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Gaze behaviour in curve driving

- Quantitative measurements of gaze velocity and yaw rate in simulated and real environments

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Tiivistelmä – Referat – Abstract

This master's thesis studies spontaneous gaze strategies when driving on a curved path. Methods used in many previous curve driving studies have not been sufficiently precise to differentiate between possible gaze strategies drivers use during cornering (Lappi, 2013, Itkonen et al. 2015). The methods in this thesis make it possible to differentiate between different gaze strategy predictions by comparing driver's horizontal gaze velocity and half of car's yaw rate.

Waypoint hypothesis (WP), where gaze follows targets on the future path, predicts negative linear correlation and specific -1:1 ratio between horizontal gaze velocity and half of car's yaw rate. Tangent point hypothesis (TP) and other travel point gaze strategies predict no correlation. In addition to previous study by Itkonen et al. (2015), the yaw rate is varied for quantitative analysis of the gaze behaviour and the experiment is conducted in two different environments, simulator and real test track, for reliability and validity.

Gaze and car telemetry data was collected during a slow acceleration on a circular path in similar simulated (n=15) and real environment (n=4). As predicted by the WP hypothesis, the results show a very strong linear negative correlation between car's half yaw rate and horizontal gaze velocity in simulator (-0.91) and strong linear negative correlation in test track (-0.75) and regression analysis shows slopes close to -1:1 ratio between the variables (simulator: -0.96 and test track: -0.79). The results can be clearly observed even on individual level. This suggests that primary gaze strategy when cornering in a curve is to pursue local flow on waypoints on the future path. The slight differences in results between simulator and test track experiment are discussed.

These quantitative results contribute to making more precise models of driver behaviour, that can help advance autonomous car designs and driver-vehicle interaction models. The results also help to make gaze strategies and visuomotor process theories more measurable and comparable in different environments.

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Tiivistelmä – Referat – Abstract

Tämän tutkielman aiheena ovat spontaanit katsekäyttäytymisstrategiat kaarreajossa. Monien aiempien kaarreajotutkimusten käyttämät metodit eivät ole riittäneet erottelemaan mitä katsestrategiaa ajaja käyttää kääntyessään ajoneuvolla (Lappi, 2013, Itkonen et al. 2015). Tämän tutkielman metodit pystyvät eriyttämään eri strategioiden tuottamat tulosennusteet toisistaan horisontaaliseen katsenopeuden ja puolikkaan auton pystykiertymänopeuden avulla.

Reittipistehypoteesin (WP) mukaan katse kohdistuu ajajan suunnitellulla reitillä oleviin pisteisiin. Tämä ennustaa, että katsenopeus ja puolikas auton pystykiertymänopeus korreloivat lineaarisesti ja niiden välinen suhde on -1:1. Tangenttipisteeseen (TP) ja muihin ajajan katsesuunnasta paikallaan pysyviin pisteisiin kohdistuvat katsestrategiat eivät ennusta mitään korrelaatiota. Pystykiertymänopeutta säädetään määrällisen analyysin mahdollistamiseksi ja kokeet suoritetaan niin simulaattorissa kuin oikealla ajoradalla reliabiliteetin ja validiteetin varmistamiseksi.

Katse- ja telemetriadata tallennettiin koehenkilöiden ajaessa ympyrärataa hitaasti kiihtyvällä vauhdilla. Koetta ajettiin toisiaan muistuttavissa simulaattori- (n=15) ja ajorataympäristöissä (n=4). Puolikkaan auton pystykiertymänopeuden ja katseen horisontaalisen nopeuden välillä simulaattorissa löydettiin erittäin vahva (-0.91) ja ajoradalla vahva lineaarinen negatiivinen korrelaatio (-0.75) ja regressioanalyysin kulmakerroin molemmissa ympäristöissä lähestyi -1:1-suhdetta (-0.96 simulaattorissa ja -0.79 ajoradalla), kuten WP-hypoteesi ennusti. Ilmiö näkyy selkeästi myös yksittäisillä koehenkilöillä. Tulokset viittaavat siihen, että ajajien ensisijainen katsestrategia kohdistuisi kohteisiin suunnitellulla reitillä. Simulaattorin ja ajoradan tulosten pieniä eroavaisuuksia pohditaan lopuksi.

Nämä kvantitatiiviset tulokset auttavat muodostamaan tarkempia malleja ajokäyttäytymisestä, mikä auttaa kehittämään itseajavia autoja ja ajoneuvo-ajaja-malleja. Käytetyt tarkat metodit ja mittaustulokset auttavat tekemään katsestrategioiden ja visuo-motoristen teorioiden mittaamisen ja vertaamisen helpommaksi eri ympäristöissä.

Avainsanat – Nyckelord – Keywords
kuljettajamalli, katsekäyttäytyminen, silmänliikemittaus, ajosimulaattori

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1 INTRODUCTION

1.1 Introducing the thesis

Where does one look when driving in a curve? Curve driving literature offers several possible control models that predicts gaze targets that drivers could use as an input in order to be able to keep the car on the road (Lappi, 2014; Salvucci & Gray, 2004). There also have been experimental tests to actually determine which theory offers the most plausible primary gaze strategy (Authié & Mestre, 2012; Kandil et al. 2009; Land & Lee, 1994). However recent studies have proposed that the used methods lack the precision to predict different results from different hypothesized gaze strategies (Itkonen et al. 2015; Lappi, 2014, 2015; Lappi et al. 2013).

This thesis continues from prior studies in curve driving literature that developed state of the art methods to analyse gaze data to directly test different theories of gaze behaviour in curve driving (Itkonen et al., 2015; Lappi, 2014; Lappi & Lehtonen, 2013; Lappi et al., 2013). When using these methods different theories predict different ratios of horizontal gaze velocity and the observer's rate of change of heading angle (yaw rate). In comparison to prior studies the thesis presents more quantitatively rigorous representation of the gaze behaviour by controlling the yaw rate and providing more precise data collection methods.

To have more accurate models of human behaviour there is a need for exact quantitative measurements. The most reliable behavioural measurements are possible in a highly controlled laboratory environment, but the more that behaviour is abstracted to fit controlled environments, the more the measurements can lose their validity with respect to the original phenomena. Thus, the reported experiments were conducted both with real car on a test track, and in a simulator.

1.2 Gaze behaviour

Humans use many information sources when controlling their self-motion within an environment such as tactile, auditory and vestibular; but visual information plays a leading role (Lappe, Bremmer, & van den Berg, 1999; MacDougall & Moore, 2005). Humans and other species have a visual system that is highly effective, fast and accurate in this semi-unpredictable world – something computer vision still tries to imitate. Eye movements have proven to be a valuable information source regarding functions of perception, attention, memory, decision making and motor control. Eye tracking informs where in the scene the fovea is directed to and thus tells about the visual input that goes to the visuomotor process as well as how visual and motor input changes eye behaviour (Wann & Swapp, 2000).

Until recent years, researching gaze strategies in natural environments with freely moving subjects was surprisingly difficult even when gaze has been studied in laboratories for decades. Advancements in eye tracking technology and gaze strategy theories has opened up new possibilities to study topics like human locomotion, planning and attention in natural environments (Kowler, 2011; Lappi, 2015; Lappi et al., 2017).

1.3 Driving behaviour

Humans have a variety of movement options, from running to crawling; on top of what humans have invented and mastered many different vehicles to move them, from horses to aeroplanes. Each movement type has interesting sensorimotoric feedback loops in itself, but even general cognitive theories of movement still have a lot of unanswered questions before they can be applied to more specific cases (Lappi, 2013).

Driving is a locomotive practice that happens in a semi-controlled environment; driving is easily instrumented; movements to control driving have only a few degrees of freedom; it is very visually oriented; and participants do not usually need special instructions to be motivated to drive without crashing.

Driver models can be seen as a well-specified case of more general locomotion behaviour. Accurate and well understood driving models could be generalized to other locomotion types as well, like cycling, walking and so forth (Lappi, 2012). In a more applied context, driver models can be applied to predict drivers' behaviour in traffic; to autonomous car technology that supports human attention; and to replace human test drivers in research and development of new cars.

1.4 Models of curve driving

When driving in a natural environment, a large number of different gaze strategies happen at high speed. Each target fixation[1] and pursuit could have a complex purpose that is not always intuitively easy to explain (Lappi, 2015; Lappi et al., 2017). Also even a simple curve driving episode has multiple parts like approaching, entering, turning and leaving a turn and all of them can produce different gaze behaviours. For simplicity this thesis focuses on cornering phase of a curve that has a constant radius. This limits gaze strategies that the driver needs to use and the scenario is easy to simulate.

1 In this thesis fixation is used in a sense that gaze is fixated to a target that can be an object or a location. Fixation does not mean that eye stays still in its socket. When targets move in relation to observer or observer moves in relation to the target or both, from an oculomotor point of view, fixations are actually pursuit movements (Lappi, 2016).

For two decades the most prominent hypothesis of eye movements in curve driving has been the one proposed by Land & Lee (1994). They measured steering angle between the car's heading direction and gaze during driving on a winding road. They observed a high concentration of gaze fixations in the region of a tangent point (TP). TP is usually defined as the point in lane edge on the inside of the curve where line of sight is tangential to the lane edge. This point is where the orientation of the visible lane edge line is reversed (figure 1). Land and Lee suggested that TP is used as a steering point in a control law: angle change in TP orientation makes the driver shift the wheel in the same direction by some definite amount so that the car stays on the road. The driver tries to keep the TP stationary relative to his/her egocentric view, which is made possible the fact that TP is a travel point, which means that it moves with the observer. This is called the tangent point hypothesis. TP-models were considered plausible theory as TP is a salient geometrical point and it provides a simple control law for adjusting steering.

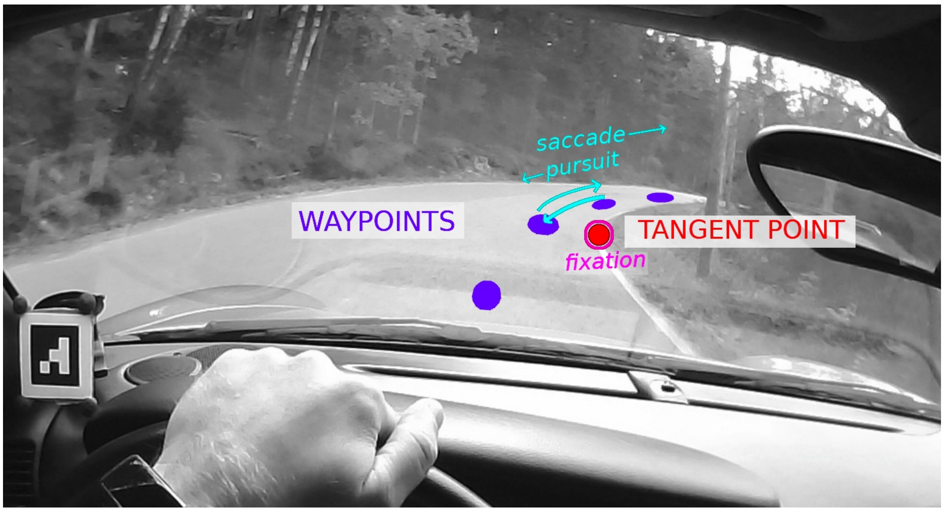


Figure 1: Tangent point (TP, red dot) is in the apex of the curve. TP hypothesis predicts that the gaze fixates on the TP, and perceived changes in tangent point angle transfers to turning the wheel. Other possible gaze strategy uses waypoints (WP, blue dots), that are on the planned future path and gaze pursues them while driver Is moving forwards. Gaze retrieves the next waypoint with a quick saccade.

