A METHOD OF PROCESSING EYE-TRACKING DATA TO STUDY DRIVER'S VISUAL PERCEPTION IN SIMULATED DRIVING SCENARIOS

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ABSTRACT

Eye tracking technology has been introduced to the human factor studies in driving behavior not only to gather driver's behavioral data but also to gather driver's cognitive data. Gaze position indicates the driver's eye movement in a driving task based on the coordinate of the driving circumstances. The number of fixations, which is an indicator of how many particular areas are more noticeable or more important to the user in certain scenario, and the pupil size changing, which is an important indicator of the human physiological status, allow assessing the varying levels of the driver's cognitive load in a driving task. Pupil size changing, as an estimator of the driver's cognitive load, has been proven reliable by a series of experiments conducted in a driving simulator. However, the treatment of eye-tracking data is not a trivial activity and it is sensibly influenced by the type of the running experiment.

This paper proposes a method to elaborate eye-tracking data in order to get a comprehensive understanding of the drivers' perception of the different element of a simulated driving scenarios. The study is based on an experimental campaign, which involved different subjects. In this study, the head-mounted eye-tracking system Pupil Labs has been used. It contains a scene camera which records what the subject is looking at, and two eye cameras that record both eyes. Before each recording, the calibration of eye camera with the scene camera transforms the x- and y- coordinates from the eye camera coordinate system to the scene camera coordinate system. The Number of Fixations (NoF) has been introduced as a parameter to measure how the user is interested/attracted in specific area of the current scenario. Fixations has been set as an eye-movement that falls to an Area of Interest (AoI) and lasts of 140-300ms according to most of the state-of-arts. The route of the driving scenario has been split into different segments according to their different characteristics, which made possible to extract and compare the NoF of each specific segment. In addition, an

overall comparison of pupil size variety allowed understanding the mental workload variation among the different experimental conditions. The result implies changes in the user's eye movement in the driving task in different driving circumstances even if the route keeps the same, which could be useful for further studies in the field especially when the aim is supposed to be comparable with the real-world studies.

1. INTRODUCTION

The aim of this study is to explore a general method for the eye movement studies of manual driving tasks in the driving simulator, based on a fixed driving route with infrastructural accessories and building density as variables. As a complex activity, driving is highly related to multimodality interactions, especially dominated by visual perception (Nagayama, 1978)(Pauzie, 2014). Indeed, 80% of the driving-related information is obtained by visual observation (Kowler, 2011). Researches have shown that by modifying the users' eye movement strategies, the driving safety and driving experience could be improved (Konstantopoulos et al., 2010). Drivers' eye movements not only reflect the drivers' driving behavior pattern but also their mental workload. The gaze position was taken into consideration to analyze the driver's visual strategy when driving around curves (Ren et al., 2015). Eye fixations were introduced to explain the drivers' visual attention change whiling driving (Underwood et al., 2003). Generally, the higher the user's driving-related mental workload is, the lower the chance is that the driver will complete the driving task with an error (Palinko et al., 2010). Pupil size is used as a measure of the driver's mental workload (Bailey and Iqbal, 2008). The analysis of eye movement has become a novel approach to give a relatively comprehensive insight into people's driving behavior.

Using a driving simulator to conduct the user's behavior test has become a widely spread method instead of the conventional field test method, because of its advantages in safety and reliability (Jamson et al., 2013). User's behavior is generally registered and analyzed in the transition of manual driving and automated driving by using a driving simulator (Shi et al., 2019b), taking advantage of the safety and high replicability of the events in such a technology. Drivers' eye movements have been introduced in the user behavioral investigation. In low and moderate demand situations, users' visual attention measured in high fidelity driving scenarios and simulators is representative of the real world (Robbins et al., 2019). This is demonstrated by some recent researches on the subject. A research group employed a driving simulator to simulate driving scenarios with different amounts of fog to measure users' visual attention in various conditions (Louw and Merat, 2017). Another research group investigated users' eye movement while driving through the curve road in the driving simulator (Ren et al., 2015). Drivers' eye movements in different weather conditions (day, night, and rain) were recorded and analyzed to understand their visual attention considering their driving experience and visibility (Konstantopoulos et al., 2010).

Currently, there are generally two types of eye tracker systems for the monitoring of eye movements, the remote eye trackers, and the wearable eye trackers (head-mounted eye trackers). Remote eye trackers are monoscopic devices usually fixed in front of the screen of the simulator, for example, the Tobii T60 device, the EyeLink 1000 device and the Eye Tribe device. These devices can offer a reliable assessment of drivers' cognitive workload in driving simulators (Palinko et al., 2010), but the operating area is severely limited and the distance between the driver and the screen is fixed with limited head and body mobility. The wearable eye trackers or head-mounted eye trackers allow the subjects to move and navigate naturally in the driving simulator, monitoring their pupillometry characteristics, for instance, the Tobii Pro Glasses and the Pupil Labs glasses.

