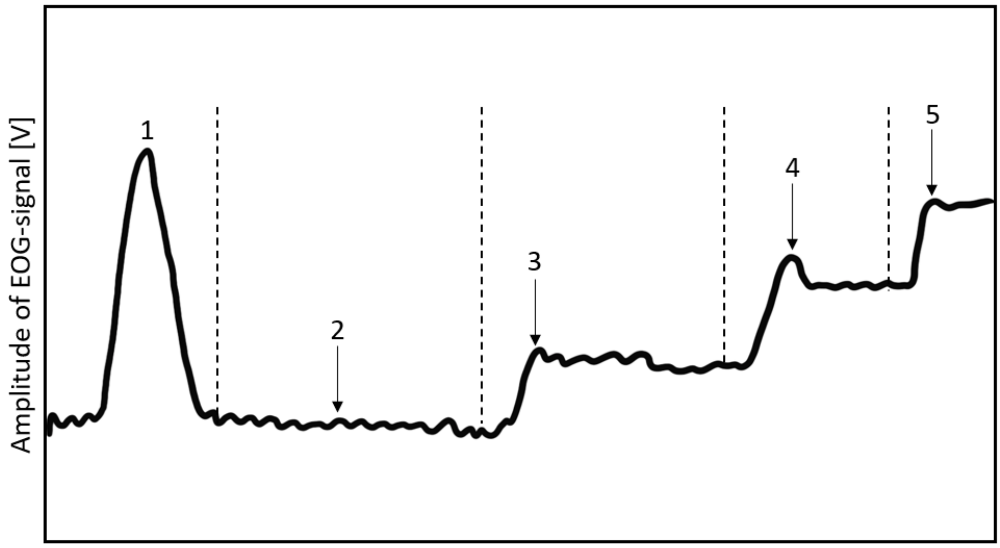

Figure 2.1: A EOG signal with different changes in amplitude due to varies eye movements: eye blink (1), fixation (2), different degree of non-zero gaze angle (3-5).

Baseline drift is a possible threat when analysing visualised waveforms of EOG signals (Ryu et al., 2019). This drift occurs when the signal changes gradually due to superposition and is regularly unrelated to the eyes movements. This phenomenon changes the value of the baseline, and the magnitude of the recorded signals increases. This could make computerised detection of eye activities challenging if it is based on a static threshold (Ryu et al., 2019).

2.1.5 Metrics in eye blink measurements

The start (onset) and the end (offset) of an eye blink can be distinguished in a visualised EOG signal by a sharp negative slope followed by a negative steep slope (Wilson, 1998). Therefore, eye blinks are generally detected by using an algorithm based on derivatives of the EOG signal. There are several ways of analysing blinks detected from the EOG signal, including blink rate (BR), inter-eye blink interval (IEBI), and blink duration (BD) (Gisler, Ridi, Hennebert, Weinreb, & Mansouri, 2015). BR is defined as the number of eye blinks appearing during a specific time period and are measured in blinks/min. Both BD and IEBI are measured in seconds. IEBI is the time between the offset of a previous blink and the onset of the next blink. BD is defined as the time between the onset and the offset of a blink. According to a study performed by Ingre, Åkerstedt, Peters, Anund, and Kecklund (2006), measuring the half amplitude duration (HBD) of an eye blink is more robust. The HBD is defined as the time between the mid-slope of the upswing and the downswing of a blink.

2.2 Mental processes and eye blinks

Studies have shown that mental processes affect blinking behaviour in different ways. Dependent on the process, the blink duration and blink rate are affected. Studies have indicated that visual attention inhibits eye blinks, causing a decrease in blink rate (Shultz et al., 2011), (Ranti, Jones, Klin, & Shultz, 2020), (Sakai et al., 2017). Other findings indicate that visual workload causes an increase of short blinks (Benedetto et al., 2011) and that cognitive workload impairs the inhibition of eye blinks, generating an increase in blink rate (Recarte et al., 2008).

2.2.1 Visual attention

Looking is an act of directing the gaze towards an observed environment, while seeing is an act of perceiving and interpret the surroundings by processing the visual stimulus received through the eyes. Visual attention is the selective mechanism that converts looking into seeing (Carrasco, 2011). A significant function of visual attention is to screen the environment of important information in order to avoid visual overload (Evans et al., 2011).

Blinks abrupt the perception of the surroundings since it causes loss of visual information (Shultz et al., 2011). Therefore, humans tend to blink when convenient and less information gets lost. A theory among several researchers is that visual attention inhibits eye blinks due to the risk of visual loss of the observed environment (Shultz et al., 2011), (Ranti et al., 2020), (Sakai et al., 2017). A study performed by Shultz et al. (2011) generated results that indicated a decrease of blinks during high levels of visual attention. They studied toddlers with Autism Spectrum Disorder and typical toddlers watching a video with physical and affective events. Children with ASD tend to lack interest in social events but have increased reactivity to physical cues. The result showed that the blinking frequency decreased in children with ASD during physical events in the video, while it decreased during affective events in typical toddlers. Based on this, the researchers concluded that the inhibition of eye blinks could measure the level of engagement and visual attention to an event. Results from other studies agree with this conclusion. In the study performed by Shultz et al. (2011), the interest in events was inherent. Another study that aimed to prove inhibition of eye blinks due to visual attention was performed by Ranti et al. (2020). Unlike the study that observed toddlers inherent interest in events, these experimenters proved their theory by investigating experimentally manipulated perceived stimulus salience by assigning tasks to their test subjects. The results showed that the blink rate of the participants in the study decreased during events significant for their assigned task. Based on this, the experimenters concluded that viewer engagement inhibits blinks. A third study validates these results by using electrodermal activity (EDA) that indicate the test subjects engagement and visual attention (Sakai et al., 2017). The test subjects performed a task while the EDA was measured. It was shown that the blink rate increased when the EDA measurement indicated high levels of engagement and increased when the engagement was low.

2.2.2 Visual workload

The visual workload is the level of demand a visual task requires (Webb, Gaydos, Estrada, & Milam, 2010). In-vehicle information systems (IVIS) and the driving task demands visual-manual-cognitive efforts. In an experiment performed by Benedetto et al. (2011), the effect of IVIS on eye blinks was investigated. The test subjects in the experiment were observed while driving in a simulator (single-task) simultaneously as an IVIS task (dual-task) that aimed to increase the test subjects´ visual workload. The results were not significant regarding the blink frequency of the test subjects, but the findings regarding blink duration were. It was found that the frequency of short blinks increased during the dual-task that involved the IVIS, which created a condition that required a high visual workload. Another study performed by Recarte et al. (2008), showed significant results regarding BR. Their results indicated that BR decreased due to inhibition of eye blinks during visual demand.

2.2.3 Cognitive workload

The cognitive workload is the amount of effort a cognitive task demands from a human (Webb et al., 2010). Cognitive tasks are tasks that demand mental processing of new information. A study performed by Recarte et al. (2008) show that performing a secondary cognitive task concurrently to a primary visual task result in increased blink rate. The increase in blink rate depends on what type of secondary cognitive task the person performs (Recarte et al., 2008). The blink rate increases more during talking or calculating secondary tasks compared to secondary listening tasks. This pattern is a consequence of refocusing attention to the secondary task, which impairs the blink inhibition process (Recarte et al., 2008).

2.3 Driving complexity

The driving task requires that the driver forecasts and analyse the road environment and the behaviour of other road users. Simultaneously, the control of the vehicle´s steering and speed needs to be maintained (Faure et al., 2016). Therefore, the traffic environment impacts the complexity of the driving task and the demand of attention (Faure et al., 2016). It also influences the car drivers´ behaviour concerning the body and eye movements (Guidetti et al., 2019).

2.3.1 Level of attention and road complexity

The driving task demand is influenced by several factors, such as traffic density, type of manoeuvre, and the complexity of the road. Numerous experiments have been performed by different researchers where the level of complexity of a road type have been defined (Faure et al., 2016). The complexity level has been investigated based on the level of information processing and vehicle control required during driving. Another factor connected to the road environment and its complexity is the number and degree of difficulty of intersections. Keeping a straight direction is the least difficult manoeuvre of the driving task, while a right turn is slightly more complicated, and a left turn that demands crossing the lane of oncoming traffic is the most difficult. Urban environments have been found to demand higher levels of attention compared to rural roads, and motorways are the least complex road type due to their monotonous nature (Faure et al., 2016).

The road complexity has been shown to have a large impact on the drivers´ workload and attention. Babu, Stapel, Mullakkal-babu, and Happee (2017) concludes that road complexity has a greater influence on the drivers´ workload than the automation level of the vehicle. Furthermore, a study performed by Merat, Jamson, Lai, and Carsten (2012) states that the drivers´ attention was consistent between highly automated driving and manual driving, without a secondary task added.

2.3.2 Saccades and driving environment

Eye movements are important during driving to keep the fovea centralis targeted at the most important visual stimuli. Therefore, saccadic eye movements are of great importance to correctly perceive the environment while driving (Guidetti et al., 2019). Intersections tend to affect drivers to perform repeated saccadic eye movements, and if the saccadic movement is greater than 20-30 degree, it is accompanied by a head movement. When entering an intersection, the gaze directs to the future path, which also induces further saccadic movement (Guidetti et al., 2019). A study performed by Cardona and Quevedo (2014) reveals that the frequency of large amplitude saccades increases with the complexity level of the driving. The majority (59.4%) of these large amplitude blinks was accompanied by movements of the head, which tended to occur while looking at the rearview mirrors. In the study, they also found that spontaneous blinks occurred simultaneously as 87.5% of the large amplitude saccades (Cardona & Quevedo, 2014). It is assumed that blinks co-occur with saccades as a mechanism to stabilise the gaze from the quick movement.

3 Method

The investigation of the usability of eye blinks as a measurement of visual attention was initiated with a literature review in order to gain necessary knowledge. The literature review was followed by a segmentation of the route from the on-road experiment. Then, the eye blinks in each segment were detected, analysed, and processed by using algorithms and functions in MATLAB. The information of the detected blinks were then used to calculate the blink rate (BR) and the half blink duration (HBD), which were used in the statistical analysis.

3.1 Literature review

The project was initiated with a theoretical literature review primarily based on books, scientific articles, and technical reports, found by using the search tools Google, Google Scholar, and searches through Chalmers library. The review was divided into three areas that cover the subjects of the project. First, a theoretical literature review was conducted to gain a deeper understanding of the phenomena of blinking by studying the human eye structure. Secondly, the literature review proceeded by searching for information about the mental processes affecting eye blinks. Lastly, the literature review was ended with reading up on the effects of road complexity on the driving task and blinking behaviour.

The first area involved theory regarding the anatomy of the human eye, eye blinks, and measurements of the eye. When searching for relevant information, the keywords used were “human eye”, “anatomy eye”, “eye blinks”, “blink types”, “muscles blinking”, “eye potential”, “eye movements”, “eye tracker”, “EOG”, and “measure eye blinks”. The purpose of examining the second area was to investigate mental processes that affect human blinking behaviour and previous research that argues for a correlation between mental operations and eye blinks. Keywords used to search for information in this area were “visual attention”, “cognitive workload”, “visual workload”, “visual attention eye blinks”, “cognitive workload eye blinks”, “visual attention eye blinks”, and “visual attention driving”. The third area aimed to investigate the influence of road complexity on driving behaviour. Keywords used to search for information in this area were “road complexity”, “driving behaviour”, “driving behaviour road complexity”, and “automation level complexity”.

3.2 On-road experiment

Data from a previously conducted on-road experiment was used to investigate the eye blinks as an indicator of visual attention. This experiment was performed to analyse the driver´s ability to engage in non-driving related tasks during automated driving. The experiment included ten test subjects (4 males and 6 females) that drove a predetermined route between the two interchanges Fiskebäcksmotet and Åbromotet, on the road Söderleden and Västerleden in Gothenburg. The test subjects drove the route eight times (four times in each direction) with a car equipped with a Wizard of Oz platform that allowed the test subjects to change between manual and simulated automated driving. The Wizard of Oz platform made the test subjects believe that the vehicle controlled the entire driving task, but it was actually one of the experimenters driving from the backseat of the car. The test subjects drove a total of 8 laps of the route, at two different occasions (session 1 and session 2), but with the same set-up and test subjects. Lap 1 was a practice lap, where the test subjects learned to change between the automation levels. In lap 2 and 8 the test subject drove manually, in lap 3 and 4 the test subject supervised the automated driving, and in lap 5 and 6 the test subject did not supervise the automated driving. In lap 7, the test subject performed a non-driving related task (NDRT) during unsupervised automated driving.

Lap 1 and 7 are hypothesised to affect the blinking behaviour due to an increase in cognitive workload. In lap 1 the test subjects practised to turn the automated driving mode on and off, which might demand mental effort. In lap 7 the test subjects performed the NDRT, which aimed to be visually and cognitively demanding. Cognitive workload could affect the blinking behaviour (Recarte et al., 2008) and these two laps are therefore excluded in this project. This leaves six laps (lap 2, 3, 4, 5, 6, and 8) for analysis of eye blinks as an indicator of visual attention.

Data was collected during the on-road experiments for all test subjects, referred to as test subjects 1 to 10. Some data aimed to assess the experience of the NDRT. These observations were not relevant for this project and were therefore excluded. Important data needed to analyse eye blinks as an indicator of visual attention were video recordings and physiological data. The video recordings displayed the traffic environment and the test subject while the physiological data was obtained from EOG measurements, including five electrodes with a sampling frequency of 256 Hz. It was found that the physical data from the second session for test subject 6 was lost. Therefore, the observations from this test subject were excluded from this project.

3.3 Classification of segments using Dewesoft

The software Dewesoft X3 was used to analyse the videos obtained from the on-road experiments (*Dewesoft X3 SP12 Released | Dewesoft*, n.d.). The software allowed the viewer to observe the experiment from four video angles. One video displayed the dashboard and the drivers' grip on the steering wheel. A second camera faced the driver side and captured the environment from the windows of the left side of the car. Another camera was located on top of the dashboard and recorded the interior of the car and the driver from the front. During the video analysis, the most important video angle faced the driving direction, which captured road signs and other details that indicated the car's position on the route. Simultaneously as the videos were displayed, the corresponding driving mode and velocity were also visualised in the Dewesoft software, facilitating the analysis.

The video analysis in Dewesoft was initialised by determining the segmentation of the route into interchange and motorway. Previous research has shown that different driving environments affect the complexity of the driving task (Faure et al., 2016). It has been stated that monotonous motorways have low complexity, while interchanges demand higher vehicle control and information processing resulting in a higher level of attention. Therefore, it was assumed that motorway driving demands less visual attention compared to interchange driving which motivated the segmentation of the route. No regard was taken to the different automation levels during motorway driving since the findings of Merat et al. (2012) indicated that a driver´s attention is unchanged between manual and highly automated driving conditions without performing a secondary task.

The start of the interchange segment was defined as the exit from the motorway, and the end of the interchange was defined as the time when the vehicle left the driveway to enter the motorway. When exiting the motorway, the test subjects were asked three questions (the questions were asked as part of the original study, and the content is not relevant for the current study). The time of the questions overlapped the beginning of each defined interchange segment. Answering questions is likely to influence the cognitive workload of the test subjects, which could increase the blink rate (Recarte et al., 2008). To eliminate this effect, the start of the interchange segments were delayed (i.e., the beginning of the interchange was removed from the analysed data). The length of the time delay (cropping of the start) was 30 seconds, which approximately corresponds to the time for asking and answering the three questions. The time of 30 seconds was determined by analysing the video recordings of a smaller sample of the interchange segments, which means that some uncertainty of the length of the delay could remain. The start of the motorway segment was defined from the first exit on the motorway after the interchange segment. The motorway segment was ended at the last driveway before entering the interchange. The segmentation of the on-road experiment is visualised in Figure 3.1.

Figure 3.1: The route between Fiskebäcksmotet (A) and Åbromotet (C) in Gothenburg from the on-road experiment. The light grey lines represents the interchange segments (A and C) and the dark grey line between point A and C represents the motorway segments (B).

The timestamps for the start and end of each segment were found and compiled in Microsoft Excel for all test subjects and sessions. For some of the experiments, the amount of collected data exceeded the data storage, which generated a loss of videos. In most cases, the lost data were recorded by the camera facing the driving direction. In order to detect the start and stop of segments in these videos, landmarks from the environment were observed from the intact videos in other angles. The landmark from the intact videos was then compared to screenshots from corresponding angles from experiments with all videos stored. Examples of landmarks are road signs, buildings, vegetation, and lampposts. The test subjects drove the car at similar velocities, making it possible to find events on the route by calculating the time between events in already analysed experiments. The combination of using landmarks and calculating time differences made it possible to ensure the position on the route, even without all videos intact. In order to allow further analysis in the MATLAB software, the timestamps for the starts and ends of each segment was compiled in an Excel document that was exported to separate text files that represented both sessions for all test subjects.

3.4 Processing and analysis of EOG signal in MATLAB

To detect the eye blinks in each segment, the EOG signal needed to be analysed and processed in MATLAB. This was performed with an algorithm that detected each blink, which also was analysed manually. Some detected blinks needed to be added, adjusted, or removed manually. The correctly detected blinks were then categorised after their occurrence with saccadic eye movements and the length of the duration.

3.4.1 Synchronisation of physical data and segments

The first step in the MATLAB software was to synchronise the start and end of the segments with the physical data obtained from the EOG measurements. This was made by creating an algorithm that generated a time matrix for each test subject and session containing four columns and 13 rows. The columns represent the start and stop of each segment relative to the time of the videos and the start and stop relative to the physical data. The rows represent the 13 segments defined for one session of the on-road experiment in Dewesoft, of which seven were interchange segments, and six were motorway segments with three different levels of automation. Table 3.1 describes the index of the segments in the time matrix. There was a delay between the recording from the physical data and the videos. This delay was taken into account when calculating the time matrix. The time matrix was then used in a blink detecting function in MATLAB.

Table 3.1: Presents the order of all 13 segments in the time matrix for one session of the on-road experiment.

Index of segment	Description
1	Interchange (Åbromotet)
2	Motorway (Åbromotet to Fiskebäcksmotet)
3	Interchange (Fiskebäcksmotet)
4	Motorway (Fiskebäcksmote to Åbromotet)
5	Interchange (Åbromotet)
6	Motorway (Åbromotet to Fiskebäcksmotet)
7	Interchange (Fiskebäcksmotet)
8	Motorway (Fiskebäcksmote to Åbromotet)
9	Interchange (Åbromotet)
10	Motorway (Åbromotet to Fiskebäcksmotet)
11	Interchange (Fiskebäcksmotet)
12	Interchange (Åbromotet)
13	Motorway (Åbromotet to Fiskebäcksmotet)

3.4.2 Blink detection algorithm and manual control of blinks

A MATLAB function developed by Volvo Cars was used to detect blinks in the EOG data. The function's inputs were the vertical EOG (VEOG) signal, the time matrix, the index of the test subject and the session, and the index of the road segment. When the function had detected all blinks based on the criterion of the algorithm, a window prompted with the VEOG signal visualised. In this window, the user was allowed to analyse the detected blinks by stepping through each detected blink, where the onset, offset, maximum, and half amplitudes were marked for the current blink while the maximum value of the following blink was marked. Figure 3.2 illustrates the prompting window with two detected blinks. The interface of the prompting window also allowed the user to process the detected blinks by adding missed blinks, removing falsely detected blinks or adjust the onset and offset of detected blinks.

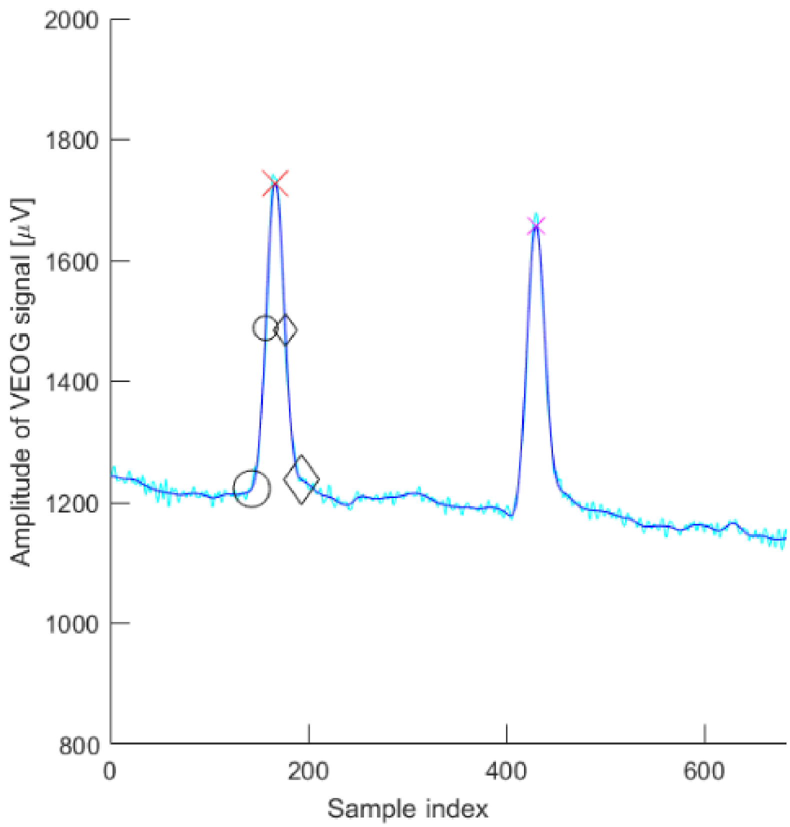

Figure 3.2: Illustration of two blinks taken from the prompting window. The onset, offset, half blink amplitude, and maximum amplitude is marked on the current blink while only the maximum amplitude is marked on the following blink.