Steering models alternative to TP-models that have been proposed are called future path (FP) models. FP is an abstract path that the driver plans to take. FP is based on a mental model more than on a simple geometrical entity in the visual field or in the visual flow although it is represented also in those levels of abstractions.

FP can have two types of steering points that move differently: travel points and waypoints. Travel points on the future path are egocentric like the TP, as they would move with the observer. It can be thought as a sliding target position that is always before the driver like a carrot hanging before a mule.

Waypoints (WP) are allocentric targets fixed in the 3D scene (Lappi, 2014; Wann & Swapp, 2000). Metaphorically speaking WPs are like “physical manifestations” of the future path, like spots on the road planned to be crossed. WP models predict that these steering points on the future path are tracked by gaze and these reference points are used to preview information of road geometry and used for correct steering.

A methodological criticism against TP-model is that empirical data that commonly used to endorse TP-theories is actually compatible with FP-theories as well. Traditionally used area of interest (AOI) methods lack precision and flexibility in a dynamically moving environment (Lappi, 2016). From the driver’s perspective, TP and FP can be geometrically only a few degrees from each other - especially FP waypoints that are beyond and in the line of TP can be really near the TP (figure 1, 2A). This area beyond the TP is also an important gaze target area in curve driving (Lappi et al. 2013). AOI-fields are usually about 3 degrees around the target. Fixations that land on the overlapping areas can’t endorse either hypothesis. This natural geometry presents a challenge for experimenters as overlapping between TP and WP points happen in an area that gaze frequently visits. The field size of AOI is dependent on measurement accuracy, and even with state of the art equipment it’s not possible to reach high enough quality (Lappi, 2016).

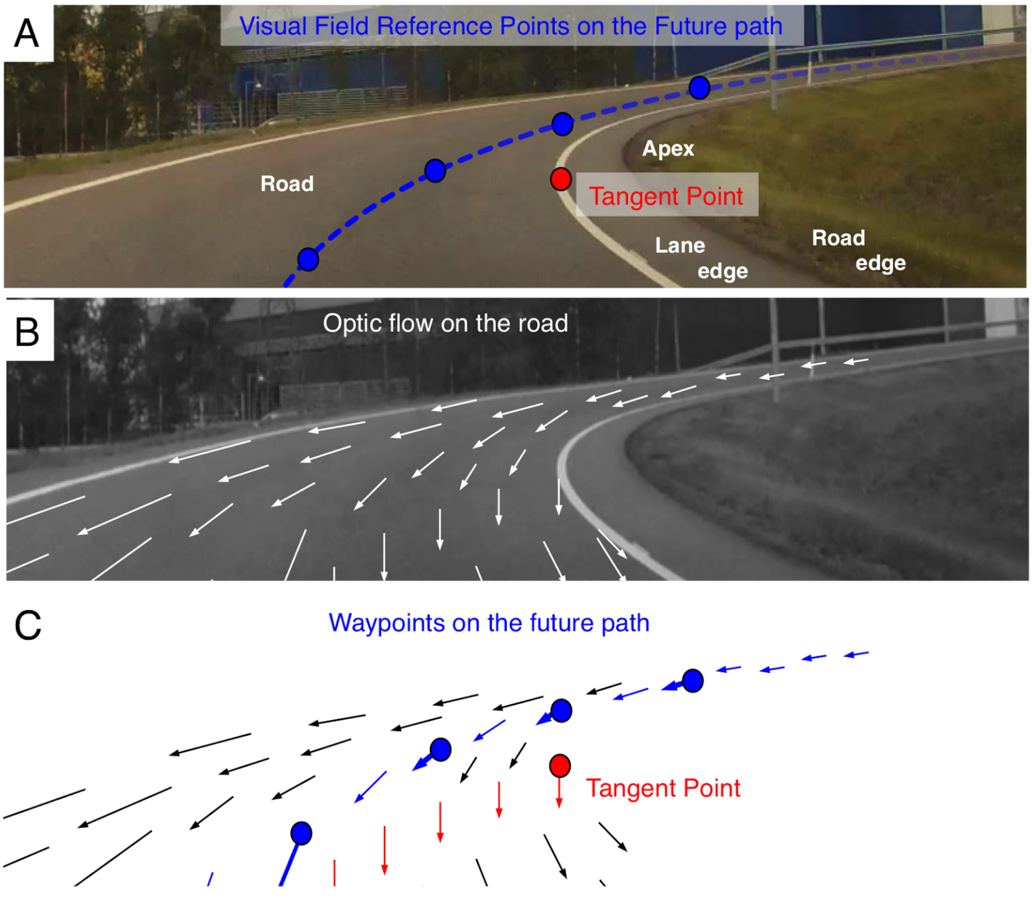


Figure 2. Future path and tangent point when cornering in a right-hand bend (from Itkonen et al., 2015). 2A: Future path (dashed blue line) is the planned trajectory of the car. Waypoints (blue dots) are visual cues of the moving road that follow FP. FP that is in vertical line with the TP is in the close proximity of it. This makes it hard to differentiate which target the gaze is actually following. 2B: Visual optic flow on the road surface (optic flow is the changing pattern of visible light that the observer sees (Lee, 1980)). 2C: FP and TP have different optic field characteristics that can be used for differentiating gaze targets. Tangent points have only vertical flow and WPs have flow speed of half yaw rate (Lappi et al., 2013). This is the basis of the methodology in this study.

1.5 Optokinetic nystagmus

Optokinetic nystagmus is triggered by coherent local optic flow and its function is to stabilize retinal image of the world. In other words it helps to follow some area of the moving visual flow. An example is when looking outside of a moving train and eyes start to make a “zig-zag” pattern. OKN consist of a slow and a fast phase. Slow phase of OKN (OKN-SP) is a succession of tracking movements (smooth pursuit and/or optokinetic response) in the direction of visual motion. Fast resetting saccades in the opposite direction are called the fast phase of OKN (OKN-FP). It has been suggested that OKN-SP and smooth pursuits could derive from same neural mechanics (cf. Barnes, 2008), and sometimes OKN-SP are called “tracking fixations”. In this thesis the term “pursuit” is used to refer to OKN-SP that follows local visual flow.

Authié & Mestre (2011) and Lappi & Lehtonen (2013) independently discovered optokinetic nystagmus (OKN) in curve driving. OKN has been found to be partially top-down controlled as observers can initiate or suppress OKN reflex by focusing in different driving tasks (Itkonen et al., 2015), so the OKN-SP is unlikely to be controlled only via bottom up OKN reflex.

1.6 Predictions

TP and FP models have different gaze targets but these are so close to one another that they can not be reliably differentiated with *positional* data alone. The road geometry can make the AOI of TP and FP easily overlap.

Luckily due to differences of local flow velocities where the points are represented, it is possible to measure their *motion* difference unambiguously. When tracking targets on the path – like TP or WP - pursuit velocities of OKN-SPs should be roughly equal to their local flow speeds assuming near perfect tracking. Local horizontal flow in the TP region should be close to non-existent (figure 2C). Local flow in the FP region follows the movement of the road, so if the driver is tracking waypoints the eye's tracking speed should mirror it. If the gaze targets are egocentric travel points and thus do not pursuit local optic flow (at least with a high gain), horizontal flow is near zero.

Angular horizontal flow speed at the future path can be geometrically shown to be negative of half of the observers yaw rate (Kim & Turvey, 1999; Wann & Swapp, 2000). An intuitive way to see this is by asking how much does your gaze turn in relation to the car when travelling towards the future path. So let there be a path that, when followed, turns the car for example 90 degrees. The driver keeps a fixation on the WP at the end of the path. When the car has driven to the end of the path, driver's eyes have turned 45 degrees (figure 3) at the same time as car has turned 90 degrees to the other direction. Same half yaw ratio holds regardless of where in the future path gaze lands (Itkonen et al., 2015).

Therefore, if curve driving gaze data shows OKN-SP behaviour, from the speed of its horizontal movement we can determine if the gaze has followed the local flow of the WP, given perfect tracking. Also high gain horizontal OKN-SPs should not be found if gaze target has no horizontal optic flow or it "moves" with the observer, like in the case of TP and travel points on the future path.

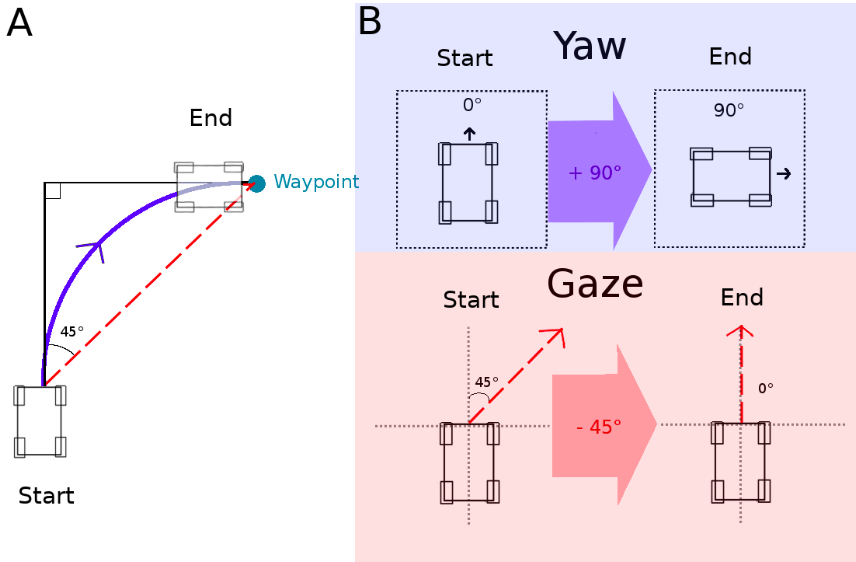


Figure 3. Illustration of angular change of the gaze when car's yaw turns 90 degrees and gaze is fixated on a waypoint. (A) visualizes how the car steers from start to end. (B) represents what happens with yaw and gaze angle in the drive. In the first position (start) gaze orientation is 45 degrees and car's yaw 0 degrees. When car has driven to the waypoint (end) car has turned 90 degrees (yaw) and gaze -45 degrees. Same -2:1 ratio between yaw rate and horizontal gaze generalises in any waypoint tracking situation with a constant radius curve.

Itkonen et al (2015) found that cornering phase driving has OKN characteristics that do not support TP models and do fit into WP model's predictions (also see Lappi et al. 2013). The experiment was performed on a motorway on-ramp on a fairly constant speed and thus constant yaw rate. Also they presented a clear difference in gaze velocities when participants were asked to drive car in a curve normally and when looking at the tangent point. When driven normally, gaze behaviour was consistent with WP models' prediction.

Even when Itkonen el al. has verified behaviour that WP-models predict, due to lack of yaw rate control in real traffic, they could not deliver perfectly satisfactory quantitative results for the argument that the two variables should have a negative linear correlation or that the ratio between half yaw and horizontal gaze would be a constant -1:1[2]. No study to date has examined the relation between OKN-SP and local visual flow with a changing observer speed i.e changing yaw rate. This study therefore set out to investigate more closely the quantitative correlation between a car's yaw rate and gaze's horizontal component, by manipulating the speed and hence yaw rate, hence local flow speed of the WP, across a range of values from walking pace to the limit of traction.

The level of control and measurement precision is much superior in simulators compared to driving outside the laboratory. Simulated driving environments are popular in gaze driving studies (Kemeny & Panerai, 2003), but as simulators do not offer as rich an environment as real driving, it is to be questioned whether results in simulators are transferable to real world environments. In most simulators, drivers lack vestibular cues, full visual fidelity, stereoscopy, and full field of view while screen artefacts such as aliasing can affect motion parallax (Kemeny & Panerai, 2003).

