Eye movements in manual driving

van Leeuwen, Peter

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Eye movements in manual driving

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Petrus Marinus VAN LEEUWEN
Master of Science in Aerospace Engineering,
Technische Universiteit Delft, Nederland
geboren te Gouda, Nederland

This dissertation has been approved by the promotors:

Prof. dr. F.C.T. van der Helm

Dr. ir. J.C.F. de Winter

Dr. ir. R. Happee

Composition of the doctoral committee:

Rector Magnificus	chairperson
Prof. dr. F.C.T. van der Helm	Delft University of Technology, promotor
Dr. ir. J.C.F. de Winter	Delft University of Technology, promotor
Dr. ir. R. Happee	Delft University of Technology, promotor

Independent members:

Prof. dr. M.P. Hagenzieker	Delft University of Technology
Prof. dr. R. Elvik	Institute of Transport Economics (TØI), Norway Aalborg University, Denmark
Dr. ir. M.M. van Paassen	Delft University of Technology
Dr. J.B.M. Terken	Eindhoven University of Technology
Prof. dr. ir. M. Wisse	Delft University of Technology, reserve member

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Summary

Driving simulators provide researchers with a flexible, controllable, safe, and economical tool for a range of applications. A pivotal aspect in the application of driving simulators is the development of measures aimed at describing the behavior and performance of the driver and providing knowledge about the way drivers are controlling their vehicle, which ultimately will benefit road safety. The driver performance is traditionally described by measures of (simulated) vehicle data and measures of subjective evaluations. This thesis provides additional measures of visual attention and driver physiology aimed at describing the driver behavior. Frequently, these measures are analyzed in isolation of the driver and vehicle performance. This thesis aims to derive relationships between concurrently recorded eye-movement and driver behavior variables in closed-loop driving tasks.

This thesis is divided in three parts; the first part focusses on the assessment of drivers using driving simulators and the second part explores the use of driving simulators for driver training. Finally, the third part provides an outlook towards real-world applications of driver state measurement.

A high level of driving simulator fidelity is often considered essential for driving simulator research. In Chapter 1, the effect of reducing the visual fidelity level on the driver performance and visual behaviour was investigated. The findings show that providing a driving environment with reduced visual information (i.e., no textures) reduces steering control and lane keeping performance during self-paced simulated driving. The gaze target during cornering remained virtually identical with diminishing visual fidelity, suggesting that drivers in the simulator adhered to the same basic visual strategy to steer their vehicle, regardless of fidelity level. This strategy could be described as a combination of the tangent point and future point models.

Chapter 2 assesses the performance and driving behaviour of racing drivers in comparison to non-racing drivers. Race car driving requires a unique set of skills in terms visual perception, cognition, and motor control. Due to the growing motorsport industry and evolving (simulator-based) training methods for (racing) drivers, knowledge about the differentiating skills between racing drivers and non-racing drivers may benefit future training methods for both racing and non-racing drivers. In this chapter the results showed better performance (i.e., faster lap times) for the racing drivers, which could be attributed to higher control activity and more optimal racing lines compared to non-racing drivers. At general psychometric and motor skill levels, the racing drivers did not differ from the non-racing drivers. Our methods were able to distinguish between two different visual control strategies for the racing drivers and non-racing drivers, where racing drivers showed a more variable gaze strategy while cornering. The racing drivers directed their gaze to different aspects of the corner (from the tangent point towards a point far ahead of the vehicle). The non-racing drivers directed their gaze more consistently towards the tangent point.

These chapters illustrate the application of driving simulators and eye movement measurements to be able to discriminate between visual gaze strategies and head movements. Furthermore, the concurrent measurements of steering behaviour, driving performance, and eye movements demonstrate the validity of simulator-based driver assessment.

In Part II the training of novice drivers in driving simulators is investigated. Novice driver are over-represented in accident statistics, also known as the young driver problem. Previous research has shown that by increasing the task difficulty during training, long term retention can be improved and overconfidence can be prevented. In Chapter 3, one group of novice drivers was deprived from near view visual information and a second group from far view visual information during a self-paced driving task and compared to a control group. Drivers were found to reduce their driving speed and change their steering behaviour compared to a control group when deprived of visual information. More specifically, drivers in the near view condition drove with a lower speed, but still made more road departures and reported a higher level of self-reported workload and lower level of self-confidence than the control group. The participants training with far view reported similar workload but drove with a smoother steering behaviour than the control group, presumably because they were unable to see their current lateral position. These findings show that besides visual perception and simulator fidelity (Chapter 1), the available (near, far or full sight) visual information greatly influences lane keeping performance, speed choice, and steering activity of simulator drivers.

In Chapter 4, a driving simulator virtual environment was augmented with additional visual information. By providing additional visual feedback during a driver training task, learners may benefit not only while the feedback is available, but also during subsequent retention and transfer, when the visual augmentation is unavailable. However, the guidance hypothesis (Salmoni, Schmidt, & Walter, 1984) predicts that learners may fail to learn the relevant task as they over-rely on the augmented visual information. This chapter shows that augmenting the simulator visuals with concurrent lane position feedback, learner drivers actively use this additional feedback cue and benefit from this augmentation by improving their lane keeping performance. Consistent with the results from Chapter 3, detailed information regarding the actual lane position error resulted in higher steering activity and subsequently led to improved lane keeping accuracy.

Besides the control of steering, eye movements play a substantial role in the detection of hazardous traffic situations. Previous research on novice driver eye movements has shown that the lack of visual search exhibited by novices is a main contributor to their poor hazard perception skills. In Chapter 5, novice drivers received visual search training aimed at improving their visual scanning behaviour. A peripheral detection task was performed using augmented simulator visuals, and the novice driver's reaction time was computed using real-time gaze-contingent eye tracking. The results show that novice drivers performing the visual search task had equivalent lane keeping performance and similar control activity while they directed their gaze to the forward road up to 10% less compared to the controls.

In Chapters 3–5 novice drivers were trained to acquire new skills relevant for safe driving. During skill acquisition, learners improve their skills as they become more familiar with the task and the learned skills become "automatic" (more unconscious and efficient). Chapter 6 investigated the short-term changes of driving performance and gaze behaviour in a sample of 52 novice drivers during four simulator training sessions. The sample consisted of all control subjects from the experiments conducted in Chapters 3–5 in which all controls drove in similar sessions, with similar instructions on in the same virtual environment. During the first 30 minutes of simulated driver training, novice drivers improved their lane keeping performance and reduced their steering activity, and subjective workload decreased. Eye movement analysis showed that drivers increased their amount of visual search and thereby reduced gaze tunnelling as they became more experienced.

The results from Part II illustrate that driving behavior and visual behavior of novice drivers can be trained and altered during a relatively short training period. During initial driver training, changes in driving behavior and eye movements were detectable with the methods used in this thesis. However, retention of training was low, possibly due to the relative short training sessions.

Part III of this thesis focussed on real-world applications of driver state estimation by combining measures of driving performance and behavior, with measures of eye movements and human physiology. In Chapter 7, a large number of performance, control, and psychophysiological indicators of driving under time pressure were compared to driving without time pressure. Drivers under time pressure drove with higher speeds and showed control behavior that resembled the control behavior of racing drivers (Chapter 2). Furthermore, when drivers were subjected to time pressure, they showed a driving strategy that was aimed at minimizing the time required to complete driving manoeuvres (such as overtaking, intersection crossing). Furthermore, the physiological measures were shown to be sensitive indicators of increased mental demands. For example, pupil diameter was found to be correlated with subjective, physiological, and performance measures. Our results also point to large individual differences in all evaluated measures of physiology and driving performance.

Estimating the driver state may find specific use in the design of adaptive in-vehicle interfaces. In Chapter 8, a real-time driver workload estimator that uses geo-specific information was pilot-tested. In an on-the-road evaluation of the real-time workload estimator, participants were tasked to drive with an experimental adaptive navigation system. The real-time workload estimator was validated against measures of driver performance, physiological, and subjective measures. During the driving task participants were requested to perform a secondary mental arithmetic task (n-back) and rate their own mental demands using a subjective rating scale. The results indicated that participants extensively gazed at the experimental navigation system and the results demonstrated the relative validity of the physiological measures during the secondary arithmetic task during a complex real driving task.

Part III of this thesis demonstrated that reliable indicators of mental demands were measured and validated in simulated and real vehicles and showed future potential for real-time driver state estimation. The results of our simulated time pressure task demonstrated large individual differences on most measures of performance, eye movements, and physiology.

In the final part of this thesis, the main conclusions are drawn and discussed. The task and manoeuvre dependency of eye and head movements are discussed with respect to the results of this thesis and the importance of concurrent measurements of eye movements and steering behavior is illustrated. Contrary to traditional methods, which often report session averaged findings, the measurement methods used in this thesis were able to discriminate changes in a driver’s eye movements and physiology during various driving manoeuvres with a temporal resolution of several seconds. The individual differences were often large in comparison to the between-subject differences on various measures of driving behavior, eye movements, and physiology. These differences should be treated on the individual level and therefore be corrected by person-specific reference measurements, when measures of eye movements and physiology are used in real-world applications.

Introduction

Driving simulators and driving performance

Driving simulators have evolved over the past decades from relatively low-cost, low tech solutions to high-tech facilities. The range of applications of driving simulators has broadened: Simulators are now used for human factors research, driver training, entertainment, road design, and more recently, vehicle automation research. With the increasing levels of technology inside vehicles (e.g., driver assistance systems), the emergence of communication technology (e.g., mobile phone use), and the growing complexity of the traffic environment, the driving task is becoming more and more complicated and multifaceted. Despite continuous efforts to advance the level of vehicle automation, at this day the driver remains a pivotal factor in traffic safety. Due to a growing demand for driver-in-the-loop testing, the role of driving simulators in measuring and understanding driver behavior seems likely to increase.

Driving simulators offer the advantage of greatly reduced cost compared to real vehicle testing. Furthermore, simulators allow for high controllability and reproducibility compared to experiments performed in real vehicles. With simulators, driving environments and traffic scenarios can be tailored to specific research aims and reproduced indefinitely. Furthermore, driving simulators allow researchers to collect a vast amount of data that can be hard to collect in a real vehicle. For example, millimeter accurate measures of vehicle position are readily available in a driving simulator but may be far more cumbersome to obtain in a real vehicle using modern GPS (De Winter, Van Leeuwen, & Happee, 2012).

Measuring driver performance and behavior

Traditionally, driving performance is quantified using recorded simulator/vehicle data, such as vehicle speed, vehicle position, and driver steering inputs. Performance measures based on simulator data provide objective information on the vehicle state, but typically provide little insight into the information-processing of the driver. That is, measures of speed and lateral position may be strongly related to a driver’s safety margins and vehicle control skills, but provide little detail regarding perception, comprehension, and hazard anticipation of the driving task environment.

In this thesis, driving is investigated by complementing simulator-based performance measures with measures of visual attention and physiological body responses. Furthermore, subjective driver evaluations are used to complement the simulator-based measures, for example for capturing driver workload and driver discomfort. Contrary to the continuously measured simulator data, subjective evaluations require an overt reaction from the driver and thus provide an indirect reflection of the driver state.

The driving task is considered to be a predominantly visual task and various visual aspects of driving (e.g., hazard perception, driver distraction) have been extensively covered in literature. According to the eye-mind hypothesis (Just & Carpenter, 1980), which states that one's area of visual attention is strongly related to one's area of cognitive attention, measurements of eye movements can provide valuable insights regarding the visual, cognitive, and attentional aspects of a driver's performance. Due to ongoing technological improvements and the reducing cost of eye tracking hardware, eye trackers have found widespread applications in the field of driving research. State-of-the-art eye trackers can also be used for head tracking, blink detection, and pupil diameter measurement.

Lateral vehicle control

When steering a vehicle, drivers perceive information regarding the vehicle state, road environment, and other road users through a variety of visual, auditory, vestibular, and haptic stimuli. By interpreting these stimuli, drivers adjust their control actions depending on their driving task and/or objectives. This process is illustrated in Figure 1 for a simulator-based driving task aimed at describing vehicle control. In this simplified model, the driver defines the input to the vehicle (steering wheel angle). The vehicle block represents the vehicle dynamics model, transferring the steering input to the vehicle state output. The vehicle state and the vehicle position in the road environment and other visual aspects (e.g., other road users) are displayed on the simulator visuals and perceived by the driver through his visual system.

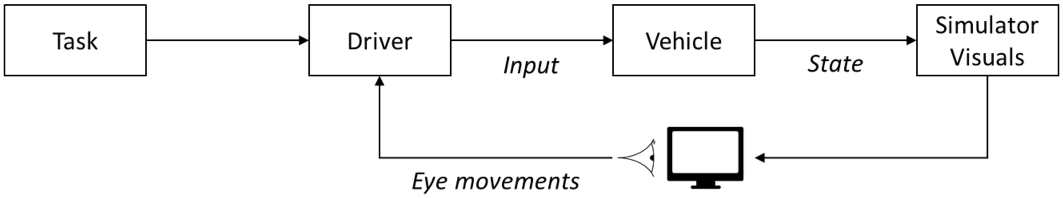

Fig 1. Simplified driver model (adapted from Flach, 1990). In this case a simulator-based driving task is assumed. In real driving, the visual stimuli are provided through the windows of the car.

In the lateral control model shown above, the driver block is simplified to a great extent; other research has focused on specifying similar models in great detail, by including components aimed at describing lateral vehicle control (Donges, 1978), longitudinal vehicle control (Brackstone & McDonald, 1999), or by adding components originating from human physiology (e.g., information-processing delays; Sentouh, 2009), or by including the neuromuscular system to the steering dynamics (Katzourakis, Droogendijk, Abbink, Happee, & Holweg, 2010).

The (driver) input, (vehicle) state, and eye movements are quantitative variables that are frequently used in driving research. However, these measures are often analyzed in isolation from each other. By combining the driver behavior, eye movements, and subjective measures in a closed-loop driving task these measures can be translated into knowledge about the way drivers control their vehicle.

The aim of this thesis is to **derive relationships between concurrently recorded eye-movement and driver behavior variables in closed-loop driving tasks**, with the eventual goal to contribute to an on-road road application that is beneficial to road safety. In this thesis, a series of experiments is conducted, aimed at driver assessment and training. Different groups of drivers (novice, experienced, and racing drivers) were tested in various experiments in which the visual display was systematically deteriorated, augmented, or manipulated. Finally, a step towards real-world applications is made by conducting an experiment in a real vehicle.