The prompting window enabled a manual correction of the result from the blink detecting MATLAB function. Each segment for each test subject was carefully reviewed and compared to the collected video recordings in the manual analysis. If it was difficult to establish the occurrence of a blink based on the EOG signal in the prompting window, the video recordings for that test subject was analysed to determine if it was a blink or not. It was found that the accuracy of the detecting function was sometimes inadequate. In some cases, maximum points were marked as blinks, but the videos revealed that there were no eye closures but other movements of the eye. Figure 3.3 illustrates such a case, where the second marked maximum point was detected as a blink, but the video revealed that the test subject was directing the gaze upwards. Therefore, this false positive blink was removed.

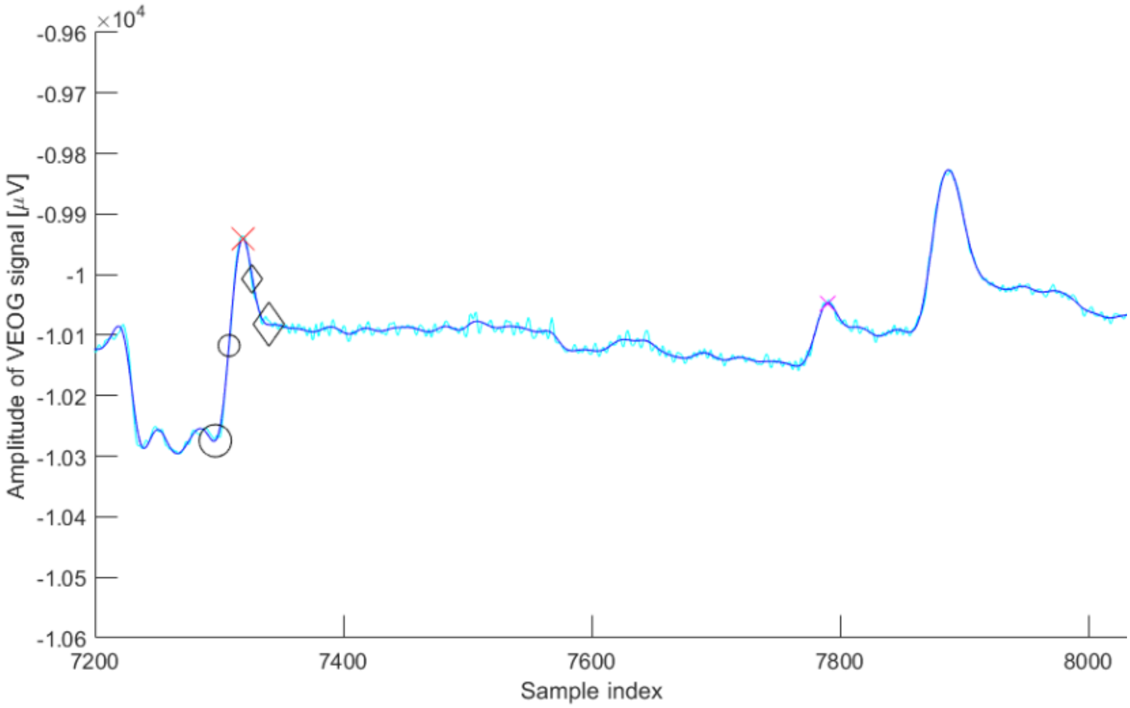

Figure 3.3: The cross marking the second blink was not an actual blink, which the video recordings revealed. Therefore, this false positive blink was removed manually.

In several other cases, the detecting function failed to identify blinks. In the manual review, these blinks were seen as unmarked maximum points, which was further inspected in the videos. If the review proved that the detecting function missed a blink, it was added manually by determining the onset and offset of the blink. Another error occurring due to the detection function was that the onset and offset of the blink were misplaced. This error was eliminated manually by adjusting the length of the blinks by moving the onset and offset mark. Figure 3.4 illustrates such an error and how the error was corrected.

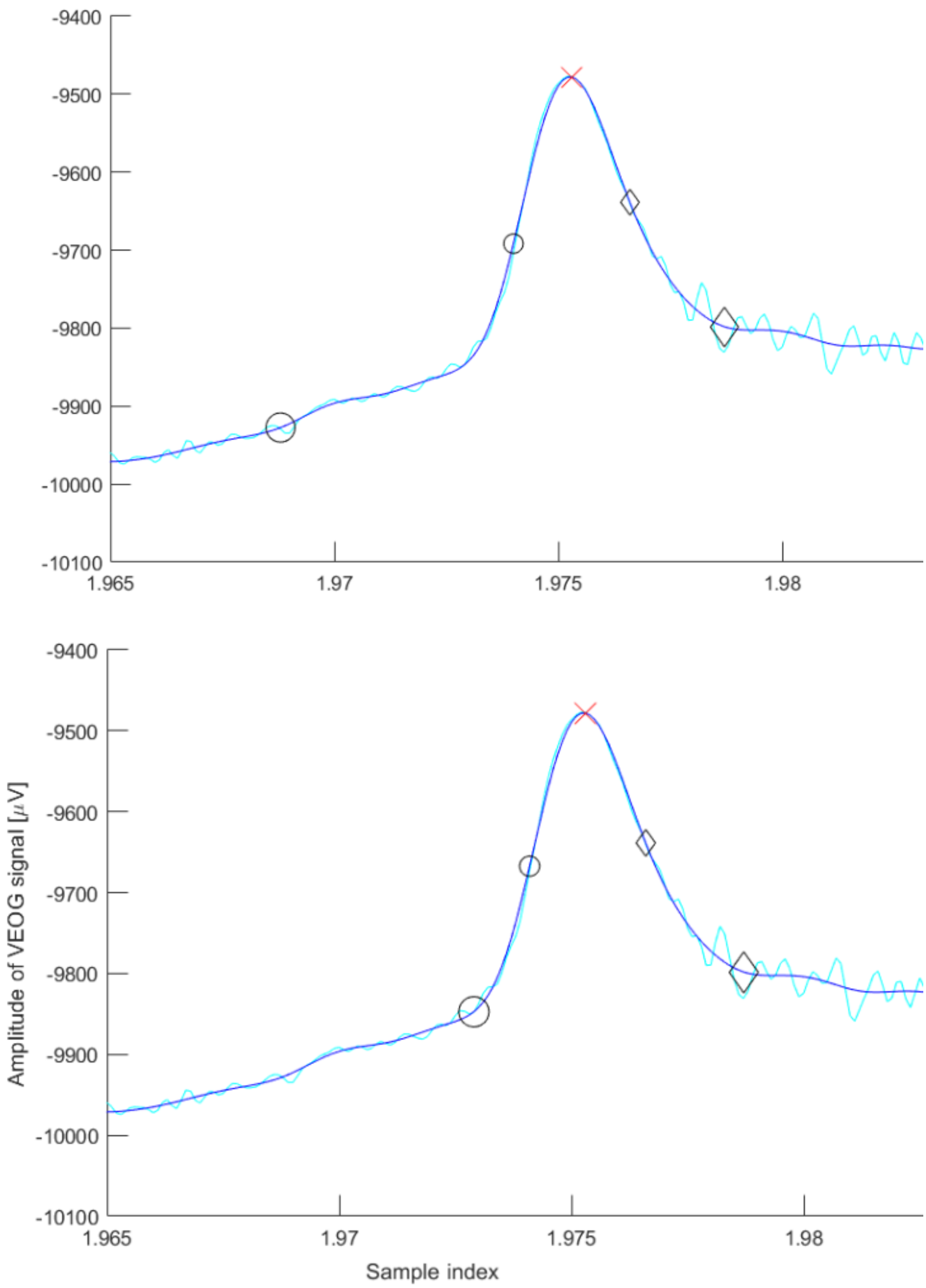

Figure 3.4: The first image illustrates wrongly detected onset of a blink. The second image shows the result after manual adjustment of the onset for that blink.

Several factors influenced the appearance and shape of the EOG signal in the prompting window. From the manual analysis of the detected blinks, it was discovered that speaking, yawning, movement of the upper body, and considerable head movements generated drifts in the EOG signals baseline position. This aggravated the detection of blinks for the MATLAB function detecting the blinks, as well as the manual analysis. An example of a baseline drift caused by a yawn is illustrated in Figure 3.5.

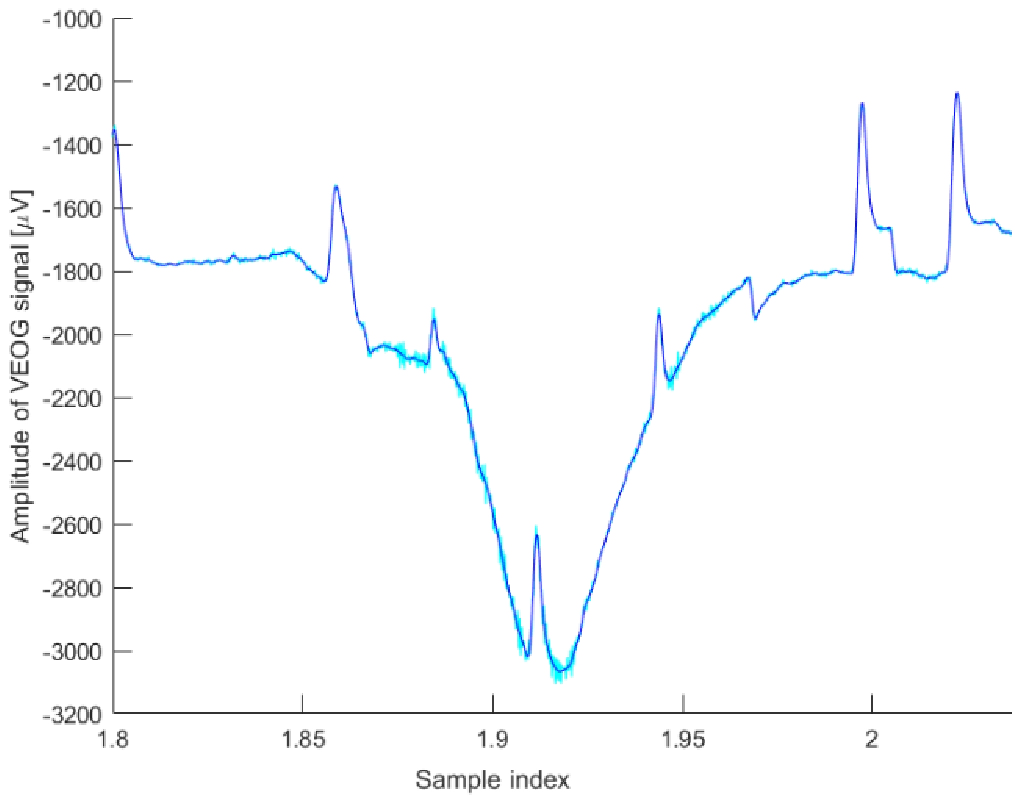

Figure 3.5: Illustration of a baseline drift caused by a yawn.

By analysing the EOG signal and comparing it to the recorded videos, it emerged that the sun also had a substantial impact on blinking behaviour. When the test subjects were exposed to extreme sunlight, the number of blinks increased distinctly. In order to eliminate this factor, periods with abnormally frequent blinks due to sunlight were removed. Figure 3.6 illustrates a period with an increase of eye blinks due to extreme sunlight, which was removed from the data. Due to the limitations of the detecting function, the number of detected blinks were affected by the manual analysis and processing in some cases. If the baseline drift had a significant effect on the EOG signal, the detection of blinks was obstructed. In these cases, it was impossible to ensure that the detected blinks were correct. Therefore, periods where the baseline drift obstructed the analysis, were also removed to guarantee an accurate result. This was made by removing blinks that occurred during extreme baseline drift or sunlight during the manual analysis and processing of the EOG signal. The removal of blinks caused time periods with incorrectly few blinks, affecting the blink statistics. To ensure correct blink statistics, the time from the offset of a correctly detected blink (before the series of removed blinks) to the onset of a correctly detected blink (after the series of removed blinks) was eliminated. The eliminated time was replaced with the mean value of the segments inter-eye blink interval (IEBI). Figure 3.7 shows an example where five blinks are removed due to extreme sunlight, and the time period between the offset of a correctly detected blink to the onset of a correctly detected blink are removed. The removed time period is replaced with the calculated IEBI for that segment.

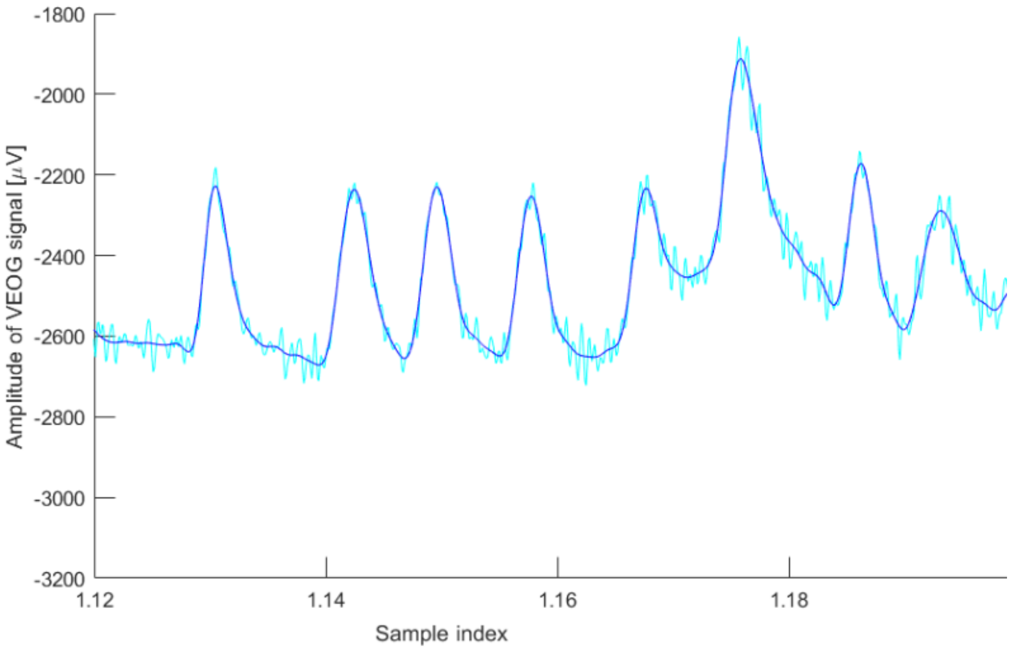

Figure 3.6: An example of an abnormal blinking behaviour due to exposure to extreme sunlight.

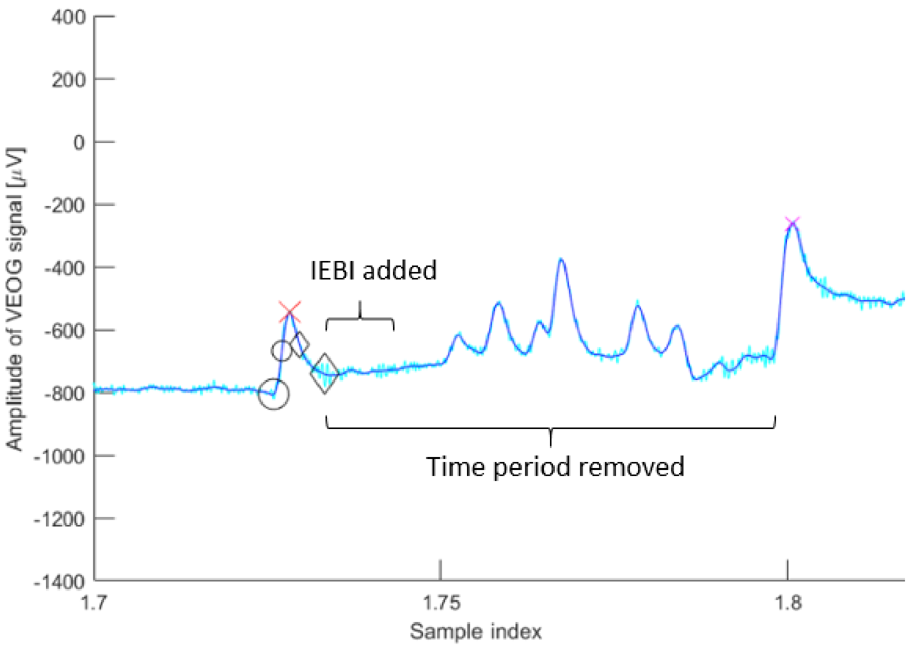

Figure 3.7: Illustration of a removed time period due to abnormal blinking behaviour caused by extreme sunlight. The removed time period is replaced with the mean IEBI for that segment.

From the analysis, it emerged that the EOG signal was highly individual among the test subjects, which appeared as differences in duration, amplitude and shape of the blinks. Hence, the first segments for each new test subject demanded a thorough comparison between the EOG signal and the recorded videos. This was made to establish the (individual specific) appearance (duration, amplitude and shape) of a blink in the EOG signal for a test subject. In some cases, it was challenging to determine the occurrence of a blink due to vague shapes in the EOG signal. From the video recordings, it was established that some of these cases emerged due to the indistinct closure of the eyes during a blink. From the comparison of the VEOG signal and the video recordings, it also arose that horizontal eye movements were pronounced in the VEOG signal in some cases. Therefore, it was necessary to investigate data from each individual electrode to determine if the electrodes were misplaced. Figure 3.8 illustrates the signals from the separate EOG electrodes. Judged by the similar shape of the two graphs, vertical movements were obtained in the electrode that aimed to capture horizontal movements and vice versa. Figure 3.9 also illustrates the EOG signal from separate electrodes but from another test subject. In this case, the two graphs are different, which means that vertical and horizontal movements are isolated and captured by the electrodes aimed for that direction. When analysing the vertical EOG signal, blinks are easier detected without the interference of the horizontal signals. This information highlighted for which test subjects the detection of eye blinks could be difficult and for whom the manual analysis and correction was extra important.

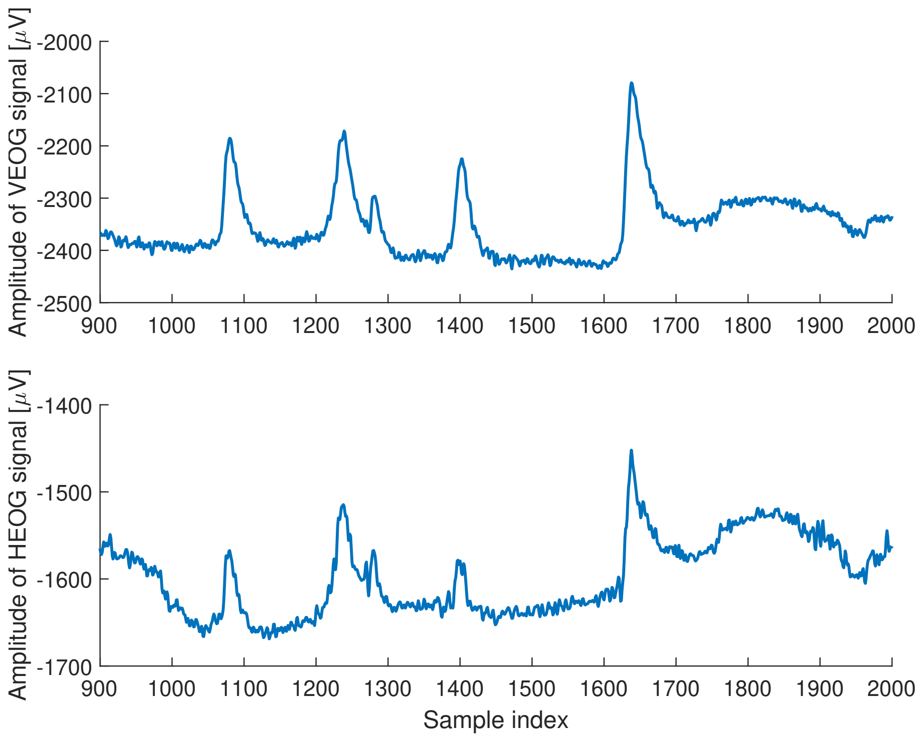

Figure 3.8: The top figure illustrates the VEOG signal. The lower figure illustrates the HEOG signal. Their similar appearance reveals that there was interference between the signals.