For the purposes of the thesis two experiments are carried out: one in simulator and one in a test track with real car. The purpose is to reliably measure found phenomena in simulator and validate the results with data from similar real world environment.

The hypothesis for this study is that gaze follows targets on the future path like was suggested in the study of Itkonen et al. 2015. Therefore study's quantitative predictions are:

(i) gaze's horizontal velocity and car's yaw rate correlate linearly with each other

(ii) gaze's horizontal velocity would be - ½ of the car's yaw rate

(iii) simulator and real life experiments will give similar results stated in (1) and (2)

Tangent point or other travel point hypotheses do not predict first or second result, but a horizontal velocity and a correlation of near zero. If correlation is observed, it would support the waypoint hypothesis as a primary gaze strategy in cornering a curve. This

2 Note that in this thesis -1:1 ratio refers to the ratio of *half* yaw rate and horizontal gaze velocity, not *full* yaw rate.

would be in contrast with similar experiments that did not observe gaze to follow local flow of the WP when driving in curve, and instead suggested that travel point strategies are preferred by the drivers (Authié & Mestre, 2011; Kandil et al. 2009; Land & Lee, 1994). Also if high reliability experiment of simulator is validated with results of real environment test track experiment, it would suggest that simulator could be used to study this phenomena further.

2 METHODS

Two experiments are run; one in simulator and one in a test track environment. The same “friction circle” task is performed in both experiments. In the friction circle task participants drive a constant radius cornering, with increasing speed. In a constant radius curve yaw rate is directly proportional to travelled speed. Experiments are maximally similar except that (i) in the simulator the driver’s speed is controlled by the computer and on test track the drivers themselves control the speed, (ii) the curve radius is bigger in the simulator (where it is safer to use higher speeds) and (iii) there are some visual differences to the layout of the simulated path (explained in detail in 2.2.3 and 2.3.3).

2.1 Eye tracker

In both experiments eye tracking was done with the Pupil Labs Binocular 120 -eye tracker. (Pupil Labs UG haftungsbeschränkt, Berlin, Germany) (figure 4). The system includes one infrared camera for each eye and a forward facing scene camera. The program distinguishes the pupil from camera image of each eye and uses calibration to combine the eye position information with the scene camera image. Gaze can be visualized live in the scene camera view with a dot indicating gaze direction relative to the headset. Video recordings of all three cameras, plus calibration data, are saved for offline gaze reconstruction and analysis.

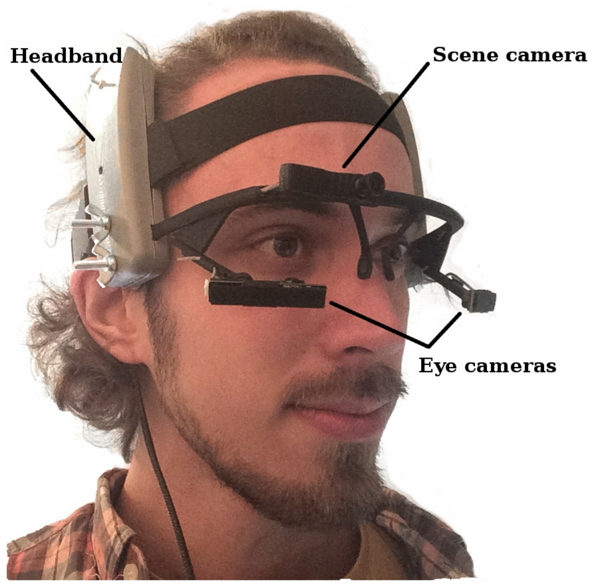


Figure 4. Pupil Labs eye tracker hardware. Two cameras record eye movements and one scene camera records the view to the front. A custom headband was used to stabilize the headset during recording.

The Pupil headset stability was improved with a custom headband to decrease movements of the headset that affects the calibration. (The custom headband was designed and fabricated by Mr. Juho-Pekka Virtanen, Institute of Measuring and Modeling for the Built Environment/Center of Excellence in Laser Scanning, Aalto University). Pupil has an open access software policy and our version included custom code made in the Traffic Research Unit. Software version was developed by Mr. Samuel Tuhkanen specifically for gaze studies for driving in both simulator and real world environment (https://github.com/samtuhka/pupil).

The field of view of the scene camera was approximately 100 degrees in the x-axis and 56 degrees in the y-axis. Eye image data was recorded in 30 Hz per seconds in 1280x720 resolution.

The horizontal gaze velocity is measured in relation to the world and not to the head, where the camera is attached. In curve driving the head does a significant amount of tilting (MacDougall & Moore, 2005). As the eye tracker's scene camera moved with the head, horizontal stabilization was done with optic markers present in the camera view (figure 5 and 8). Stabilization was done in reference to the screen in simulator and to the car in test track experiment. Thus measured gaze movement was actually a combination of eye and head movements. After some pilot testing it was concluded that markers did not interfere with driving.

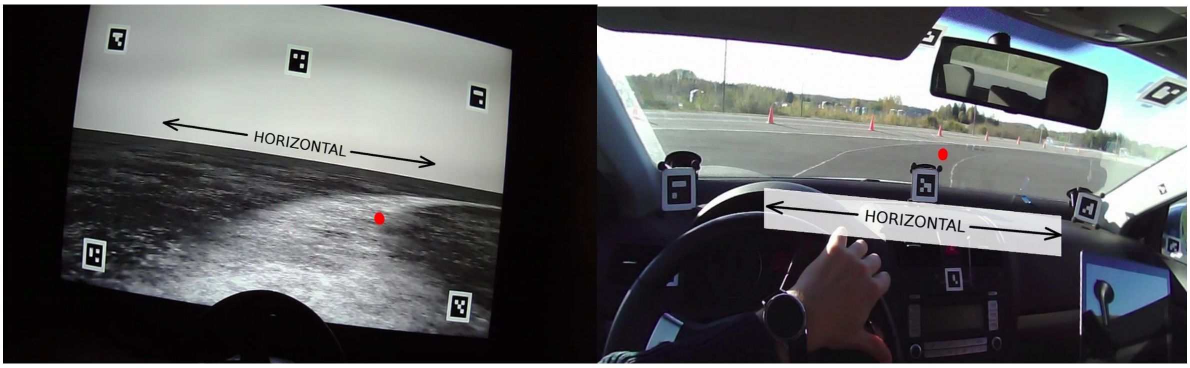


Figure 5. View of the scene camera in simulator experiment (left) and test track experiment (right). Markers are seen as black and white squares in both pictures. Referred horizontal axis in simulator is the screen and in the test track the car's horizontal axis. Red dot is estimated gaze position.

2.2 Simulator experiment

2.2.1 Subjects

Table 1. Simulator participants and their driving experience

n	15 (9 women, 6 men)
Age	20-46 years, median 28
Reported driving experience in the past 12 months	Total range between 1 000 - 30 000 km, median between 5 000 - 10 000 km
Reported total driving experience	Total range between 1 000 km - 500 000 km, median between 30 000 - 100 000 km

Participants were recruited through university email lists, except for three, who also took part in the track driving experiment and were recruited by Dr. A. Tuononen. These three participants were useful to see if eye behaviour was consistent between the experiments and in line with other simulator subjects. Each participant filled a standard consent form and everyone had normal or corrected vision, and none reported eye-movement related neurological diseases.

2.2.2 Equipment

The experiment was conducted in Traffic Research Unit at the Helsinki university campus of Behavioural sciences. The physical set-up of the simulator can be seen in figure 6. The wheel (Logitech G25, Logitech, Fremont, CA) was fastened to a table at 62 cm height, and the screen was placed directly in front of the participant. The exact viewing distance to the screen depended on the participant's preference, but was approximately 85 cm. This creates an approximately 70 degree viewing angle to the 55” screen (LG Ultra HD 4K TV). Participants were seated in a distance-adjustable gaming chair (Playseat Evolution Alcantara, Playseats B.V., The Netherlands) that had no height control, so exact view height changed with participant's height. The median eye height was approximately 97 cm.

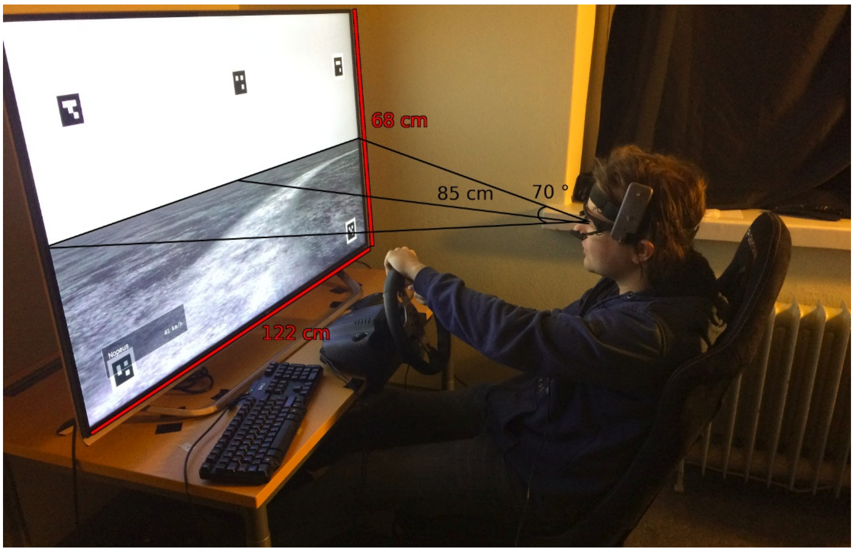


Figure 6. The physical setup of the simulator. The room's lights were turned off during the actual test. Keyboard was used for typing background information.

Virtual camera eye height was set 1.53 m: this sets the virtual point of view to be higher than in the natural experiment, as clear seeing along the simulated curved road was deemed important. Simulated engine noise was presented through the screen's speakers to give a more natural feeling of driving a car. Pedals were not used in this experiment as speed was controlled by the simulation software. The simulation was run at 1920x1080 pixel resolution in 60 Hz frame rate. Computer used was HP ENVY Phoenix 860-081no, Intel Core i7-6700 K with Linux Debian kernel 4.2.6.

2.2.3 Simulated track

Driving simulation was conducted with an in-house custom made driving game coded by Mr. Jami Pekkanen and contributed by Mr. Tuhkanen and the author. (https://github.com/prinkkala/webtrajsim). The game had customizable surroundings, graphics and dynamics, among other parameters. Fifty meter radius in the simulated environment was determined after pilot experimenting with different setups; with a 50 meter radius turn, the road can be seen further from the screen; with a smaller radius the road would turn off screen earlier. Geometry of the road corresponds the one used in Lappi et al (2013) and Itkonen et al (2015).

Path[3] and ground texture (figure 7) used “Brownian noise” (beta = 2.0) as a texture element (Timmer & Koenig, 1995). This texture was chosen after extensive piloting because it can show patterned information in different resolution frequencies and does not produce aliasing patterns that would be seen as stationary targets on the screen. Texture was in greyscale so that the texture would have no distinctive or semantically meaningful patterns that could be interpreted as grass, sand or such.

Path edges were faded out. Previous simulator studies have represented the road using clear-cut road edges (Authié & Mestre, 2011; G. Kountouriotis et al. 2012; G. K. Kountouriotis et al. 2016) but the decision to leave out edge lines was to prevent leading gaze to any particular point on the ground. This tries to give participants a driving environment free of visual suggestions to use certain gaze strategy. Any relevant point on the path can be followed via their local flow characteristics.