Thesis outline

This thesis is divided into three parts. Within each part, the chapters consist of self-contained research papers which can be read in isolation and have been published as journal or conference papers. **Part 1** of this thesis focusses on the use of driving simulators for **driver assessment**. Emphasizing the visual nature of the driving task, Chapter 1 investigates the effect of visual fidelity of a driving simulator on the driving performance and eye movement behavior of drivers in a self-paced driving task. Chapter 2 examines differences in visual behavior between racing drivers and non-racing drivers using a racing car simulator.

Part 2 investigates the effects of manipulating the visual information presented to novice drivers while **learning to drive** in a driving simulator. By manipulating the intrinsic visual information novice drivers can be guided to improve their task performance or be made aware of the relevance of specific task intrinsic visual information. In each of the experiments in Part 2, similar methods were used: all experiments consisted of a training and a control group and took place in the same driving simulator and same virtual environment. In each experiment, a visual manipulation training consisted of several training sessions followed by an immediate retention session. In Chapters 4 and 6 a transfer paradigm (Schmidt & Bjork, 1992) was used, whereas Chapter 5 evaluated delayed retention to assess the training effectiveness. Chapter 3 investigates the effectiveness of visual occlusion (Senders, Kristofferson, Levison, Dietrich, & Ward, 1967) in a driver training task, in Chapter 4 visual feedback is used to augment the existing visual information perceived by novice drivers, and Chapter 5 uses a peripheral detection paradigm to improve novice drivers' hazard perception skills. Part 2 concludes with Chapter 6, in which the methods and results from Chapters 3–5 are combined and discussed, exploring novice' drivers gaze behavior during initial driver training.

Besides using eye movements as measures of a driver's visual attention, eye blinks and measures based on pupillometry are closely related to a driver's cognitive demands. Past research has positively correlated these physiological responses to, for example, driver alertness or drowsiness (Wierwille, Wreggit, Kirn, Ellsworth, & Fairbanks, 1994) and the driver's cognitive demands during, for example, mental arithmetic tasks (Recarte, Conchillo, & Nunes, 2008).

In the third part of this thesis the measures based on eye-lid and pupil movement are complemented with physiological measures based on the human cardiovascular, respiratory, and proprioceptive systems. These measures of human cognitive and physical demands have extensively been reviewed in the literature (e.g., Brookhuis & De Waard, 2010) and have shown to be valid indicators of cognitive demands during various tasks. Eye-based and physiological measures were implemented in a driving simulator and a real-vehicle experiment, with the aim to work **towards a real-world application of driver state measurement**. In Chapter 7, drivers were subjected to time pressure during a simulated driving task. In Chapter 8, a small group of drivers performed a mental arithmetic task while driving a real vehicle in a project together with partners TomTom and the HAN University of Applied Sciences.

Finally, in Chapter 9 the findings of the studies in this thesis are discussed and general recommendations are presented.

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Part I

Use of driving simulators for driver assessment

Chapter 1

Effects of visual fidelity on curve negotiation, gaze behaviour, and simulator discomfort

Abstract

Technological developments have led to increased visual fidelity of driving simulators. However, simplified visuals have potential advantages, such as improved experimental control, reduced simulator discomfort and increased generalisability of results. In this driving simulator study, we evaluated the effects of visual fidelity on driving performance, gaze behaviour and subjective discomfort ratings. Twenty-four participants drove a track with 90 deg corners in (1) a high fidelity, textured environment, (2) a medium fidelity, non-textured environment without scenery objects and (3) a low fidelity monochrome environment that only showed lane markers. The high fidelity level resulted in higher steering activity on straight road segments, higher driving speeds and higher gaze variance than the lower fidelity levels. No differences were found between the two lower fidelity levels. In conclusion, textures and objects were found to affect steering activity and driving performance; however, gaze behaviour during curve negotiation and self-reported simulator discomfort were unaffected.

Van Leeuwen, P. M., Gómez i Subils, C., Ramon Jimenez, A., Happee, R., & De Winter, J. C. F. (2015). Effects of visual fidelity on curve negotiation, gaze behaviour and simulator discomfort. *Ergonomics, 58*, 1347–1364.

1.1 Introduction

1.1.1 Driving simulators in Human Factors/Ergonomics research

Driving simulation has been part of automotive Human Factors/Ergonomics research for over half a century (Blana 1996). Simulators are widely used to study the effects of driver training, automotive interfaces, vehicle automation and road design on driver behaviour, performance and safety (e.g. Banks, Stanton, and Harvey 2014; Birrell, Young, and Weldon 2013; Fisher et al. 2011; Flemisch et al. 2014; Pinto, Cavallo, and Ohlmann 2008; Reimer et al. 2014; Salmon et al. 2014). Based on a search with the bibliometric tool Scopus, we counted 2752 papers published between 2000 and 2013 that included 'driving simulator' in the title, abstract or keywords (cf. Boyle and Lee 2010 for a similar observation using Web of Science). Technological advancements have fostered the development of driving simulators and will continue to do so in the future (Hancock 2009).

1.1.2 The limitations of high physical fidelity

By definition, a simulator imitates real-world systems, and therefore is not perfectly realistic. The degree of realism of a simulator is often expressed in terms of 'physical fidelity', a non-psychological engineering viewpoint of the extent to which the simulator represents its real-world counterpart. Physical fidelity is usually defined in terms of visual factors (e.g. field of view, luminance, resolution), vehicle interior factors (e.g. the dashboard design), software characteristics (e.g. the vehicle dynamics model), as well as motion/force and auditory aspects. The present experimental study focuses on visual fidelity, which is a key factor considering the visual nature of the driving task (e.g. Sivak 1996).

The development of driving simulators tends to be technology driven (Verstegen and Van Rooij 2003), and it is often argued that driving simulators need to be sufficiently 'realistic' (e.g. Kaptein, Theeuwes, and Van der Horst 1996). A clear case can be made that simulators of low physical fidelity do not and cannot elicit realistic driving performance nor a credible psychological driving experience (cf. Air Line Pilots Association 2007, for a strong argumentation in favour of high fidelity flight simulation).

However, there are also certain disadvantages of high physical fidelity. First, high fidelity simulators may undermine experimental control and limit data collection (Lee 2004). Since high fidelity simulators are usually expensive, and include complex hardware and software architecture, a large number of factors need to be considered when designing an experiment on a high fidelity simulator, which in turn compromises experimental control and replicability. Hancock and Sheridan (2011) explained:

> "Current advances have seen high-fidelity, multi-million dollar facilities. The advantage is that they provide capacities now coming very close to the Turing test for simulated reality. The disadvantage is that they are so expensive as to be almost unique and so no replicable science is conducted on them."

A second presumed disadvantage of high fidelity simulators is that they may lead to simulator discomfort (Lee 2004; Parkes 2005) which can lead to reduced data quality (Bittner, Gore, and Hooey 1997; Cobb et al. 1999) and increased participant dropout rates (Brooks et al. 2010). Simulator discomfort is known to be induced by sensory conflicts between the visual and vestibular system (i.e. when the perceived self-movement from the visual system does not coincide with vestibular cues) (Hettinger and Riccio 1992; Mollenhauer 2004). As such, one may be inclined to believe that high fidelity simulation provides a remedy against simulator discomfort. However, the empirical evidence shows that simulator discomfort remains a concern even for the highest fidelity simulators (e.g. Dziuda et al. 2014). Reducing the perceived self-movement experienced in a driving simulator may result in less simulator discomfort resulting from sensory conflicts (Hettinger et al. 1990; Kennedy, Berbaum, and Smith 1993). The perceived self-movement can be reduced by lowering the amount of optical flow or by removing visual objects in the virtual scenery. Kennedy, Berbaum, and Smith (1993) argued that the perception of self-motion in a simulator both determines the realism of the simulation experience and how much the simulator promotes simulator discomfort. Karl et al. (2013) argued that “the visual scene should include only as many objects that encourage optical flow, like trees, houses and so forth, as are needed in order to provide the perception of motion on the one hand and to reduce simulator sickness on the other hand. (46)”

A third limitation of high physical fidelity simulation is that certain types of visual information (such as scenery objects) may not be required for performing, or may even be distracting from, the main driving tasks of interest. Kaptein, Theeuwes, and Van der Horst (1996) argued that ‘in some cases a deliberate deviation from reality might even result in more realistic task performance’. Perhaps not surprisingly, many research simulators do not aim to exactly reproduce visual reality, but instead focus on the ‘functional fidelity’ of specific driving tasks, such as steering control, hazard perception or decision making. A reduction of visual information could be beneficial for research applications in which the aim is to obtain generalisable outcomes as opposed to a phenomenologically realistic driving experience. Low visual fidelity could also be beneficial in driver training, and high fidelity simulators have been said to ‘dilute’ training effectiveness (Lee 2004; Parkes 2005; Dahlstrom et al. 2009).

1.1.3 The importance of visual information for vehicle control and the choice of driving speed

As mentioned above, visual information is considered the most important source of sensory information during driving. When traversing through a real or simulated environment, the relative motion of objects, surfaces and edges between the observer and the visual scene results in a pattern of apparent motion. This optical flow pattern is used to estimate the vehicle heading, speed and travelled distance (Gibson 1958; Warren, Morris, and Kalish 1988; Lappe, Bremmer, and Van den Berg 1999; Lappe et al. 2000). Increasing the optical flow (by increasing the dot-density when traversing on a simulated random dot-plane) has been shown to improve the translational (Warren, Morris, and Kalish 1988) and circular (Warren et al. 1991) heading perception. In a driving simulator environment, increased ground texture has been shown to reduce the lateral error in a cornering task (Chatziastros, Wallis, and Bülthoff 1999) and the number of out-of-lane errors (Levine and Mourant 1996). Lower lateral position errors were found when increasing the density of randomly distributed dots on the ground plane during a simulated straight path driving task (Li and Chen 2010). In another driving simulator study, Kountouriotis et al. (2013) showed a systematic bias in the lateral position when cornering with different textures on either side of the path, with the vehicle position closer to the non-textured side. In addition to optical flow, other sources of non-visual and visual information are used when steering. Extra-retinal information, such as head and eye rotations (Lappe et al. 2000), and visual-direction information, such as the visual angle between the target and a reference point (e.g. vehicle dashboard), provides heading information with respect to the direction of travel. A driving simulator study by Wilkie and Wann (2002) suggests that steering relies on a weighted combination of flow information, extra-retinal flow information and visual-direction information.

Research shows that drivers slow down if the optical flow is increased by increasing the amount of texture (Levine and Mourant 1996; Pretto and Chatziastros 2006). However, increasing the optical flow by adding signposts (Kallberg 1993) or lane markers (Steyvers and De Waard 2000) provides visual guidance to drivers and can lead to increased driving speeds (De Waard, Steyvers, and Brookhuis 2004). In addition to optical flow, other visual mechanisms provide perception of motion (see Fischer, Eriksson, and Oeltze 2012 for a review). For example, if luminance is reduced, drivers reduce their driving speed (Pritchard and Hammett 2012).

1.1.4 Gaze behaviour during curve negotiation: the tangent point versus future point strategies

When steering along a curved trajectory, the visual-direction information obtained from the visual angle between the vehicle and a reference point in the scenery may be used to guide the steering process (Boer 1996). Land and Lee (1994) found that on winding roads, gaze is predominantly directed at the tangent point (TP), that is, the point where the inside road edge reverses direction (Land and Lee 1994). These authors further demonstrated the geometric relationship between the TP, the corner curvature and the required steering input. Recently, Authié and Mestre (2012) showed that path-curvature discrimination during simulated self-motion is optimal when gaze is directed towards a location where the local optical flow speed is minimal. They also demonstrated that the TP location provides a location of minimal optical flow speed in the visual scene, supporting the idea that TP location is a major source of visual information for the control of steering. TP cornering strategies have also been demonstrated in real-world driving (Chattington et al. 2007; Kandil, Rotter, and Lappe 2009, 2010; Land and Lee 1994; Mourant and Rockwell 1972), with up to 80% of fixations in the proximity of the TP when cornering.

An alternative location of visual information to guide the control of steering was proposed by Wann and Swapp (2000). These authors demonstrated that fixating at a point on the future path results in a retinal flow field where the flow lines on the ground plane are straight when steering towards a target (see also Kim and Turvey 1999). When under- or over-steering with respect to a target, these flow lines are curved, and this perceived curvature of flow lines is hypothesised to guide steering control. Wilkie and Wann (2003b) showed that gaze was directed on the road centre in the vicinity of the future path 30% of the time in a simulated cornering task. Robertshaw and Wilkie (2008) found that by stimulating drivers to direct their gaze at the TP, drivers adopted a racing line. In similar driving simulator experiments, Wilkie et al. (2010) demonstrated that participants adopted a future point (FP) strategy, fixating the future point 1 to 2 s ahead of the vehicle when they were instructed to drive in the centre of the lane. A limited number of field studies have focused on FP strategies (Kandil, Rotter, and Lappe 2009, 2010; Lappi, Lehtonen, et al. 2013; Lappi, Pekkanen, and Itkonen 2013, and see also Lappi (2014) for a recent review). Kandil, Rotter, and Lappe (2009) argue that FP strategies were not observed as the retinal flow of participants was disturbed by an irregular vehicle and body motion. Lappi, Pekkanen, and Itkonen (2013) reported that during steady-state cornering, drivers frequently direct their gaze to the far zone beyond the TP, a finding which is in line with FP steering models.

1.1.5 Previous empirical research on 'minimum-fidelity' driving simulation

While visual perception has been extensively studied, the lowering of visual feedback to its essential minimum has been the topic only of few studies. Rizzo et al. (2003) and Severson et al. (2007) used an abstract representation of a straight road to assess the decision-making abilities among drivers with neurological impairments. A single-screen desktop simulator and a scenario design guided by cognitive neuroscience were used to test the Go/No-Go decision-making of cognitively impaired drivers. Statistically significant differences were found in the task completion times and decision-making errors between neurologically impaired subjects and age-matched controls. One of the most well-known studies on the topic of minimal visual fidelity (Reed and Green 1999) compared the highway driving performance of 12 participants between driving a real vehicle and a simulator with detailed visual scenery or monochrome visual scenery. The authors did not find important differences in the driving behaviour between the two simulated visual levels. Levine and Mourant (1996) found that driving in a flat shaded virtual environment resulted in fewer lane excursions and lane keeping closer to the centre of the lane compared to driving with a wireframe display. However, the small number of participants and incomplete data-set in the Reed and Green (1999) experiment and the low frame rates (9–9.7 frames/s) of the Levine and Mourant (1996) simulator limit the replicability and validity of both studies.