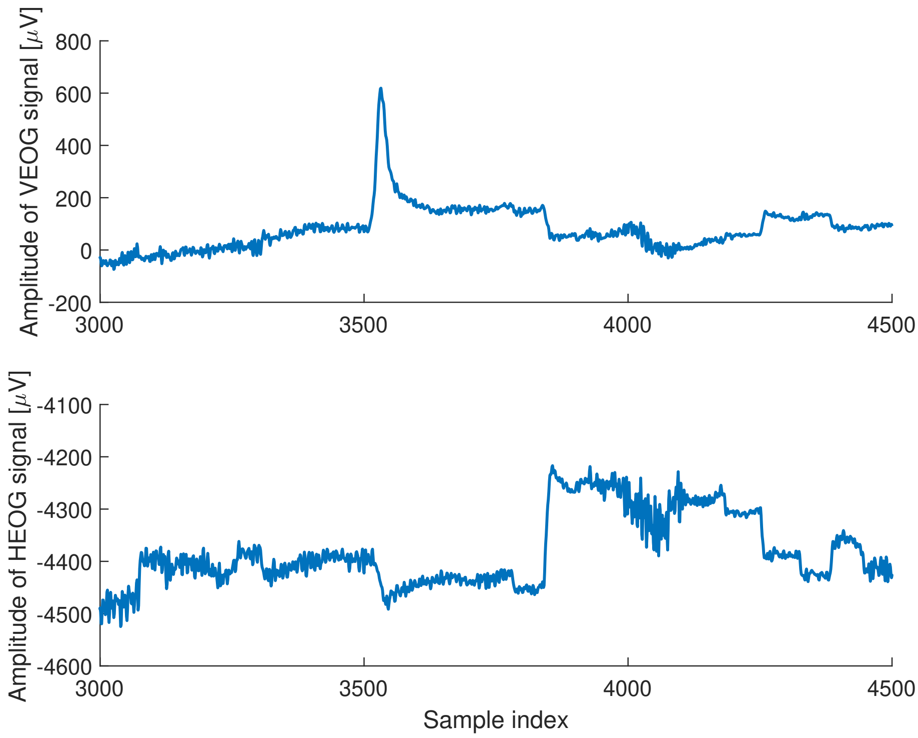

Figure 3.9: The top figure illustrates the VEOG signal. The lower figure illustrates the HEOG signal. There was no interference between the signals in this case, since the appearance of the signals are different.

When each segment was analysed and processed manually, the data were saved in a matrix containing sample index of blink onset (start index), sample index of blink offset (end index), sample index of blink peak, blink duration (ms), and half blink duration (ms). The saved data was then used to categorise blinks after their duration and simultaneous eye movements. For test subject 2, the manual analysis showed that this individual had an inconsistent blinking behaviour with long eye closures rather than eye blinks during some segments. Therefore, it was chosen to exclude the data from this test subject. With test subject 6 excluded as well, the observations from eight test subjects were used for further analysis.

3.4.3 Categorising blinks into blinks with and without large saccadic eye movement

After identifying all blinks, the blinks were categorised based on if they occurred during a large saccadic eye movement or not. A difference in the amplitude of the EOG signal is an indication of a saccadic eye movement (Ryu et al., 2019). Therefore, a change in the amplitude of the onset and offset of a blink implied that the blink occurred during a saccade. An algorithm that detected blinks with and without large saccadic eye movements based on the VEOG and HEOG signal was developed in MATLAB. The algorithm calculated the amplitude difference between onset and offset for each blink for the VEOG signal and the HEOG signal. A higher and a lower threshold were decided in order to categorise the blinks into three groups. The lower threshold value was 30 μV, and the higher threshold was 60 μV, which correspond to approximately 1.5 and 3 degrees of change in the gaze angle. The theory regarding the amplitudes of saccades suggests that small saccades are lower than 5 degrees (Thomas, 1969) and that microsaccades are lower than approximately 0.5 degrees (Ko et al., 2010). Even during fixation, microsaccades occur (Ko et al., 2010). Therefore, according to the literature, the threshold for blinks without saccadic eye movements should have been chosen to 0.5 degrees and 5 degrees as a higher threshold to define larger saccades. These thresholds were tested in the algorithm and showed that many segments did not contain blinks agreeing with the thresholds. Therefore, the thresholds were adjusted to 1.5 and 3 degrees, which generated observations in all groups. The thresholds were compared to the amplitude differences in order to distinguish blinks with and without large saccadic eye movements. The lower threshold determined the highest amplitude difference for a blink occurring without a large saccadic eye movement (Group 1), while the higher threshold determined the lowest amplitude difference for a blink occurring with a large saccadic eye movement (Group 2). A third category was introduced to ensure that each category only included blinks with or without large saccadic eye movements. This category included blinks with an amplitude difference between the two thresholds and was referred to as the grey zone (Group 3).

3.4.4 Categorising blinks into short, medium, and long duration

The identified blinks were also categorised based on the length of the half blink duration. The blinks were divided into three categories: short, medium, and long. A similar grouping of blink duration was performed in a study by Benedetto et al. (2011). To decide the limits for the categorise, Benedetto et al. used the method of k-means clustering analysis. Therefore, the limits for the categories were determined with a k-mean clustering analysis that was performed using the *kmeans* function in MATLAB. From this, short blinks were decided to be less than 100 ms, medium blinks longer than 100 ms but less than 180 ms, and long blinks longer than 180 ms. An algorithm that compared each blink duration towards the decided limits iteratively was created in MATLAB and generated three new data sets with the blinks sorted depending on the blink length. The three new data sets were referred to as Group short (>100 ms), Group medium (100-180 ms), and Group long (<180 ms).

3.5 Calculation of eye blink parameters

The blink rate (BR) for each segment and test subject was calculated by the number of blinks occurring during the segment divided by the total time for the segment. Four different blink rates were calculated for each segment and test subject depending on the categorisation of the blinks: all blinks (BR), blinks without large saccadic eye movement (BR Group 1), blinks with saccadic eye movements (BR Group 2), and blinks in the grey zone (BR Group 3). When analysing the blink duration of each blink, the half blink duration (HBD) was used. In EOG signals, the exact onset and offset of blinks are challenging to identify (Ingre et al., 2006). By calculating the blink duration from the half amplitude of the blink, the exact onset and offset are not needed, which made the definition of the blink duration consistent throughout the data set. The calculations of BR and HBD were then used in the statistical analysis.

3.6 Statistical analysis of calculated eye blink parameters

The observations (BR and HBD) in the data set were not independent since a correlation between the blinking behaviour, and a test subject may be assumed. Therefore, linear mixed-effects models were used for the statistical analysis of the eye blink parameters. Linear mixed-effects models take both random and fixed effects into account. The eight test subjects are a sample of the population and are supposed to account for variability among the total population. Therefore, the test subjects are the random effect in the mixed-effects model. On the other hand, the fixed effects are expected to operate in a predicted way across the sample. The random effect consists of grouping variables and the fixed effects of predictor variables. The data to be fitted were the observations (BR and HBD) and are called the response variables. The statistical analysis was performed in MATLAB by using the function *fitlme*. This function fitted the observations in the data set to the linear mixed-effects model and returned statistical parameters of the fitted model. Parameters of interest in this statistical analysis were p-value and estimate. In the *fitlme* function, the linear mixed-effects model was specified by a formula which structure differed dependent on the data that was analysed. The residuals of a linear mixed-effects model are assumed to be normally distributed. Therefore, the distribution of the residuals obtained from the linear mixed-effects model was investigated after the use of the *fitlme* function in order to state how well the data became fitted. This was made with a null hypothesis test performed with the MATLAB function *lillietest*. By using the residuals as input and specifying that the null hypothesis was that the residuals are normally distributed, the function returned 1 if the null hypothesis was rejected and 0 if the null hypothesis was accepted at a 5% significance level. The statistical analysis consisted of multiple comparisons. When using multiple statistical testing, multiple testing correction is needed to decrease the risk of false positives. The Bonferroni correction method implies that the p-value of one test should be lower than the significance level divided by the number of performed tests. No further analysis was made regarding the multiple testing correction, except for highlighting, when appropriate, that the Bonferroni correction should be considered. The p-values are provided to allow the readers to interpret the results themselves.

3.6.1 Statistical analysis of blink rate depending on road type

To enable the analysis of the BR with the *fitlme* function in MATLAB, a table was created. Table 3.2 is an outline of the table. The table stated the BR for all 13 segments for both experiment sessions for the eight test subjects. This gave a table with 208 blink rate observations (13 x 2 x 8). The second column states the number of the test subject (1, 3, 4, 5, 7, 8, 9, 10). The third column presents if the BR in that row was obtained in experiment session 1 or 2. The last column road type described if the BR was obtained from an interchange (I) or a motorway (M) segment.

Table 3.2: Table categorising each BR into test subject, session, and road type. x_1-x_{208} represents the different BR.

BR	Test subject	Session	Road type
x_1	1	1	I
$\vdots$	$\vdots$	$\vdots$	$\vdots$
x_{208}	10	2	M

Before analysing the differences in BR between the two road types with the linear mixed-effects model, it was needed to determine possible differences in BR between the two driving sessions for each test subject. This was needed since the grouping of the data affects the result from the fitted model, and it may be assumed that an individual has a specific blinking behaviour that is consistent for both sessions. Since blinking behaviour might differ depending on the complexity level of the road type, the differences between the blink rate for the two sessions were analysed for both motorway and interchange together (Group I & M, 13 segments), motorway (Group M, 6 segments), and interchange (Group I, 7 segments) separately. The linear mixed-effects model was used to evaluate the differences between the two sessions, with the session as a predictor variable (fixed effect) and the blink rate as the response variable. The formula specifying the model used for the statistical analysis of session on an individual level is seen in table 3.3. As stated in the table, the formula used for analysis lacks the grouping variable since the linear mixed-effects model was applied to the data separately for each test subject. To do so, the observations from the created table were picked out based on the number in the second column in Table 3.2, specifying the test subject. The *fitlme* function was performed in MATLAB for all of the three groups eight times with the observations for each test subject. The returned results from the *fitlme* function revealed if there were any differences between the two sessions for the test subjects and how this factor needed to be accounted for in the steps that followed in the statistical analysis. The differences between the sessions were visualised with a scatter plot where each coordinate described the changes in BR for a segment. The distribution of the residuals obtained from the linear mixed-effects model was investigated to see if any model assumptions were violated. This was made with the MATLAB function *lillietest*.

Table 3.3: The formula that specified the linear mixed-effects model in the MATLAB function *fitlme*. BR is the response variable and session is the predictor variable.

Level	Formula
Individual	'BR $\sim$ 1 + Session'

When the grouping of the observations was determined based on the correlation between the sessions, the statistical analysis of the differences in BR among the two road types could be performed. A linear mixed-effects model was used for this analysis as well. The formulas specifying the model used for analysis on a group level and an individual level are stated in Table 3.4. In the formula used for analysis on a group level, the last term takes the sessions' interaction effect into account. By assigning the road types (interchange or motorway) as the predictor variable, the function *fitlme* returns the correlation in blink rate between interchange and motorway. As in the analysis of the session, the statistical analysis on an individual level was performed for each of the test subjects separately, with the data for each test subject extracted from the table described in Table 3.2, with random effects from the session. The differences in BR between the two road types were visualised with bar plots. Each bar illustrates the BR in one segment, and the colour of the bar corresponded to the road type. For all the fitted models, the residuals' distribution was investigated to examine the applicability of the linear mixed-effects models. Like previous, this was made by using the MATLAB function *lillietest*.

Table 3.4: The formulas that specified the linear mixed-effects model in the MATLAB function *fitlme* when analysing the differences in BR between interchange and motorway.

Level	Formula
Group	'BR $\sim$ 1 + RoadType + (1|TestSubject)+(1|TestSubject:Session)'
Individual	'BR $\sim$ 1 + RoadType + (1|Session)'

Since the driving behaviour is different depending on the traffic environment complexity, it was of interest to investigate the differences in interchange and motorway based on if blinks occurred during large saccadic eye movements or not. For this analysis, a second table was needed before using the linear mixed-effects model. The outline of the second table is seen in Table 3.5. This table contained three different blink rates calculated by the number of blinks in Group 1, Group 2, and Group 3 in each segment.

Table 3.5: Table categorising BR for Group 1, Group 2, and Group 3 into test subject, session, and road type. Where x_{GroupN_1}-$x_{GroupN_{208}}$ represents the different BR for each segment and group (N = 1, 2, 3).

BR Group 1	**BR Group 2**	**BR Group 3**	**Test subject**	**Session**	**Road type**
x_{Group1_1}	x_{Group2_1}	x_{Group3_1}	1	1	I
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$x_{Group1_{208}}$	$x_{Group2_{208}}$	$x_{Group3_{208}}$	10	2	M

When the second table was created, the formula specifying the linear mixed-effects model was set up. The formulas used for this analysis was the same as in the analysis of the differences in road type (see Table 3.4), but the observations in the data set were different. In this case, the linear mixed-effects model was applied to the three groups of blink rates separately. The differences in BR between interchange and motorway for each group were illustrated with bar plots. Separate bar plots were created for each group, where the bars represented the BR for one segment, and the colour of the bar visualised the road type of the segment. The distribution of the residuals of the models was then used to evaluate the fit by using the MATLAB function *lillietest* once again.

3.6.2 Statistical analysis of half blink duration depending on road type

The BR was a parameter describing several numbers of blinks in one segment with one value. The HBD, on the other hand, is a parameter describing each blink (across all data), generating a much larger data set with 21460 observations. As for the BR, the statistical analysis of the HBD was initiated by creating a table that categorises each blink and states to which test subject it belonged to, in which driving session it occurred, and if it was obtained during motorway (M) driving or interchange (I) driving. A describing example of the table is seen in Table 3.6.

Table 3.6: Table categorising the HBD into test subject, session and road type. y_1-y_{21460} represents the HBD for all blinks.

HBD	**Test subject**	**Session**	**Road type**
y_1	1	1	I
$\vdots$	$\vdots$	$\vdots$	$\vdots$
y_{21460}	10	2	M

Since the data set changed from the analysis of BR, the correlations between sessions needed to be re-evaluated. This was made with the linear mixed-effects model, where the predictor variable was the sessions. The formula specifying the analysis model on an individual level is seen in Table 3.7. For the individual analysis, data was extracted from the table that concerned each test subject, respectively. For this analysis, the data was also divided into three groups. The first group contained all observations (Group I & M), the second group contained all observations obtained during motorway driving (Group M), and the third group contained observations obtained during interchange driving (Group I). This meant that the linear mixed-effects model was performed three times for each test subject. To perform the linear mixed-effects model, the MATLAB function *fitlme* was used with the formula and the three data sets created for each test subject. The differences in the HBD distribution between the two sessions for each group were illustrated with box plots. The normality of the distribution of the residuals was then investigated with the MATLAB function *lillietest* in order to decide if the residual normality model assumptions were violated.

Table 3.7: The formula specifying the linear mixed-effects model in the MATLAB function *fitlme*.

Level	Formula
Individual	'HBD $\sim$ 1 + Session'

When the difference of the sessions was determined, the formulas specifying the models for analysing the differences in HBD between motorway and interchange could be set up. The formulas used in the linear mixed-effects models are seen in Table 3.8. As seen in the table, the road type was the fixed effect for the model in both the group and individual formula. In the formula specifying the model for analysis on a group level, the interaction effect of the session was taken into account. For the analysis on an individual level, the grouping variable is changed to only account for differences in session. The differences in the distribution of HBD between interchanges and motorways were illustrated with box plots. The distribution of the model residuals were examined with the function *lillietest* in MATLAB. If the distribution was normal, the model was applicable to the data, and if not, the model assumptions were violated.

Table 3.8: The formulas specifying the linear mixed-effects model in the MATLAB function *fitlme* when analysing the differences between interchange and motorway for HBD.

Level	Formula
Group	'HBD $\sim$ 1 + RoadType + (1|TestSubject)+(1|TestSubject:Session)'
Individual	'HBD $\sim$ 1 + RoadType + (1|Session)'

Previous research has shown that the duration of blinks varies dependent on the visual workload, which in turn is affected by the road environment complexity (Benedetto et al., 2011)(Faure et al., 2016). Therefore, a statistical analysis was performed that investigated the differences in long, medium, and short blink duration between the two road types interchange and motorway. To enable this analysis, three tables containing short (Group short), medium (Group medium), and long blinks (Group long) separately were set up. The proportion of short, medium, and long blinks were calculated by dividing the number of blinks in each group by the total number of blinks. The changes in proportions between motorway and interchange were investigated in MATLAB with the function *fitlme*, where the formulas in Table 3.8 specified the models. The differences in Group short, Group medium, and Group long between interchange and motorway were illustrated with two line plots, representing the two road types. The residuals obtained from the linear mixed-effects model were analysed with the MATLAB function *lillietest* in order to decide if the distributions were normal.

A statistical analysis investigating the effect of large saccadic eye movements on the HBD during motorway and interchange driving was performed. Each blink had been categorised dependent on if they coincided with a large saccadic eye movement or not. In order to apply the linear mixed-effects model to this data, three new tables were needed. These tables had the same design as in Table 3.6, but they only contained the duration of blinks from Group 1, Group 2, and Group 3 separately. The linear mixed-effects model was performed on all of the three groups on a group level and an individual level. The formulas specifying the models was the same as in Table 3.8. As in previous analyses, the MATLAB function *fitlme* was used to conduct the linear mixed-effects model. The differences of the HBD distribution between interchange and motorway for the three groups were illustrated with box plots. The analysis of the differences in blink duration for interchange and motorway with regard to saccadic eye movements was ended with an investigation of the distribution of the residuals from the model. This was performed by using the MATLAB function *lillietest*, which revealed if the distribution of the residuals were normal or not.

4 Result

Linear mixed-effects models were used to analyse the two research questions. The results obtained from analysing the differences in BR between interchange and motorway is presented first, followed by the results achieved by investigating the differences in HBD between the two road types.

4.1 Difference between blink rate and road type

The following section presents the differences in BR between session 1 and session 2, the differences in BR between interchange and motorway, and the differences in BR Group 1, BR Group 2, and BR Group 3 between interchanges and motorways.

4.1.1 Differences in blink rate between session 1 and 2

The purpose of analysing differences in BR between session 1 and session 2 on an individual level was to determine whether an interaction effect between test subject and session needed to be considered when using linear mixed-effects models. In order to assess the difference in BR between the two sessions, a linear mixed-effects model was performed for Group I & M, Group I, and Group M separately, since the blinking behaviour might differ depending on the level of road complexity.

The results obtained from the analyses are presented in Table 4.1. As seen in the table, test subject 1, 4, 5, 8, and 9 have no significant p-values, indicating no difference in BR between session 1 and sessions 2. What stands out in the table are the results for test subject 3 and 7. These two test subjects have significant p-values and high positive estimate values (8.36-14.22 blinks/min) for all groups, indicating that the BR is higher during session 2 than during session 1. It is seen in the table that test subject 10 has a significant p-value and a high positive estimate value (=9.94 blinks/min), which suggests that this test subject tend to blink more frequently during interchanges in session 2 than during interchanges in session 1. The data in the table shows that only test subject 3 (Group M) has a non-normal distribution of the residuals. This implies that the model assumption is violated for test subject 3 when performing the fit linear mixed-effects model for Group M.

Table 4.1: The results from analysing the differences in BR between session 1 and session 2 on an individual level. A significant p-value (<0.05), is highlighted with a grey cell.

Individual level				
Test subject	**Group**	**p-value**	**Estimate (blinks/min)**	**Residuals' distribution**
1	I & M	0.25	-2.22	normal
	I	0.49	-1.81	normal
	M	0.33	-2.69	normal
3	I & M	1.65e-06	11.30	normal
	I	0.0098	8.79	normal
	M	1.51e-08	14.22	non-normal
4	I & M	0.071	-5.40	normal
	I	0.15	-6.67	normal
	M	0.12	-3.93	normal
5	I & M	0.20	-2.84	normal
	I	0.22	-4.61	normal
	M	0.72	-0.77	normal
7	I & M	0.00033	8.79	normal
	I	0.0041	9.15	normal
	M	0.0036	8.36	normal
8	I & M	0.91	0.34	normal
	I	0.46	2.00	normal
	M	0.51	-1.59	normal
9	I & M	0.51	-1.83	normal
	I	0.16	-5.46	normal
	M	0.51	2.40	normal
10	I & M	0.063	5.39	normal
	I	0.0067	9.94	normal
	M	0.97	0.081	normal

The figure illustrates the relationship between BR for session 1 and BR for session 2. In the figure, the grey circles represent the distribution of BR in Group I and the black squares show the distribution of BR in Group M. As seen in the figure, an overall trend is that the distribution of grey circles and black squares are evenly distributed around line $x = y$ between the two sessions. This trend suggests that there is no difference in BR between the two sessions. However, few individuals show the opposite trend, with a difference in BR between session 1 and session 2. In this cases, BR is higher during session 2, which is seen in Figure 4.1 by having most of the grey circles and black squares above line $x = y$.