In a wearable eye tracking device comparison, the Pupil labs 120Hz Binocular glasses showed significantly more accurate than SMI ETG 2.6 and Tobii Pro Glasses 2. The precision of Pupil Labs glasses was similar with that of SMI, which both of them were higher than that of Tobii (MacInnes, 2018). The eye tracking device used in this study is the Pupil Labs Core Binocular glasses, Figure 1.

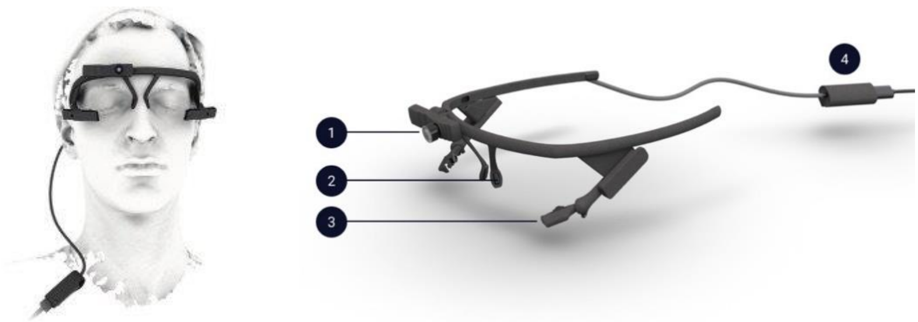


Figure 1. Pupil Labs Binocular glasses. On the left is the wearing state on a participant, on the right the four components are shown: 1, world camera; 2, nose support; 3. Eye cameras (adjustable); 4. USB-C connector clip (connecting the Pupil Core headset to the computer).

Pupil Labs (https://pupil-labs.com/) has an open platform for pervasive eye tracking and mobile gaze-based interaction. The supplied software Capture can record and mapping the gaze position in real time. In figure 2, the function of Capture is shown. 1a, the decompressed camera image streams of the eye; 1b, the decompress camera image streams of the outward world. 2, the pupil is detected in the eye image. 3, mapping of the detected pupil position into the scene space. 4, Execution of additional functions and plugins.

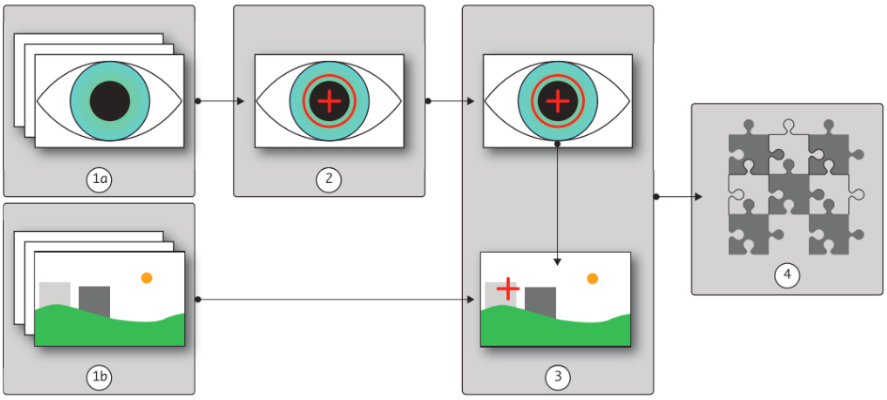


Figure 2. Overview of Capture functions. (Kassner et al., 2014)

However, Pupil Labs does not give instruction on the usage of wearable eye trackers in the driving simulator. In this study, the authors explored to set up a method of applying the Pupil Labs eye tracker glasses in driving behavior study.

2. METHODOLOGY

The proposed methodology is based on the use of a fixed-based driving simulator. Driving simulators are widely used in the driver's behavioral studies (Fisher et al., 2002; Mulder et al., 2008; Ariansyah et al., 2018; Shi et al., 2020) since the driving environmental circumstances, i.e. fog, rain, etc., and the visual stimuli, i.e. signals, road signs, etc., can be strictly controlled. The driving simulator used for the test, includes a realistic driver seat, with a force-feedback steering wheel, gear shifter, and pedals, a three-monitor visualisation system, which provides a 175-degree horizontal field of view, and a surrounding audio system. The software used for the simulation is the IPG CarMaker (https://ipg-automotive.com/), which is a professional driving simulator software that enables to make the driving experience realistic, e.g. in terms of driving styles preference study (Shi et al., 2019a). The Pupil Labs software runs onto a dedicated computer, to avoid reducing the performance of the simulation and to simplify the calibration of the entire system. On the same computer, a background application allows synchronizing the Pupil Labs data capturing with the simulation by monitoring specific trigger events on CarMaker through the network connection between the two computers. This synchronization allows simplifying the subsequent processing of the acquired data. The architecture of the testing platform is shown in Figure 3.