Path width was 2,35 m with 0.62 m fading in both sides. Path width was chosen to be quite narrow but to have some room for comfortable driving. There were no instructions

3 In this thesis word “path” is used instead of road to give the concept more general environmental framework. See more in discussion.

to follow the middle of the path as explicit instructions could change gaze patterns (Itkonen et al., 2015).

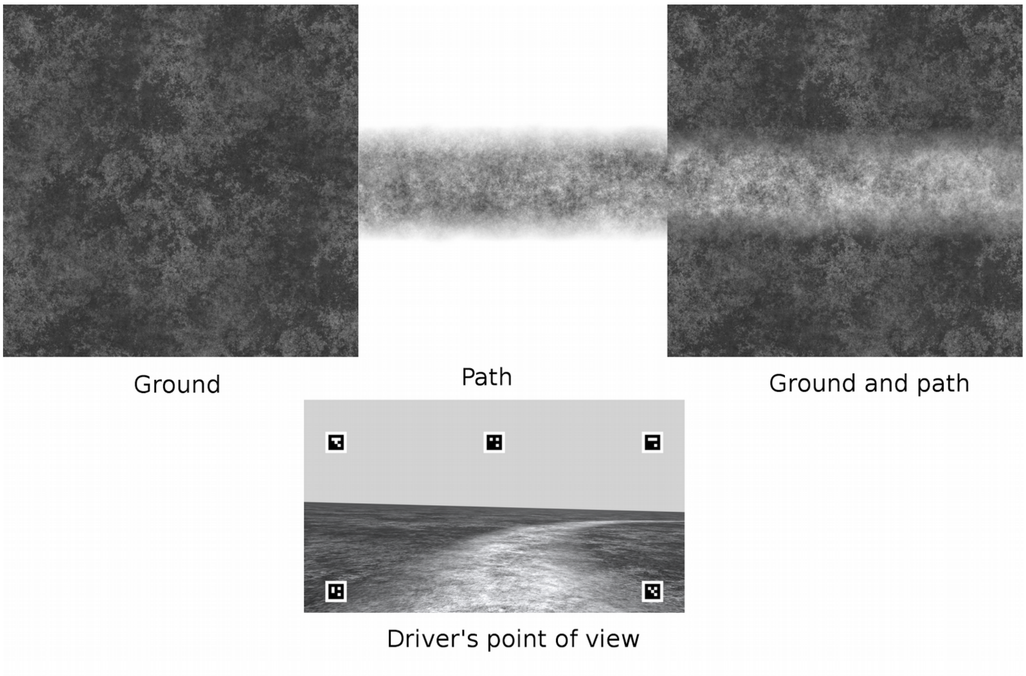


Figure 7. Top: ground texture, faded road texture and combination texture. Ground texture has a bit darker noise layer mask on top to add contrast to the ground. Bottom: the driver's view with head positioning markers.

2.2.4 Calibration

A 22-point-calibration was performed in the beginning of each trial. In the calibration participants fixated on sequentially appearing stationary markers with their eyes. Calibration was done five times during the whole experiment to ensure that all calibration errors could be noticed and corrected offline. During the tests, that are analysed in this thesis, there were two calibrations. Calibration accuracy was measured using difference between measured gaze and target point in the frames of the next calibration sequence. Median accuracy during calibrations was 1.0 degrees (variance 0.47), median horizontal accuracy 0.59 degrees (variance 0.25) and median vertical accuracy 0.70 degrees (variance 0.40).

2.2.5 Procedure

Procedure in the driving simulation experiment started with briefing the participant with relevant information about the experiment. They signed an informed consent form. The eye tracking equipment were dressed and secured. Background information was filled with computer before the test. Questions were permitted during the test, but precise information about the studied phenomena were given only after the experiment. Instructions were: “Your task is to drive along the track”.

There were total of four different tests in the experiment, though only data from third test was used in this thesis. Between each test and at the beginning and end of the experiment, there was a calibration. Each calibration served as a verification to the former test. The experiment was arranged into short 1 minute trials to avoid fatigue. Left and right turns were altered to prevent dizziness.

First test of the experiment was a practice run, where participant familiarizes with the simulation and steering equipment. There was 84 m straight between turns followed by half circles of 50 m radius to altering directions. The second test consisted only of half circles of 50 m radius to altering directions creating an extended sequence of S bends. In the second test speed was set to constant velocities of 41, 53, 66 km/h in different trials. Total drive time for completing these two tests was approximately 8 minutes.

The experiment reported here, the third test, contained a 50 m radius full circle that was driven with a constant acceleration of 0.34 m/s from 0 to 73 km/h producing rotation speeds from 0 to 23 degrees/s. One trial lasted 60 seconds and was repeated twice in each direction - four times total.

The fourth test was a series of S bends with added short poles to the middle of the road every 15 m (approximately 1/second). Added instructions were so that the driver should “drive over the poles”.

After the experiment participants were given a Smartum voucher worth 5 € as a compensation. The experiment took 30 to 40 minutes.

2.3 Test track experiment

2.3.1 Subjects

Table 2. Test track participants and their driving experience

n	4 (4 men)
Age	24 - 39 years, median 27,5
Reported driving experience in the past 12 months	Range between 15 000 - 30 000 km , median between 15 000 - 20 000 km
Reported total driving experience	Range between 100 000 km - 500 000 km, median between 100 000 - 300 000 km

The subjects were recruited by Dr. A. Tuononen (Vehicle Engineering, Department of Engineering Design and Production, Aalto University) through personal contacts. Recruiting process took into account that the experiment required good driving skills so that the subject could handle the car at speeds approaching the limit of traction, and control their speed according to instructions.

Participants had normal or corrected vision and a valid driver’s licence. Originally eight participants drove the driving task. Information about neurological symptoms in the eyes such as strabismus were asked after the experiments. One participant reported to have strabismus and another participant reported having been diagnosed with eye-related neurological disease. One participant had difficulties with performing the task as instructed as well as a very poor gaze signal. Finally, the car's telemetry data from one participant were lost due to a computer error. Data from these participants were not included to the analysis leaving 4 accepted datasets.

2.3.2 Equipment

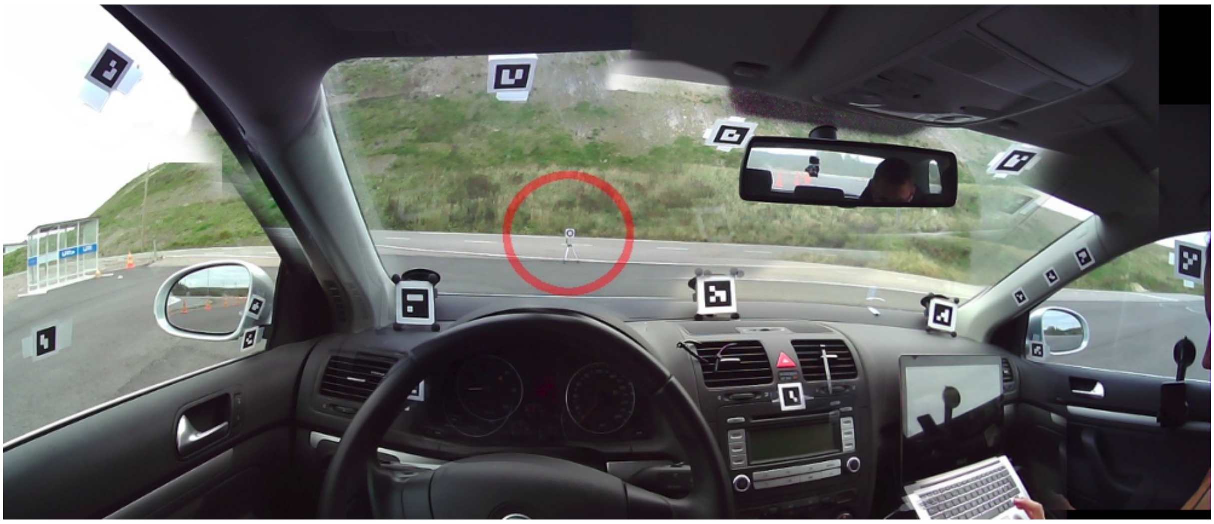


Figure 8. Test track car interior from driver's point of view. Markers are for 3D model identification to determine the horizontal axis of the car. Calibration target marker can be seen on a tripod in front of the car, highlighted by a red circle.

The car used was model year 2007 Golf V Variant 1.9TDI with manual transmission. Vehicle telemetry was recorded from CAN-bus with 100 Hz sample frequency. Markers were placed in the wind shield, side windows and dashboard so that in every head pose at least 3-4 markers would be visible, even when lighting conditions change inside the car or when markers would cause a glare in the wind shield (figure 8). Markers were constructed with open source code (https://gist.github.com/willpatera/7908319#file-make_square_markers-py).

The computer used for gaze tracking was a laptop, ASUS Zenbook UX303LB, with Linux Debian kernel 4.2.6. A mobile phone, (Samsung Galaxy II GT-I9100 with Android version 4.0.4), was connected to the laptop and gathered GPS and acceleration data using custom TRUSAS data collection software (https://github.com/prinkkala/trusas0).

2.3.3 Test site

The experiment took place in a driving course in Vantaa, Finland (60°20'11.8"N 24°55'26.4"E). The place offered a wide and safe area to drive around in a circle. Surroundings had an obstacle-free area if the car would for some reason drift wide of the line.

The circular track itself was marked with chalk spray and its outer diameter was 25 m and inner 22 m (figure 9). Spray chalk was chosen to draw track edges as it has several advantages over other options like cones: it is flat, has no distinctive features to fixate eyes on, it is safe to run over, removable and sufficiently easy to use. Diameter was chosen to be as big as possible considering the surroundings and safety.

The experiments took place on two separate days, the first in September and the second in October. On each day 4 subjects were measured. The first day’s weather was cloudy (final n = 1) and the second was sunny (final n = 3), both dry and warm.

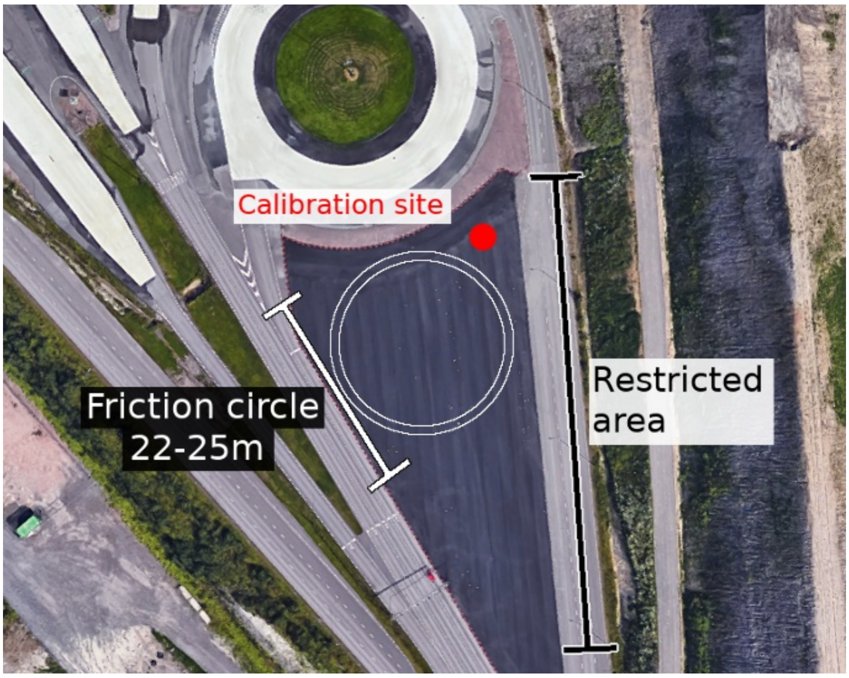


Figure 9. Double circle drawn to the map indicates the test track painted on the asphalt. (Google maps, 19.3.2018)

2.3.4 Calibration

Before proceeding to test site, eye cameras and scene camera's focus were adjusted. Calibrations were performed before and after the test. After calibrations a verification was performed. An extra verification was performed in the middle of the test, and if unsuccessful a new calibration was performed.