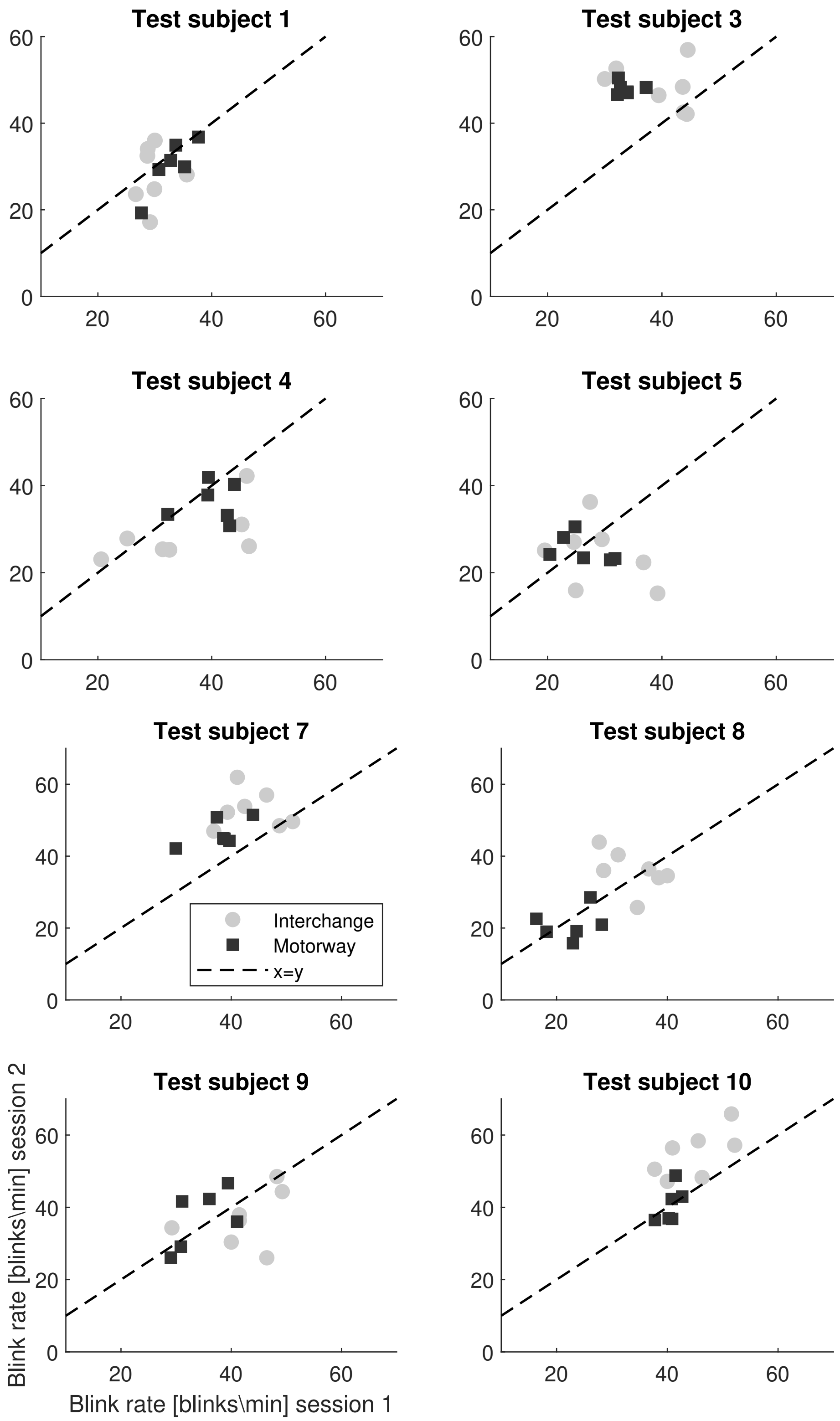

Figure 4.1: The relationship between BR for session 1 and BR for session 2 for each test subject. All coordinates represents the distribution of BR for Group I & M. The grey circles represents the distribution of BR for Group I and the black squares represents the distribution of BR for Group M.

4.1.2 Differences in blink rate between interchange and motorway

The first research question aimed to analyse differences in BR between interchange and motorway on a group level and an individual level. Based on previous findings (Faure et al., 2016), interchanges are assumed to have higher road complexity than motorway segments. Hence, interchange segments demand higher levels of visual attention. Therefore, the hypothesis is that BR is lower during interchange segments due to inhibition of eye blinks due to a higher level of visual attention.

The results derived from analysing differences in BR between the two road types on a group level and an individual level are summarised in Table 4.2. It is seen that all of the distributions of residuals are normal, which indicate that the model assumptions are fulfilled for all the fitted models. As seen in the table, the p-value for group level is significant, which implies a significant difference in BR between interchange and motorway. The negative estimate value of -3.41 blinks/min (group level) suggests that test subjects tend to blink less frequently during motorway segments than interchange segments. This result contradicts the hypothesis of a lower BR during interchange segments compared to motorway segments. The distribution of BR between interchange and motorway on a group level is visualised in Figure 4.2. The blue bars represent the BR calculated with the number of blinks occurring during an interchange segment, while red bars show the BR calculated with the number of blinks occurring during a motorway segment. The BR is plotted in ascending order, clarifying that the BRs tend to be higher during interchange segments.

The results for individual level in Table 4.2 shows that there is no difference in BR between the two road types for test subject 1, 3, 5, and 9. It is seen in the table that test subject 4, 7, 8, and 10 have a significant difference between interchange and motorway. Interestingly, the data in the table shows that test subjects 7, 8, and 10 have negative estimate values while test subject 4 has a positive value of the estimate. A negative estimate implies that test subjects 7, 8, and 10 tend to blink less during motorway segments than during interchange segments. The results for these three test subjects contradict the hypothesis. A positive estimate indicates the opposite trend, suggesting test subject 4 tends to blink more during motorway segments than interchange segments. The result for test subject 4 agrees with the hypothesis. Figure 4.3 shows the distribution of BR with regard to the two road types for each test subject. The blue bars represent the BR calculated with the number of blinks occurring during an interchange segment, while red bars show the BR calculated with the number of blinks occurring during a motorway segment. As seen in the figure, there is a cluster of blue bars towards the right side of the distribution for test subjects 7, 8, and 10. What stands out in the figure is the distribution for test subject 4. It is seen that there is a cluster of red bars towards the right side of the distribution.

Table 4.2: The results from investigating the differences in BR between interchange and motorway on a group level and an individual level. A significant p-value (<0.05), is highlighted with a grey cell. Note that one p-value is close to 0.05, which may not be considered significant if Bonferroni´s multiple test correction is applied.

Group level			
p-value		**Estimate (blinks/min)**	**Residuals' distribution**
0.00015		-3.41	normal
Individual level			
Test subject	**p-value**	**Estimate (blinks/min)**	**Residuals' distribution**
1	0.17	2.68	normal
3	0.079	-3.22	normal
4	0.039	6.14	normal
5	0.74	-0.76	normal
7	0.0026	-6.06	normal
8	1.90e-07	-13.08	normal
9	0.17	-3.79	normal
10	0.00032	-9.18	normal

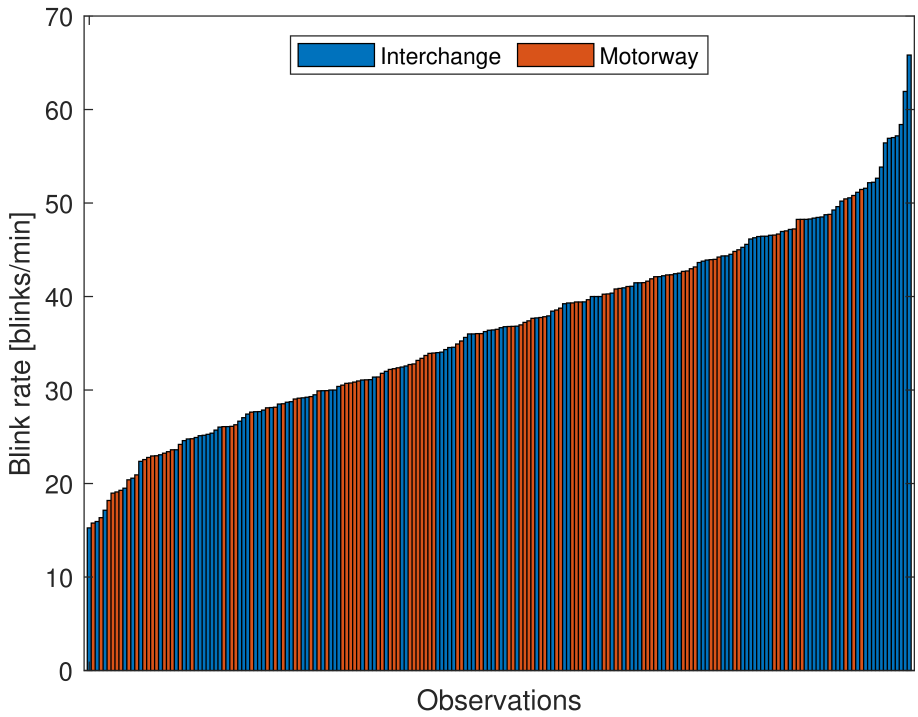

Figure 4.2: Bar plot illustrating the distribution of BR for all test subjects and segments. There is a cluster of blue bars at higher BR and a cluster of red bars at lower BR.

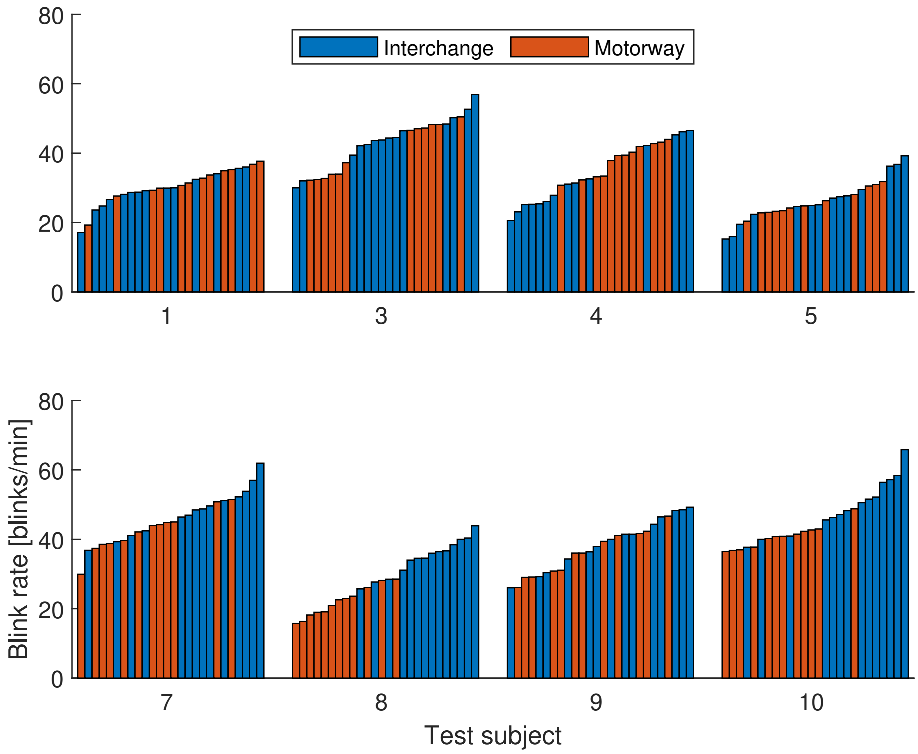

Figure 4.3: Bar plot illustrating the distribution of BR with regard to motorway and interchange for each test subject. Test subject 7, 8, and 10 have similar appearance with more blue bars at the right side of the distribution while test subject 4 shows the opposite trend.

4.1.3 Effects of saccadic eye movements

The driver behaviour is assumed to differ between interchange and motorway, based on their varying complexity levels. Previous studies have indicated that the number of saccades increases with the traffic environment complexity and that the majority of large amplitude saccades are accompanied by eye blinks (Guidetti et al., 2019), (Cardona & Quevedo, 2014). Therefore, a hypothesis is that the number of eye blinks co-occurring with saccadic eye movements is higher in interchange segments than motorway segments. Therefore, the difference in BR Group 1, BR Group 2, and BR Group 3 between motorway and interchange segments are analysed.

The results obtained from analysing the differences in BR Group 1, BR Group 2, and BR Group 3 between motorway and interchange are presented in Table 4.3. As seen in the table, each group on a group level have a significant p-value. This implies a significant difference in BR between the two road types with respect to Group 1, Group 2, and Group 3. It can be seen from the data in the table that Group 1 and Group 3 have positive estimate values. This means that it is more common with blinks occurring during a more steady gaze (Group 1) in motorway segments compared to interchange segments. It is also more common with blinks categorised in the grey zone during motorway segments than interchange segments. Group 2 has a high negative estimate, indicating that blinks co-occurring with a large saccadic eye movement are more common during interchange driving than motorway driving. For Group 1 and Group 3 the distributions of the residuals are non-normal, which means that the model assumptions for these fitted models are violated. Figure 4.4 illustrates the distribution of BR between interchange and motorway on a group level for Group 1, Group 2, Group 3 separately. Blue bars represent BRs calculated during interchange segments, and red bars represent BRs calculated during motorway segments. As seen in Figure 4.4, Group 1 have a cluster of red bars with an increased BR. The opposite behaviour can be seen for Group 2. For Group 2 there are a majority of blue bars in the right parts of the distributions. No clear division of blue and red bars are distinguished for the distribution of BR between the two road types for Group 3.

The results obtained from analysing the differences in BR Group 1, BR Group 2, and BR Group 3 between interchanges and motorways on an individual level are seen in Table 4.3. Test subject 3, 5, and 10 have significant p-values for each group. The estimate value is positive for Group 1 and Group 3, while Group 2 have a negative estimate value for these three test subjects. A positive estimate implies that the BR for that group is higher during motorways than during interchanges, and a negative estimate value indicates the opposite. For test subject 1, 7, 8, and 9, only one of three groups have a significant p-value. Test subject 1 has a significant p-value for Group 1 and a positive estimate value, which means the test subject has more blinks occurring with a more steady gaze during motorway driving than interchange driving. Test subject 7 and 8 have significant p-values for Group 2 and negative estimate values, indicating that these two test subjects tend to have a higher number of blink-saccadic pairs during interchange segments than motorway segments. Test subject 9 has a significant p-value and a negative estimate value for Group 3, which indicates that the number of grey zone blinks is lower during motorway segments. It is seen in the table that some p-values are above 0.05, indicating no difference in BR between motorway and interchange when considering different types of blinking (groups). As seen in the table, test subject 4 (Group 2), 9 (Group 1), and 10 (Group 1) have non-normal distributions of the residuals. For these fitted models, the model assumptions are not fulfilled.

Table 4.3: The results from evaluating the effects of saccadic eye movements by the differences in BR Group 1, BR Group 2, and BR Group 3 between the two road types on a group level and an individual level. A significant p-value (<0.05), is highlighted with a grey cell. Note that some of the p-values are close to 0.05, which may not be considered significant if Bonferroni´s multiple test correction is applied.

Group level				
Group		**p-value**	**Estimate (blinks/min)**	**Residuals' distribution**
1		4.35e-08	1.69	non-normal
2		7.036e-13	-6.08	normal
3		0.0015	0.99	non-normal
Individual level				
Test subject	**Group**	**p-value**	**Estimate (blinks/min)**	**Residuals' distribution**
1	1	0.00045	3.75	normal
	2	0.72	-0.65	normal
	3	0.64	-0.41	normal
3	1	0.00013	1.96	normal
	2	5.15e-05	-8.29	normal
	3	6.32e-05	3.10	normal
4	1	0.064	1.45	normal
	2	0.14	3.56	non-normal
	3	0.14	1.13	normal
5	1	0.0012	3.73	normal
	2	0.00033	-7.24	normal
	3	0.0022	2.75	normal
7	1	0.18	0.97	normal
	2	3.61e-05	-7.66	normal
	3	0.52	0.63	normal
8	1	0.87	-0.066	normal
	2	2.88e-08	-13.56	normal
	3	0.29	0.55	normal
9	1	0.74	0.38	non-normal
	2	0.33	-1.85	normal
	3	0.029	-2.32	normal
10	1	0.034	1.32	non-normal
	2	1.96e-05	-12.97	normal
	3	0.0011	2.46	normal

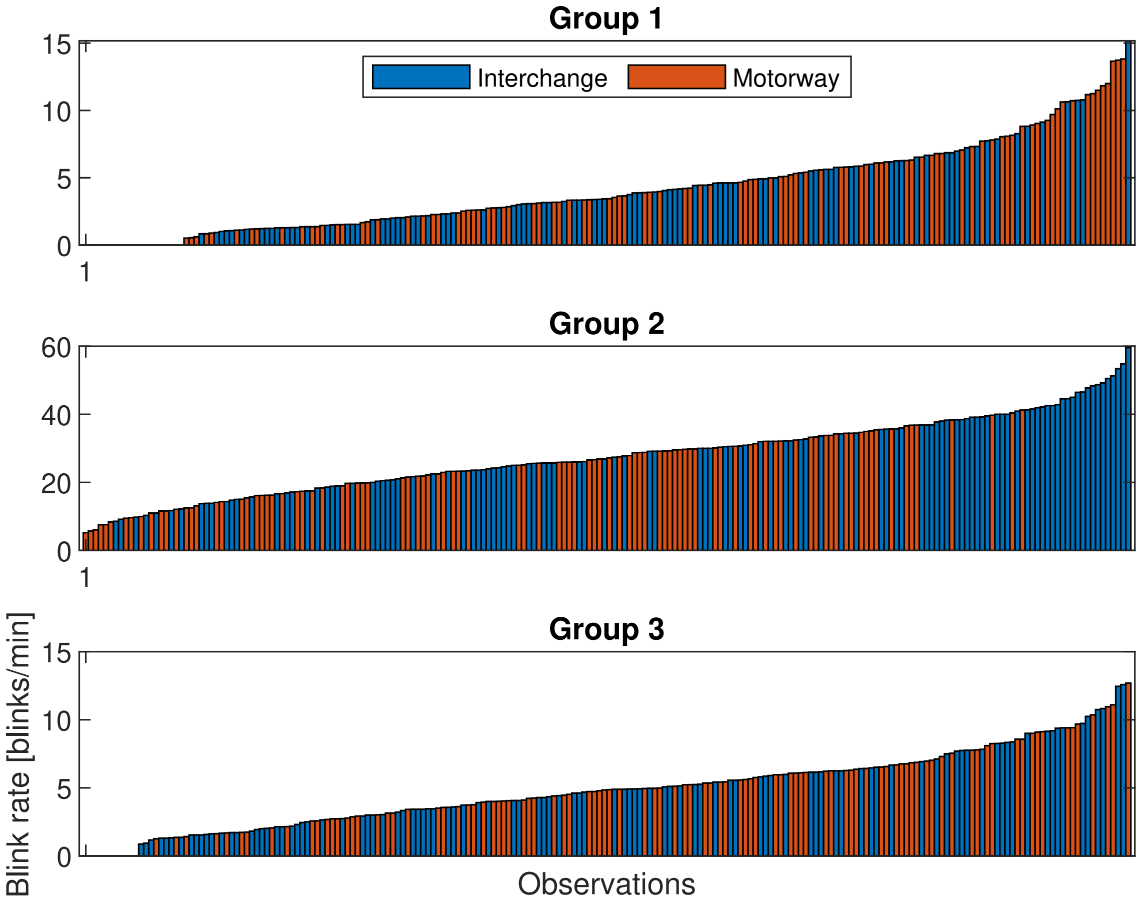

Figure 4.4: Bar plot of the distribution of BR Group 1, BR Group 2, and BR Group 3. In the plot for Group 2 there is a distinct cluster of interchange segments with higher BR. The opposite pattern is seen for Group 1, while the pattern is more vague for Group 3.

Figure 4.5, 4.6, and 4.7 illustrates the distribution of BR between the two road types for Group 1, Group 2, and Group 3 separately. Blue bars represent the BRs obtained from interchange segments, and red bars represent BRs calculated from motorway segments. Figure 4.5 shows the distribution of BR calculated based on blinks from Group 1. It is seen in the figure that test subject 1, 3, 5, and 10 have more red bars to the right in the distributions. Figure 4.6 illustrates the distribution of BR calculated based on blinks from Group 2. What stands out in Figure 4.6 is the distinct division of red and blue bars for test subject 3, 5, 7, 8, and 10. For these test subjects, blue bars are clustered at the right side of the distributions. Figure 4.7 display the distribution of BR calculated based on blinks from Group 3. As seen from the figure, test subject 3, 5, and 10 have more red bars with higher BR, while the opposite trend is seen for test subject 9. Figure 4.5-4.6, shows the overall tendency that blinks-saccadic pairs (Group 2) increases during interchanges while blinks occurring without large saccades (Group 1) increases during motorway segments.