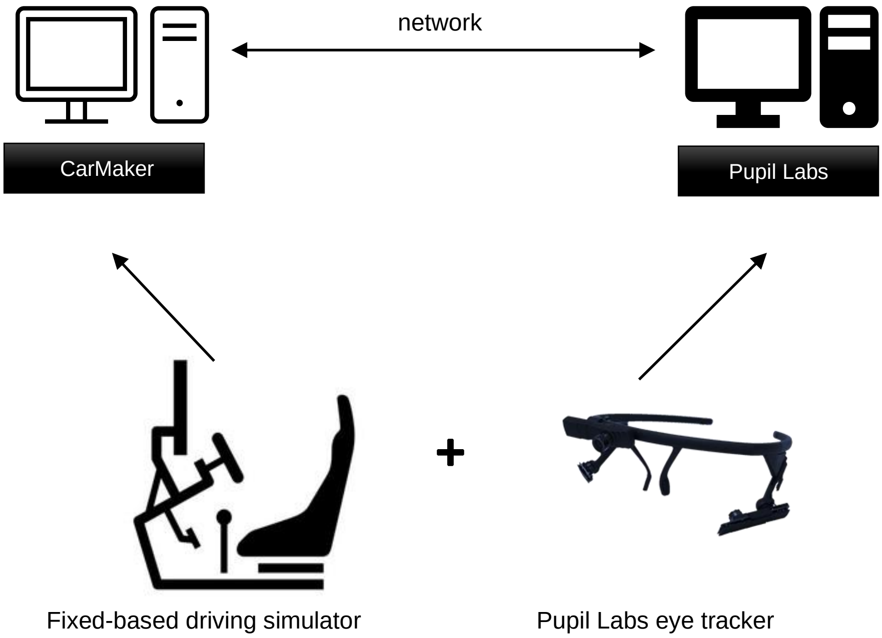


Figure 3. System architecture of driving simulator and eye tracker setup.

2.1 Participants

29 volunteer students of Politecnico di Milano were involved in the research. 10 of them are female. The age range is 21-26, and the average age is 23.31, with a standard deviation of 1.168. All the participants hold a driving license. 13 of them (45%) have more than 5 years of driving experience. The rest 16 participants have 2-5 years of driving experience. All the participants have domestic cars in their family. 10 of the participants drive every day, 17 participants drive two to three times a week, while the other two of the participants never drove during the last three months before the experiment.

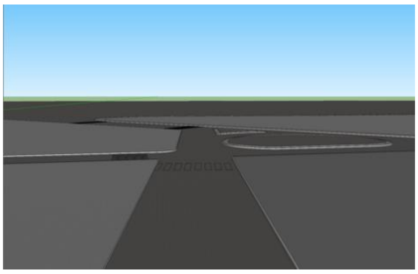
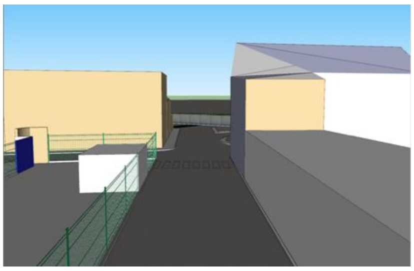
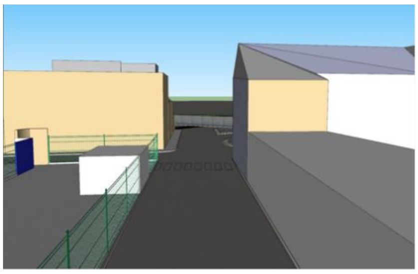
According to the drivers' self-reported driving history, four of the participants had experienced one crash in the past, while the rest of them had never been involved in any car accident. Eight of the participants have violated the highway code while driving and have been fined. These eight participants were not the same people involved in car accidents.

2.2 Design

Four testing scenarios formed the core of the study. Each scenario followed the single variable principle, only one variable was changing, i.e. the Level of Details (LOD) of the virtual driving environment. The driving route and traffic rules were the non-varying variables. LOD 0 is the testing scenario with lowest details, LOD 3 the one with the highest level of detail (Table. 1). All participants drove the four testing scenarios, but they were divided into four different sequences:

- Sequence A: LOD 0 – LOD 1 – LOD 2 – LOD 3
- Sequence B: LOD 1 – LOD 2 – LOD 3 – LOD 0
- Sequence C: LOD 2 – LOD 3 – LOD 0 – LOD 1
- Sequence D: LOD 3 – LOD 0 – LOD 1 – LOD 2

Table 1. Four Levels Of Detail (LOD) and their contents

LOD	LOD 0	LOD 1
		
Details	Route	Route + Blocks of the building without roof
LOD	LOD 2	LOD 3
		
Details	Route + Blocks of the building with roof	Route + Building with roof and textures + Supplementary details

The routes of the four testing trials were the same, a circuit road modeled in the virtual reality environment as the landscape of La Masa Campus of Politecnico di Milano (Figure 4).