1.1.6 Aim and approach of the present study

Lowering the visual fidelity level by removing textures and scenery objects has various potential advantages compared to photorealistic environments, such as improving the generalisability of experimental results, reducing simulator discomfort and improving training effectiveness. Taking into account that valid experimental results can be obtained from low-fidelity simulators (Kaptein, Theeuwes, and Van der Horst 1996; Levine and Mourant 1996; Parkes 2005; Santos et al. 2005; Severson et al. 2007), we reduced the visual fidelity level of the virtual environment in a driving simulator. We evaluated three levels of visual fidelity: a realistic, textured high fidelity (HF) level, a medium fidelity (MF) level without textures and scenery objects, and a low fidelity (LF) level consisting solely of lane markers. These levels were selected based on their degree of visual abstraction, as we aimed to investigate how reducing visual realism of the virtual environment affects the behaviour and performance of drivers during an ecologically valid, self-paced lane-keeping task.

With diminishing visual fidelity, we expected poorer overall lane-keeping performance, due to the lack of heading information present in the virtual environment. A poorer perception of speed, and consequently a higher driving speed, was expected for the lower fidelity levels. Furthermore, we hypothesised that participants would adopt a TP steering strategy when reducing visual fidelity, as, with minimal optical flow, drivers were expected to be unable to use the optical flow required for a FP steering strategy. Finally, we expected immersion to reduce with diminishing fidelity, resulting in a reduced subjective workload and less simulator discomfort.

1.2 Method

1.2.1 Participants

Twenty-four participants (19 males and 5 females) were recruited from the TU Delft student and employee community. Participants were in possession of a driver’s license. Before starting the experiment, participants completed an intake questionnaire with the following two polar (i.e. yes vs. no) questions: (1) previous participation in a driving simulator experiment and (2) wearing glasses or contact lenses while driving. The following free response items were also included in the questionnaire: (3) number of experiments participated in a driving simulator, (4) number of driven kilometres in the past 12 months with a car or a van and (5) number of driven kilometres in the past 12 months with a moped. Furthermore, participants indicated the (6) number of times playing racing or video games in the past 12 months, (7) number of times driving a car in the past 12 months and (8) number of times driving a moped in the past 12 months with the following response options: everyday/4–6 days a week/1–3 days a week/about once a fortnight/about once a month/less than once a month/never.

The participants’ mean age was 23.8 years (*SD* = 5.1 years), and five participants reported that they were wearing contact lenses or glasses during driving in the simulator. On average, participants had held their license for 6.0 years (*SD* = 5.6). Participants on average drove 4654 km (*SD* = 7003) with a car or a van and drove on average 251 km (*SD* = 1021) with a moped in the past 12 months. See Table 1 for an overview of the driving experience questionnaire. Participants received a compensation of e5 prior to the start of the experiment. The research was approved by the Human Research Ethics Committee of the Delft University of Technology, and all participants provided written informed consent.

Table 1. Driving experience (number of responses in 24 participants)

	Every day	4–6 days/week	1–3 days/week	About once a fortnight	About once a month	Less than once a month	Never
Computer games			2		4	9	9
Drive a car or a van	1	3	8	3	5	4	
Drive a moped	1				1	2	20

1.2.2 Apparatus

The experiment was conducted with a fixed-base driving simulator (Green Dino; classic model) with a 180 deg horizontal and 45 deg vertical field of view. Surround sound resembled wind, engine and tyre noise. The accelerator, brake, steering wheel, ignition key and seat resembled those of an actual car. Gear changing was automated. The steering force feedback was passive, and the vehicle and engine model represented that of a middle class passenger car. Three LCD projectors were used to project the virtual environment. The central screen image shown on the front projector (NEC VT676, brightness 2100 ANSI lumens, contrast ratio 400:1, resolution 1024 x 768 pixels) included the dashboard and the rear-view mirror, and the two lateral projectors (NEC VT470, brightness 2000 ANSI lumens, contrast ratio 400:1, resolution 800 x 600 pixels) also showed the lateral rear-view mirrors.

The gaze direction was measured and recorded using a SmartEye eye-tracking system (Smart Eye, software version 5.9). It consisted of three remotely mounted cameras (Sony XC-HR50) with two infrared illuminators. The simulator model was updated at 100 Hz, and the visual update rate was 75 Hz. The screen frame rate was estimated at a minimum of 30 Hz and was sufficiently large to guarantee a smooth visual projection in all three visual fidelity levels. The driving simulator and eye tracker data were sampled and stored synchronously at 60 Hz.

1.2.3 Independent variable

Participants drove in the simulated environment with three different levels of visual information. The high, medium and low visual fidelity environments were created by removing textures, virtual scenery objects and colours. The high fidelity (HF) level showed a realistic environment, with textures and colours. Road signs were removed to not influence the participants in choosing their speed. The medium fidelity (MF) level showed an environment where only the road, the horizon and its colours were visible. No textures were shown at this level, and all roadside objects and environment scenery were removed. At the low fidelity (LF) level, the scenery was black, only showing the lane markers and the road centre line in white. Roadside objects (trees, signs, buildings) and the horizon were not visible. To ensure that drivers only perceived their driving speed from the visual and auditory cues, the speedometer was disabled for all visual fidelity levels. We did not provide speed-limit information/instructions, because our aim was to study the participants' choice of speed, not to study how accurately drivers can adhere to a speed limit. Figure 1 shows the driving simulator and the three driving visual fidelity levels.

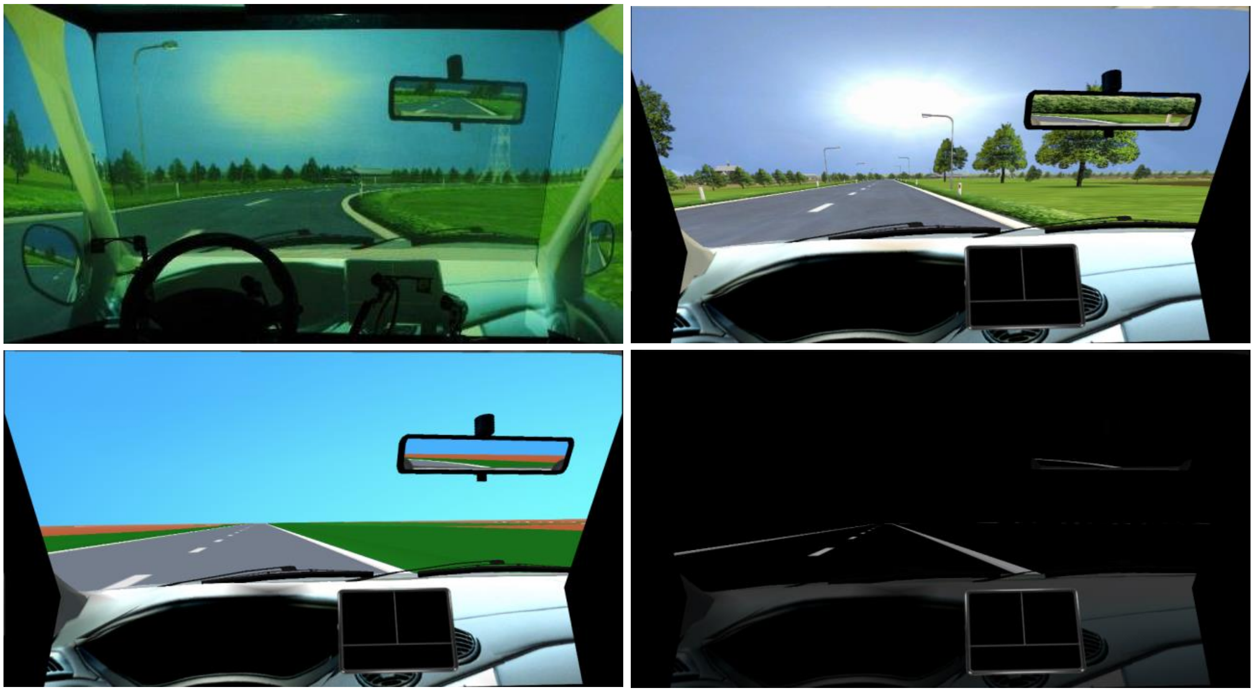

Fig 1. Top left: Photo of driving simulator used in the experiment with high fidelity (HF) visuals. Top right: Screenshot of center screen for the high fidelity (HF) level; Lower Left: Screenshot of center screen for the medium fidelity (MF) level; Lower right: Screenshot of center screen for the low fidelity (LF) level.

1.2.4 Procedure

Prior to starting the experiment, participants received an intake questionnaire and a paper handout explaining the experiment and procedures. After signing the consent form and receiving the e5 compensation, the participants were seated in the driving simulator. A series of head and eye movements were recorded for each participant to calibrate the eye tracker. Participants drove three sessions of 9.5 min, and each session was followed by a 5-min break outside the simulator. During the break, participants were asked to fill out a questionnaire containing the NASA task load index (TLX) questionnaire for measuring their workload (Hart and Staveland, 1988), a questionnaire evaluating their feeling of presence, and a discomfort questionnaire based on the Simulator Sickness Questionnaire (Kennedy, Lane, et al. 1993). Participants were tested in fully balanced order using the Latin square design.

1.2.5 Driving task

To increase the ecological validity of the simulation, participants were required to steer, accelerate and brake, and the simulated environment consisted of realistic 908 corners. The three sessions took place on a two-lane rural road of 7.5-km length, with a 5-m lane width (De Groot et al. 2011; De Groot, Centeno Ricote, and De Winter 2012; Van Leeuwen et al. 2011; Van Leeuwen, Happee, and De Winter 2013). The road consisted of 25 curves (i.e. 22 left- and right-hand 908 corners, two smooth chicanes and one 180 deg corner), one tunnel and two hills with a 4-m elevation. Figure 2 shows a top view of the road geometry, the distribution of the centre line corner radii and a typical speed. All sessions commenced with the vehicle in the centre of the right lane with zero speed, and the simulation did not include other traffic.

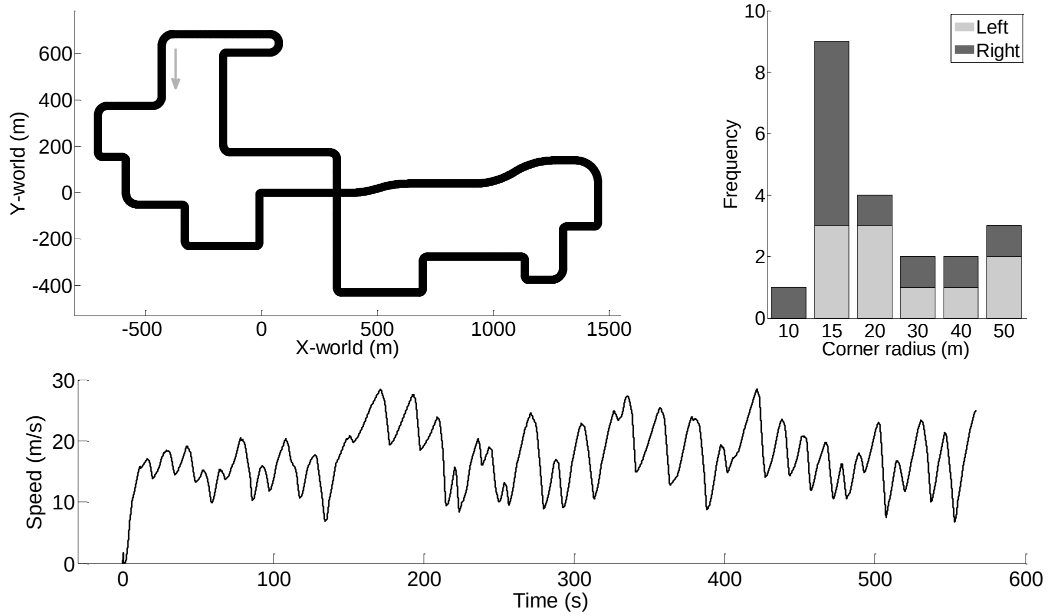

Fig 2. Top left: Top view of the road geometry, the starting position and direction are indicated by the gray arrow. Top right: The distribution of the road centreline corner radius for the 90-degree corners. The lane centreline corner radii are 2.5 m larger or 2.5 m smaller for left- and right-hand corners, respectively. Bottom: Speed trace for a typical participant, showing the variation in speed as a result of road geometry.

Participants received written instructions to drive safely and at a normal, comfortable speed and to drive as accurately as possible in the centre of the right lane. Participants were also instructed that the speedometer would be disabled in all sessions and that the gearbox was automatic, meaning that they did not have to use the clutch pedal and gear lever.

Before each session, the visual environment was explained with the following instructions displayed on the simulator central screen: ‘In this session, you will drive along a rural road in a fully realistic environment’, ‘In this session, you will drive along a rural road in a semi-realistic colored environment; only the road and the horizon will be visible’ and ‘In this session, you will drive along a rural road in a black and white environment; only the lines on the road will be visible’, for the HF, MF and LF visual fidelity levels, respectively. Furthermore, the driving instructions were repeated on-screen stating: ‘The gear shifting is automatic’, ‘Please fasten your seatbelt’, ‘If you crash, the car will restart immediately’, ‘Drive safely and at a normal, comfortable speed’ and ‘Drive accurately in the centre of the right lane’.