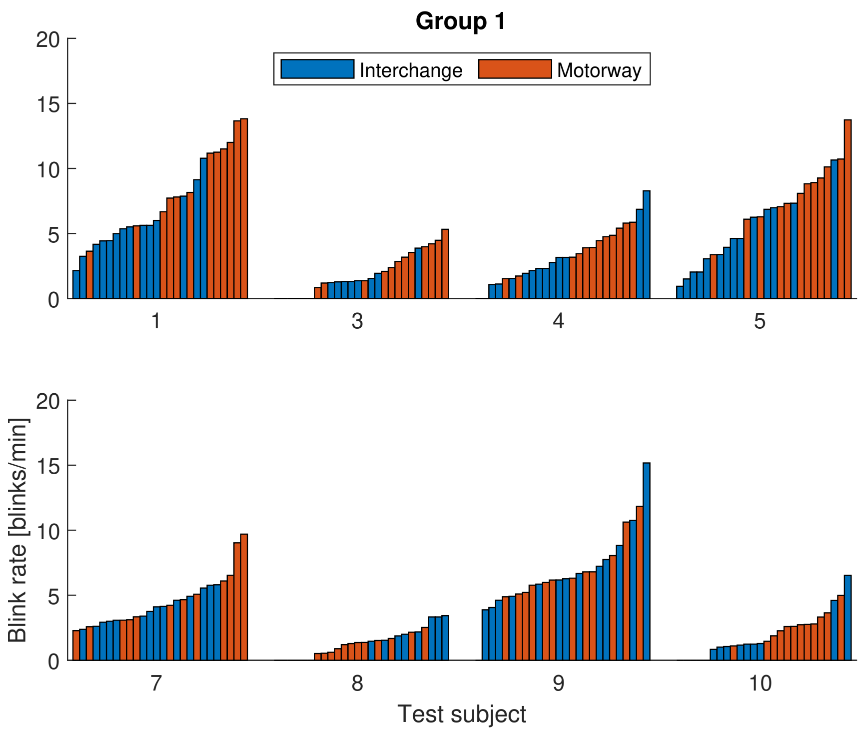

Figure 4.5: Bar plot of the distribution of BR calculated from blinks categorised in Group 1 for each test subject.

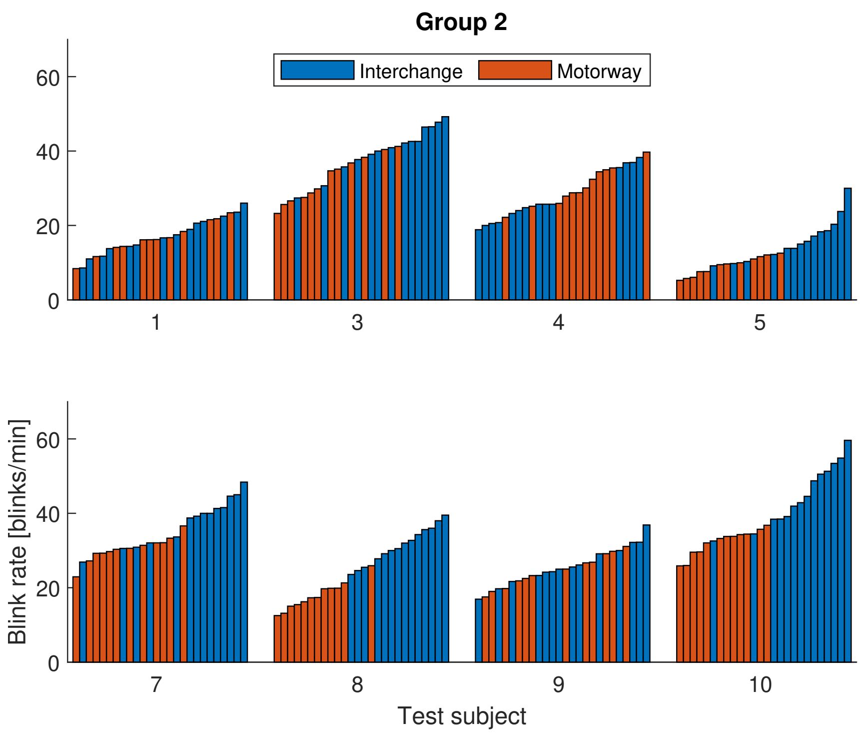

Figure 4.6: Bar plot of the distribution of BR calculated from blinks categorised in Group 2 for each test subject.

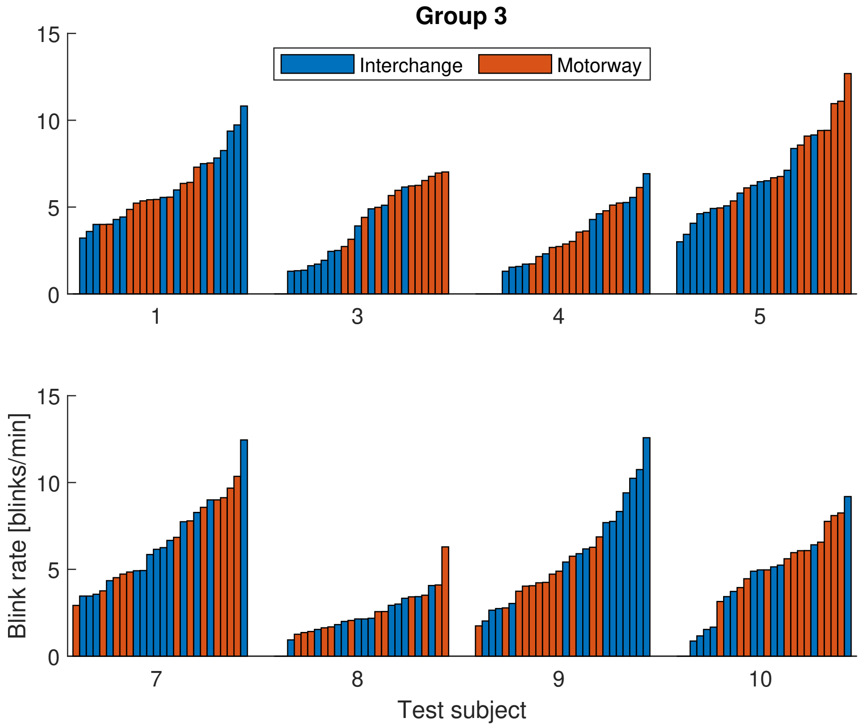

Figure 4.7: Bar plot of the distribution of BR calculated from blinks categorised in Group 3 for each test subject.

4.2 Differences in half blink duration depending on road type

Initially, the results concerning differences in HBD between session 1 and session 2 are presented, followed by the results from analysis of the differences in HBD between interchange and motorway. After that, the results obtained from investigating the differences in proportion of short, medium, and long half blink duration between interchange and motorway are presented. Based on the findings from previous research performed by Benedetto et al. (2011), it can be assumed that the proportion of short blinks will increase during interchange segments. Lastly, the results from evaluating the difference in HBD Group 1, HBD Group 2, and HBD Group 3 between interchange and motorway are presented.

4.2.1 Differences in half blink duration between session 1 and 2

The reason for analysing differences in HBD between session 1 and session 2 on an individual level is to evaluate if the sessions needs to be considered in the linear mixed-effects models. In order to determine the differences in HBD between the two sessions, a linear mixed-effects model was performed for Group I & M, Group I, and Group M separately, since the level of road complexity might affect the blinking behaviour.

In Table 4.4 the results obtained from analysing the difference in HBD between the two sessions on an individual level are summarised. As seen in Table 4.4 eight out of 24 p-values are not significant. However, it is seen in the table that test subject 1, 3, 4, 7, 8, 9, and 10 for Group I & M and Group M have significant p-values. This implies that these test subjects have significant differences in HBD Group I & M and HBD Group M between the two sessions. Of these test subjects, test subject 4, 7, 8, 9, and 10 have positive estimate values. This indicates that these test subjects tend to blink longer during session 2 than session 1 for the entire on-road experiment and during motorway segments. The opposite trend can be seen for test subject 1 and 3 that have negative estimate values. The table shows that most of the p-values for Group I are not significant, except for test subject 4 and 7. The estimates for these test subjects are positive, implying that they tend to blink longer during interchange segments in session 2. Worth noting is that several of the estimates are relatively small. It is also seen in the table that all residuals' distributions are non-normal, meaning that the model assumptions are violated.

Table 4.4: The results from analysing the differences in HBD between session 1 and session 2 on an individual level. A significant p-value (<0.05), is highlighted with a grey cell. Note that some of the p-values are close to 0.05, which may not be considered significant if Bonferroni´s multiple test correction is applied.

Individual level				
Test subject	**Group**	**p-value**	**Estimate (ms)**	**Residuals' distribution**
1	I & M	0.013	-2.02	non-normal
	I	0.19	-3.72	non-normal
	M	0.034	-1.77	non-normal
3	I & M	1.29e-14	-4.20	non-normal
	I	0.38	-0.88	non-normal
	M	1.63e-17	-5.13	non-normal
4	I & M	1.65e-17	4.66	non-normal
	I	0.00046	3.87	non-normal
	M	1.43e-14	4.61	non-normal
5	I & M	0.098	-3.47	non-normal
	I	0.88	0.52	non-normal
	M	0.063	-4.52	non-normal
7	I & M	5.27e-06	4.44	non-normal
	I	0.015	7.87	non-normal
	M	5.27e-05	3.91	non-normal
8	I & M	1.51e-10	5.54	non-normal
	I	0.37	1.021	non-normal
	M	3.74e-11	6.93	non-normal
9	I & M	0.0021	2.81	non-normal
	I	0.79	-0.56	non-normal
	M	0.0094	2.59	non-normal
10	I & M	1.51e-06	3.43	non-normal
	I	0.99	-0.00080	non-normal
	M	7.79e-08	4.15	non-normal

Figure 4.8 shows a part of the distribution of HBD between the two sessions separately for each group. For the entire distribution of HBD, see Figure A.1-A.8 in Appendix A. As seen in Figure 4.8, the median HBD tends to be generally higher in session 2. The differences between the median values for session 1 and session 2 are relatively small, and sometimes they appear to be equal. In these cases, the significant p-value derives from the distribution of outliers.

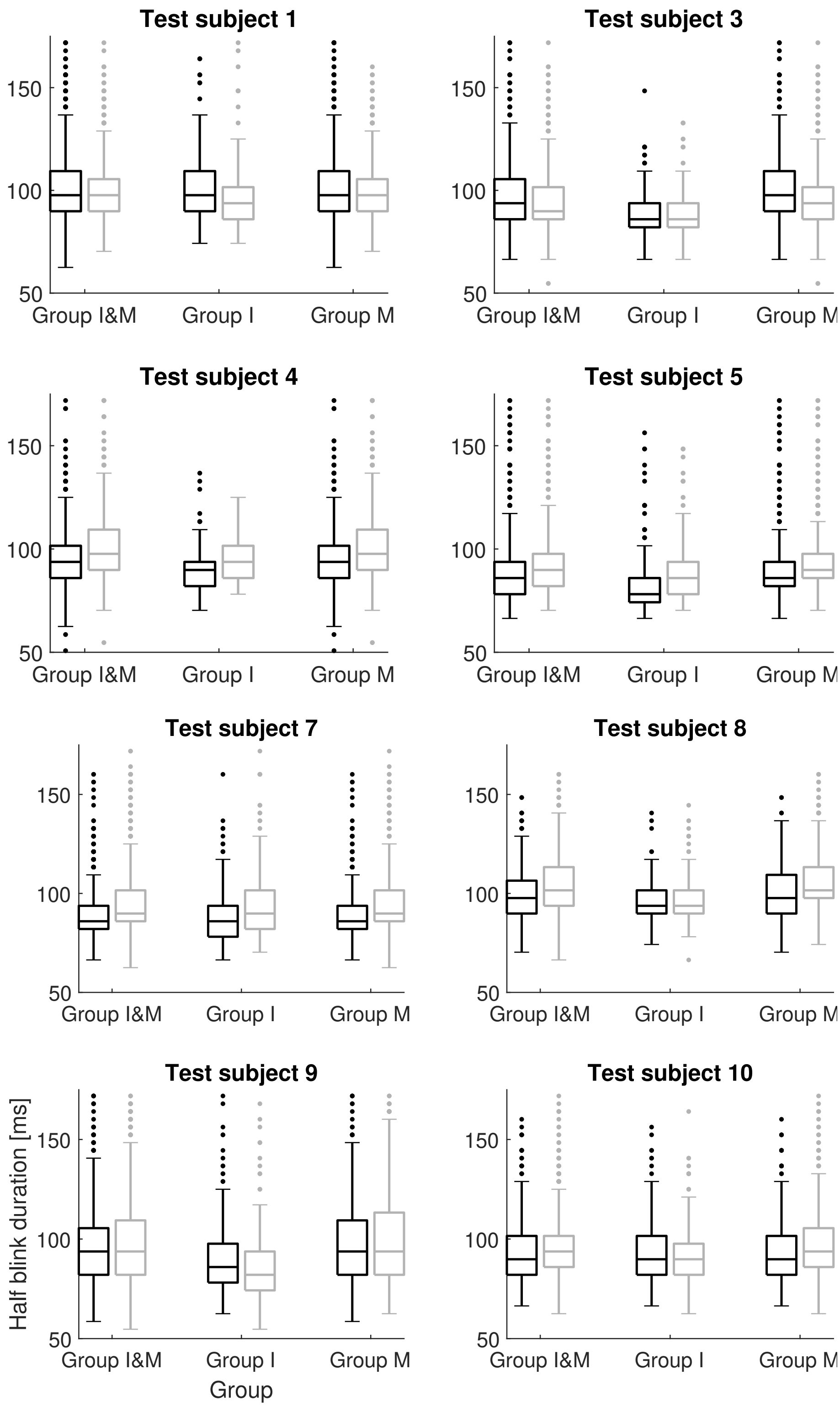

Figure 4.8: Box plot illustrating parts of distribution of HBD between session 1 (black) and session 2 (gray) separately for Group I & M, Group I, and Group M. The y-axis is set to 175 ms, therefore outliers above 175 ms are excluded.

4.2.2 Differences in half blink duration between interchange and motorway

Eye blinks causes loss of visual information, which is the reason for inhibition of blinks during high levels of visual attention. By decreasing the duration of blinks, the information loss is reduced. Therefore, a hypothesis is that the HBD is shorter during interchange segments.

The results obtained from evaluating the differences in HBD between interchange and motorway on a group level and an individual level are presented in Table 4.5. As can be seen from the table, the distributions of the residuals are non-normal on a group level and for all test subjects on an individual level. This means that the model assumptions are not fulfilled performing the linear mixed-effects model. In the table, it is seen that the p-value is considerably lower than 0.05 and is therefore significant on a group level. The estimate value in the table is positive, meaning that the duration of blinks is estimated to be 4.5 ms higher during motorway segments than interchange segments on a group level. The distribution of the HBD is visualised in Figure 4.9. The upper box plot in the figure shows parts of the distribution of HBD for interchange and motorway separately, while the lower box plot illustrates the entire distribution of HBD. Overall, the median of HBD is slightly higher in the motorway road type, meaning that the duration of the blinks tends to be longer for motorway driving. As seen in the lower box plot in the figure, the outliers are higher and more numerous for motorway than interchange.

In Table 4.5 shows the results obtained from investigating differences in HBD between the two road types on an individual level. As the table show, all test subjects except test subject 1 and 10 have significant p-values. Test subject 3, 4, 5, 8, and 9 have positive estimate values, implying that these five test subjects tend to have 5.97-11.19 ms longer HBDs during motorway segments than during interchange segments. The estimate value for test subject 7 is negative, indicating the opposite trend than test subject 3, 4, 5, 8, and 9. The tendency of test subject 7 is to have 3.38 ms shorter HBDs during motorway segments compared to interchange segments. The results for test subject 7 contradicts the hypothesis that HBD is shorter during interchanges. The differences in HBD between interchange and motorway for each test subject are illustrated in the box plots in Figure 4.10. The lower plot visualises the full distribution of HBD, while the upper plot is zoomed in on parts of the distribution. There is a distinct trend of higher median value for motorway segments for all test subjects. All test subjects showed a significant difference in HBD between the road types, except for test subject 1 and 10. The figure shows that the upper adjacent value is lower for motorways than interchange for these two test subjects, which differs from the appearance of the other test subjects.

Table 4.5: The results from investigating the differences in HBD between interchange and motorway on a group level and an individual level. A significant p-value (<0.05), is highlighted with a grey cell.

Group level			
p-value		**Estimate (ms)**	**Residuals' distribution**
4.51e-23		4.50	non-normal
Individual level			
Test subject	**p-value**	**Estimate (ms)**	**Residuals' distribution**
1	0.61	-0.63	non-normal
3	2.34e-31	8.82	non-normal
4	1.71e-13	6.02	non-normal
5	4.32e-05	11.19	non-normal
7	0.0085	-3.38	non-normal
8	8.44e-09	5.97	non-normal
9	9.41e-16	9.99	non-normal
10	0.061	1.74	non-normal

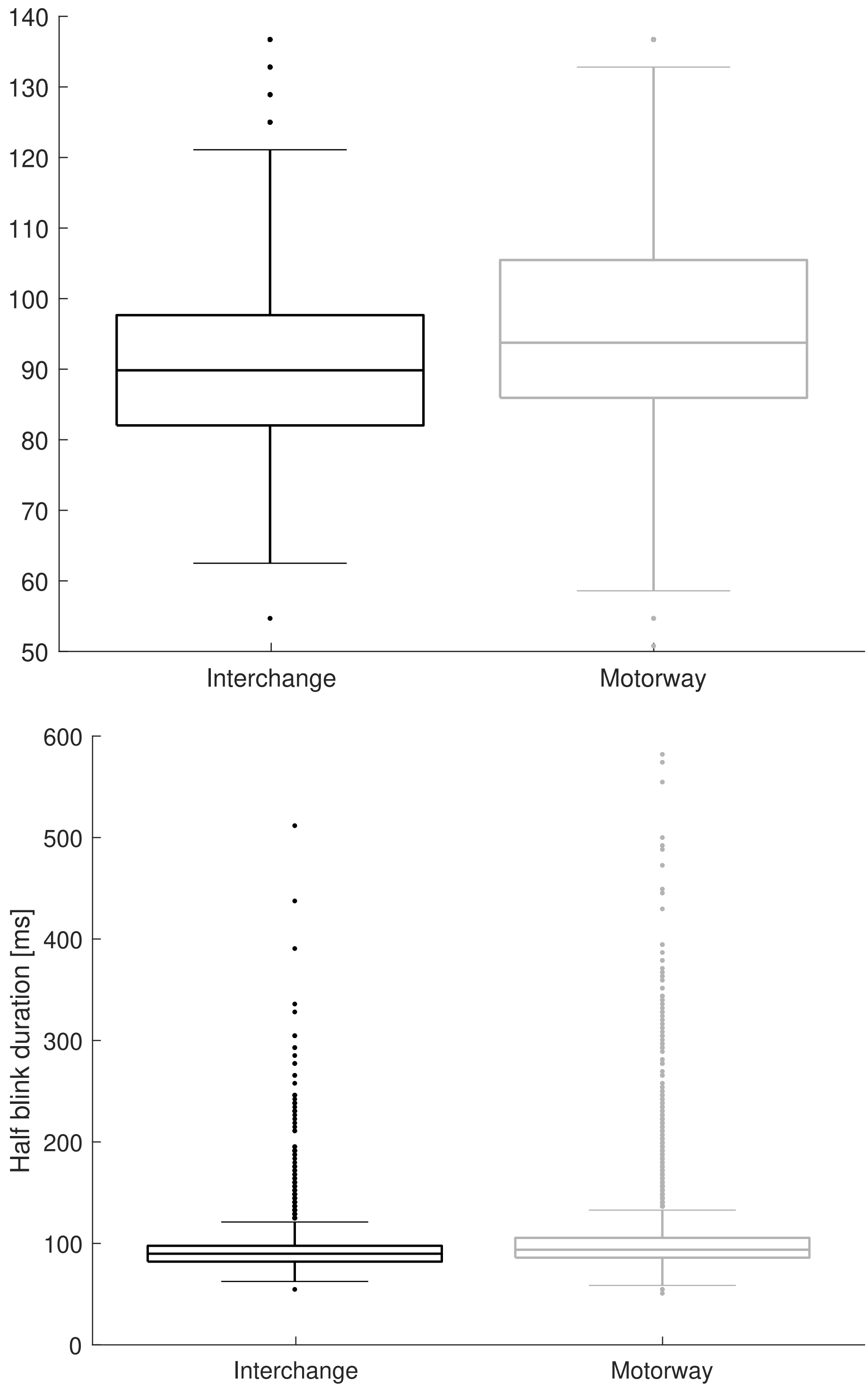

Figure 4.9: The distribution of HBD for interchange and motorway separately for all test subjects. The upper figure is a zoomed-in image of the lower graph.