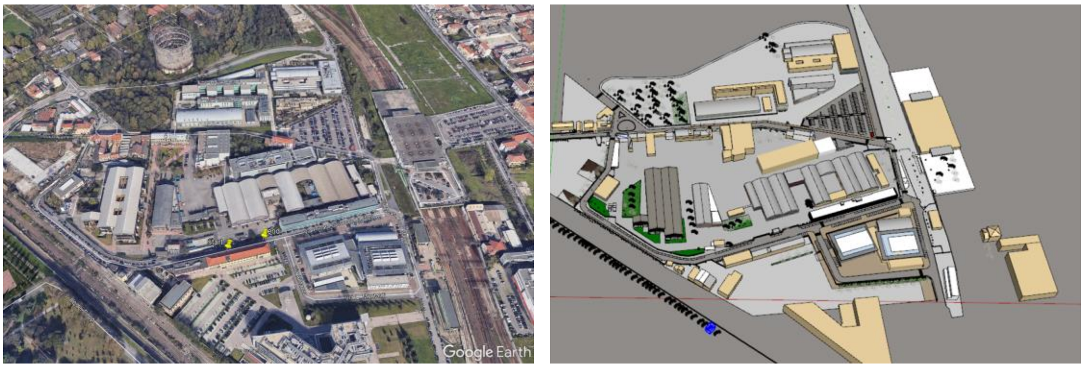


Figure 4. Comparison of the satellite map of La Masa Campus and the testing scenario route

The driving route was a one-way lane, all the drivers started at the same point and drove for two loops, then stopped at the same position in all LODs. The participants were requested to respect the traffic code and avoid over-speed driving. The speed limit of this circuit road was 50km/h.

2.3 Procedure

A brief introduction to the experiment was presented to participants. Before starting the first testing session, participants did an adaptation session riding the driving simulator to get familiar with it. The adaptation session last 3 minutes. Then, the testing session started, following a different LOD sequence as described before. Each testing session lasts from 50 seconds to 4 minutes, according to the participants' average speed. During each testing session, there was a short break that lasts a few minutes.

2.4 Measurement

Since the drivers' eye movement are highly related to the front scenes at time (Miyoshi and Nakayasu, 2011), some parameters cannot be treated by the time range of the whole testing session, for instance the gaze heatmaps. The whole circuit route was cut into small segments according to their geometric characteristics and classified into two categories: curvilinear segments and straight segments (Figure 5). Because of the irregular performance, the starting and ending segments were excluded from the data analyzing.

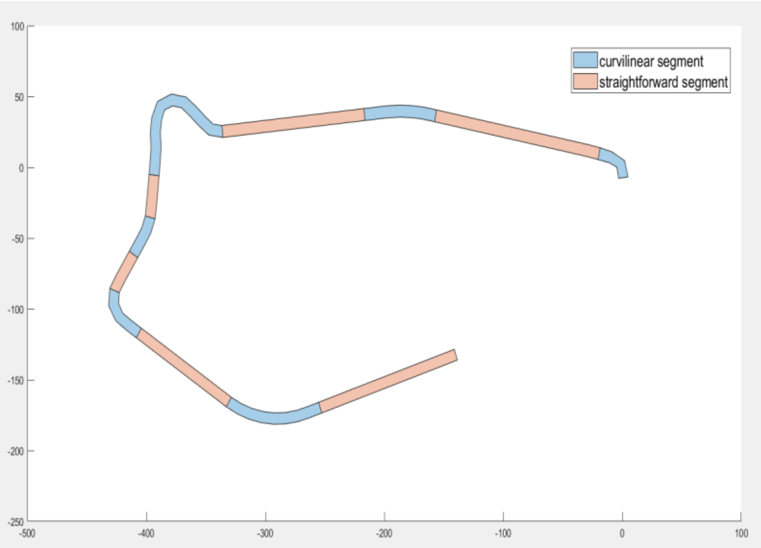


Figure 5. The segments of the circuit split by the geometric characteristics.

Pupil diameter, or pupil dilation is shown in the other researches to be sensitive to changes in mental workload in the highly controllable environments, such as driving simulators (Marquart et al., 2015)(Chandra et al., 2016). There is a clear correlation with the increase of task difficulty to the increase in the pupil diameter with the increase of the cognitive load level (Čegovnik et al., 2018). The pupil diameter can be analyzed based on a specific segment and can be analyzed based on a relatively long period in order to reveal the mean mental workload level of the participant along the experiment. The average pupil diameter was measured upon 10 minutes to investigate the fatigue (Morad et al., 2000). Particularly, the pupil diameter is usually measured separately for the left and right eye, even if in the research of Palinko et al., only the left eye's data was considered (Palinko et al., 2010).

Eye fixation can be elaborated from two dimensions: the number of fixations and the fixation duration. First of all, the definition in ISO15007 suggests that the fixation is the alignment of the eyes, so that the image of the fixated area of interest falls on the fovea for a given time period, for example from 100 ms to 2 000 ms (ISO15007, 2014). It is worth noticing that the alignment of the eyes is not fixed but moves in a tiny dispersion. The maximum of this dispersion is 1.0 deg in the current study, as the common standard (Borowsky et al., 2010). The general threshold of the sampling time is wide, normally 100ms-500ms, but this range is considered for daily life activities, i.e. reading and walking. In this study the threshold of the sampling time is narrowed down to 140ms-300ms, considering the driving velocity and the route setup (Salvucci and Goldberg, 2000; Velichkovsky et al., 2002). Both the number of fixations and the fixation duration are parameters related to the drivers' mental workload (Marquart et al., 2015). Long fixation duration is typically associated with high processing load, as it is shown in a study on the driving hazards (Reimer et al., 2010).