Instead of multiple targets, calibrations used only one fixed target marker on a tripod (size approximately one A4 paper) that was placed approx 7 meter in front of the car (figure 8). When calibrating, the participant was instructed to move their head in different positions while fixating on the target. This moved target to different parts of the visual field of the scene camera. For each calibration 21 calibration points were recorded. As verification participants were instructed to tilt their head in the same positions. The calibration was similar to the one used in Lappi et al. 2017. Achieved positional accuracy error of the eye movements were under 2 degrees.

2.3.5 Procedure

In the car were the participant, the experimenter operating the eye tracker in the passenger seat and in the back-seat a member of the research team handling vehicle telemetry data collection. The experimenter also supervised the safety of the experiment.

The instruction was that for each run participants would “drive along the track” four times around with a steadily accelerating speed up to the limit of friction. Participants received no instructions where to look on the road other than “drive as usual”, if they asked. Clear and easily executed driving instructions were needed as the desired slow rate of acceleration needed to be as steady as possible. The instructions were tested by piloting to be unambiguously understandable to an experienced driver. The instructions, translated from Finnish, given before the test were as follows:

i) Drive first round with first gear with a minimal amount of gas given with a constant speed.

ii) Drive second round with first gear and accelerate slowly and steady so that when entering the next round acceleration is smoothly continued with the second gear

iii) Drive third round with second gear so that the maximum speed is reached when entering the fourth round

iv) Drive fourth round with maximum limit speed. The limit speed means either that participant's feeling of safety is in its limit or the limit that the car begins to drift and electronic stability control activates.

Each run was driven until the maximum speed was met for at least one round. All participants drove to the car’s limit and no one expressed feelings of anxiety (indeed they were quite enthusiastic). No precise target speeds were given as glances to the speedometer were not desired, although not forbidden. Further task corrections and clarifications were given between rounds if needed, especially to maintain as smooth as possible acceleration. Participants were reminded to drive so that they feel safe driving the car.

The total driving amounted to 4 runs of right hand turns and 2 runs of left hand turns. Each run took between 84 and 101 seconds with mode of 92 seconds. We chose to do more right hand turns as the A-pillars of the car blocked part of the view when turning left possibly biasing data.

After the experiment was over, two Smartum voucher worth 10 € were given as a compensation of the participant's time. Total time of the experiment was approximately 50 minutes per participant.

2.4 Preprocessing

Several stages of preprocessing were necessary to connect eye tracking data and yaw rate data (real and simulated), as there were movement in several levels: eye movement in relation to the camera, camera movement (head and torso movement) in relation to car's/screen's frame of reference and finally car movement/simulated car movement in relation to world/simulation.

In both experiments first a custom Pupil Labs software was used to distinguish pupils from the eye videos better. The software was also used to review how successful each calibration was and if video showed any global calibration shifts. Bad calibrations were discarded and replaced with better calibration parameters from other calibrations. Camera distortion was corrected with cv2 distort tool.

Gaze was projected in the frame of reference of the car (test track) and the screen (simulator) (figure 5). Software for simulator's gaze projection analysis was provided by Mr. Tuhkanen and the author. In the test track experiment, markers were used to create a 3D model of the marker configuration fixed to the car's frame of reference (figure 8). From the 3D model, head position and gaze direction was calculated for each frame. Software for marker 3D identification was developed by Mr. Pekkanen. In the model head movement and tilt could be measured accurately in respect to car's vertical and longitudinal axes.

Smooth pursuits were identified from raw (unfiltered) horizontal gaze position data using a custom made de-noising and event detection method called naive segmented linear regression (NSLR) (Pekkanen & Lappi, 2017). Found linear segments can be seen in red in figure 10. *NSLR* is a robust segmentation algorithm that approximates a maximum likelihood linear segmentation from the data points and draws a line between found initiation and termination points of the segment. Angular horizontal gaze velocity is computed from the parsed pursuit's linear segmentation. This segment is used as a data point in further correlation and regression analysis (named "pursuit" in figure 11 B and C).

Segments were filtered so that gaze fixation and pursuit type characteristics passed through. Accepted segment time was set between 0.14 s and 1.5 s. Minimum segment time was determined from the data so that it would filter most of the saccades but still include most of the OKN-SPs. Maximum segment was not as important as the data didn't show pursuits even over 1 second. A low-pass filter for absolute horizontal angular speed of the segment was set at 30 deg/s.

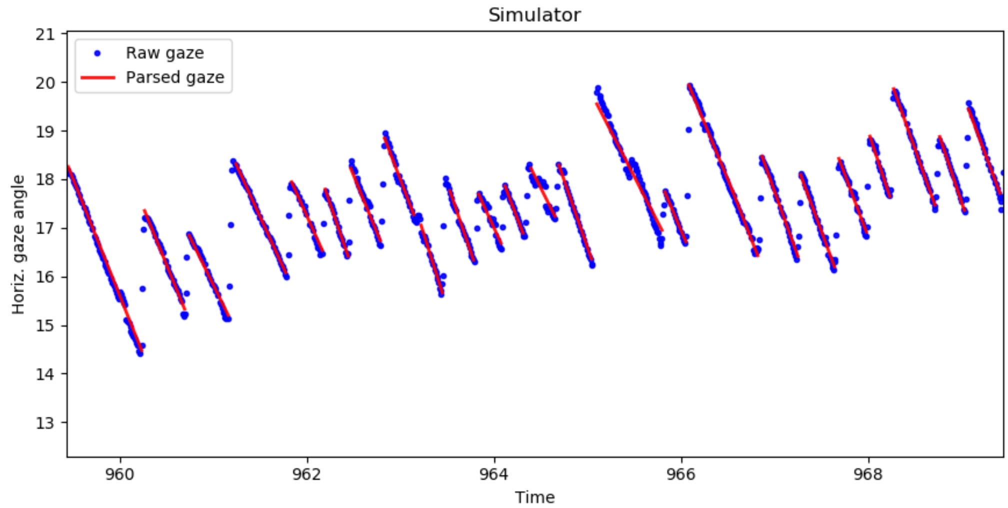


Figure 10. Gaze data from a right hand turn. Blue dots are horizontal gaze positions that supposedly form OKN-SP pursuits and OKN-FP saccades. NSLR method is used to parse pursuit segments from the data and parsed pursuits are drawn in red. Gaze forms a continuous pursuit segment that goes in the opposite direction to the curve bend. Blue data points outside red lines are outliers (supposedly saccades or noise) and are not included in further data processing.

The Unix timestamps from each data source were used to combine the data from different sources. Yaw rate from the CAN-bus data was synchronized with gaze data via matching CAN-bus data's velocity signal with a mobile phone's velocity-signals. This made possible to link timestamps from the eye recorder-computer-phone system with timestamps from the CAN-bus.

In test track experiment there was a need to re-evaluate the start and end of each run. When car reached it's limit speed its Vehicle Stability Control System (VSC) started to kick in. Drivers needed to turn the wheel to compensate the movement fluctuation caused by shifts between a drift and the effect of the VSC. This caused drivers to jerk the steering wheel which resulted to quick changes in the yaw rate data. Compared to the steady cornering in the acceleration phase, this fast and intensive limit driving seemed starkly different than rest of the data. Also worth noting is that drifting shifts the car's dynamics so that yaw-rate measurements might not be so reliable. So it was decided that limit driving as a driving behaviour is too different from normal curve driving and thus the limit speed driving from the data of each run was cut off. This meant removing approximately 8 seconds of data from every approximately 92 second run.

3 RESULTS

The experiments were set out to investigate the relation between driver's half yaw rate and horizontal gaze velocity. According to waypoint hypothesis there should exists a negative linear correlation and a -1:1 regression slope ratio between the variables. Travel point hypotheses, like TP hypothesis, predict no correlation. Additionally same experiment was conducted both in simulated and real life environment to see if the data is similar in both conditions. These experiments adds methodologically to previous similar ones (Itkonen et al., 2015; Lappi & Lehtonen, 2013) with added speed manipulation and more precise eye tracking methods.

Horizontal gaze position formed a clear "sawtooth" pattern that is characteristic to OKN (figure 10, figure 11A and figure 12A). OKN SP-pursuits were found successfully from every participant in both experiments in every acceleration segment.

In both experiments participants gaze was almost completely oriented on the path targets and visual exploration of the scenery was extremely rare.

3.1 Between-subjects results

Pearson's correlation coefficient was chosen to evaluate correlation as a near linear correlation can be expected from the hypothesis. Each pursuit was a data point paired with interpolated yaw rate in each timestamp.

Between subjects, simulator experiment had a very strong correlation median of -0.93 and a mean of -0.92 (95% confidence interval: [-0.96, -0.87]), while p-value was nearly 0 in every case (maximum being $7{,}77*10^{-189}$). Pursuit count (i.e. *n* of the correlation statistics) median was 603 per participant (table 3).

Test track experiment's correlations were strong with median of -0.74 and mean of -0.77 (95% CI: [-0.85, -0.70]) between subjects (maximum p-value was $1.54*10^{-187}$) (table 4). Pursuit count median was 1126.

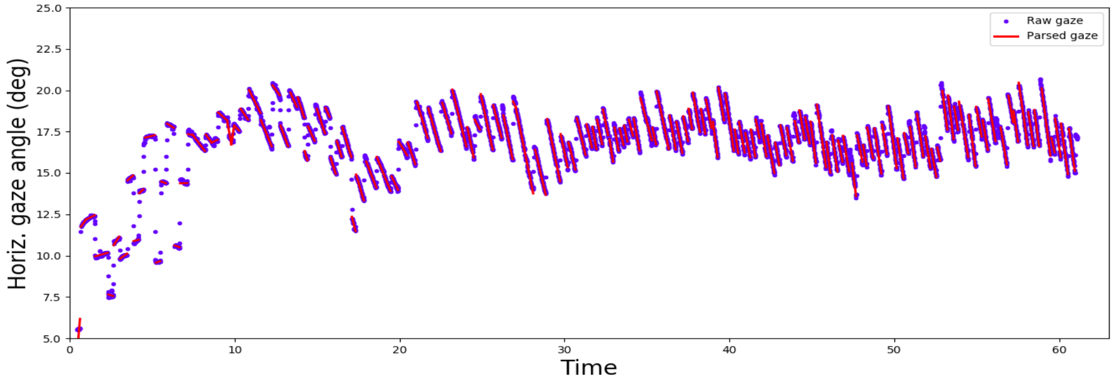
Spearman's and Pearson's correlation coefficient were compared within each subject but differences were all under 0.025 in both experiments, which suggests linear type of correlation.

In simulator absolute maximum median yaw rate between subjects was 24,6 deg/s. In test track the absolute maximum median yaw rate was as high as 46,4 deg/s as test track had more fluctuation and noise in the yaw signal. A small median filter (window size of 3) should give a clearer picture, as when used absolute maximum median yaw rates between subjects in simulator and test track were 24,5 and 30,3 deg/s respectively. Either way raw data was used in the final calculations.