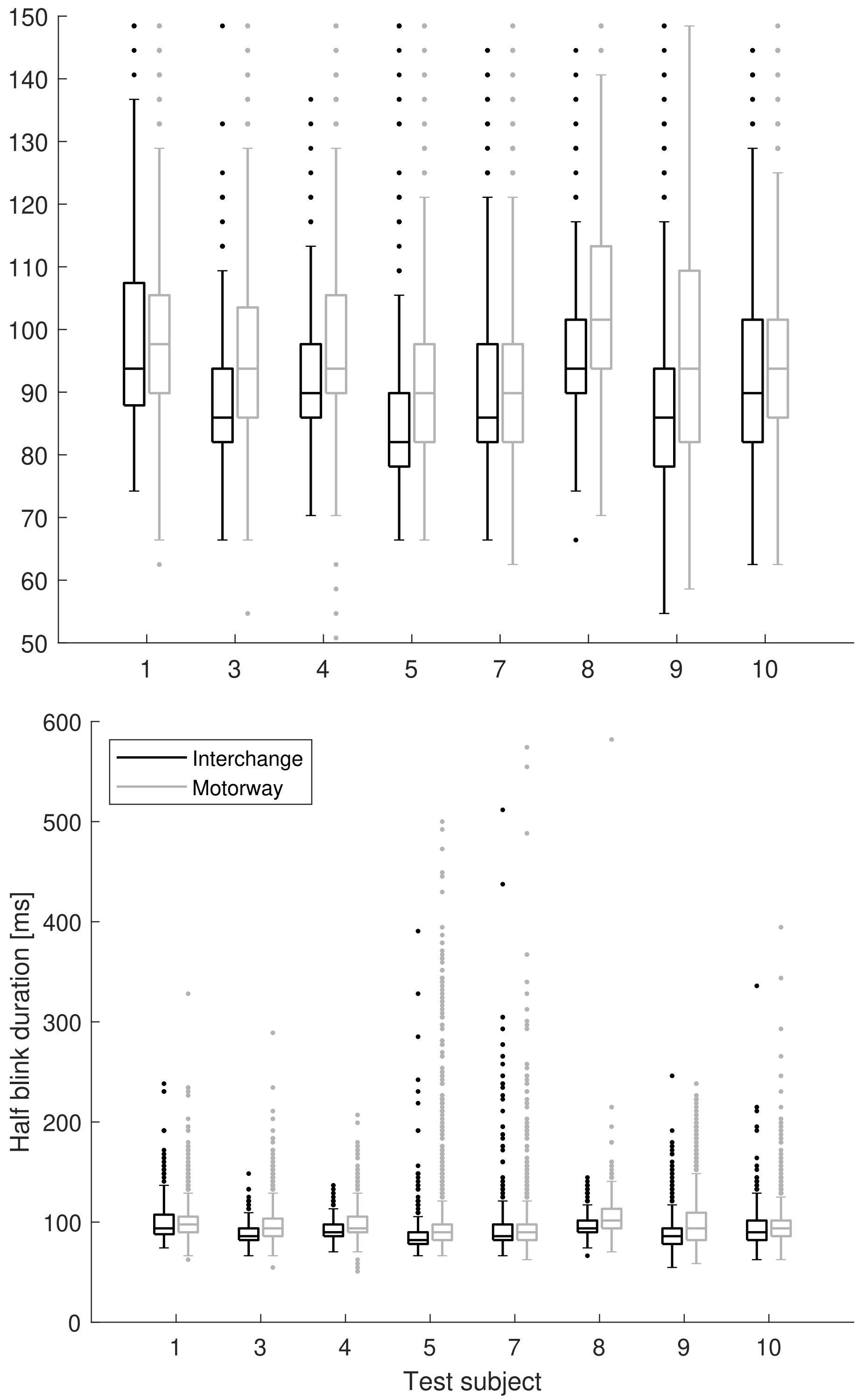

Figure 4.10: The distribution of HBD for interchange and motorway separately for each test subject. The upper figure is a zoomed-in image of the lower graph. The lower plot illustrates the full distribution of HBD.

4.2.3 Effects of short, medium and long blinks

The results obtained by analysing the differences in the proportion of short, medium, and long blinks between interchange and motorway on a group level and an individual level are summarised in Table 4.6. As seen in the table, Group short and Group medium have significant p-values and estimate values of -12% and 12%, respectively, on a group level. This implies that short blinks occur more frequently during interchange segments than during motorway segments, while the opposite trend is seen for medium blinks. As seen in the table, Group long has a non-normal distribution of the residuals. Therefore, the model assumptions for Group long is violated performing the linear mixed-effects model. Figure 4.12 visualise the relationship in the proportion of short, medium, and long blinks between interchanges and motorway segments. It is seen in the figure that the proportion of short blinks are larger during interchange segments compared to motorway segments. The opposite tendency can be seen for blinks categorised in Group medium, where the proportion is larger during motorway driving than during interchange driving.

The results obtained from analysing the differences of short, medium, and long blinks between the two road types on an individual level are presented in Table 4.6. From the table, it is seen that test subject 1 and 10 have no significant p-value for any of the groups. This indicates that the proportion of short, medium, and long blinks are similar between interchanges and motorways. Test subject 3, 4, 5, 8, and 9 have significant p-values and negative estimate values ($\leq$ -5.9%) for Group short. This means that the portion of short blinks is larger during interchange segments. For Group medium, test subject 3, 4, 8, and 9 have significant p-values and positive estimate values ($\geq$ 18%), which indicates that the four test subjects tend to have a higher portion of medium blinks during motorway segments. For Group long, test subject 3, 5, 7, and 9 have significant p-values. The estimate values are positive for test subject 3, 5, and 9, which suggests that the proportion of long blinks is higher during motorway segments. Test subject 7 have a negative estimate value which implies the opposite trend. From the table, it emerges that most distributions of the residuals are normal on an individual level. It can be seen that test subject 3 (Group short, Group medium, and Group long), test subject 1, 4, 5, 8, 9, and 10 (Group long) have non-normal residuals' distributions. This means that the model assumptions are violated for these cases. Figure 4.12 visualise the relations between the proportions of short, medium, and long blinks for the two road types. As seen in the figure, test subject 3, 4, 8, and 9 have similar relations between the three groups, with a distinct difference between interchange and motorway for Group short and Group medium.

Table 4.6: The results from analysing the differences in proportion of short, medium, and long blink duration between interchange and motorway on a group level and an individual level. A significant p-value (<0.05), is highlighted with a grey cell. Note that some of the p-values are close to 0.05, which may not be considered significant if Bonferroni´s multiple test correction is applied.

Group level				
Group		**p-value**	**Estimate (proportion)**	**Residuals' distribution**
short		1.80e-17	-0.12	normal
medium		9.72e-19	0.12	normal
long		0.99	-5.53e-05	non-normal
Individual level				
Test subject	**Group**	**p-value**	**Estimate (proportion)**	**Residuals' distribution**
1	short	0.15	-0.056	normal
	medium	0.053	0.076	normal
	long	0.10	-0.020	non-normal
3	short	8.21e-06	-0.22	non-normal
	medium	8.95e-06	0.21	non-normal
	long	0.013	0.0029	non-normal
4	short	1.14e-05	-0.18	normal
	medium	1.19e-05	0.18	normal
	long	0.11	0.00084	non-normal
5	short	0.036	-0.059	normal
	medium	0.15	0.029	normal
	long	0.015	0.033	non-normal
7	short	0.63	0.012	normal
	medium	0.43	0.014	normal
	long	0.048	-0.026	normal
8	short	6.6e-06	-0.21	normal
	medium	8.33e-06	0.21	normal
	long	0.27	0.0018	non-normal
9	short	3.30e-10	-0.22	normal
	medium	1.79e-09	0.21	normal
	long	0.022	0.0087	non-normal
10	short	0.24	-0.038	normal
	medium	0.21	0.04	normal
	long	0.72	-0.0016	non-normal

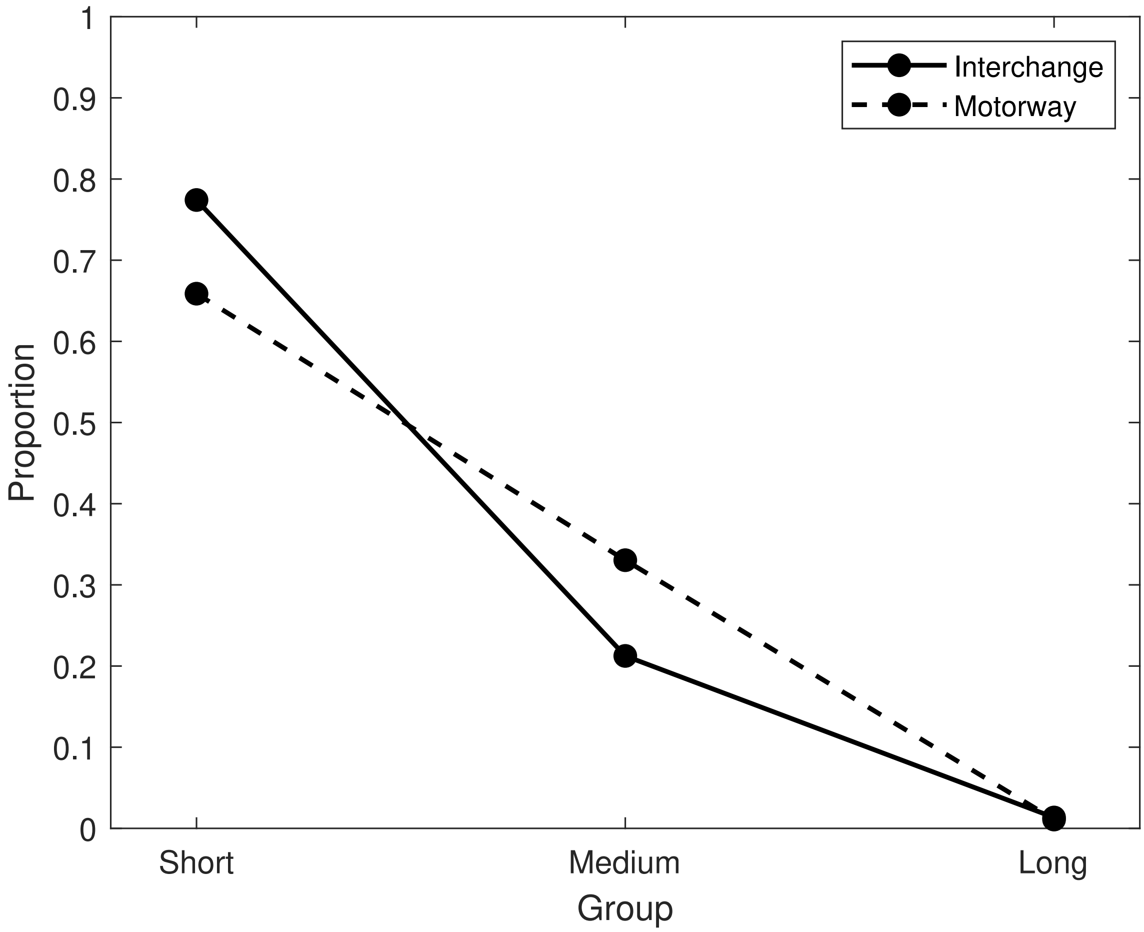

Figure 4.11: The proportion of short, medium, and long HBD with respect to the road type interchange or motorway for all segments and test subjects.

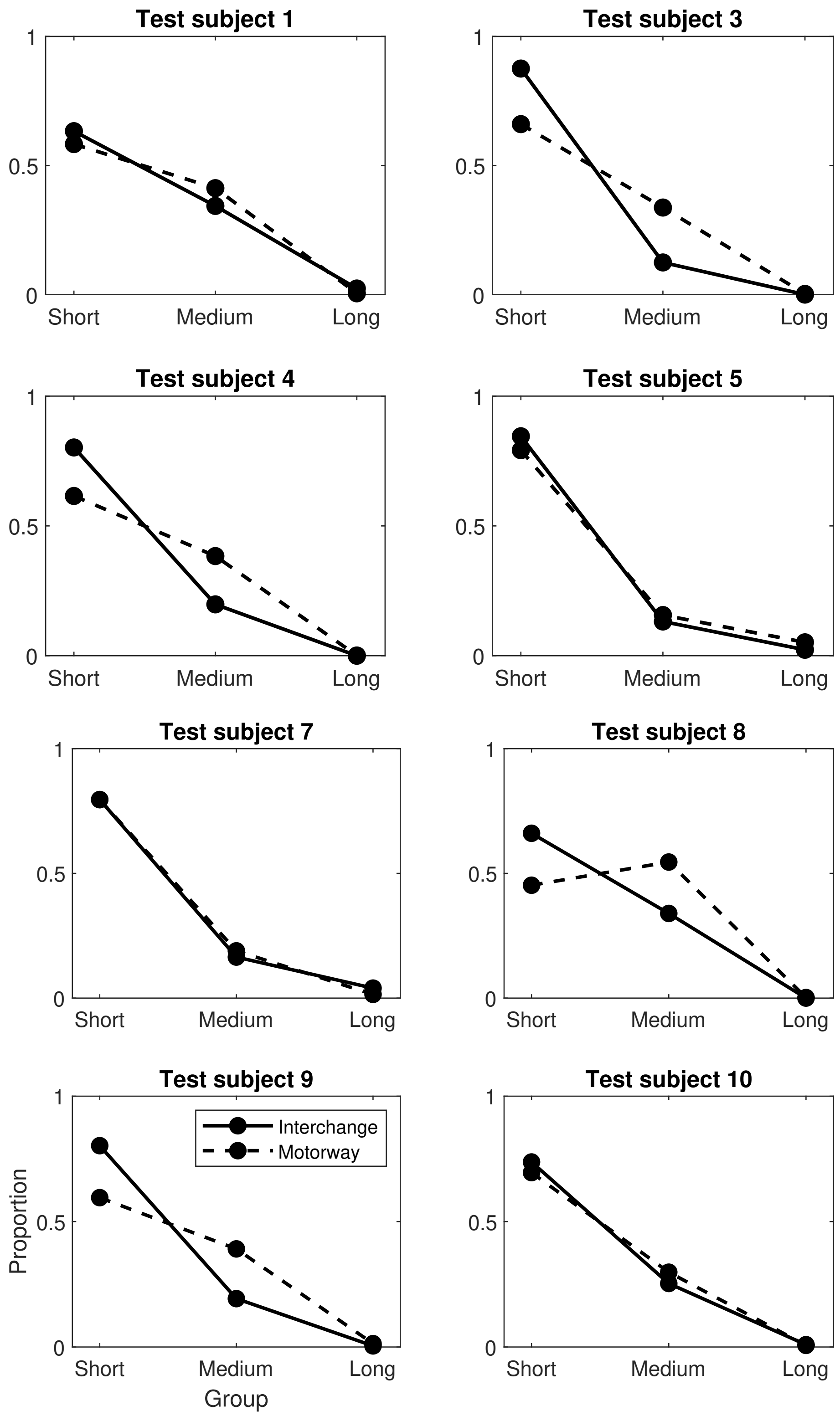

Figure 4.12: The proportion of short, medium, and long HBD with respect to road type interchange or motorway for all segments and test subjects separately.

4.2.4 Effects of saccadic eye movements

The effect of saccadic eye movements on the HBD is investigated by analysing the HBD for Group 1, Group 2, and Group 3. The results obtained from investigating the differences in HBD Group 1, HBD Group 2, and HBD Group 3 between the two road types on a group level and an individual level are shown in Table 4.7. As seen in the table, none of the residuals' distributions is normal, meaning the model assumptions are not fulfilled for any of the fitted models. Group 2 generated a significant p-value and a positive estimate value, which means that blink-saccadic pairs tend to be 5.17 ms longer during motorway segments compared to interchange segments. The fitted model also returned a significant p-value for Group 3. The positive estimate value indicates that the HBD Group 3 (blinks categorised in grey zone) tends to be 3.4 ms longer in motorways than interchanges. The results for Group 1 is not significant, which means that there is no difference in HBD for blinks occurring without large saccades between interchange and motorway. Figure 4.13 visualise the distribution of Group 1, Group 2, and Group 3 for the two road types separately. The overall trend for all groups is a higher median value, upper adjacent value, and outliers with longer duration for motorway segments. The differences in HBD between motorway and interchange are only significant for Group 2 and Group 3, which have more outliers in the distributions of motorway segments.

The results from the linear mixed-effects models on an individual level are seen in Table 4.7. As seen in the table, only test subject 9 has a significant p-value for Group 1. For Group 2, on the other hand, the p-value is significant for test subject 3, 4, 5, 8, 9, and 10. For these six test subjects, the estimate values are positive, meaning that the HBD for blink-saccadic pairs tends to be longer during motorway segments compared to interchange segments. For test subject 1 and 7, the p-value is not significant for Group 2. For Group 3, the result shows significant p-values for test subject 3, 4, 5, 7, 8, and 9. For these six test subjects, except for test subject 7, the estimate values are positive and indicate longer HBD for Group 3 during motorway segments than interchange segments. Group 3 for test person 7 deviate from the majority by having significantly longer HBD during interchanges than during motorways. Figure 4.14, 4.15, and 4.16 illustrates the distribution of HBD between interchange and motorway for each group independently. For HBD Group 1, HBD Group 2, and HBD Group 3 the overall trend is that the median value and upper adjacent for motorway are higher than for interchanges. In Figure 4.14, it is seen that the difference in the median between interchange and motorway is larger for test subject 9, which is the only test subject with a significant p-value for Group 1. Test subject 3, 4, 5, 8, 9, and 10 have significant p-values for Group 2, and it is seen in Figure 4.15 that these test subjects have a slightly larger difference in the median value between the two road types than test subject 1 and 7. Another difference between these test subjects is that the distributions of test subject 1 and 7 overlaps more than for test subject 3, 4, 5, 8, 9, and 10. For Group 3, the differences in HBD between interchange and motorway are significant for test subject 3, 4, 5, 8, and 9. In Figure 4.16, it is seen that the median value for these test subjects is higher during motorway segments.

Table 4.7: The results from evaluating the effects of saccadic eye movements and differences in HBD in Group 1, Group 2, and Group 3 between the two road types on a group level and an individual level. A significant p-value (<0.05), is highlighted with a grey cell. Note that some of the p-values are close to 0.05, which may not be considered significant if Bonferroni´s multiple test correction is applied.

Group level			
Group	**p-value**	**Estimate (ms)**	**Residuals' distribution**
1	0.12	2.55	non-normal
2	8.056e-26	5.17	non-normal
3	0.012	3.40	non-normal

Individual level				
Test subject	**Group**	**p-value**	**Estimate (ms)**	**Residuals' distribution**
1	1	0.49	0.88	non-normal
	2	0.88	-0.28	non-normal
	3	0.13	2.62	non-normal
3	1	0.14	6.09	non-normal
	2	1.64e-34	9.55	non-normal
	3	0.044	7.2224	non-normal
4	1	0.32	1.23	non-normal
	2	7.50e-15	7.29	non-normal
	3	0.040	2.91	non-normal
5	1	0.16	9.51	non-normal
	2	0.0099	9.15	non-normal
	3	0.0068	15.00	non-normal
7	1	0.071	-8.03	non-normal
	2	0.53	-0.93	non-normal
	3	0.00011	-12.55	non-normal
8	1	0.12	-4.71	non-normal
	2	2.50e-07	5.89	non-normal
	3	0.044	7.28	non-normal
9	1	0.032	5.037	non-normal
	2	3.70e-13	11.58	non-normal
	3	0.0012	6.53	non-normal
10	1	0.93	-0.45	non-normal
	2	0.049	2.013	non-normal
	3	0.40	2.065	non-normal

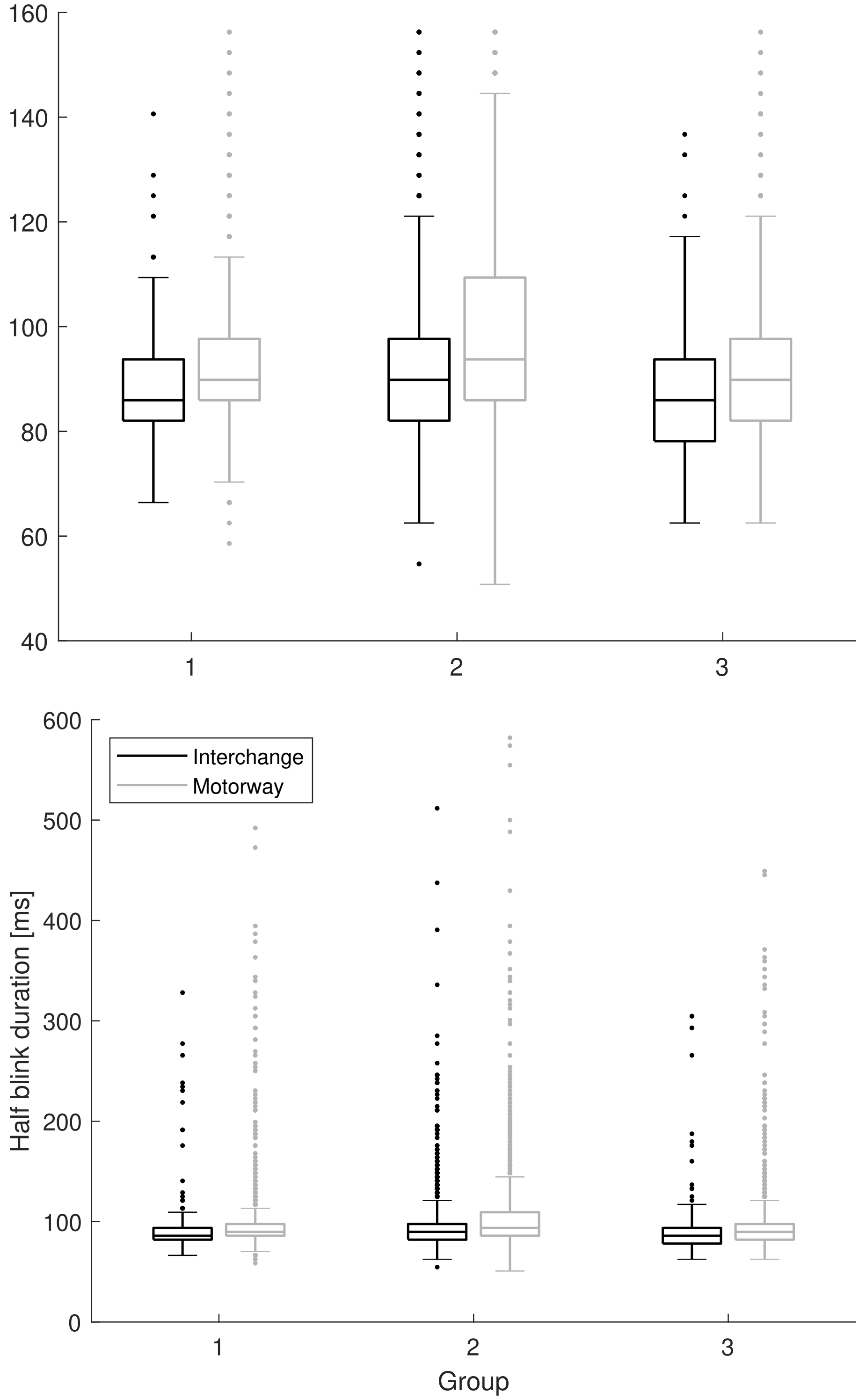

Figure 4.13: The distribution of HBD for Group 1, Group 2, and Group 3 with respect to the road types interchange or motorway.