The gaze position reflects the sight movement of the driver. Especially, the vertical gaze position is used to explain the participants' sight distance and their frequency of glances to the dashboards (Reimer, 2009). Using the gaze position data, a heatmap can be generated to demonstrate the participant's Area of Interest (AoI)(ISO15007, 2014). This heatmap is also called "Attention map" and it used in some researches to describe the gaze distribution of the participants (Čegovnik et al., 2018; Voßkühler et al., 2008).

3. DATA PROCESSING

The scene and eye videos are recorded by the Pupil Labs' Capture application, together with the detected pupil and gaze position data aligned to the frame timestamps. In this study, data processing has been done with the Pupil Labs' Player application. The embedded algorithms can help to transform the pupil diameter data from 2D pixels into the measurement in 3D, with the unit of millimeters.

Eye fixation can be detected both in the recording phase and afterward. In the current case, the fixation detection was conducted afterward. Since the Pupil Core's fixation detectors implement a dispersion-based method (Salvucci and Goldberg, 2000), three parameters form the detection threshold: maximum dispersion, minimum duration, and maximum duration.

Markers were applied physically to the screens of the driving simulator, in order to help the eye tracker to track the AoI, which is named as 'surface' in Capture (Figure.6). In detail, surfaces (AoIs) can be defined according to one or more markers in the Capture application. Gaze heatmaps can be generated in two modes: gaze within each surface, and gaze across the different surfaces. Since in our case, the main components were all in the middle surface, the gaze within surface model was applied for the data processing. Gaze heatmaps demonstrate the distribution of drivers' visual attention, also named attention maps.

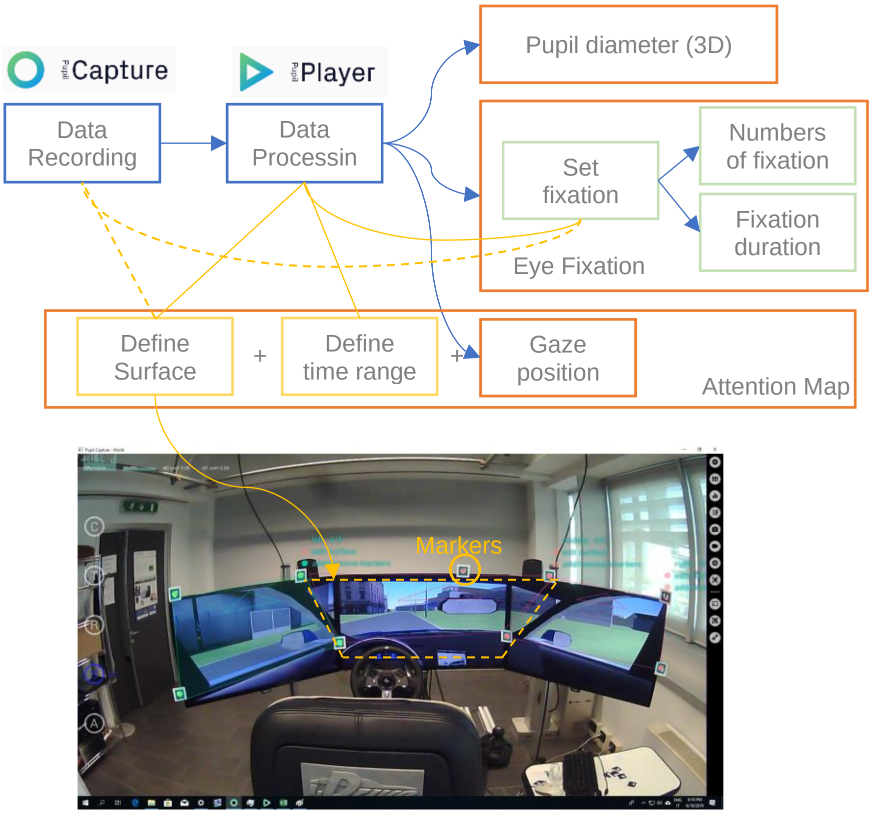


Figure 6. The framework of eye movement data processing

4. RESULTS AND DISCUSSIONS

4.1 Pupil diameter

The pupil diameter is related to the visual attention (Reimer et al., 2010). Participants' pupil diameter was elaborated separately by left eye and right eye. In this study, only the data with a confidence higher than 0.8 was taken into consideration. The results shown in Figure 7 suggest that both the pupil diameter of the left eye and that of the right eye increased with LOD, no matter if in curved segments or straight segments with a significance $p<<0.05$ in one-way ANOVA test. The result shows that participants' visual attention increased with the increasing of the complexity of the scenario.