1.2.6 Dependent measures

The data from the first 2 min of each session were regarded as lead-in and were discarded from the analysis. The data were resampled to 50 Hz prior to processing. The gaze angle data were filtered at 10Hz with a second-order low pass filter. To remove noise from the steering sensor, the signal was filtered with a 3 Hz second-order low pass filter. Gaze behaviour and driving performance during cornering were analysed separately for three different corner radii: large radius corners, from 328 to 430m (mean = 379 m; 2 corners), medium radius corners, from 30 to 50m (mean = 41 m; 7 corners) and small radius corners, from 10 to 20m (mean = 18 m; 14 corners). Each individual corner was analysed once, as some participants completed the lap within 9.5 min and therefore encountered the same corner twice. Figure 2 (right) shows the distribution of the different corner radii. The different radii were analysed separately, as gaze behaviour and cornering behaviour are known to depend on corner radius (Authie´ and Mestre 2011, 2012; Gawron and Ranney 1990; Jurgensohn, Neculau, and Willumeit 1991; Kandil, Rotter, and Lappe 2010). The following dependent measures were calculated in each session for every participant:

1.2.6.1 Driving performance

Number of departures. Road departures occurred when the participant left the road boundaries with all edges of the vehicle. Road departures can be a consequence of inaccurate lane-keeping performance or high vehicle speeds resulting in a loss of control. After a road departure, the car was automatically placed back in the centre of the right lane at zero speed. The data recorded 10 s prior to and 20 s after the departure were removed from the analysis (cf. De Groot et al. 2011; De Winter et al. 2007).

Mean absolute deviation lateral position (MAD) (m). This measure describes the mean of the absolute error of the lateral position of the vehicle to the lane centre. MAD is a measure of lane-keeping accuracy.

Standard deviation lateral position (SDLP) (m). The standard deviation of the lateral position of the vehicle centre was used as a measure of lane-keeping precision.

Mean and maximum driving speed (m/s). The mean and maximum driving speed were used as measures of driving speed. The perceived speed was expected to affect the driving speed (Hurwitz, Knodler, and Dulaski 2005).

Steering wheel steadiness (% of time). This measure is defined as the percentage of time that the steering wheel's absolute angular velocity was smaller than 18/s. Steering wheel steadiness was also used in our previous research, and was found to be a robust measure of steering behaviour (Van Leeuwen et al. 2011; Van Leeuwen, Happee, and De Winter 2013). Specifically, a reduced steering wheel steadiness is related to an increased amount of steering wheel movements, and hence, indicative of a greater steering effort.

1.2.6.2 Gaze behaviour

Horizontal gaze variance straight (deg^2). This measure was calculated on straight road segments and determined as the variance of the 10 Hz low pass filtered gaze yaw angle signal.

Horizontal gaze variance corners (deg^2). This measure was calculated on corner segments, starting from corner onset until corner exit. This measure was calculated from the 0.5 to 10 Hz bandpass filtered gaze yaw angle signal. The variance was calculated from the bandpass filtered signal instead of the original 10 Hz low pass filtered signal to remove the low-frequency component of the gaze angle that results from turning through the corner. This measure was calculated from corner onset until corner exit and averaged across the 21 small and medium radii corners.

Mean TP error (deg). This measure is defined as the difference between the horizontal gaze angle (θ_G) and the angle of the line from the vehicle centre to the TP (θ_{TP}). The TP locations were calculated from the road edge geometry and the centre of gravity position of the vehicle. For left-hand corners, the TP error is determined from the road centre TP (Chattington et al. 2007; Lappi, Lehtonen, et al. 2013), while the lane boundary was used for the right-hand corners. Positive TP-error values correspond to a gaze angle to the right side of the TP.

Mean future point (FP) error (deg). This measure is defined as the difference between the horizontal gaze angle (θ_G) and the angle of the line from the vehicle centre to the instantaneous future point (θ_{FP}). Future points were defined as the vehicle position 1.5 s ahead of the actual vehicle position (Wilkie et al. 2010). A positive FP-error value corresponds to horizontal angular positions to the right side of the future point. Both the mean TP error and mean FP error measures were calculated from the corner onset until corner exit and averaged across the twenty-one 908 small and medium radii corners. Figure 3 shows a definition of the TP and FP locations, the gaze angle, the TP angle and the future point angle for left- and right-hand corners.

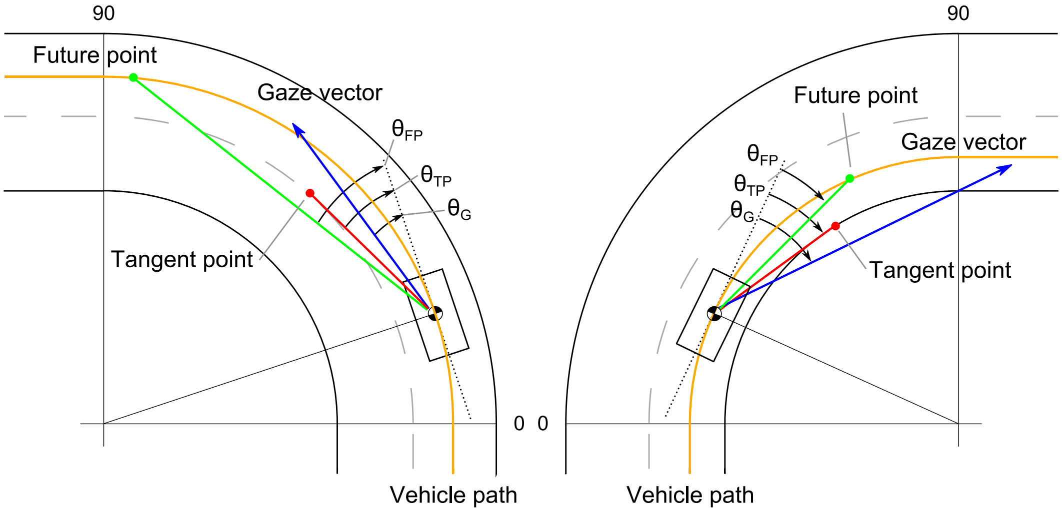

Fig 3. Definitions of the TP- and FP-positions, and of TP angle (θ_{TP}), FP angle (θ_{FP}), and gaze angle (θ_G) with respect to the vehicle heading angle. Definitions are given for left- and right-hand 90-degree corners. Both figures indicate a positive TP and FP angular error of approximately 10 and 20 degrees, respectively. The corner starting point and corner endpoint are indicated by 0 and 90 degrees, and the vehicle path is indicated in orange.

1.2.6.3 Subjective measures

NASA TLX (%). The NASA TLX questionnaire was used to determine the participants' workload on the following six aspects: mental demand, physical demand, temporal demand, performance, effort and frustration (Hart and Staveland 1988; NASA TLX, n.d.). The scores were marked on a 21-

tick horizontal bar with anchors on the left (*very low*) and right sides (*very high*). For the performance item, the anchors (*perfect*) and (*failure*) on the left and right side were used.

Presence questionnaire (%). The participants' feeling of immersion was evaluated with a questionnaire that contained the following six dimensions: reality awareness, interaction, motivation, visual involvement, auditory involvement and moving sense. All statements were inspired by the presence questionnaire by Witmer and Singer (1998). The questionnaire contained the following questions: 'To what extent did you feel consciously aware of being in the real world whilst being in the simulator?', 'To what extent did you feel that you were interacting with the simulation environment?', 'To what extent did you feel motivated while driving?', 'How much did the visual aspects of the environment involve you?', 'How much did the auditory aspects of the environment involve you?' and 'How compelling was your sense of moving around inside the virtual environment?'. Scores were marked on a 21-tick horizontal bar with anchors on the left side (*not at all*) and the right sides (*very much*).

Discomfort questionnaire (%). This questionnaire was based on the three dimensions of the Simulator Sickness Questionnaire (Kennedy, Lane, et al. 1993): oculomotor discomfort, disorientation and nausea sensation. The questionnaire contained the following questions: 'I experienced oculomotor discomfort (eyestrain, difficulty focusing, blurred vision or headache)', 'I experienced disorientation (dizziness, feeling of motion while stationary)', 'I experienced nausea (nausea, stomach, awareness, increased salivation, burping)' and a general discomfort question: 'I felt uncomfortable'. The scores were marked on a 21-tick horizontal bar with anchors on the left side (*not at all*) and the right sides (*very much*). All questionnaire items were expressed on a scale from 0% (the lowest rating on all items) to 100% (highest ratings on all items).

1.2.7 Statistical analyses

Remote-mounted eye trackers can be sensitive to the loss of gaze tracking as a result of the system´s inability to track a participant's facial features, pupils or corneal reflections. The data obtained 0.2 s before and after missing data segments due to tracking loss or blinks were removed. If more than 60% of data were removed in a session, the eye tracker data of the respective session were excluded from the analysis.

The dependent measures per session were standardised to z-values per session number (1, 2 or 3) in order to correct for practice effects. For the number of departures (a variable having a highly skewed distribution), a rank transformation instead of a z-transformation was applied (see also Van Leeuwen, Happee, and De Winter 2014). Next, the obtained numbers were compared between the three fidelity levels using a repeated measures analysis of variance (ANOVA). Differences between two visual fidelity levels were compared using paired t-tests. Differences between dependent measures were declared statistically significant if $p < 0.01$. We chose a conservative alpha value because we examined a relatively large number of dependent variables.

1.3 Results

On average, 18% of eye tracker data were discarded, and two entire sessions were removed due to data loss exceeding 60%. The eye tracking data of one participant were excluded due to the inability of the eye tracker system to capture the relevant facial features required for gaze tracking, which resulted in five discarded sessions in total. Table 2 shows the details of the discarded eye tracker data.

Table 2. Number of discarded eye tracker sessions and mean and standard deviation (in parenthesis) of percentage of missing eye-tracker data among the 24 participants

	Missing Sessions	Percentage of missing data
High fidelity	2	19.0 (10.9)
Medium fidelity	1	17.7 (12.9)
Low fidelity	2	18.5 (15.1)

Table 3. Means, standard deviations (between parentheses), and F and *p* values for the repeated measures ANOVA. Significance between LF and HF and MF and HF is indicated with LF-HF and MF-HF, respectively

Dependent variable	Visual fidelity level			Significance		
	Low	Medium	High	F	p	Between levels
Driving performance						
Number of departures (#)	2.4 (1.9)	2.3 (2.4)	1.5 (1.4)	3.74	.031	
Mean abs. deviation lateral position	0.72	0.72	0.63	7.21	**.002**	LF–HF & MF–HF
Standard deviation lateral position	0.96	0.96	0.80	6.12	**.004**	LF–HF & MF–HF
Mean speed (m/s)	18.1 (2.0)	18.2 (1.8)	19.1 (1.5)	10.9	**.000**	LF–HF & MF–HF
Max speed (m/s)	29.8 (3.9)	29.6 (3.0)	32.0 (4.2)	4.56	**.002**	LF–HF & MF–HF
Steering wheel steadiness (% of time)	15.5 (4.2)	15.6 (4.5)	10.6 (2.0)	52.4	**.000**	LF–HF & MF–HF
Gaze behavior						
Horizontal Gaze Variance straights	52.8	55.7	87.4	5.48	**.008**	LF–HF & MF–HF
Horizontal Gaze Variance corners	10.9 (9.5)	11.5	13.0	0.55	.583	
Mean TP error (left) (deg)	-1.36	-1.10	-2.9 (4.8)	1.79	.185	
Mean TP error (right) (deg)	-3.19	-3.20	-3.22	0.21	.809	
Mean FP error (left) (deg)	-5.38	-5.79	-5.72	0.20	.823	
Mean FP error (right) (deg)	6.29 (4.4)	7.25 (4.1)	6.36 (3.6)	0.42	.660	
Workload measured with NASA TLX						
Mental demand (%)	50 (23)	45 (24)	45 (25)	1.01	.372	
Physical demand (%)	31 (23)	24 (17)	25 (19)	2.92	.064	
Temporal demand (%)	31 (16)	29 (13)	31 (21)	0.11	.898	
Performance (%)	40 (19)	45 (24)	42 (20)	0.51	.605	
Effort (%)	54 (20)	54 (20)	48 (21)	1.37	.264	
Frustration (%)	37 (22)	36 (27)	29 (19)	2.09	.135	
Self-reported presence						
Reality awareness (%)	39 (24)	43 (24)	51 (19)	2.26	.116	
Interaction (%)	56 (24)	65 (17)	66 (17)	3.06	.056	
Motivation (%)	53 (23)	58 (19)	61 (17)	1.96	.152	
Visual involvement (%)	34 (25)	51 (24)	68 (19)	22.3	**.000**	LF–HF & MF–HF
Auditory involvement (%)	55 (23)	52 (21)	55 (17)	0.63	.538	
Moving sense (%)	44 (23)	50 (17)	61 (18)	6.86	**.002**	LF–HF
Self-reported discomfort						
Discomfort (%)	23 (28)	15 (20)	23 (24)	2.10	.134	
Oculomotor (%)	15 (23)	21 (26)	23 (30)	1.15	.326	
Disorientation (%)	11 (22)	14 (21)	16 (23)	0.92	.404	
Nausea (%)	8 (17)	8 (17)	8 (17)	0.02	.980	

1.3.1 Driving performance

Table 3 shows that the driving performance did not significantly differ between the LF and MF levels. The HF level resulted in better driving accuracy and precision than both the MF and LF levels, which is indicated by the smaller MAD and SDLP values. In the HF level, drivers adopted higher mean driving speeds than drivers in the MF and LF levels.

An additional analysis of the medium and small radius corners showed that the three visual fidelity levels resulted in similar corner cutting behaviour, as illustrated in Figure 4. In all fidelity levels, drivers approached the apex of the corner before reaching the 45 deg angular position and returned to the centre of the lane after the 90 deg angular position.