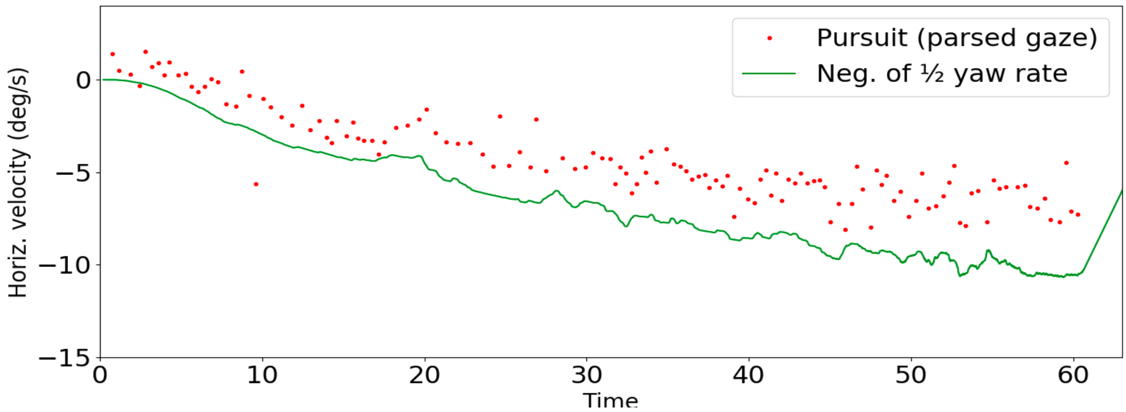
Typical results from simulator (figure 11) and test track (figure 12) are seen next side by side for an easy comparison between the experiments. Subject's gaze patterns during a run, where subject is in a constant slow acceleration, can be seen in 11-A & 12-A. Gaze speed and yaw rate are compared with each other in 11-B and 12-B during the same run. Yaw rate and gaze speeds from all the runs of the subject are compared against each other in 11C & 12 C.

Figure 11: Simulator

A



B



C

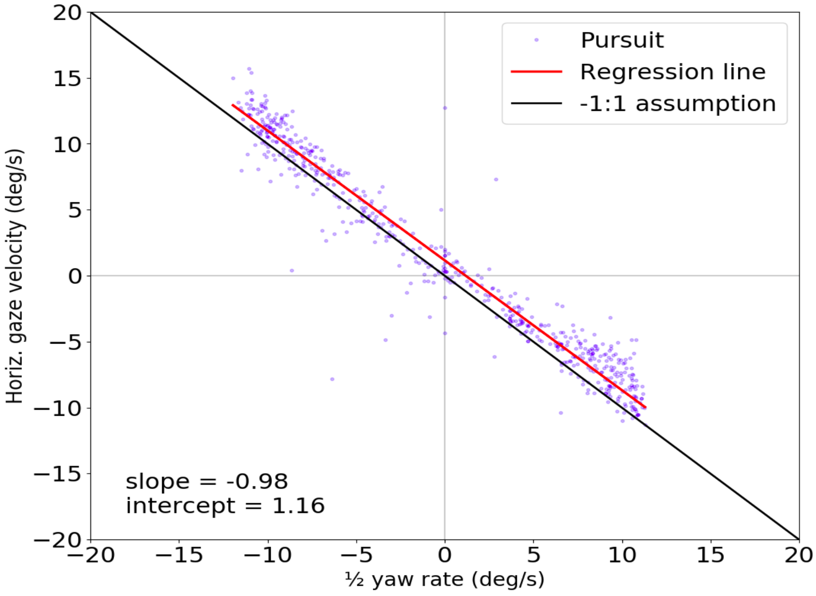
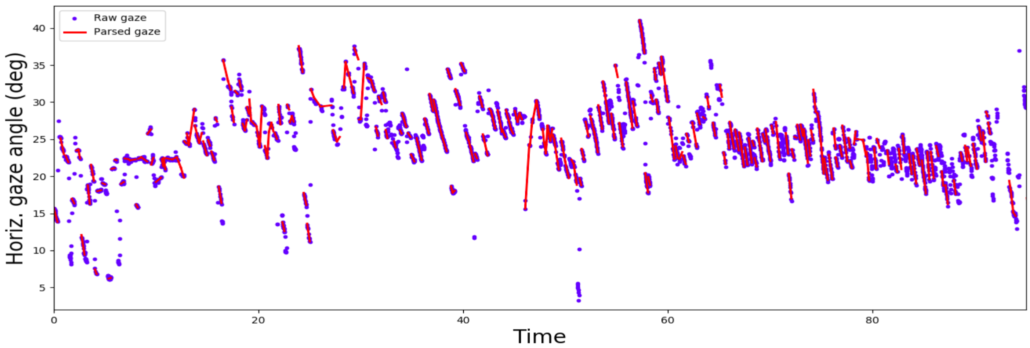
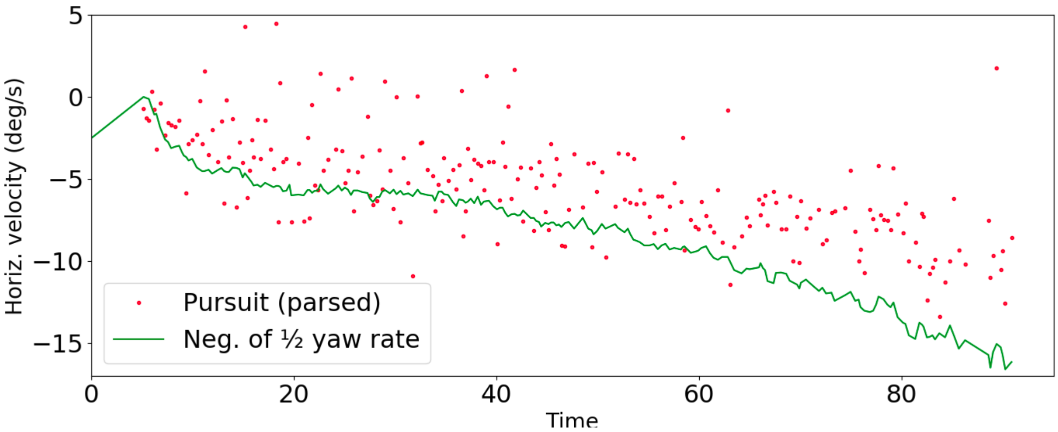


Figure 12: Test track

A



B



C

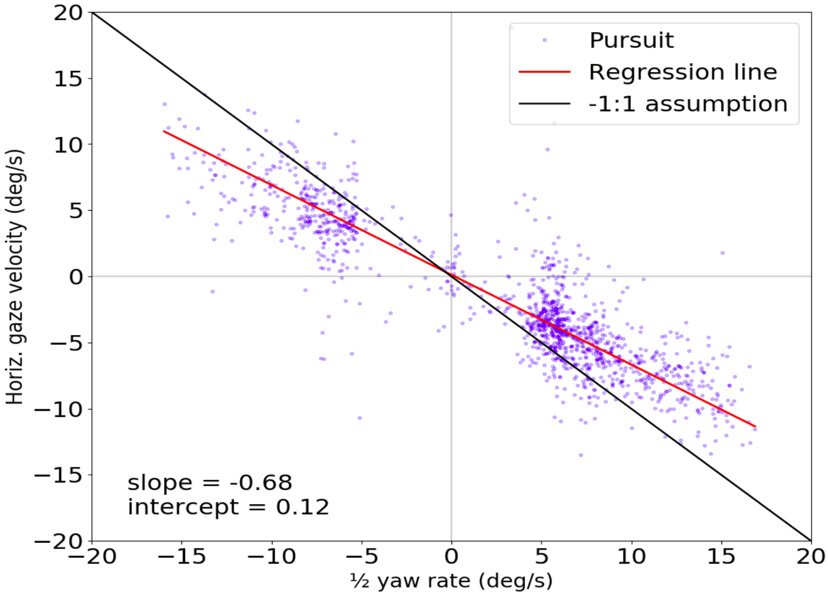


Figure 11: Simulator & Figure 12: Test track

11-A & 12-A: Horizontal gaze angles during one trial (blue dots). Recognized parsed pursuits are drawn in red. Constant acceleration of the car can be seen as the angles of the parsed pursuits steepen.

11-B & 12-B: Parsed pursuit speeds (red dots) and negative half yaw rate (green line) from the same trial as A. An illustrative plot where we can see the speed of the pursuit and car's negative half yaw rate correlate with each other.

11-C & 12-C: Comparison of parsed pursuit speeds and half yaw rate of all the runs of a participant. Blue dots are pursuits in each yaw rate, black line is -1:1 correlation prediction of WP hypothesis, and red line is a orthogonal regression line. With test track (figure12-C), there is more deviation from the -1:1 assumption than in the simulation (figure 11-C). Comparison plots for all subjects can be found in the appendix.

Table 3. Simulator correlations (n = 14)

Participant	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Pearson's r	-0.97	-0.96	-0.60	-0.93	-0.92	-0.93	-0.97	-0.96	-0.93	-0.94	-0.87	-0.96	-0.97	-0.92	-0.92
p-value	~0.0	~0.0	~0.0	~0.0	~0.0	~0.0	~0.0	~0.0	~0.0	~0.0	~0.0	~0.0	~0.0	~0.0	~0.0
n	585	511	646	664	705	549	587	706	608	565	605	590	662	621	681

Table 4. Test track correlations (n = 4)

Participant	1	2	3	4
Pearson's r	-0.89	-0.74	-0.73	-0.74
p-value	~0.0	~0.0	~0.0	~0.0
n	1276	1062	1170	1081

Pearson's correlation coefficient describes linear correlation but it does not describe the ratio of the variables. As the linear correlations are high, it is reasonable to conduct a linear regression analysis. Orthogonal regression fitting algorithm[4] finds best fitting linear line for the data by minimizing the distance from the data points to the regression line. Regression slope tells us in which ratio the two variables correlate in.

Our WP hypothesis predicted -1:1 ratio (I.e. -1.0 slope and 0.0 intercept) between half yaw rate and horizontal gaze velocity. As the WP hypothesis suggest, figure 11-C and figure 12-C show a clear negative linear correlation and a regression slope near -1:1 between the two variables. This shows clearly with every participant in simulator and somewhat clearly in test track experiment. Data from the rest of the participants can be seen in the appendix 1 and 2.

Simulator's median regression slope of half yaw rate and horizontal gaze velocity between subjects was -0.96 (mean -0.96 and 95% CI: [-1.01, -0.91]). Median intercept was 0.19 (mean 0.31 and 95% CI: [0.02, 0.60]) (Table 5).

Test track's median regression slope between subjects was -0.72 (mean -0.83 and 95% CI: [-1.13, -0.53]. Median intercept was 0.71 (mean 0.079 and 95% CI: [-0.10, 1.68]) (table 6).

Participants who participated in both experiments were analysed in comparison to those who drove only in simulator. Participants who participated in both experiments (n = 3) had a median correlation of -0.92 (mean -0.94 and 95% CI: [-0.97, -0.90]) and median regression slope of -0.90 (mean -0.93 and 95% CI: [-1.03, -0.84]). Participants who drove in simulator but not in test track (n = 12) had a median correlation of -0.94 (mean -0.91 and 95% CI: of [-0.97, -0.85]) and median regression slope of -0.97 (mean -0.97 and 95% CI:

4 Orthogonal regression fitting differs from simple linear regression as it calculates the distance from data point to regression line in both x- and y-axis, where the simple uses just y-axis. So orthogonal regression is less prone to errors from a real world gaze data that has as much errors in x-axis as in y-axis.

of [-1.02, -0.91]). As 95% confidence intervals overlap with both slope and correlation, these results do not suggest a statistical difference between these participant groups in correlation or regression slope.