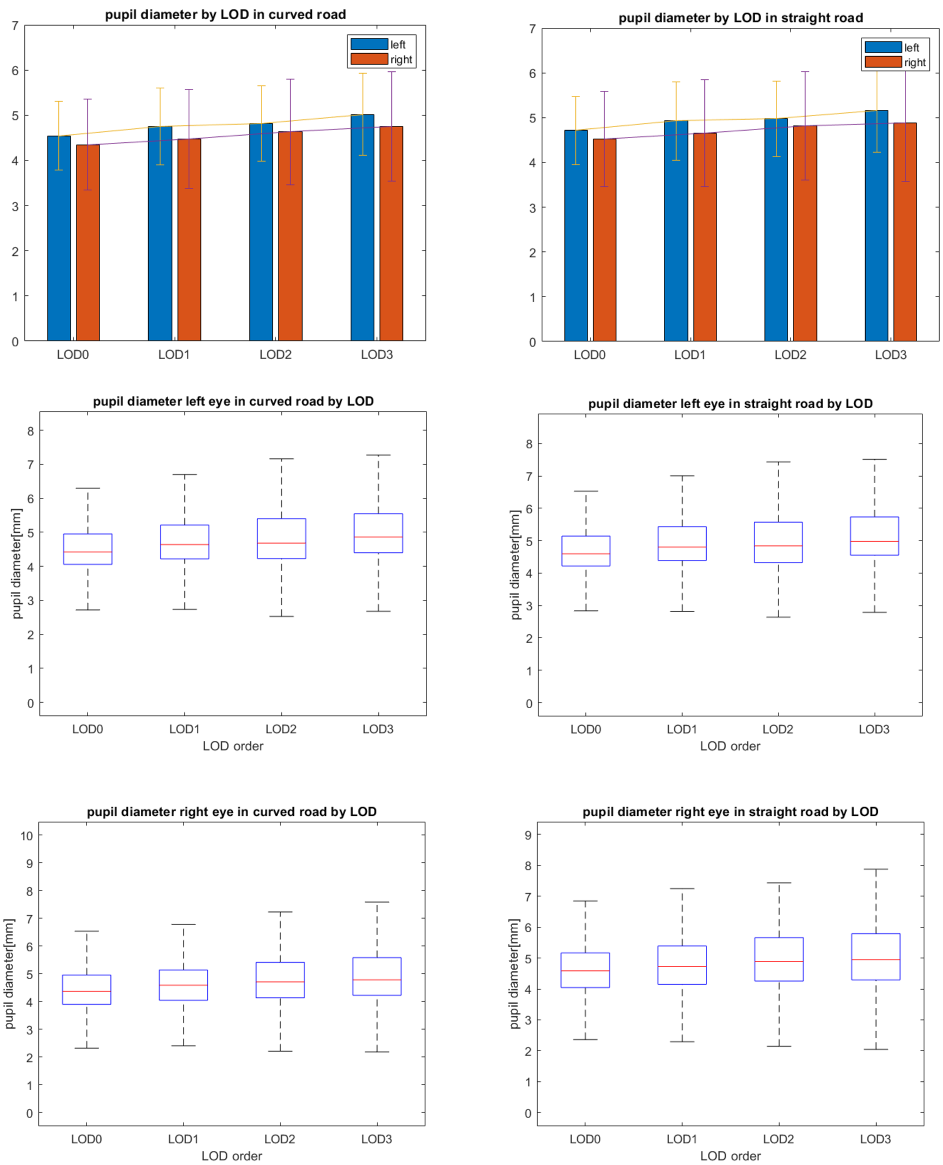


Figure 7. Pupil diameter of left/right eye in curved and straight segments by LOD.

4.2 Number of fixations

Number of fixations were calculated based on the constrains mentioned in the previous section: with a maximum dispersion of 1.0 deg, and a duration from 140ms to 300ms. The sampling period lasts as the entire testing session. In Figure 8, it is shown that generally the number of fixations in curved segments is greater than that in straight segments but, the difference between LOD is not statistically significant ($p \gg 0.05$), which can be explained as the mental workload did not change between different LODs.