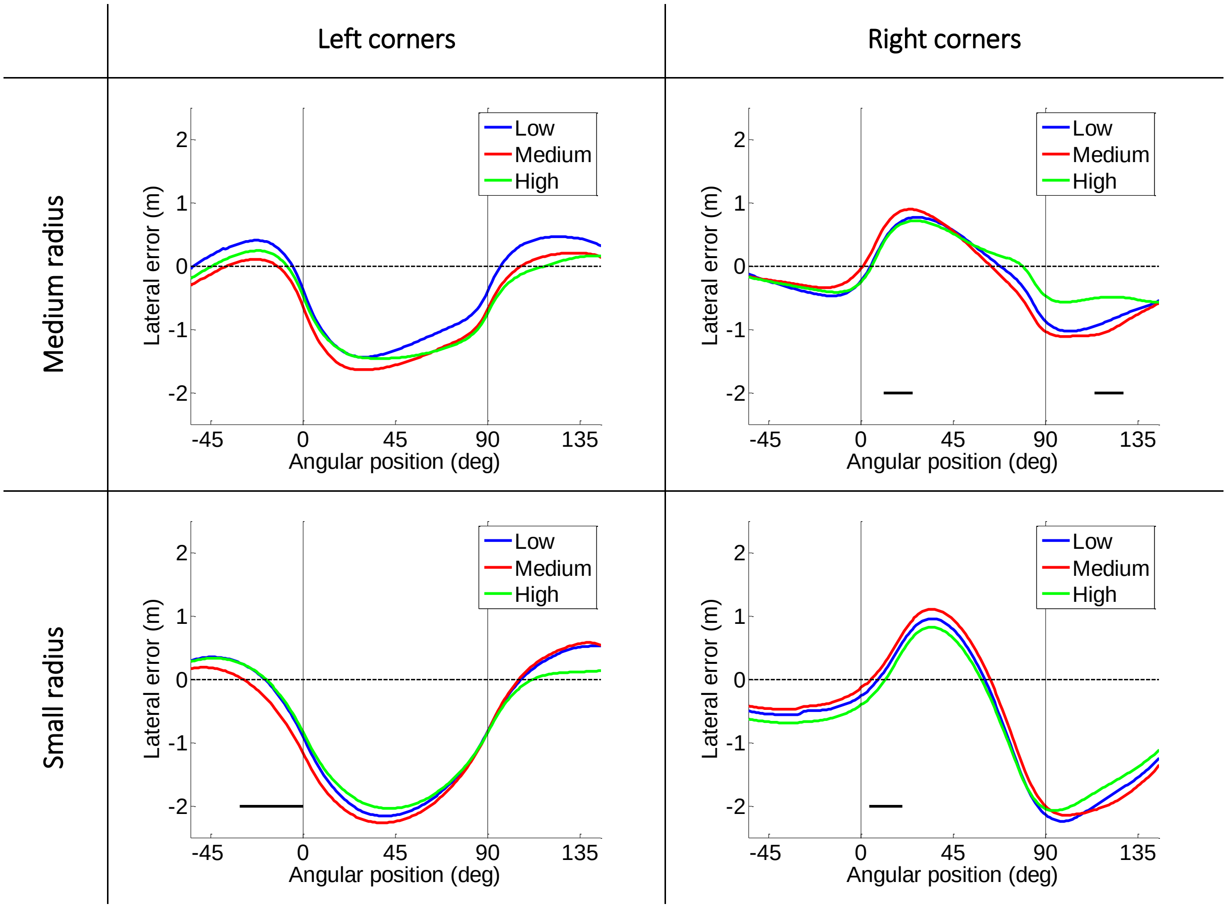

Fig 4. Mean lateral deviation from lane center, averaged across all participants. The left figures show the lateral error of left-hand corners for the medium corner radii, (top panel) and small corner radii (lower panel). The right figures show the lateral error of right-hand corners for medium corner radii, (top panel) and small corner radii (lower panel). Positive values are to the left side of the road for all figures (this position corresponds to the inside of the corner for left-hand corners and outside of the corner for right-hand corners). Significant differences (repeated measures ANOVA, p<0.01) are indicated by horizontal black lines. The lane center is indicated by the horizontal dashed line, and the corner onset and corner end are indicated by the vertical lines at the 0- and 90-degree angular positions.

Driving in the HF level resulted in higher steering activity than driving in the LF and MF visual levels, which was indicated by a considerably higher steering wheel velocity (Figure 5) and a considerably lower steering wheel steadiness (Table 3). Figure 5 (left) shows that the steering activity in the HF level was increased compared to those in the LF and MF levels. Increased steering activity was found for steering wheel velocities in the range of -10 deg/s to 10 deg/s, which indicated that the differences occurred on the straight road segments. Figure 5 (centre) shows the steering wheel steadiness as a function of driving speed; specifically, this figure shows that the steering steadiness in the HF level was lower than that in the LF and MF levels in the range of 12–27 m/s, with the HF level showing a trend similar to that of the LF and MF levels. Figure 5 (right) shows there were no significant differences between the three visual fidelity levels in the steering activity during cornering. For all visual fidelity levels, participants entered the corner more smoothly than their corner exit, as indicated by higher steering velocities at the 90 deg angular corner position.

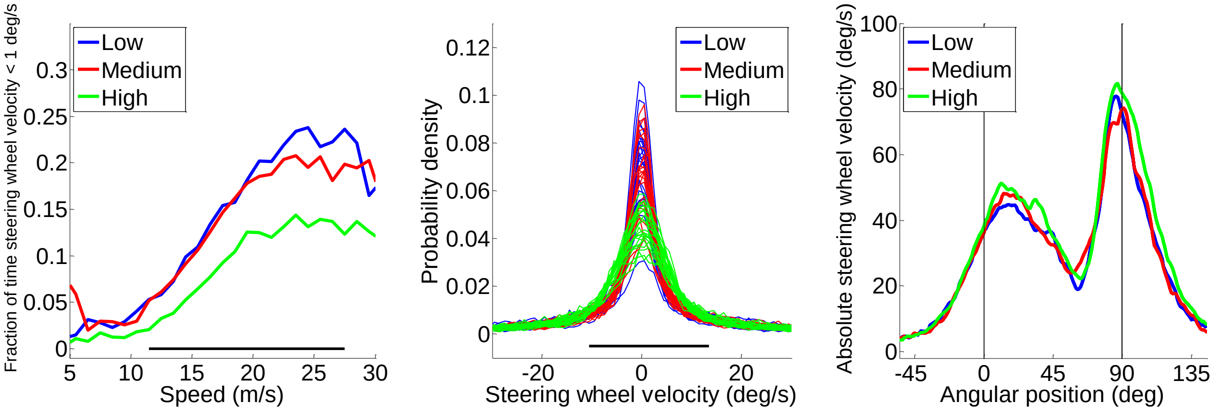

Fig 5. Left: Steering wheel velocity as a function of driving speed derived over 1 m/s bins and averaged per bin. Center: Distribution of steering wheel velocity of individual participants for the three visual fidelity levels. The distribution was derived over 1 deg bins. Right: Mean absolute steering wheel velocity during all corners for the three visual fidelity levels. Corner start and end are indicated by vertical lines at 0 and 90 deg, respectively. Significant differences (repeated measures ANOVA, $p<0.01$) are indicated by horizontal black lines. The corner onset and corner end are indicated by the vertical lines at the 0- and 90-degree angular positions (right figure).

1.3.2 Gaze behaviour

Table 3 shows significantly higher horizontal gaze variance on the straight road segments for HF than on the two lower visual fidelity levels, and no significant differences in the horizontal gaze variance in corners between the three visual fidelity levels. Visual fidelity did not significantly affect the gaze angles relative to the TP and the FP. In medium and small radius corners, the gaze strategies differed between left- and right-hand corners. In both medium and small radii left corners, gaze was directed to the left of the TP (negative TP angles), towards the opposite lane. In medium and small radii right corners, gaze was also directed to the left of the TP (negative TP angles), directed ahead of the vehicle. Figure 6 shows an illustration of the different gaze strategies during left and right corners.

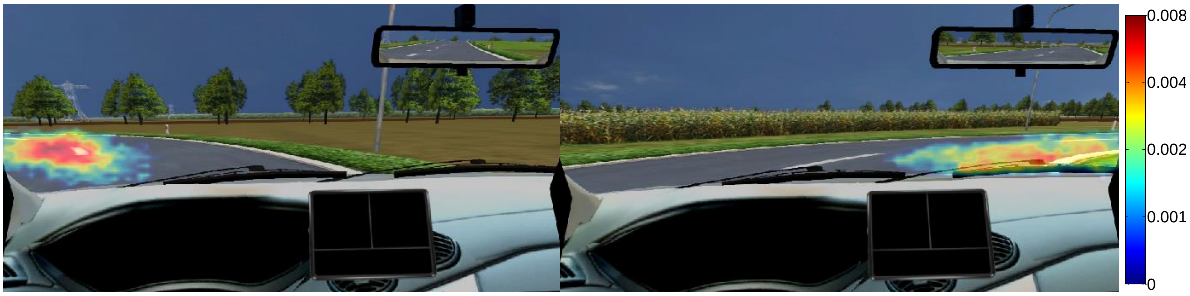

Fig 6. Heatmap of the gaze probability density function during all left- (left) and right-hand (right) corners of all medium and small radii corners for the high visual fidelity level. Gaze distributions were determined by aggregating gaze data from the corner onset until corner exit of all participants in one-by-one degree bins and are displayed on a logarithmic scale.

Figure 7 shows the horizontal gaze angle (θ_G) for large corner radii for the three visual fidelity levels. The gaze patterns in large radii corners did not show statistically significant differences between three visual fidelity levels. For all levels, participants on average directed their gaze in the vicinity of the TP. Figure 8 shows the horizontal gaze angle (θ_G) and the FP angle (θ_{FP}) for three different preview times: 3 s, 2 s and 1 s ahead of the vehicle, for the same corners and fidelity levels. The figure shows that gaze is directed close to the 2 s FP in the large radii corners. Figures 7 and 8 also illustrate only a small difference between the TP angle and 2 s FP angle in large radius corners.

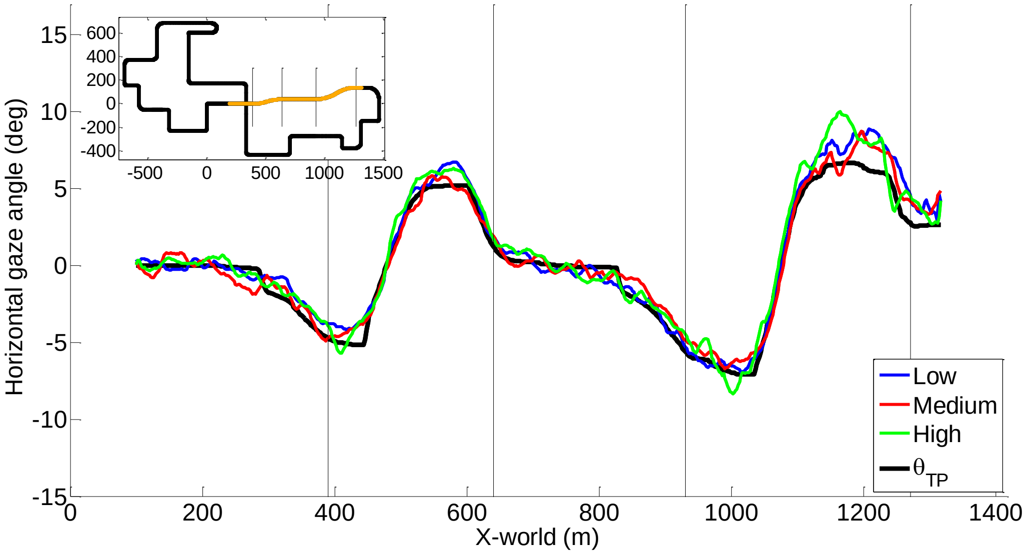

Fig 7. Horizontal gaze angle (θ_G) for large corner radii for the three visual fidelity levels averaged across all participants. The black line shows the angle to the tangent point (θ_{TP}) averaged over all levels and participants. The vertical straight lines indicate the corner onset and corner end, which are also indicated in the window that shows a top view of the respective course section in orange.

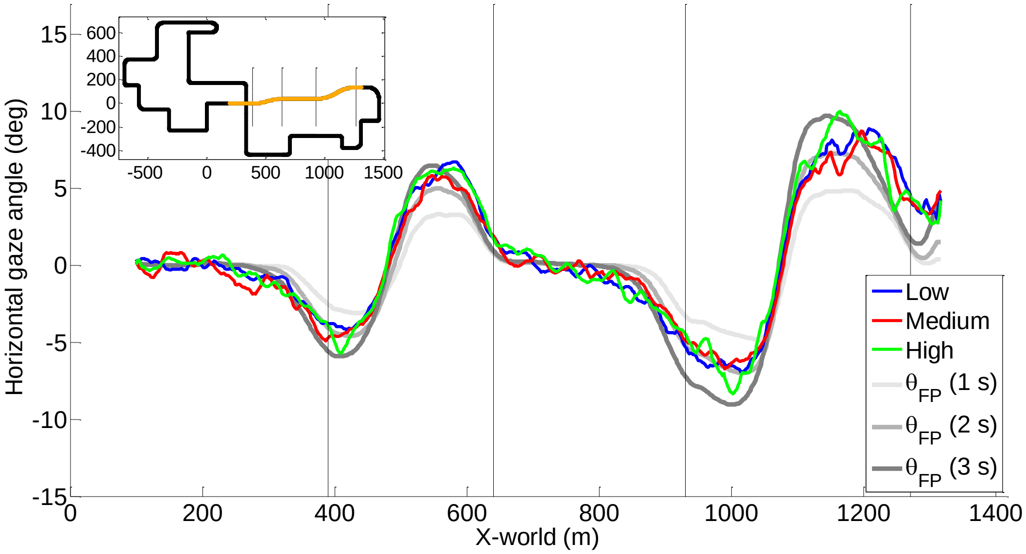

Fig 8. Horizontal gaze angle (θ_G) for large corner radii for the three visual fidelity levels averaged across all participants. The gray lines show the angle to the future point (θ_{FP}) for preview times of 1, 2, and 3 s averaged across all levels and participants. The vertical straight lines indicate the corner onset and corner end, which are also indicated in the window that shows a top view of the respective course section in orange.

In Figure 9, the horizontal gaze angle (θ_G), the TP angle (θ_{TP}) and the 1.5 s FP angle (θ_{FP}) are shown for medium and small radii corners. Again, these values did not significantly differ between the visual fidelity levels. In the medium radii left corners, participants' gaze followed the TP and was directed to the left of the TP in the middle of the corner. In right medium radii corners gaze tracked the TP until the corner onset and remained left of the TP for all visual fidelity levels. For small radii corners, gaze was directed towards the TP approaching the corner in both left- and right-hand corners. At the corner onset, gaze moved to a FP 1.5 s ahead of the vehicle and followed this FP until the midpoint of the corner. Gaze was directed towards the TP in the left corners and to the right of the lane in the right-hand corners when exiting the corners.