Table 5. Simulator regression statistics (n = 15)

Participant	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Regression slope	-0.98	-1.02	-1.15	-1.03	-0.79	-0.85	-1.11	-0.94	-0.88	-0.89	-0.96	-0.97	-1.03	-0.90	-0.88
Regression intercept	1.18	-0.31	-0.30	0.17	0.52	0.94	0.19	-0.48	0.08	0.51	0.02	0.32	0.59	-0.23	1.46

Table 6. Test track regression statistics (n = 4)

Participant	1	2	3	4
Regression slope	-0.68	-0.60	-1.28	-0.76
Regression intercept	0.12	-0.07	1.30	1.80

3.2 All subjects

When combining data from all participants, simulator experiment had a really strong negative linear correlation (-0.91) and test track had a strong negative linear correlation (-0.75) (figure 13). The analysis software lacked the precision to calculate the p-value and indicated it to be 0. Simulator data's and test track data's regression slope were -0.96 and -0.79 and intercepts of 0.32 and 0.66 respectively (table 7).

Table 7. Statistics for all subjects

Experiment	Pearson's r	p-value	n (pursuits)	Regression slope	Regression intercept
Simulator	-0.91	~0.00	9285	-0.96	0.32
Test track	-0.75	~0.00	4673	-0.79	0.66

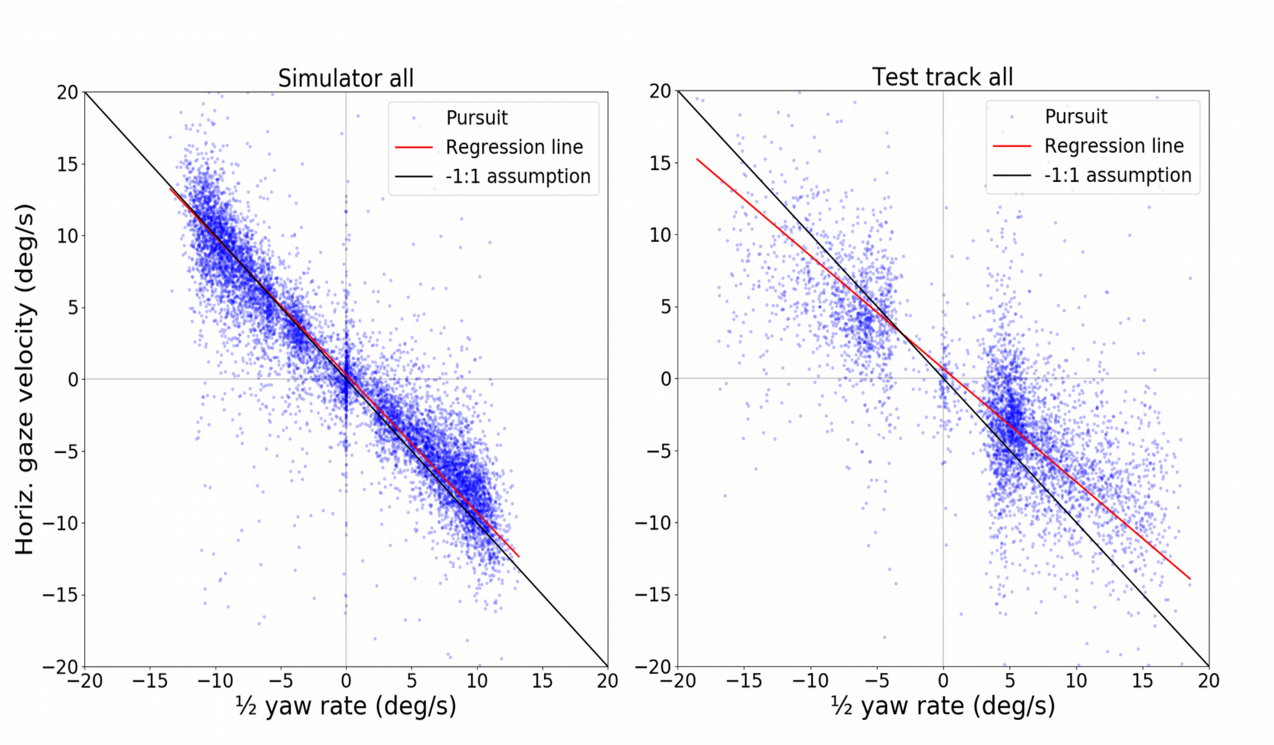


Figure 13. Horizontal gaze velocity (individual pursuits) and ½ yaw rate of all participants in both simulator experiment (left) and test track experiment (right). Linear correlation is significant in both and drawn regression line is close to -1:1 assumption. Test track data has less data points in small speeds and shows more variance in general than simulator data.

4 DISCUSSION

The study in this thesis was carried out to measure spontaneous gaze behaviour in curve driving with state of the art methods that allow to make differing predictions from different gaze strategies. Our method solves some previous problems when studying gaze behaviour with AOIs or gaze landing points with moving subjects (Authié & Mestre, 2010, 2012; Kandil et al., 2009). Angular gaze velocity and yaw rate was measured to determine what local optic flow the gaze pursues and thus what gaze target it follows. Experiments were conducted in simulator and in the field where subjects drove a circular path in a slowly accelerating speed.

Data from the simulator and the test track experiment were strikingly similar: similar pursuit behaviour, similar correlations of gaze speed and half yaw rate and comparable regression slopes were found. Differences were found mainly in the strength of the correlation, steepness of the slope, variance in the gaze signal and test track had more uneven and larger distribution of different yaw rates.

Results show Pearson's correlation coefficient between half yaw rate of the car and horizontal gaze speed of the whole dataset from simulator experiment is really strong (-0.91, p-value ~ 0.0) and test track correlation is strong (-0.75, p-value ~ 0.0). Note that every pursuit (or fixation) event is a data point and thus one should interpret Pearson's p-value (practically 0 with every participant) carefully.

Regression slopes in both experiments are quite close to -1:1 (between subject range is between [-1.15, -0.79] in simulator and [-1.28, -0.68] in test track), which suggests that gaze follows waypoints on the future path at the same rate within driven speeds. Although test track results should be interpreted with caution as the participant count was small (n = 4). Regression intercept was close to 0 that was hypothesized by the WP hypothesis (range between [-0.48, 1.46] in simulator and [-0.07, 1.80] in test track).

Strong correlations and slopes close to -1:1 are seen even within individual participants especially in simulator experiment (see figures in appendix).

These results are in line with the WP strategy hypothesis and in contrast to TP strategy hypothesis. This suggests that pursuing waypoints is a preferred strategy when cornering a bend in simulator and the phenomena can be validated in real world scenario in promising extent.

4.1 Differences between simulator and test track experiments

Test track experiment had lower correlation between gaze speed and half yaw rate (test track: -0.75 vs simulator: -0.91) and their regression slope was further from -1:1, that WP hypothesis predicted (test track: -0.79 vs simulator: -0.96). Also intercept was somewhat greater in test track (test track: 0.32 vs simulator: 0.66), which could suggest that something in the test track experiment was more asymmetrical when turning in different directions.

There could be several reasons for the differences in slopes and correlations. One possible reason could be that the driver has a different kind of mental model of the vehicle in simulator and in a real car, which could affect the shape and location of the future path. In simulator, there was no representation of a three dimensional car around the driver (expect for the wheel). It could be that in simulator, “the future path” is projected to where the “the head” (or a vertical projection of the head) of the driver is going. In the test track experiment, to drive properly, driver needs to have some kind of mental model of the car’s dimensions and “the future path” could be as wide as the the space between the tyres. If the gaze pursues future path of the tyre on the inside curve, the chosen “tyre-FP” is closer to the path edge and tangent point than the FP that we used in this thesis and thus the gaze would not reach half yaw rate speeds. Yet this hypothesis still would predict there to be pursuit movements, but only with lower horizontal gaze velocity. Further research is needed on the subject.

Other possible reason for the differences between the experiments is the the quality of the test track data. There were smaller number of participants (4 against 16) and some possible noise from the measurement devices, such as car vibration and head tilt. Also test track offered more challenging marker recognition, which is used for estimating the horizontal axis of the car. Measurement errors in horizontal axis affects the measured horizontal speed of the pursuits. The test track experiment was also a clearly more demanding driving task as drivers were responsible for the speed and gear handling.

Finally the test track had a small path edge line as simulator had a faded edges which may have an effect on the gain of the pursuit, as the gaze could perhaps more easily “slide” along the edge line.

4.2 Relation to previous research

Results are in line with the study of Itkonen et al. (2015), where OKN-SP speeds, that were in line with WP hypothesis’ prediction, were discovered on a motorway ramp. With more variability in used speeds than in the study of Itkonen et al., current thesis’s correlations and regression analysis endorsed the WP to be preferred gaze strategy by drivers.

Neither current experiment shows any inclination to use a TP gaze as the primary gaze strategy which is in contrast to studies of Authié & Mestre (2010), Kandil et al. (2009) and Land & Lee (1994). TP oriented stationary gaze strategy would cause a clump of data points along the x-axis of figures such as figure 13, which was not the case. This also goes against other gaze strategy hypothesis that are based on travel points.

It is noteworthy that in the present analysis only the horizontal angular speed of the gaze is in interest, not where it lands. This is an upside of the methodology as exact gaze orientation calibration is not needed as long as relative calibration holds. This is an improvement in accuracy in contrast to methods that project gaze to the world (like in Kandil et al., 2009). If local flow was to be determined by gaze projection, even a very small angular error (especially in y-axis) would cause a severe error in the estimated speed of local flow at the gaze landing point.

A clear OKN pattern was found in the data. Authie & Mestre (2010) suggested that gaze points that are targeted near TP could cause OKN reflex that is involuntary and would not be part of the TP gaze strategy. Found correlations and slopes in this study between changing gaze and yaw velocities suggest that OKN-SP were produced by orienting gaze near the FP and not the TP.

This thesis did not compare different variables like placing artificial gaze targets on the path (Authié & Mestre, 2012; Robertshaw & Wilkie, 2008) or evaluate driving quality with difference to the centre of the path (Kountouriotis et al., 2012) but only recorded spontaneous gaze behaviour with quantitative measures. We'd argue that the lack of artificial targets or arbitrary grading systems enhance the ecological validity of these results.

It would seem that the lack of binocular disparity and vestibular input do not reduce the accuracy of the WP strategy in fixed-base 2D simulators, which was suggested by Itkonen et al (2015) in response to results of Authie & Mestre, 2010.

4.3 Limitations and further advancements

When the study of driver gaze strategies moves closer to more general visuomotoric cognitive models, it would be useful to have a better understanding and definition of what is “path”. More generally, is “path” the road ahead or is it the geometric projection of the mental model of the trajectory path you are planning to take in a 3D space? Also how “path edge” should be defined? In more natural environments clear cut edges or edge lines are not the only indication of a path. In current literature there are no clear definitions for the words.

This understanding is important also when defining the future path. As mentioned in section 4.1, If a three dimensional projection of the car’s dimensions (or at least some kind of mental representation of it) in the planned future is counted as a future path, the future path of the wheels could be closer to the inside of the bend and the TP than the future path of the head of the driver. This could explain differences in results between the simulation and the real world experiment. Further research could be done with different vehicles, like bikes and cars with different width between tyres, and see if they produce different rates between yaw rate and horizontal gaze speed. Also changing the simulated car’s visual representation could be interesting.

A loose definition for path used to create simulator’s environment was: “an area on the ground that is differing from the background in some distinctive way, and that is used as a target for guiding locomotor movement”. Such a distinction can be made in many ways and in this experiment it was made via texture.

The differences in the road textures and the results of the experiments raises a question if path texture differences had an effect on the used gaze strategy. At least removing near or far path-edge information changes the use of flow information in simulator experiments (Mole et al., 2016). This could suggest interesting research possibilities to determine if path disparity could affect on which gaze strategy drivers prefer, and if high disparity could enhance road safety.