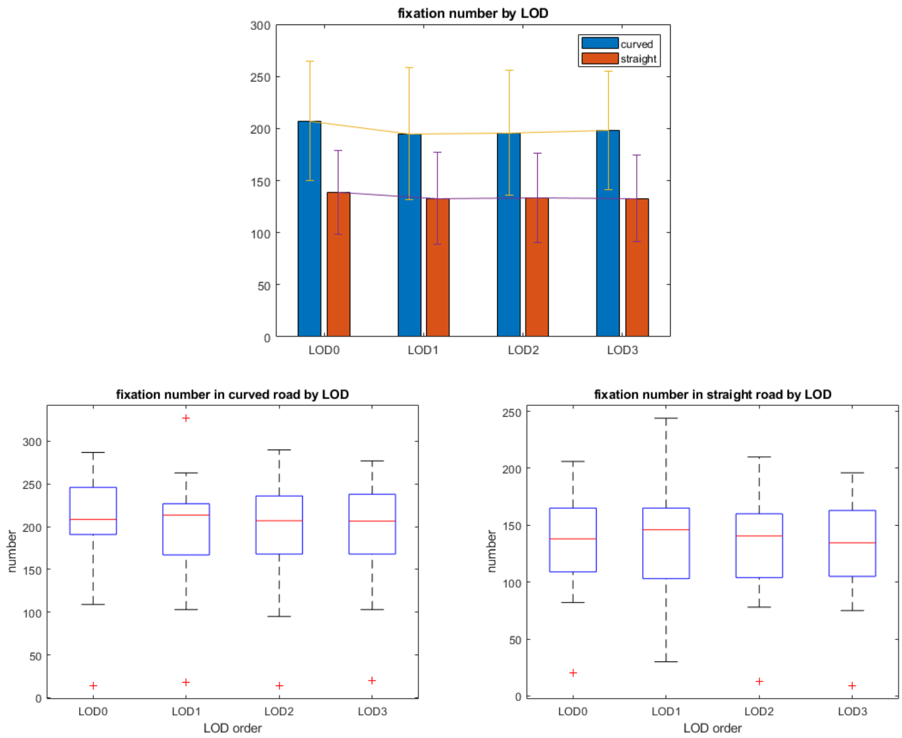
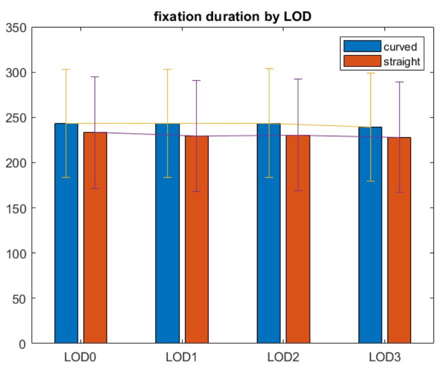


Figure 8. Number of fixation in curve/straight segments by LOD.

4.3 Fixation duration

Similar to the number of fixations, the fixation duration was also calculated along the entire testing sessions, and the standard of eye fixation remained the same. The average of fixation duration in each LOD is shown in Figure 9, with the unit of millisecond. In general, the fixation duration in curved segments was longer than that in straight segments, which is a similar result as the number of fixations. It confirms that the curved segments require higher mental workload. The decreasing of fixation duration in LOD 3 (with $p<0.05$) suggests that with all the elements present in the road environment (more similar to the real world), the participants spent less mental effort in the driving task.



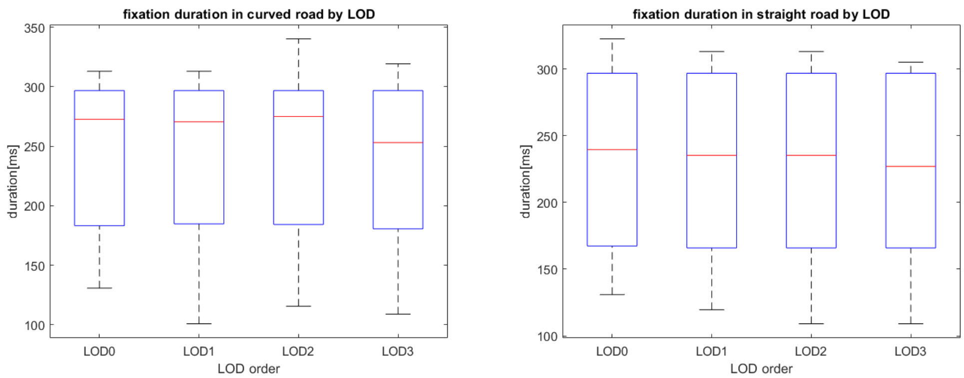


Figure 9. Fixation duration (ms) in curve/straight segments by LOD.

4.4 Attention maps

Using the markers in the video registered by the world camera to define a surface in the Pupil Labs software, and then selecting a time period, the heat map can be generated by the gaze position coordinates regarding to this specific period of time. Unlike the previous considered parameters, this method is not suitable for an aggregated analysis of the whole sample. It is more suitable for the investigation of a specific user's behavioral pattern. Taking participant 5 as an example, a typical straight segment and a typical curve segment is selected (Figure 10). σ_x refers to the standard deviation of gaze position in horizontal direction.