1.3.3 Subjective measures

The perceived visual involvement significantly increased from the LF level to the MF and HF levels according to the subjective measures (Table 3). Furthermore, the moving sense in the HF level was significantly higher than that in the LF level. None of the self-reported workload items or the simulator discomfort items differed between visual fidelity levels. Overall, discomfort levels were low, and none of the participants ended the experiment due to simulator discomfort.

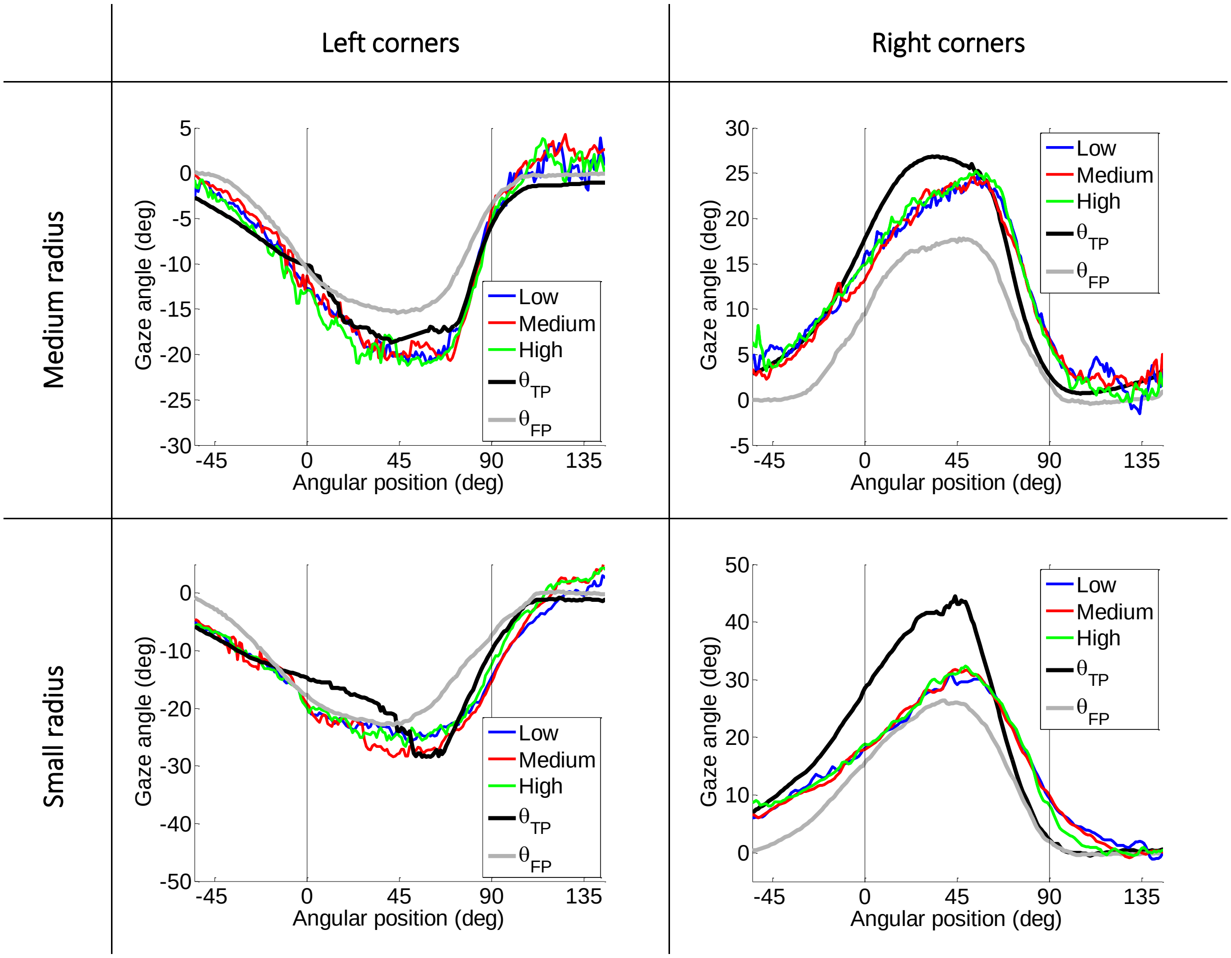

Fig 9. Horizontal gaze angle (θ_G) for medium and small corner radii averaged across all participants. The left figures show the gaze angle (θ_G) in left corners for medium (top) and small (lower) corner radii. The right figures show the gaze angle (θ_G) in right corners for medium (top) and small (lower) corner radii. The black line shows the angle to the TP (θ_{TP}) averaged over all participants, and the gray line shows the angle to the FP (θ_{FP}) (1.5 s ahead of the current position). The corner onset and corner end are indicated by the vertical lines at the 0- and 90-degree angular positions.

1.4 Discussion

This study aimed to investigate differences in driving performance, steering behaviour, gaze behaviour, subjective workload and discomfort between environments with low visual fidelity and a standard state-of-the-art high fidelity visual environment during a self-paced lane-keeping task.

The main hypotheses were that the driving accuracy would decrease due to the absence of textures and optical flow when visual fidelity was diminished (Chatziastros, Wallis, and Bülthoff 1999) and that the speed perception would be impaired, which would increase the driving speed (Mourant et al. 2007). Furthermore, the absence of optical flow was expected to result in more TP-oriented gaze behaviour during cornering for the lower fidelity levels. Finally, lower workload, less immersion and less discomfort were expected for the lower fidelity levels because the visual-information density and, therefore, the mental demand to process that information would decrease.

The main result is that almost all of the studied performance and behaviour variables did not significantly differ between the two lower visual fidelity levels. However, statistically significant differences in the steering activity, lane keeping and speed choice were found between the two lower fidelity levels and the high fidelity level. Given that none of the driving performance and behaviour variables significantly differed between the low and medium levels and that the optical flow and texture density are virtually the same in both levels, it appears that having a coloured environment and a horizon has no detectable influence on the driving measures.

The steering activity on the straight road segments for the high fidelity level was much higher than that for the two lower fidelity levels. This effect can be explained by the lower amount of optical flow in the two lower levels, which prevented LF and MF drivers from perceiving the smaller heading changes and resulted in fewer trajectory corrections compared to the high fidelity level. As a consequence, the reduced amount of optical flow at the LF and MF levels resulted in poorer lane keeping accuracy and precision. These results are consistent with our hypothesis and are similar to the findings of Li and Chen (2010), who reported a decreased lane-keeping performance when reducing the optical flow on a simulated straight road. A possible explanation could be that on the straight road segments, the steering activity is mainly caused by small heading corrections compared to the larger heading changes perceived in corners.

Previous research has shown that reducing the optical flow resulted in an underestimation of the driving speed and, consequently, higher driving speeds (Mourant et al. 2007; Pretto and Chatziastros 2006). However, contrary to our hypothesis, the driving speeds for the low fidelity levels were actually lower than those for the high fidelity level. This finding could be attributed to drivers experiencing difficulties in perceiving their speed and heading at the lower fidelity levels. The road may have been perceived as more challenging at the lower fidelity levels as a consequence of the poorer perception of speed and heading and the realistic road geometry. Participants possibly drove slower at the two lower fidelity levels as a precaution to maintain an acceptable driving performance. Alternatively, the presence of roadside objects (lamp posts and hectometer markers) provided a higher level of guidance at the high fidelity level and may have resulted in higher driving speeds (De Waard, Steyvers, and Brookhuis 2004). Similar results have been observed in real traffic, where improving the quality of visual information by means of road lighting resulted in increased driving speeds (Assum et al. 1999). This phenomenon is more commonly known as ‘risk compensation’ or ‘behavioural adaptation’, see Elvik (2004) and Martens and Jenssen (2012) for theoretical frameworks.

The two major theories in gaze strategy during curve negotiation describe either the TP or the future point as an important gaze target. In the absence of optical flow at the low and medium levels, drivers were expected to direct their gaze predominantly at the TP, as the FP strategy relies on the presence of optical flow (Wilkie and Wann 2003a). Consistent with the TP model, our results showed that drivers showed TP fixation as they approached small radii corners irrespective of the visual fidelity level; however, contrary to the TP model, drivers moved their gaze away from the TP to a point in the vicinity of the FP 1.5 s ahead of the vehicle during corner entry. Possibly in the small radii corners, the TP locations were located at extremely eccentric locations, which may have only allowed a poor angular estimate of the TP location and resulted in drivers shifting their gaze to the lane centre ahead of the vehicle, using the lane centre as a visual-direction reference. In large radii corners, the horizontal TP angle coincided with the horizontal angle of the FP 2 s ahead of the vehicle, making a TP or FP tracking strategy indistinguishable with our method (see discussion in Lappi, Lehtonen, et al. 2013). In conclusion, drivers neither adhered exclusively to the TP or FP visual strategies in small radii corners, whereas the small angular difference between the TP and the FP in large radii corners prevented effective arguments in favour of either the TP or the FP strategy.

When driving through corners, similar corner-cutting strategies were adopted for all visual fidelity levels. Furthermore, the horizontal gaze angle and gaze strategies did not markedly differ between the three visual fidelity levels during corners of different radii. Based on our findings on straight road segments and during cornering, the effect of optical flow may be more dominant on straight roads than on relatively tight corners, where visual-direction information might be more effective in guiding steering than optical flow. This hypothesis is consistent with Wilkie and Wann (2002, 2003a), who suggested a steering model in which drivers use a weighted combination of optical flow, extra-retinal direction and visual direction information to guide steering. This weighting of different information sources may change as a result of conditions (Wilkie and Wann 2002), such as lighting conditions and possibly road curvature.

The horizontal gaze variance was larger on straight road segments for the high fidelity level than for the lower levels and equivalent during cornering. This finding can be attributed to the absence of roadside objects at the lower levels: drivers will not look off the road, as there is nothing to see. The lower horizontal gaze variance and consequent fixation ahead of the vehicle may have resulted in more stable steering control (Mars 2008), a finding that is consistent with the two-level models of steering (Donges 1978; Land and Horwood 1995; Salvucci and Gray 2004). According to these models, distant visual information is used to anticipate steering control. During cornering, drivers in all three visual fidelity levels likely directed their attention primarily to the cornering task, which resulted in equivalent horizontal gaze variance.

In our experiment, simulator discomfort did not significantly decrease in the lower visual fidelity levels when compared to the high fidelity level, contrary to what we hypothesised. The self-reported discomfort levels were low for all participants, and this effect may be attributed to the young age of our population, as simulator discomfort is more common among older adults (Roenker et al. 2003). Furthermore, 79% of our sample was male, and it is known that males are less prone to simulator discomfort than females (Johnson 2005). Our findings are consistent with those of Luke, Parkes, and Walker (2006) who did not find reductions in simulator discomfort as a result of the reduced visual complexity of the simulated environment. The visual involvement and moving sense were significantly higher for the high fidelity level than for the two lower visual fidelity levels, which is consistent with the effect of optical flow on perceived self-motion.

In summary, removing the colours and horizon from a scene does not affect the driving performance and behaviour if the optical flow and texture density are the same. Removing textures and scenery objects from a high fidelity environment results in lower driving speeds, less steering activity on straight road segments, and less accurate and precise lane-keeping performance. On straight roads, where the heading disturbances are smaller, the optical flow allows drivers to perceive these small disturbances, resulting in more steering corrections than in situations when optical flow is unavailable.

Our findings do not modify the current paradigm of visual fidelity in driving simulators, because the effects of optical flow on speed perception and lane-keeping performance correspond to existing information in the literature. Our results demonstrated that driving in the lower fidelity levels results in similar gaze and steering behaviour during curve negotiation as compared with driving in the high fidelity level. Driving with a reduced visual fidelity level may be of interest in applications where visual realism is not essential during a curve negotiation task, such as in driver assessment studies in which relative individual differences or group comparisons are of interest.

Many previous experiments on human perception have used artificial paradigms focusing on one specific manipulation (e.g. dot density, colour, luminance or disparity) at pre-set locomotion speeds. In our experiment we degraded the visual fidelity level of a photorealistic driving environment in a self-paced car driving task. Accordingly, the virtue of our work lies in realism, ecological validity and practical relevance. The resulting degradation of the visual fidelity led to reduced optical flow levels as a result of diminished textures and removed scenery objects. In future studies regarding the visual control of steering, a distinction could be made between the optical flow resulting from textures and the optical flow originating from scenery objects.

Differences in the perception of speed and depth between simulated and real driving have been demonstrated (Panerai et al. 2001), but there is a limited number of studies that demonstrate the role of optical flow and scenery objects in visually guided steering in real vehicles (e.g. Van der Horst 1990). Unfortunately, only a small (but growing) body of literature has been published on the actual relationship between driver behaviour in the simulator and driver behaviour in the real vehicle under similar circumstances (De Winter, Van Leeuwen, and Happee 2012; Kaptein, Theeuwes, and Van der Horst 1996).

Our results did not show reduced simulator discomfort when lowering the visual fidelity level during our 9.5 min sessions. Additional experiments with participants prone to simulator discomfort (e.g. older persons), discomfort-prone driving environments (Mourant and Thattacherry 2000) or longer duration experimental sessions (Kolasinski 1995) are recommended and may show the expected differences in simulator discomfort between the three visual fidelity levels. Eighteen percent of eye tracker data were discarded during the post-processing of our results, a number comparable with other eye tracker research (Ahlstrom et al. 2012; Holmqvist, Nyström, and Mulvey 2012). As the data-loss often occurred due to random events (e.g. eye blinks), and since there were no structural differences in the amount of discarded data between the three groups (Table 2), we expect no systematic bias in our gaze results. The 24 participants in our experiment were recruited from a technical university campus; a larger and more representative sample may benefit the generalisability of our results.

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Implications for driver assessment

This chapter assessed the steering behavior and eye movements of drivers performing a self-paced driving task with different levels of visual fidelity. The quality of the simulator visuals affected eye movements, steering control, and lane keeping performance. The results also illustrate the different eye and head movements during cornering and straight road sections. The findings of this chapter show the importance of measuring both steering and eye movements synchronously. That is, eye-movements alone are not informative; they should be interpreted in conjunction with the steering behavior of the driver.