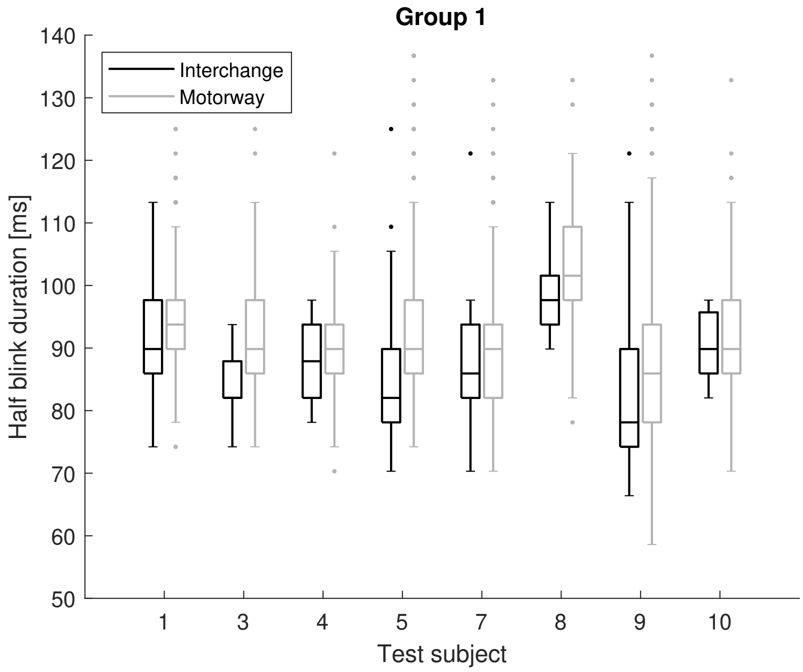

Figure 4.14: Boxplot visualising the distribution of half blink duration for each test subjects in interchange and motorway separately for blinks occurring without large saccadic eye movements. Part of the outliers are not shown, the full image is seen in Appendix A, Figure A.9

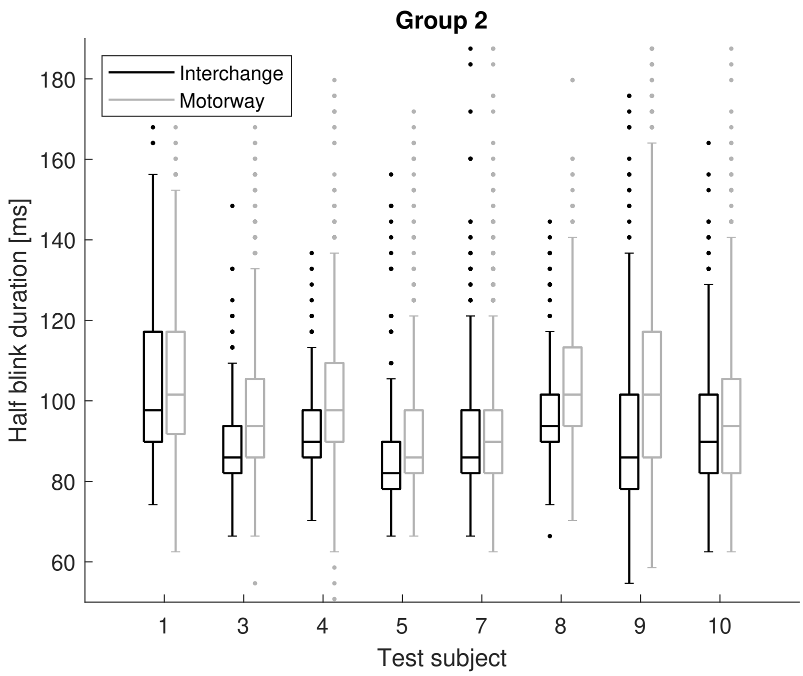

Figure 4.15: Boxplot visualising the distribution of HBD for each test subjects in interchange and motorway separately for blinks occurring during large saccadic eye movements. Part of the outliers are not shown, the full image is seen in Appendix A, Figure A.10

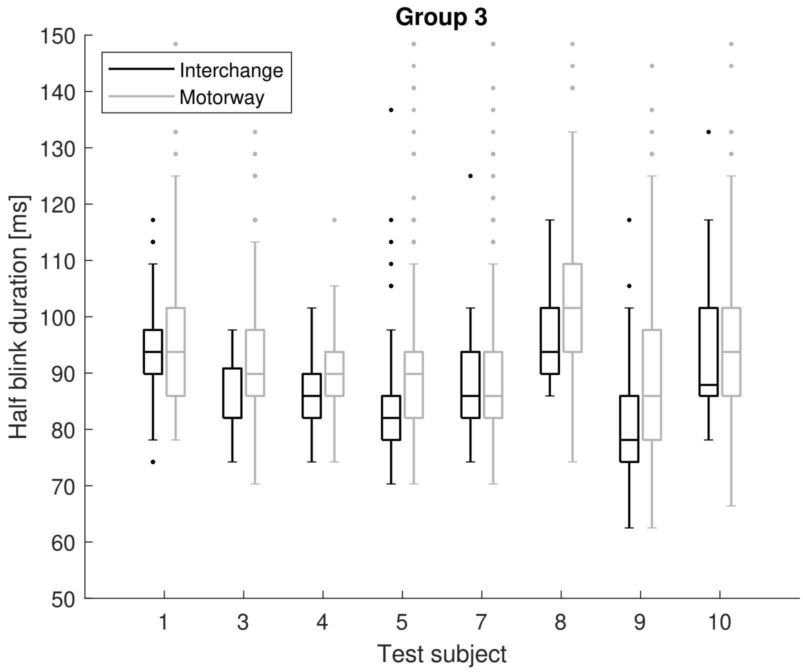

Figure 4.16: Box plot visualising the distribution of HBD for each test subjects in interchange and motorway separately for blinks categorised in the grey zone. Part of the outliers are not shown, the full image is seen in Appendix A, Figure A.11

5
Discussion

The purpose of the thesis was to investigate eye blinks as an indicator of a car drivers' visual attention. Two research questions were defined to assess the aim of the thesis. The first research question aimed to analyse differences in BR between interchange and motorway and the second question aimed to examine the differences in HBD between interchange and motorway. As mentioned in the literature review, different road complexity requires various levels of visual attention (Faure et al., 2016). Based on the discoveries from Faure et al. (2016), interchange segments were assumed to demand a higher level of visual attention of the driver. A theory among researchers is that visual attention inhibits eye blinks as a mechanism to not lose important information about the surroundings (Shultz et al., 2011). Therefore, a hypothesis was that BR is lower during interchanges due to inhibition of blinks as a result of a higher level of visual attention needed in that segment. Analysing the difference in BR between the two road types suggests that BR is higher during interchange segments on a group level and for three test subjects on an individual level. These results contradict the hypothesis that BR is assumed to be lower during interchange segments. A possible explanation is the differences in the driving behaviour between the two road types. Cardona and Quevedo (2014) suggests that saccadic eye movement increases during intersections, and blinks co-occur with saccades as a mechanism to stabilise the gaze from the quick movement. In order to explore this, the differences in BR Group 1 (blinks without large saccades), BR Group 2 (blinks with large saccades), and BR Group 3 (blinks categorised in grey zone) between interchange and motorway was analysed. Group 1 contains blinks occurring without large saccades, and Group 2 consists of blinks co-occurring with large saccadic eye movement. Group 3 includes both blink-saccadic pairs and blinks occurring without large saccadic eye movements. This analysis indicates that the number of blink-saccadic pairs is higher during interchanges, while blinks occurring without large saccadic eye movements are more frequent during motorway segments. Therefore, the hypothesis is assumed to be contradicted due to the test subjects driving behaviour in interchanges, that evokes blink-saccadic pairs.

Previous studies have shown that the blink duration decreases with increased visual attention (Benedetto et al., 2011). Therefore, a hypothesis is that HBD is shorter during interchange segments. The overall findings from analysing the differences in HBD between the two road types implies that HBD is longer during motorway segments, which agrees with the second hypothesis. In a study of Benedetto et al., (2011), the proportion of short blink duration increased as the visual workload increased. Therefore, differences in short, medium, and long HBD between interchange and motorway was analysed to verify if interchange demands a higher level of visual workload than motorway segments. This is accomplished by k-mean clustering analysis generating three groups: Group short (>100 ms), Group medium (100-180 ms), and Group long (<180 ms). The results from this analysis suggest that the proportion of short blinks increases during interchange segments. Because the number of blink-saccadic pairs was higher during interchanges, the differences in HBD Group 1, HBD Group 2, and HBD Group 3 between interchange and motorway were analysed. This analysis shows that the duration of blink-saccadic pairs is generally longer during motorway segments.

5.1 Differences in BR and HBD between session 1 and session 2

The findings of the differences in BR between session 1 and session 2 indicate that most individuals have similar blink frequency between the two sessions. However, some individuals had a significant difference in BR between the two sessions. For these individuals, BR was higher during session 2 than session 1. The analysis of the difference in HBD between the two sessions implies that the majorities of individuals had a significant difference in HBD between session 1 and session 2. Some individuals tend to blink longer during motorway than during interchange segments, while others showed the opposite behaviour. The test subjects performed the on-road experiment on two different occasions and therefore external and internal factors could explain why some individuals had a difference in BR and HBD between the sessions. External factors refer to conditions the driver can not affect, while internal factors refer to the physiological conditions of the test subjects.

An external factor that could affect the complexity of the driving task and the demand of visual workload is different weather conditions. From the manual analysis of the detected eye blinks, it was found that exposure to sunlight generated an abnormal blinking behaviour with an increase of blinks. During the manual analysis, periods of extreme sunlight were removed, but there is a possibility that some effect remained. Thus, sunlight (in the face of the driver) could be one potential explanation for the variability in BR between sessions. Eye closures protect the eye from light (Tortora & Derrickson, 2015), and therefore, it can be assumed that sunlight also causes longer HBD. It is also possible that rain aggravates the driving task and increases the demand of visual workload. This would potentially generate a decrease in BR and HBD to minimise the loss of visual input.

Another external factor that can impact the BR and HBD is traffic density. A higher traffic density is assumed to increase the visual workload (Faure et al., 2016), resulting in a decrease in BR and HBD during these periods. The on-road experiment has been performed at different times of the day, and it could therefore be assumed that the traffic density varies between sessions.

Internal factors could also affect the blinking behaviour of the test subjects. Fatigue is shown to cancel the inhibition of eye blinks during visual attention, which could result in an increase of BR and prolonged HBD (Benedetto et al., 2011). Dryness of the eyes is another possible factor that can affect the BR since the eyes are lubricated during eye closures (Tortora & Derrickson, 2015). The effect of external and internal factors that could affect the blinking behaviour were not included in the scope of this thesis. Therefore, their influence on the result were not investigate further.

All distributions of the residuals from the fitted models analysing differences in BR between session 1 and session 2 fulfil the model assumptions, except for test subject 3 Group M. In the case of HBD and differences in session, all models violate the model assumptions. From Figure 4.1 the distribution of BR based on motorway segments clearly shows that BR is higher in session 2 than session 1, which verifies the positive estimate value.

5.2 Differences in BR between interchange and motorway

The overall findings of the differences in BR between interchange and motorway indicate that BR is higher during interchanges. On a group level, test subjects tend to blink more frequently during interchanges compared to during motorways. This trend was also seen for three test subjects on an individual level. These findings contradict the hypothesis about BR decreasing during more complex road environments (interchange segments). The results regarding the effects of saccadic eye movement could explain the contradicted hypothesis. It was shown that the occurrence of blink-saccadic pairs increased significantly during interchange segments. During interchanges, the driving behaviour induces saccadic eye movements due to intersections and scanning of the traffic environment. According to (Cardona & Quevedo, 2014), blinks occur simultaneously as saccadic eye movements as a mechanism to stabilise the gaze. Therefore, the driving behaviour could explain the high BR in interchange segments. The overall results showed that BR was higher during motorway segments for the blinks occurring without large saccadic eye movements. This means that the hypothesis is supported by the results when the effect of large saccadic eye movements are eliminated.

The Lilliefors tests revealed that the model assumptions were violated for Group 1 and Group 3 (group level), for test subject 9 and 10 (individual level) regarding Group 1, and test subject 4 (individual level) regarding Group 2. Violated model assumptions mean that the distribution of the residuals is non-normal and, therefore, that the results for these fitted models are not entirely trustworthy. Especially, the value of the estimates could differ from the actual value when the model assumptions are violated (Schielzeth et al., 2020). The result for Group 1 on a group level is supported by the bar plot in Figure 4.4. It is seen that the BR tends to be higher during motorway segments, which the positive estimate value suggested as well. Due to the violated assumptions, the estimate could differ from the true value, but the figure corroborates the positive outcome. For Group 3 on a group level, it is more difficult to distinguish differences supporting the result in the bar plot in Figure 4.4. A vague difference is illustrated where the BR tends to be lower in interchange segments, corroborating the small positive estimate obtained from the model. On an individual level, for test subject 10 (Group 1) the model resulted in a significant p-value and a positive estimate. Even though the model assumptions were not fulfilled, the bar plot in Figure 4.5 shows that the differences in BR between motorway and interchange segments are pronounced. Since the results for test subject 9 (Group 1) and 4 (Group 2) were not significant, their estimates are not further analysed.

5.3 Difference in HBD between interchange and motorway

The overall discoveries from the analysis of differences in HBD between interchange and motorway segments revealed that the HBD tends to be longer during motorway segments. The results from the analysis on a group level and the majority on an individual level (test subject 3, 4, 5, 8, and 9) are consistent with positive estimate values. Only one test subject (individual level) had the opposite result, which was shown by the negative estimate value and therefore tends to blink shorter during motorway segments. The overall findings confirms the hypothesis about longer HBD when driving on roads with lower complexity (motorway segments). The results from the analysis of the proportion of short, medium, and long blinks in interchanges and motorways are also consistent with the hypothesis. The analysis on a group level and the majority on an individual level indicated that the proportion of short blinks are higher during interchange segments. These findings agree with the results presented by Benedetto et al. (2011), which suggested an increase of short blinks during high demands of visual workload. During interchange segments, the complexity level of the traffic environment is assumed to be higher, which should increase the drivers´ visual workload.

The overall discoveries for the effect of saccadic eye movements between interchange and motorway imply that HBD for Group 2 and Group 3 is longer during motorway segments. This means that the HBD for blinks occurring during large saccadic eye movements are shorter during interchanges, at the same time as the number of blink-saccadic pairs is higher during these segments. No differences in HBD between interchange and motorway segments were found for blinks occurring without large saccadic eye movements (Group 1). Since the results for Group 3 indicate the same findings as for Group 2, it could be assumed that most blinks categorised in the grey zone are actually blink-saccadic pairs.

5.3.1 Limitations and future work

The results from this thesis imply that eye blinks have the potential to indicate the level of visual attention in car drivers. To truly determine the usability of eye blinks, further investigations need to be performed. To begin with, the scale of the experiment needs to be extended and include considerably more test subjects to ensure changes in the blinking behaviour throughout the entire car driving population. It would also be preferable if the experiment was designed differently, with the aim to investigate the changes in eye blinks between different complex traffic environments. According to the presented literature, urban roads with intersections and high vehicle control demand are the most complex road. Perhaps the results would have been more unanimous if BR and HBD were obtained from urban roads and motorways. It would also be interesting to investigate the changes in blinking behaviour from a more situation based perspective. The eye blinks could be measured while test subjects drives a route where events that demand different levels of visual attention occur alternately. In this case, it would probably be preferable to measure the electrodermal activity to ensure periods of engagement in a subjective way, just as Sakai et al. (2017) did in a study. Then, the differences in the blinking behaviour between periods of high and low visual attention and engagement could be compared and analysed.

EOG measurements provide detailed data and numerous variables about an eye blink. However, it is an invasive technique and therefore difficult to apply outside laboratory setups. If eye blinks are proven to indicate car drivers´ visual attention, it could become an established method applied in future vehicles. In that case, an EOG could not be used. For further analysis, it could therefore be preferable to use a camera-based eye-tracking technique in order to ensure that the results are applicable in real-world situations. For the on-road experiment, a sampling frequency of 256 Hz was used to obtain the EOG data, which means that the data were sampled every 3.9 ms. This means that the blink duration of each blink could differ by 7.8 ms (3.9 x 2) depending on how the onset and offset of a blink coincide with the sampling time. The estimates from the linear mixed-effects model are based on mean values from several eye blinks, which means that the uncertainty derived from the sampling frequency have less effect on the results. However, it might be worth considering a higher sampling frequency for further work, since this would allow analysis of the duration in each eye blink separately.

Many model assumptions were violated when analysing the HBD, except for Group short and Group medium. The data sets of HBD includes outliers with higher HBD. Since most model assumptions are fulfilled regarding Group short and Group medium, the outliers in Group long are assumed to affect the results when analysing the entire data set. Perhaps, the distributions of the residuals would have been normal if the outliers in Group long were excluded from the data. In that case, the model assumptions of the linear mixed-effects model would have been fulfilled, and the results more trustworthy. For further studies, it is worth considering exclusion of the outliers if linear mixed-effects models are used for the statistical analysis.

When performing multiple statistical tests, it is essential to prevent false positive outcomes by using multiple testing corrections. Bonferroni correction have been regarded to some extent in this thesis by highlighting results close to 0.05, but not as thoroughly as needed to prove a significant result. Therefore, it is suggested to consider the Bonferroni correction (or another multiple testing correction method) more carefully in further work.

5.3.2 Applications of result

If the findings of further investigation also show significant differences in BR and HBD between low and high levels of visual attention, this could substantially improve the safety of future vehicles. Eye-trackers could become implemented as a common technique in highly automated vehicles to ensure that the driver is ready to intervene when necessary.

6
Conclusion

This thesis aimed to investigate the usability of eye blinks as a measurement of car drivers´ visual attention. Based on previous studies, the hypothesis was that the blink rate and the half blink duration decreases during high demands of visual attention. To investigate the hypothesis, the route of an on-road experiment was categorised into segments of high and low demands of visual attention. Interchanges were assumed to demand higher levels of visual attention since they include intersections and vehicle control. Motorways are more monotonous and were therefore assumed to demand lower levels of visual attention. The results indicated that the blink rate increased during interchanges, which contradicted the hypothesis of a reduction in blink frequency during higher demands of visual attention. Further investigations indicated that the contradicted results probably depend on the driving behaviour during interchanges, which involves an increase of large saccadic eye movements that induce eye blinks. When analysing the blinks occurring without large saccadic eye movements separate, the results were in line with the hypothesis of a decrease in blink rate during interchanges. The results regarding the half blink duration were in line with the hypothesis and indicated that the half blink duration was shorter during interchanges than motorways.

Based on the results obtained from this thesis, it is assumed that the blink rate (based on blinks occurring without large saccadic eye movements) and the half blink duration have the potential to indicate visual attention in car drivers. Since the results in this thesis are based on only a few test subjects and an experiment that was aimed for another analysis, the results needs to be evaluated further on a larger scale with an experiment adapted to the purpose. However, the results imply that eye blink measurements could indicate the level of visual attention. Therefore, it has the potential to be used for threat assessment in future safety systems that aims to ensure engaged drivers´ that are ready to intervene in the driving task.