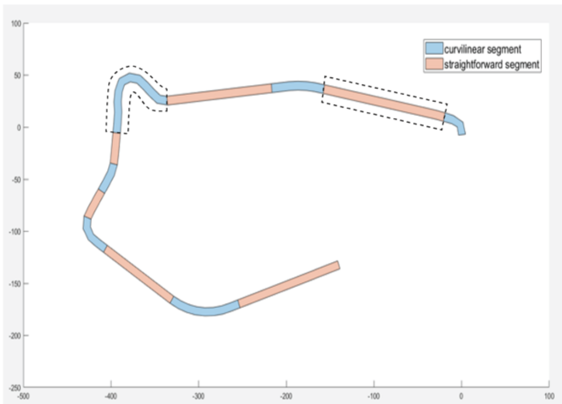
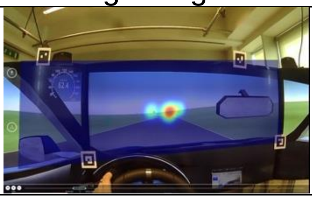
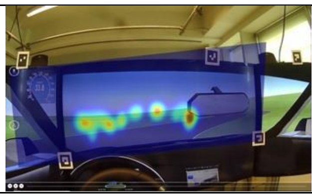
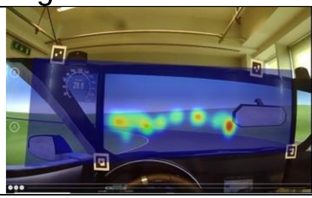
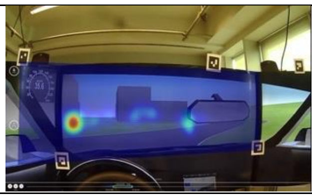
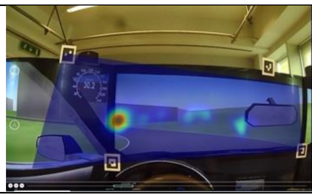
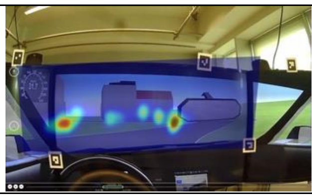
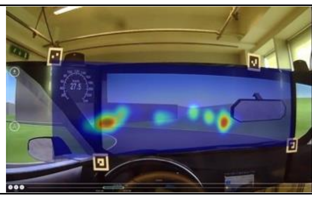
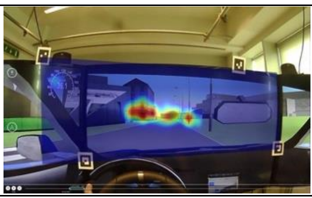
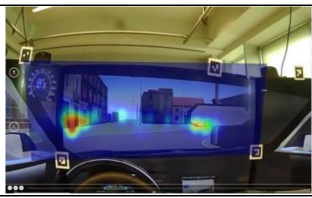
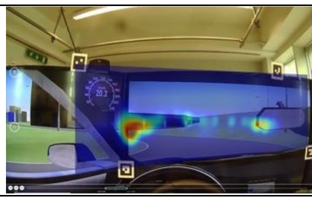


Figure 10. Sampling segments of Participant 5, the straight segment and the curve segment.

In the straight segment, the participant 5's gaze was focused on the center of the road in LOD 0. In LOD 1 and LOD 2 there was a little focus dispersion, due to presence of the building. While in LOD 3, the dispersion became more evident.

In the curve segment, two frames are shown in Table 2 for each LOD: the first one is curve entering, and the second one is in the middle of the curve. It is clearly shown that the participant's gaze was mostly allocated on the edges of the road, especially in LOD 1, LOD 2, and LOD 3, which coincide with the findings of (Ren et al., 2015). In LOD 0, there was only the route in the front scene, the participant was forced to change visual strategy to seek for reference. The comparison of results obtained for the two road geometries shows a great difference in driver behavior between straight and curved segments and also how it is differently conditioned by LOD. It can also explain differences in trajectory keeping which is generally more correlated in curved segments.

Table 2. Attention maps of Participant 5 in different LODs with standard deviation of horizontal gaze position.

	Straight segment	Curvilinear segment	
LOD 0			
σ_x	0.062	0.0691	
LOD 1			
σ_x	0.0801	0.0889	
LOD 2			
σ_x	0.0504	0.1004	
LOD 3			
σ_x	0.0902	0.0873	

5. CONCLUSION

As a dominant interaction modality in driving task, drivers' visual movement has been profoundly investigated. The pupillometry data, such as the pupil diameter has been recorded to explain drivers' cognitive and mental workload. Eye fixation is a parameter well defined in driving behavior study. Both of the Number of fixations (NoF) and the fixation duration are indexes related to driver's workload. Attention maps are usually used to demonstrate a specific area of interest (AoI) in a non-quantitative way.

In this paper, a method of conducting driver behavior studies from the perspective of eye movement in the driving simulator has been introduced. The mainstream devices for the eye movement measurement are of two types: the remote eye trackers and the

wearable eye trackers. The wearable eye trackers have advantages in enlarging the operational range of user. In the current study, Pupil Labs Core glasses were employed because of its better performance respect to other wearable apparatus.
Taking the elements in the simulated driving circumstances as the variable, four different driving scenarios were created and experienced by every one of the 29 participants. The results suggested that the complexity level of the driving scenario influenced the drivers' mental workload. By measuring the participants' pupil diameters, we can say that the more detailed driving scenario was, the participants were more engaged. From the point of view of NoF, no significant change in mental workload was found, but the most completed detailed scenario yielded shorter fixation duration. Moreover, the attention map has been introduced to investigate individual behavior patterns in driving.

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