Chapter 2

Differences between racing and non-racing drivers: A simulator study using eye-tracking

Abstract

Motorsport has developed into a professional international competition. However, limited research is available on the perceptual and cognitive skills of racing drivers. By means of a racing simulator, we compared the driving performance of seven racing drivers with ten non-racing drivers. Participants were tasked to drive the fastest possible lap time. Additionally, both groups completed a choice reaction time task and a tracking task. Results from the simulator showed faster lap times, higher steering activity, and a more optimal racing line for the racing drivers than for the non-racing drivers. The non-racing drivers' gaze behavior corresponded to the tangent point model, whereas racing drivers showed a more variable gaze behavior combined with larger head rotations while cornering. Results from the choice reaction time task and tracking task showed no statistically significant difference between the two groups. Our results are consistent with the current consensus in sports sciences in that task-specific differences exist between experts and novices while there are no major differences in general cognitive and motor abilities.

Van Leeuwen, P. M., De Groot, S., Happee, R., & De Winter, J. C. F. (2017). Differences between racing and non-racing drivers: A simulator study using eye-tracking. *PloS one*, *12(11)*, e0186871. https://doi.org/10.1371/journal.pone.0186871. (adapted with minor changes)

2.1 Introduction

Motorsport has evolved from the recreational level into a high-profile international sport attracting millions of viewers worldwide (Aversa, Furnari, & Haefliger, 2015; Bell, Smith, Sabel, & Jones, 2016). The goal of a racing driver is typically to achieve the fastest possible lap time by driving the vehicle at the limit of tire grip in an optimal manner (Braghin, Cheli, Melzi, & Sabbioni, 2008; Metz & Williams, 1989). Unlike the extensive body of knowledge on the technological aspects of racecars, comparatively little is known about the motor, perceptual, and cognitive skills of athlete performance in motorsports (Klarica, 2001; Owen, King, & Lamb, 2015; Potkanowicz & Mendel, 2013). Knowledge of these skills may aid in designing training methods for racing drivers and improve driver-vehicle interfaces for not only motorsport applications but also road vehicles (e.g., Baldisserri et al., 2014; De Winter & De Groot, 2012; Lappi, 2015).

2.1.1 Differences between experts and non-experts

It is well established that practice is a prerequisite for achieving high levels of performance at a task. Ericsson, Krampe, & Tesch-Römer (1993) reported that the amount of accumulated practice for expert musicians exceeded 10,000 hours at the age of 20 years. Similar findings in other domains (Ericsson & Lehmann, 1996) have resulted in the notion that 10,000 hours of deliberate practice is required to obtain expert-level performance. However, a recent meta-analysis by Macnamara, Moreau, & Hambrick (2016) showed that deliberate practice accounts for only 18% of the variance in sports performance. These authors recommended that in order to understand the determinants of expertise, findings from cognitive ability, personality psychology, behavioral genetics, and sports sciences need to be considered.

The literature suggests that experts do not differ from non-experts in elementary abilities such as visual acuity, color vision, or peripheral response time (Memmert, Simons, & Grimme, 2009). Instead, differences have been found to occur in the sport-specific processing of information (Abernethy & Wood, 1992). A meta-analysis by Mann et al. Mann, Williams, Ward, & Janelle (2007) showed that experts in sports respond faster and more accurately to task-specific cues than non-experts (see also Ward & Williams, 2003)). For example, experts in interceptive sports (e.g., tennis, soccer) are well able to predict the future behavior of the ball based on the opponent’s movements (Abernethy, 1990; Aglioti, Cesari, Romani, & Urgesi, 2008; Rodrigues, Vickers, & Williams, 2002; Savelsbergh, Williams, Van der Kamp, & Ward, 2002).

2.1.2 Relevance of perceptual-cognitive skills in (high-speed) driving

A large amount of research has been dedicated to studying the effects of visual stimuli on steering control. Land and Lee (Land & Lee, 1994) formulated a model that describes how regular (i.e., non-racing) drivers steer their vehicle. These authors found that drivers directed their gaze predominantly at the tangent point (defined as the point where the inside road edge reverses direction), and they illustrated a geometrical relation between the tangent point location, corner curvature, and required steering input. The tangent point at a specific moment in time coincides with the apex point of a corner. The apex point is a fixed location on the inside road edge of a corner and is strongly related to the racing line the driver takes while cornering (Theodosis & Gerdes, 2011). Other models suggest that drivers control steering by means of optical flow information (Wann & Swapp, 2000) and that they direct their gaze on their future path, approximately 1 to 2 seconds ahead of the vehicle (Wilkie & Wann, 2003). These results correspond to various other findings showing that humans use optical flow to perceive their heading (Warren, Mestre, Blackwell, & Morris, 1991; Warren, Morris, & Kalish, 1988).

Research has also shown that experienced drivers direct their gaze further ahead than novices (Falkmer & Gregersen, 2005; Mourant & Rockwell, 1972). Furthermore, experienced drivers exhibit greater gaze variance than novices, which can be explained by the fact that they scan the environment more actively (Crundall & Underwood, 1998; Underwood, Crundall, & Chapman, 2002). Finally, it has been found that experienced drivers rely less on foveal vision and more on peripheral vision for their steering control (Summala, Nieminen, & Punto, 1996).

2.1.3 Previous research on racing drivers

Backman, Häkkinen, Ylinen, Häkkinen, & Kyröläinen (2005)] compared nine open-wheel racing drivers to nine rally drivers and nine regular drivers. Their results indicated differences in grip strength as measured with a dynamometer, with higher grip strengths for the rally drivers and open-wheel racing drivers compared to the normal drivers. Backman et al. (2005) also found higher relative neck strength for the open-wheel racing drivers compared to the other two groups. Baur, Müller, Hirschmüller, Huber, & Mayer, (2006) observed significantly faster reaction times for eight racing drivers on a reaction time task when compared to ten normal drivers. However, no significant differences were found for postural stability, leg extensor strength, arm strength, or arm endurance.

Bernardi et al. (2013, 2014) compared the brain activity of experienced racing drivers with that of normal drivers. Eleven professional drivers and eleven age-matched drivers watched video clips from the drivers' viewpoint of Formula One cars in an MRI scanner. Results indicated that compared to the non-racing drivers, the racing drivers showed more consistent recruitment of brain areas devoted to motor control and spatial navigation. The authors indicated that "exceptional driving abilities may acquire the acquisition of a specific behavioral and functional motor repertoire that is different from the one associated with common 'every day driving'" (p. 9).

In a literature review on brain imaging in relation to driving expertise, Lappi (2015) argued that differences in brain activity between racing drivers and regular drivers may be due to the racing drivers' task familiarity. The author argued that "whereas for a naïve participant steering a series of bends may effectively be reduced to a simple path-following visuomotor routine, to the expert with detailed survey knowledge of the track and a deep understanding of cornering techniques (cued by landmarks), many additional cognitive operations may be performed". The regions of brain activity indicated by Bernardi et al. (2014) are used during the control of pursuit and saccadic eye movements (Lappi, 2015), suggesting that differences in brain activity are related to eye movement strategies.

In an on-track study, Land and Tatler (2001) measured the eye movements of a professional single-seater racing driver while driving at racing speed. They found that the driver directed his gaze at a horizontal offset from the tangent point and that this offset was different for each corner. These findings illustrate that the tangent point itself was not the main area of visual attention while driving through corners. The authors also found a strong correlation between the driver's head rotation (in yaw) and the vehicle's rotational speed approximately one second later, and that the eyes-in-head angle remained relatively constant throughout the lap. They further argued that the driver used this relationship between the vehicle's rotational speed and the visual information to control the vehicle path.

2.1.4 Aim of this study

Previous findings in the domain of racing drivers' expertise have mainly focused on physiological differences between racing drivers and normal drivers. Furthermore, one study has reported the eye movement behavior of a single racing driver. No studies seem to exist on the task-specific driving skills and the processing of visual information of racing drivers compared to normal drivers.

In our racing simulator experiment, we investigated differences in car control, visual strategy, and driving performance between racing drivers and non-racing drivers who completed four sessions on a racing circuit. To evaluate both groups on non-domain specific motor skills, we tested their performance on a first-order dynamic tracking task and a choice reaction time task.

We expected the racing drivers to show better driving performance in terms of faster lap times and fewer crashes. Additionally, we expected the racing drivers to adapt their path strategy to specific sections of the circuit, aiming to benefit from the racing line. Moreover, based on Land and Tatler (2001), we anticipated that the racing drivers would direct their gaze less often at the tangent point as compared to the normal drivers. Finally, due to task familiarity, we expected the racing drivers to experience lower self-reported workload than the normal drivers.

2.2 Materials and methods

2.2.1 Participants

Seven male racecar drivers competing in international race categories (Formula 3, GP2, and Porsche Supercup) and ten males from the Delft University of Technology campus were recruited for this experiment. Before starting the experiment, participants completed an intake questionnaire consisting of general items (e.g., age, wearing contacts or glasses, simulator experience, racing games experience), 14 items detailing their racing experience (e.g., number of years racing in cars, number of participated go-kart races), 8 items about their driving experience (e.g., annual mileage, number of accidents, number of traffic fines), and 11 items about violations and errors. The 11 items were derived from the Driving Habits Questionnaire (Owsley, Stalvey, Wells, & Sloane, 1999) and the Driving Behaviour Questionnaire (Reason, Manstead, Stradling, Baxter, & Campbell, 1990).

The racing drivers' mean age was 19.9 (*SD* = 1.8), and the non-racing drivers' mean age was 21.6 (*SD* = 1.7) years. Fifteen participants (six racing drivers and nine non-racing drivers) were in possession of a driver's license. Participants had an average annual mileage of 14,070 km (*SD* = 19,196). The racing drivers had on average 8.4 (*SD* = 3.0) years of experience racing in cars and go-karts, and on average had participated in 82.3 (*SD* = 64.5) go-kart races during their go-karting career. Both the racing drivers and non-racing drivers reported playing racing games, on average for 3.3 (*SD* = 3.2) and 0.2 (*SD* = 0.6) hours per week, respectively. All racing drivers and one non-racing driver reported previous experience in racing simulators. All participants provided informed written consent before starting the experiment, and the research was approved by the Human Research Ethics Committee of the Delft University of Technology.

2.2.2 Apparatus

The experiment was conducted in a fixed-base racing simulator based on a Tatuus Formula Renault 2.0 chassis used for racecar driver training (SimDelft, the Netherlands). The simulator was equipped with the components originating from the original car: steering wheel, throttle pedal, brake pedal, custom-made seat. The steering wheel force feedback was provided by a control loader (SimSteering v1), and the brake and throttle pedal passive stiffness resembled those of the original car. The simulator was equipped with a dashboard on the steering wheel showing speed, engine rpm, lap, and lap sector times. The visual system consisted of three 55-inch Plasma screens (Panasonic TX-P55VT30E, refresh rate of 60 Hz) spanning a horizontal and vertical field of view of 130 and 27 degrees, respectively. Each screen had a resolution of 1920 x 1080 pixels, and the simulation ran with a frame rate exceeding 100 frames per second. Auditory feedback was provided through headphones. The virtual environment, vehicle dynamics, and force feedback were simulated by rFactor software (v1.255). We used the rTrainer vehicle model, a rear wheel driven formula-style racecar (115 bhp, 573 kg). All driving aids (ABS, ESC, traction control) were disabled, and gear shifting was automated.

Head and eye movements were recorded using a remote eye tracker from Smart Eye (v5.8), consisting of three remote mounted cameras (Sony XC-HR50) and two infrared illuminators mounted above the steering wheel on the simulator chassis (see Fig 1 for a photo of the racecar simulator and eye tracker). Eye-tracker data were sampled at 60 Hz, and all eye-tracker and simulator data were recorded and stored synchronously at 100 Hz.

Fig 1. Overview of the racing simulator and eye tracker.

2.2.3 Procedures

Before the simulator experiment commenced, participants received a paper handout explaining the experiment and procedures, and filled out the intake questionnaire. After completing the intake questionnaire, participants were seated in front of a desktop computer, received the instructions for the Deary-Liewald choice reaction time (CRT) task (Deary, Liewald, & Nissan, 2011), and completed 10 practice and 40 measurement trials. After completion of the CRT task participants received the instructions for the visual-motor task (MMSLab) and performed six trials of the MMSLab task (De Winter, Dodou, De Groot, Abbink, & Wieringa, 2009).

After the MMSLab task, participants entered the simulator cockpit and received oral instructions regarding the simulator operation, the procedure to resume driving after a road departure, and the steering wheel dashboard information (e.g., vehicle speed, current lap time, best lap time). A series of head and eye movements followed to calibrate the eye-tracker equipment before the first session commenced. Participants drove four sessions, each session lasting 10 minutes. After the first and the third session, a 5-minute break followed during which participants remained seated in the simulator and completed the NASA-TLX questionnaire (Hart & Staveland, 1988) for measuring workload. After the second session, a 10-minute break followed during which participants completed the NASA-TLX questionnaire outside of the simulator. After completing the NASA-TLX questionnaire of the final session, participants completed a questionnaire concerning their subjective performance and the perceived vehicle handling quality for each corner.

2.2.4 Experimental tasks

The choice reaction time task consisted of four horizontally placed white squares displayed on a PC-monitor and a keyboard with four assigned keys, one key corresponding to each square's location. Participants were requested to press the corresponding key as quickly as possible after one of the four squares showed a black cross. The MMSLab task consisted of a one-dimensional (horizontal) compensatory tracking task. A green error symbol and a white target box were displayed on a black background. Participants were required to use the computer mouse to minimize the error (distance between the error symbol and the static target box). The controlled dynamics of the mouse were a first-order integrator, whereby the object's velocity was proportional to mouse displacement.

During the simulator sessions, participants were instructed to drive the fastest possible lap time while keeping their vehicle on the road (i.e., they were not allowed to cut corners). Participants were instructed to use the steering wheel, throttle pedal, and brake pedal to operate the vehicle, and they were informed that gear shifting was automated. The sessions started with the vehicle from a standstill in the pit lane (participants were required to drive the vehicle onto the track after the session started).

2.2.5 Driving environment

All driving sessions took place on a virtual representation of the racetrack Mallory Park in Leicestershire, United Kingdom, as in Land and Tatler (2001). None of the participants had driven on this racetrack before. The circuit, with a length of 2,172 m, consisted of a large-radius right-hand corner (minimum corner radius = 128 m), a right corner, directly followed by a short left corner (minimum corner radius = 120 m), a sharp hairpin (minimum corner radius = 14 m), and a left-hand corner (minimum corner radius = 118 m). See Fig 2 for an overview of the circuit layout and the corner radii for the various corners.