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A
Appendix 1

Appendix 1 contains figures visualising the results obtained in Chapter 4.2.1 and 4.2.4. Figure A.1-A.8 illustrates the full distribution of HBD including all outliers for session 1 and session 2 separately for each test subject and group.

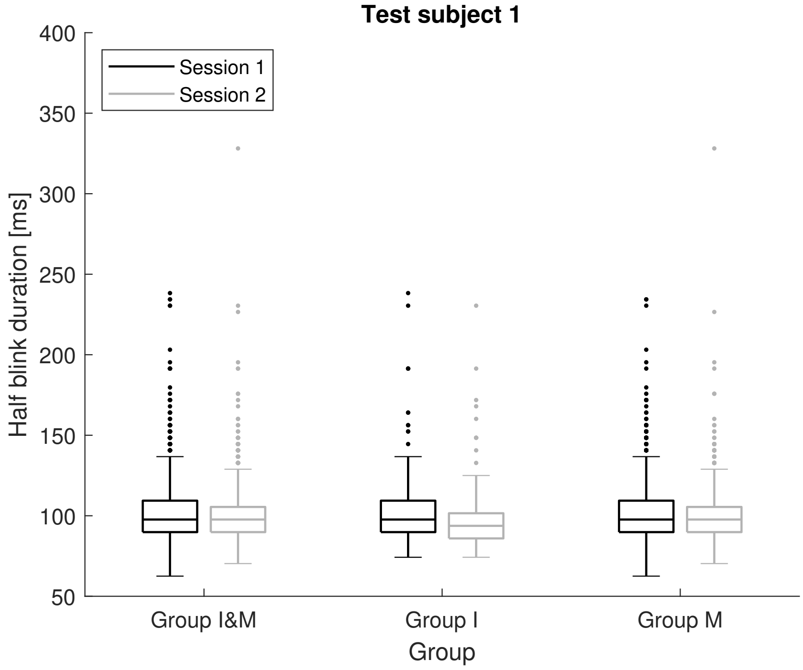

Figure A.1: Box plot illustrating the distribution of HBD between session 1 and session 2 separately for test subject 1 and Group I & M, Group I, and Group M.

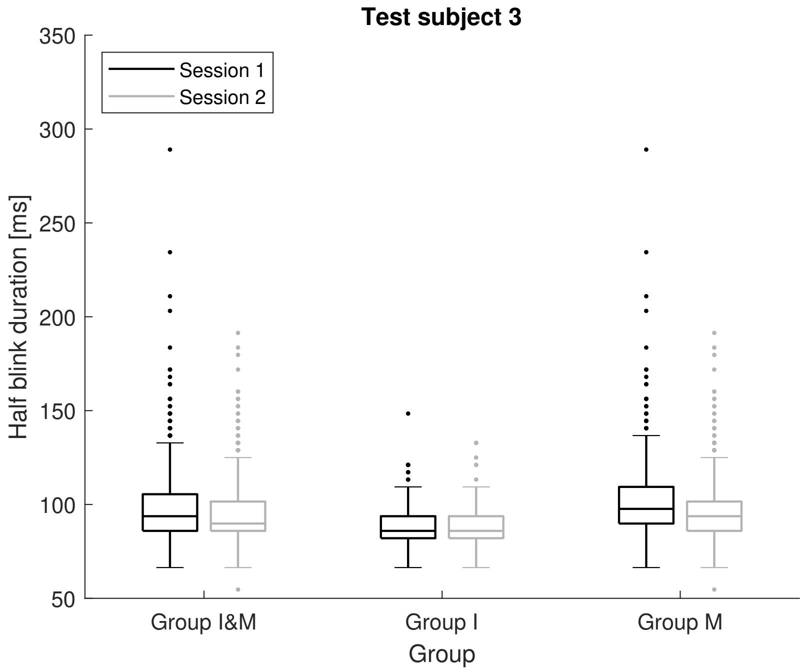

Figure A.2: Box plot illustrating the distribution of HBD between session 1 and session 2 separately for test subject 3 and Group I & M, Group I, and Group M.

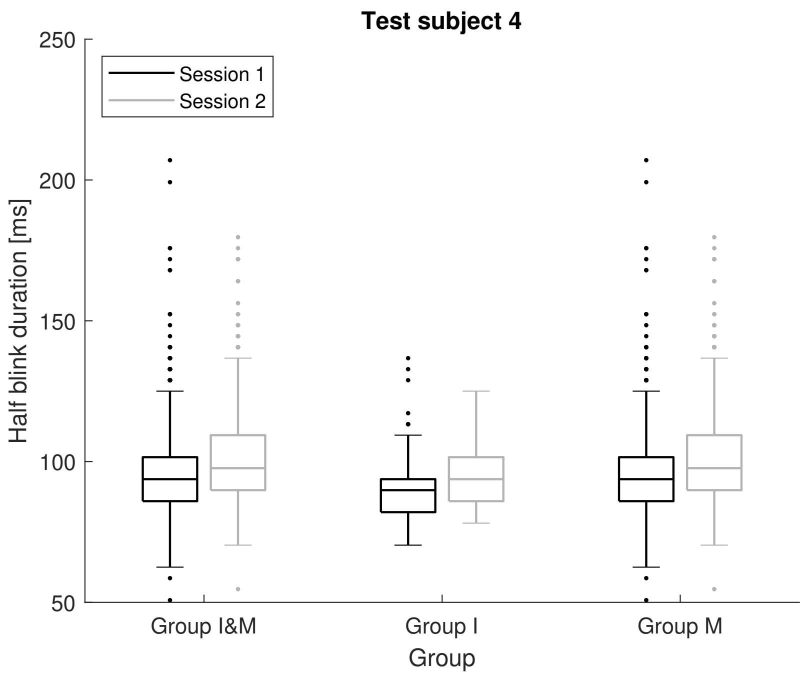

Figure A.3: Box plot illustrating the distribution of HBD between session 1 and session 2 separately for test subject 4 and Group I & M, Group I, and Group M.

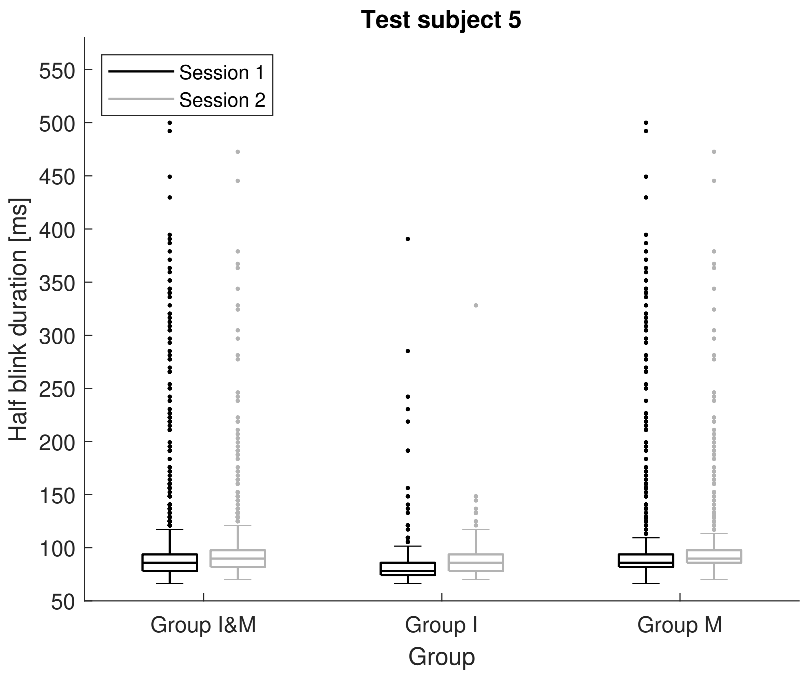

Figure A.4: Box plot illustrating the distribution of HBD between session 1 and session 2 separately for test subject 5 and Group I & M, Group I, and Group M.

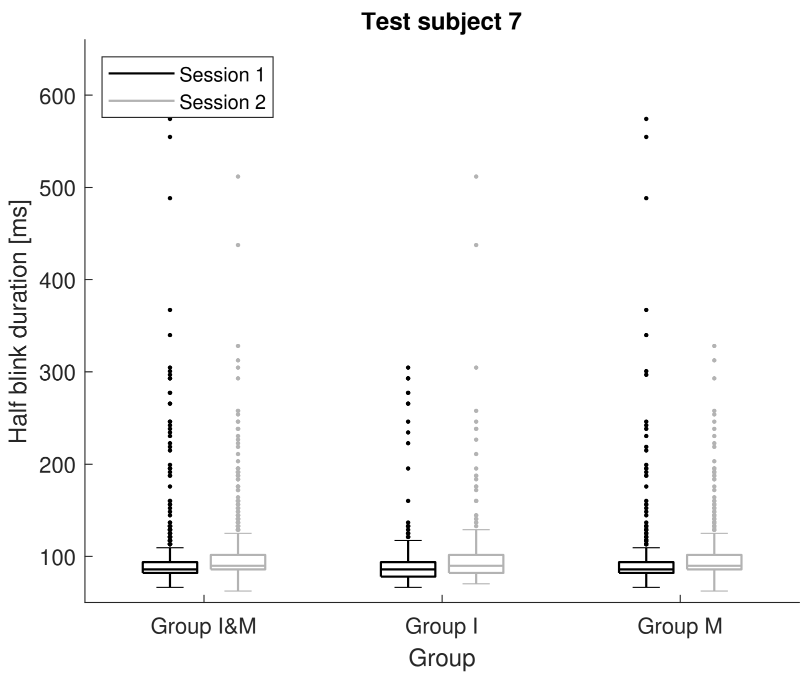

Figure A.5: Box plot illustrating the distribution of HBD between session 1 and session 2 separately for test subject 7 and Group I & M, Group I, and Group M.

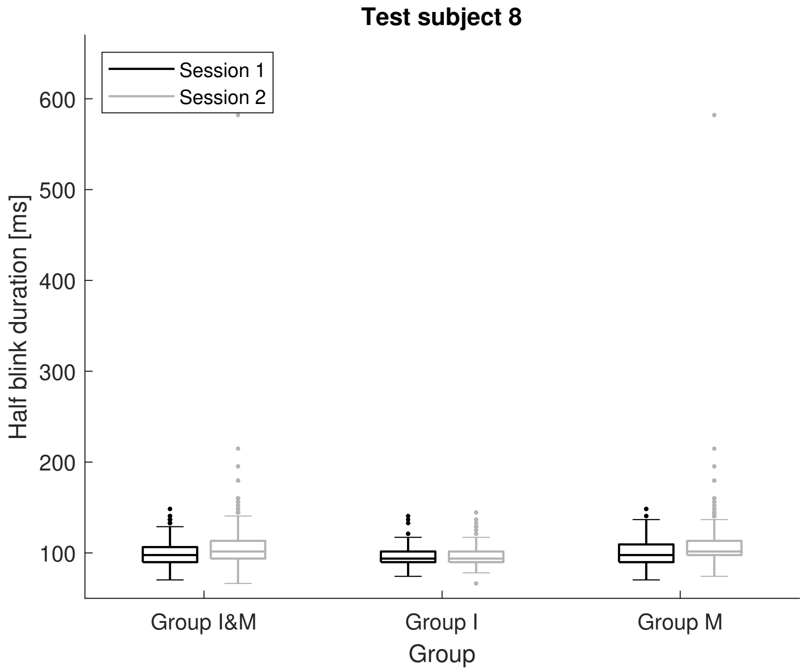

Figure A.6: Box plot illustrating the distribution of HBD between session 1 and session 2 separately for test subject 8 and Group I & M, Group I, and Group M.

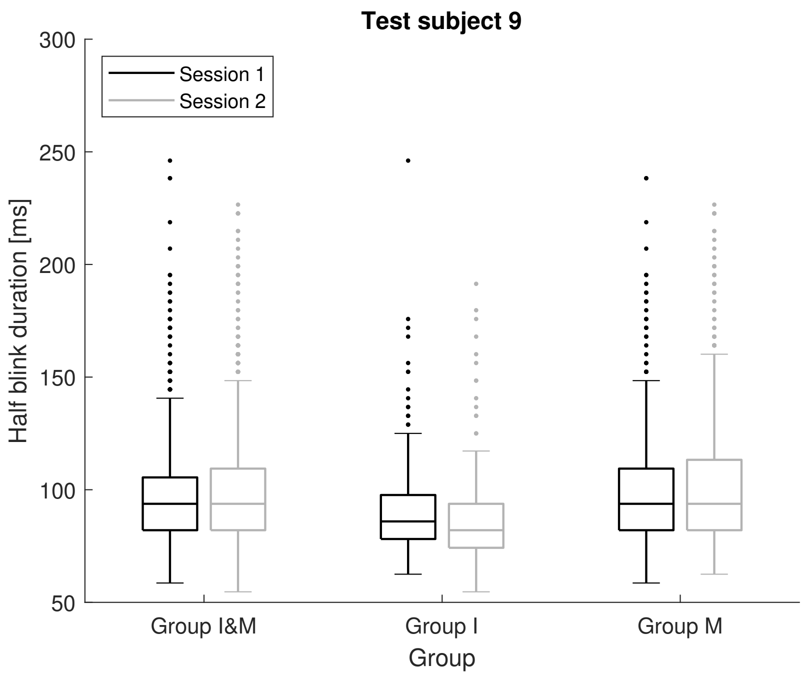

Figure A.7: Box plot illustrating the distribution of HBD between session 1 and session 2 separately for test subject 9 and Group I & M, Group I, and Group M.

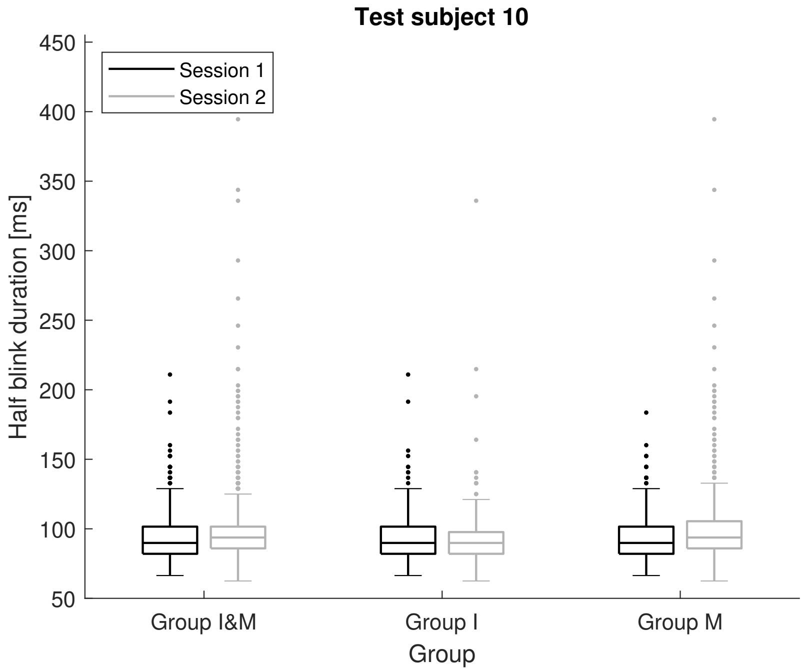

Figure A.8: Box plot illustrating the distribution of HBD between session 1 and session 2 separately for test subject 10 and Group I & M, Group I, and Group M.

Figure A.9-A.11 visualise the full distribution of HBD Group 1, HBD Group 2, and HBD Group 3 for interchange and motorway separately for each test subject.

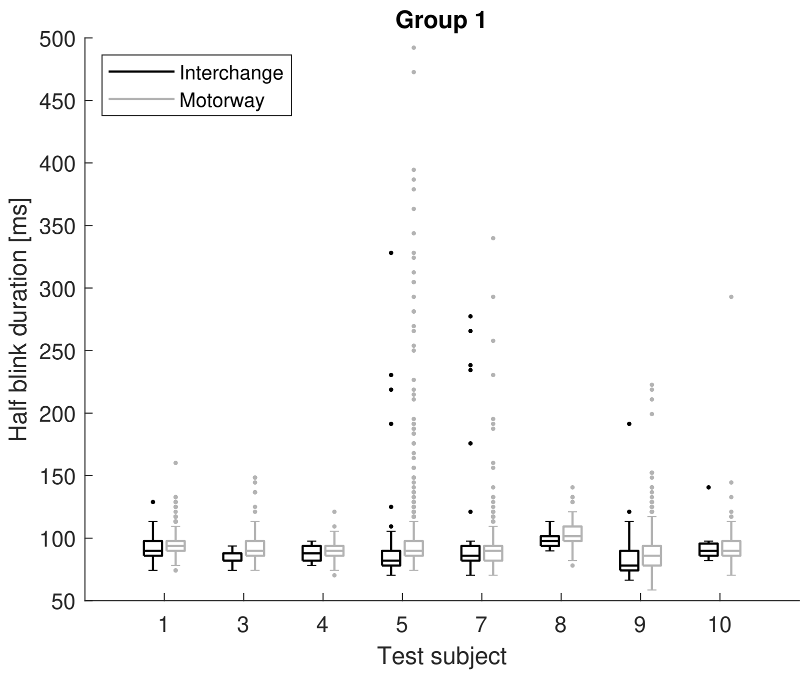

Figure A.9: Box plot illustrating the distribution of HBD of Group 1 between interchange and motorway separately for all test subjects.

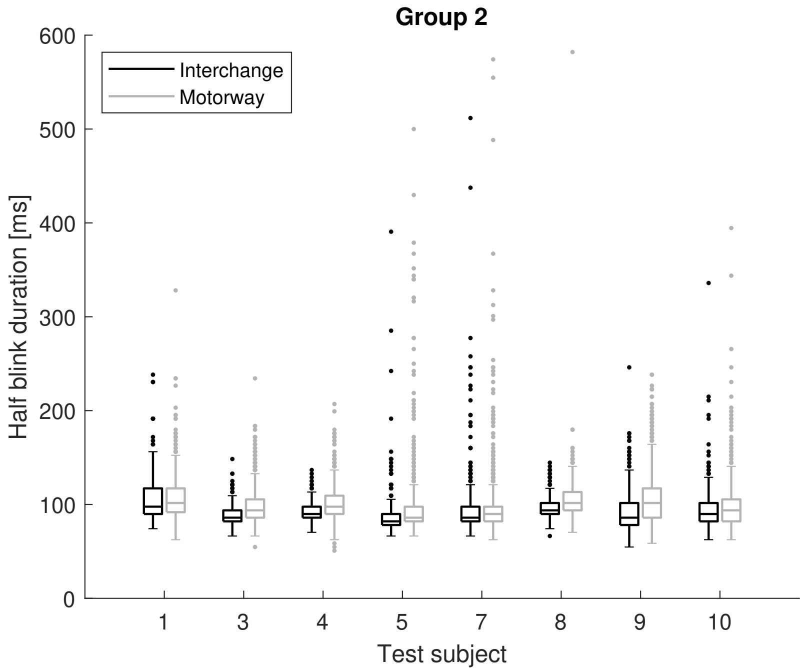

Figure A.10: Box plot illustrating the distribution of HBD of Group 2 between interchange and motorway separately for all test subjects.

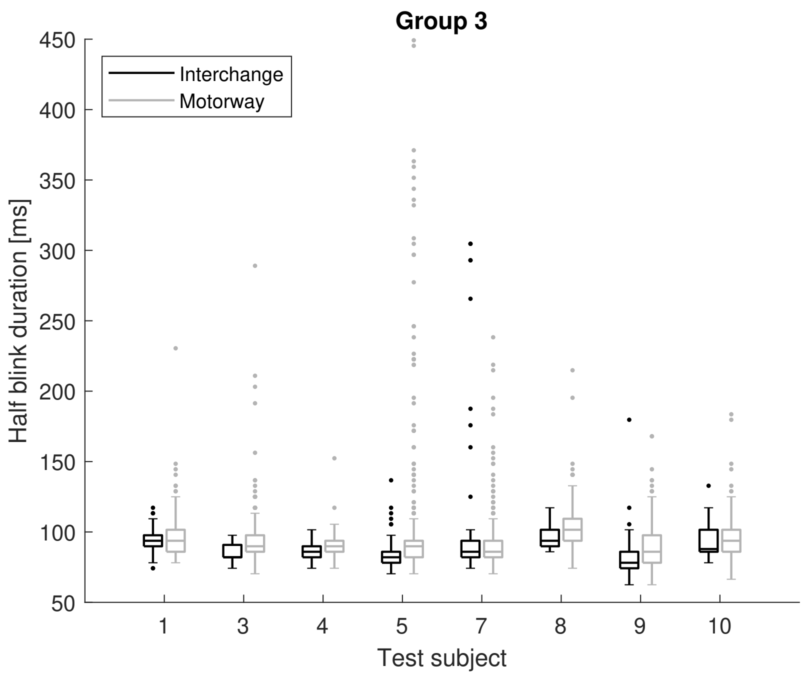

Figure A.11: Box plot illustrating the distribution of HBD of Group 3 between interchange and motorway separately for all test subjects.

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