In relevant note, it would be interesting to study how gaze strategies are affected by the need to scan the path for surface irregularities such as rocks and other objects. An unresolved related fundamental issue is how much gazes on the path edges (like TP oriented gazes) seek to map the territory of the path and how much they function as means to control the movement.

Studies have shown that driver’s control strategies on curved roads make use not only of visual, but also of extra-visual information, such as vestibular and proprioceptive cues (Kemeny & Panerai, 2003). Using more multisensory integration in movement strategies could be preferred over more gaze focused strategies. It would be interesting to see how gaze strategies chance when new sensory data is introduced and modified in a driving simulation.

4.4 Conclusion

In this thesis we have presented qualitative results that suggest that the gaze strategies that WP hypothesis predicts are preferred by drivers in curve driving. These methodologically fresh experiments have shed some light on the from the basic strategies and mechanics of human visuo-motoric processes that are especially used in modelling driving behaviour in curve driving. These models are crucial when developing simulations of driver-vehicle behaviour. These simulations are used in producing better driving dynamics for cars, and developing autonomic cars. The more accurate driver-vehicle interaction models can be constructed, the more complicated scenarios can be tested computationally. Old models of driver behaviour have been used since 1980s but they have been lacking in psychological and physiological details and accuracy. This leads to using live subjects, which is time consuming, and expensive. Better simulations make it easier to estimate how human drivers behave in traffic, thus making possible safer, more comfortable, and more ecological driving and traffic.

With clear qualitative data and well designed methods, like the ones presented in this thesis, it is easier to compare results of navigating a bend in different environments (such as simulated and real world driving) and movement types (such as driving, cycling and walking), and thus getting more clearer picture of gaze strategy dynamics and the processes behind them.

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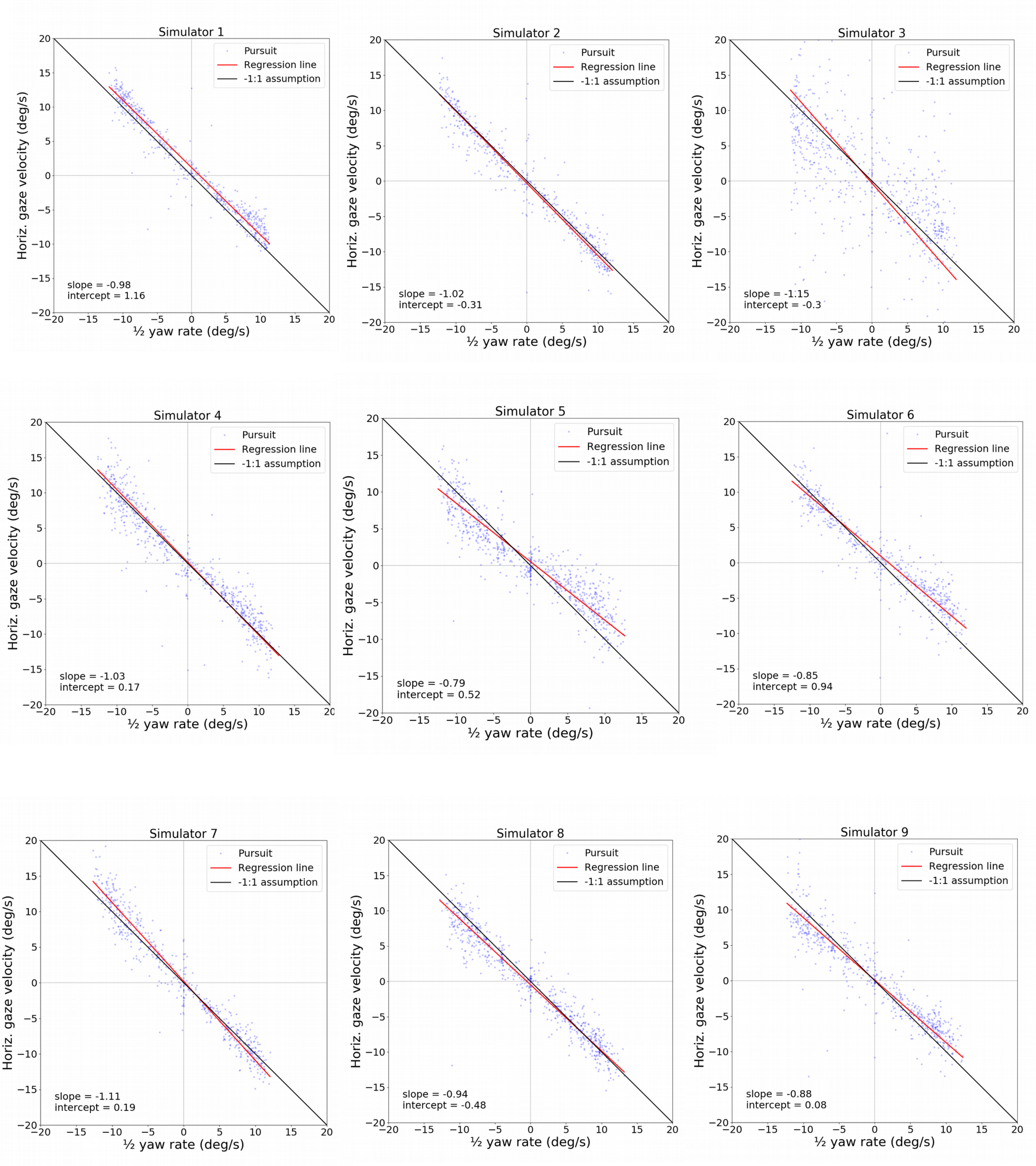
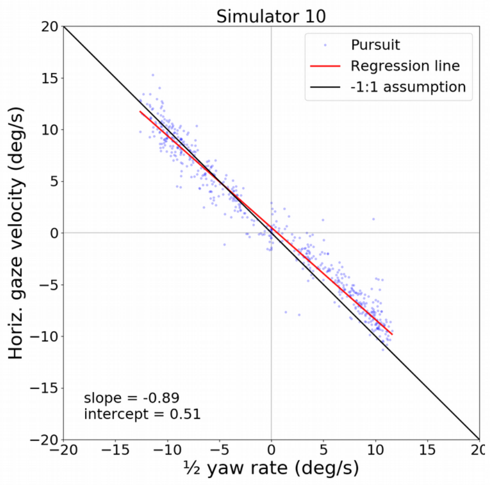
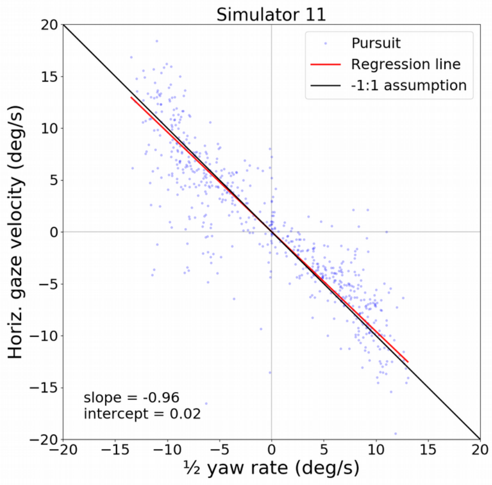
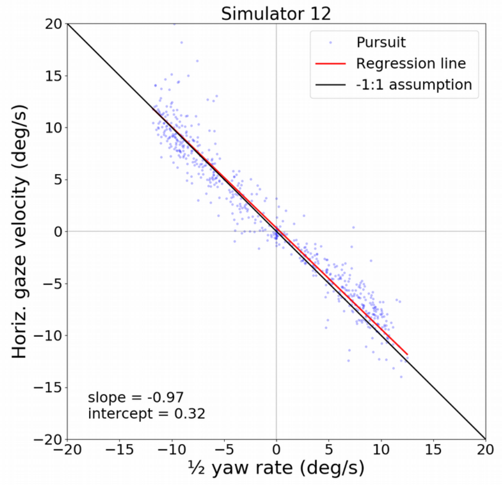
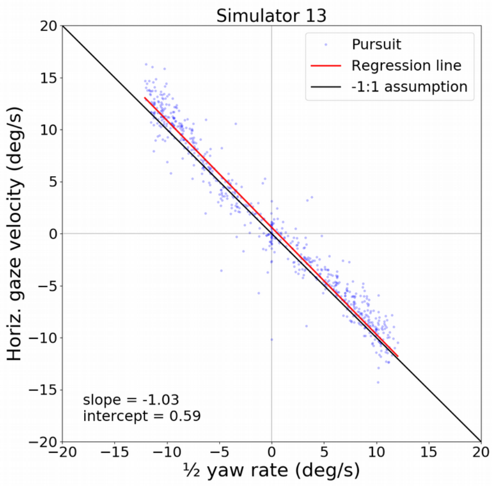
APPENDIX 1: Regression statistics of participants in simulator experiment

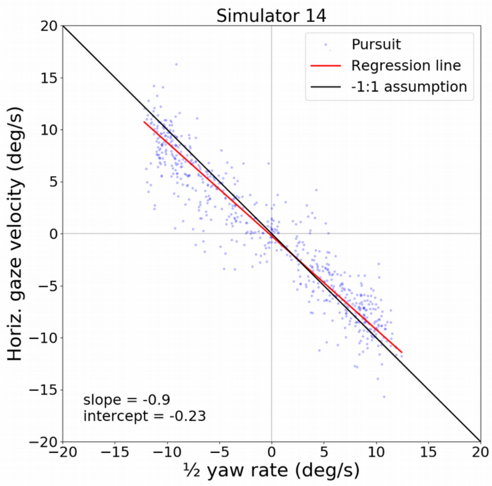


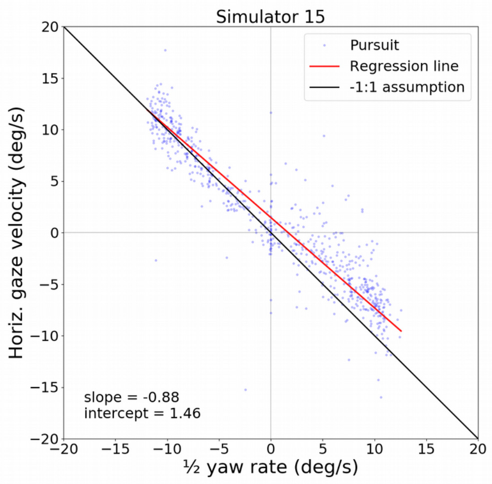

Simulator 10
Pursuit
Regression line
-1:1 assumption
slope = -0.89
intercept = 0.51
Horiz. gaze velocity (deg/s)
½ yaw rate (deg/s)


Simulator 11
Pursuit
Regression line
-1:1 assumption
slope = -0.96
intercept = 0.02
Horiz. gaze velocity (deg/s)
½ yaw rate (deg/s)


Simulator 12
Pursuit
Regression line
-1:1 assumption
slope = -0.97
intercept = 0.32
Horiz. gaze velocity (deg/s)
½ yaw rate (deg/s)


Simulator 13
Pursuit
Regression line
-1:1 assumption
slope = -1.03
intercept = 0.59
Horiz. gaze velocity (deg/s)
½ yaw rate (deg/s)


Simulator 14
Pursuit
Regression line
-1:1 assumption
slope = -0.9
intercept = -0.23
Horiz. gaze velocity (deg/s)
½ yaw rate (deg/s)


Simulator 15
Pursuit
Regression line
-1:1 assumption
slope = -0.88
intercept = 1.46
Horiz. gaze velocity (deg/s)
½ yaw rate (deg/s)

APPENDIX 2: Regression statistics of participants in test track experiment