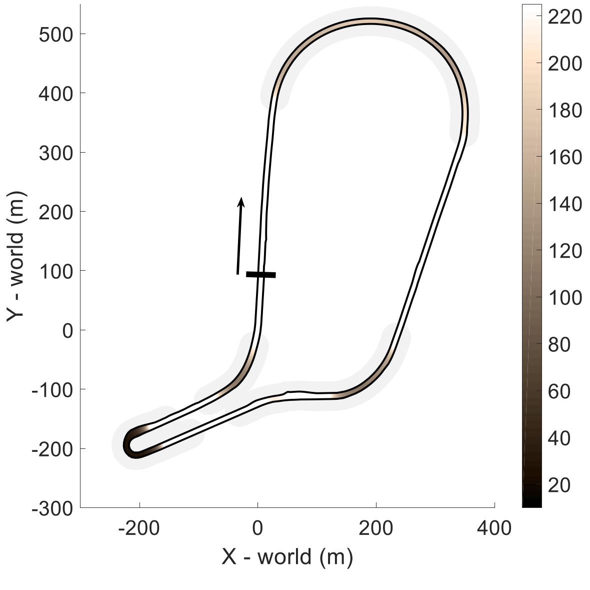

Fig 2. Overview of the circuit layout and centerline corner radius in meters. The start/finish line and driving direction are indicated by the black line and arrow, respectively. Grey shaded areas indicate the corner segments.

2.2.6 Dependent measures

Prior to the analysis, data from the steering sensor, brake pedal, and throttle pedal were low-pass filtered at a 3 Hz cutoff frequency to remove high-frequency noise. Furthermore, eye and head movements were low-pass filtered at 10 Hz and 5 Hz cutoff frequencies, respectively. Missing eye-tracker data (e.g., due to camera obstruction from hands on the steering wheel, or eye blinks) were removed from the dataset (Van Leeuwen, Happee, & De Winter, 2014). Gaze data from 0.2 s before to 0.2 s after segments of missing data were also removed. If the eye-tracker data loss of a session exceeded 60%, the complete eye-tracker dataset of the respective session was removed from the analysis. The following dependent measures were calculated from the fastest lap data for each participant and session:

2.2.6.1 Reaction time and visual-motor performance

Choice reaction time (CRT; ms) and root mean square of the MMSLab tracking error (-) were calculated as measures of basic cognitive skill and visual-motor performance. Reaction time is related to general cognitive ability (Deary, Liewald, & Nissan, 2011) and has frequently been used as a performance measure of motor reaction tasks (Backman et al., 2005; Bernardi et al., 2013). The root mean squared MMSLab tracking error was calculated as the root of the arithmetic mean of the squares of each measured tracking error.

2.2.6.2 Driving performance

Drivers were assessed on performance measures of best lap time (s), median lap time (s) (m/s), and the number of road departures. A road departure was counted as an event in which all four wheels were outside of the road boundaries. If a road departure occurred, the lap was declared invalid, and the data were excluded from the analysis. A maximum of one road departure per lap was counted.

2.2.6.3 Vehicle control

The mean steering speed (deg/s) and throttle variance (%2) were used as measures of control activity and consistency when driving in corners (Van Leeuwen, Happee, & De Winter, 2015; Rendon-Velez, Van Leeuwen, Happee, Horváth, Van der Vegte, & De Winter, 2016). Furthermore, the maximum brake pedal position on a scale of 0 (minimum) to 100% (maximum) was used as a measure of braking performance [46]. The time from the initial brake pedal actuation to the maximum brake pedal position during a braking maneuver was used as a measure of brake efficiency (De Groot, De Winter, Wieringa, & Mulder, 2009).

2.2.6.4 Eye and head movements

Gaze direction and head rotation data were collected to compute the difference between the horizontal gaze angle and the angle of the line from the vehicle center to the tangent point [47]. A positive value means that drivers looked at the right of the tangent point, and a negative value means that drivers look to the left of the tangent point. The tangent point locations were calculated from the circuit edge geometry and the center of gravity position of the vehicle. As mentioned above, the tangent point bears a close relationship to the apex point, used by racing drivers as a visual reference point while driving (Land & Tatler, 2001).

2.2.6.5 Subjective measures

The NASA-TLX (0–100) questionnaire (Hart & Staveland, 1988) was used to assess the participants' self-reported workload on the following six items: mental demand, physical demand, temporal demand, performance, effort, and frustration. The responses were marked on a 21-tick horizontal bar with anchors on the left (very low) and right sides (very high). For the performance item, the anchors (perfect) and (failure) on the left and right side were used. After the simulator sessions, participants were requested to rate the handling quality of the vehicle for each individual corner by answering the following question: "The vehicle handling was good" on the following levels: disagree, somewhat disagree, neutral, somewhat agree, agree.

2.2.7 Statistical analysis

Means and standard deviations across participants were computed for the best lap of each participant in each session. Differences between sessions were statistically analyzed with paired t tests ($\alpha = 0.05$). The results of the number of road departures and the averaged absolute vehicle yaw rate during road departures were fractionally ranked (Conover & Iman, 1981) per session, because of the skewed distribution of these variables.

2.3 Results

The eye-tracker data for 1 of out 17 participants were removed due to malfunctioning of the eye tracker. Furthermore, four sessions of eye-tracker data were removed due to the data loss exceeding the 60% threshold. Of the remaining 60 sessions (i.e., 17 participants x 4 sessions – 8 missing sessions), 13% of eye-tracker data were removed from the analysis (e.g., due to blinks). Data from the CRT task of one participant (from the racing drivers group) were removed due to failure to adhere to the task instructions (i.e., the participant misunderstood the task instructions). Furthermore, the MMSlab data from one participant (from the racing drivers group) were unavailable due to a data logging error.

2.3.1 Reaction time and visual-motor performance

No statistically significant differences were found in the CRT between the racing drivers and the non-racing drivers. The average reaction time (averaged across 40 trials) was 431.6 ms (*SD* = 35.8 ms) for the racing drivers and 439.5 ms (*SD* = 34.2 ms) for the non-racing drivers ($t(14) = 0.437$, $p = 0.6689$). Furthermore, the racing drivers' results of the motor skill task did not significantly differ from the non-racing drivers. Specifically, the RMS error (averaged across all six trials) was 0.222 (*SD* = 0.078) for the racing drivers and 0.178 (*SD* = 0.033) for the non-racing drivers ($t(14) = 1.588$, $p = 0.1346$).

2.3.2 Driving performance

The racing drivers drove statistically significantly lower best lap times than the non-racing drivers (Table 1). In Fig 3 all included lap times for all participants are shown, ranked per fastest lap of the participant. The figure also shows the number of laps excluded for each participant; this number provides an indication of individual differences in the number of road departures.

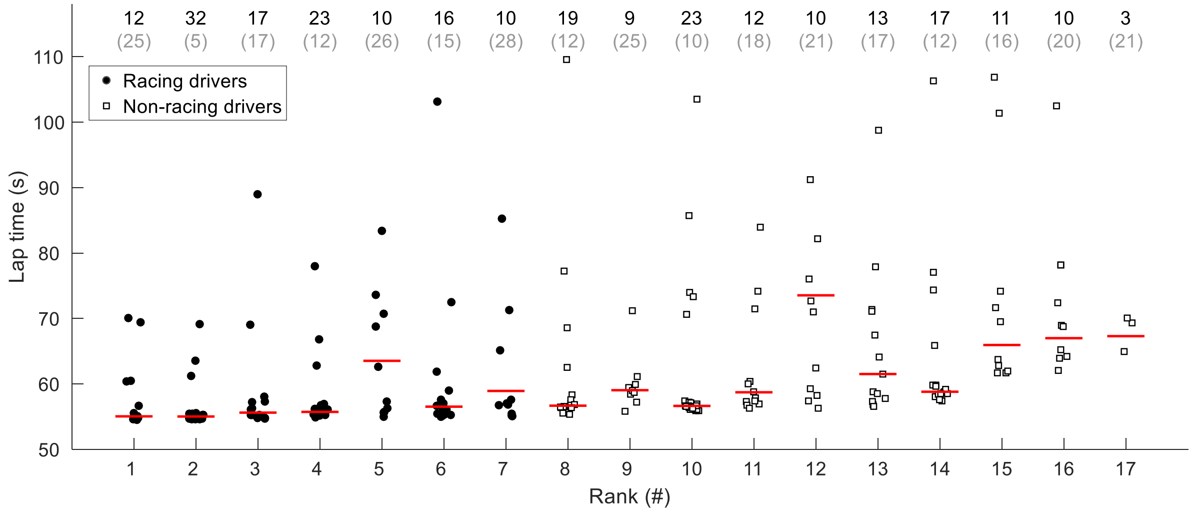

Fig 3. Overview of all lap times of all sessions per participant. Ranking is based on the best lap time and each rank corresponds to one participant. The lap time median per participant is shown in red. Markers were given a random offset from -0.25 to 0.25 on their rank, to reduce the overlap of markers. The numbers above the graph correspond to total number of completed laps and the number of discarded laps (in parentheses) per participant.

The session means, standard deviations, and Pearson correlation coefficients between the third and the fourth session are shown in Table 1 for both the racing drivers and the non-racing drivers. Similar to Fig 2, the table shows significant differences in best and median lap times of the racing drivers compared to the non-racing drivers in all four sessions. Furthermore, both the racing drivers ($t(6) = 3.55$, $p = 0.012$) and the non-racing drivers ($t(9) = 2.80$, $p = 0.021$) significantly improved their best lap time from the first to the last session. The Pearson correlations in Table 1 indicate that between-subject differences remain consistent over the third and the last session.

Table 1. Session means (standard deviations in parentheses) of the dependent measures for the four sessions. *p* values are indicated for comparisons between both groups of drivers. Pearson correlation coefficients are shown between the first and fourth session and the third and fourth session

Dependent measures					Pearson correlation
	Session 1	Session 2	Session 3	Session 4	S3-S4
Best lap time (s)					
Racing drivers	55.9 (0.85)	55.3 (0.35)	54.9 (0.28)	54.8 (0.21)	0.714
Non-racing drivers	57.9 (0.67)	59.0 (2.78)	59.1 (3.95)	58.1 (2.55)	0.899
p value	**0.0008**	**0.0033**	**0.0149**	**0.0047**	
Median lap time (s)					
Racing drivers	56.5 (0.68)	55.6 (0.29)	55.2 (0.26)	55.2 (0.27)	0.071
Non-racing drivers	58.5 (0.95)	61.2 (4.39)	59.9 (3.83)	59.2 (3.26)	0.942
p value	**0.0010**	**0.0047**	**0.0059**	**0.0055**	
Road departures (#)*					
Racing drivers	4.86 (2.19)	5.29 (3.04)	4.00 (2.71)	4.14 (2.41)	0.111
Non-racing drivers	5.90 (0.57)	3.90 (1.79)	3.80 (2.1)	3.60 (1.58)	0.578
p value	0.6118	0.3392	0.9252	0.5374	
Steer speed corners (deg/s)					
Racing drivers	20.93 (7.3)	18.36 (5.7)	16.46 (4.2)	16.76 (4.0)	0.752
Non-racing drivers	17.85 (4.3)	13.69 (2.9)	12.39 (3.4)	11.99 (3.4)	0.933
p value	0.3840	**0.0404**	**0.0432**	**0.0187**	
Throttle variance corners (%^{2})					
Racing drivers	1618 (117)	1699 (46.0)	1664 (100)	1719 (115)	0.571
Non-racing drivers	1421 (114)	1357 (137)	1343 (140)	1366 (159)	0.788
p value	**0.01084**	**<0.0001**	**0.0001**	**0.0002**	
Max brake (0–100)					
Racing drivers	74.6 (14.8)	78.2 (15.2)	82.9 (14.7)	83.0 (14.1)	0.964
Non-racing drivers	79.4 (17.5)	65.8 (16.6)	75.2 (13.6)	69.4 (16.5)	0.835
p value	0.60621	0.1382	0.2873	0.0960	
Mean absolute head rotation (deg)					
Racing drivers	7.64 (4.12)	8.27 (3.16)	7.81 (3.84)	11.2 (4.35)	0.800
Non-racing drivers	4.20 (2.13)	5.16 (2.57)	4.03 (2.11)	4.60 (2.49)	0.950
p value	0.1204	0.0555	**0.0279**	**0.0025**	
TLX mental demand (0–100)					
Racing drivers	39.3 (25.2)	41.7 (28.9)	41.7 (24.6)	40 (21.7)	0.993
Non-racing drivers	56.5 (15.8)	56.5 (18.9)	56.0 (24.0)	64 (18.4)	0.651
p value	0.1280	0.2897	0.2630	**0.0277**	
TLX physical demand (0–100)					
Racing drivers	8.60 (10.7)	12.9 (12.9)	11.4 (9.9)	16.4 (12.5)	0.881
Non-racing drivers	41.5 (22.2)	55.0 (22.2)	58.0 (21.5)	61.5 (24.0)	0.909
p value	**0.0026**	**0.0004**	**<0.0001**	**0.0004**	
TLX temporal demand (0–100)					
Racing drivers	19.3 (16.9)	16.4 (17.7)	20.7 (20.3)	25.0 (16.8)	0.817
Non-racing drivers	51.0 (14.1)	51.0 (18.1)	50.5 (19.4)	60.0 (19.2)	0.959
p value	**0.0005**	**0.0018**	**0.0048**	**0.0018**	

(table continues)

Table 1. (continued)

TLX performance (0–100)					
Racing drivers	47.1 (19.6)	47.1 (18.7)	31.4 (18.4)	34.3 (21.5)	0.434
Non-racing drivers	68.0 (21.4)	52.0 (16.9)	54.0 (15.6)	45.5 (13.4)	0.798
p value	0.0584	0.5840	**0.0155**	0.2035	
TLX effort (0–100)					
Racing drivers	41.4 (30.1)	53.6 (23.9)	51.4 (21.0)	59.3 (16.7)	0.800
Non-racing drivers	63.5 (11.3)	68.0 (13.2)	72.0 (10.3)	74.5 (12.1)	0.808
p value	**0.0495**	0.1300	**0.01659**	**0.0452**	
TLX frustration (0–100)					
Racing drivers	28.6 (32.2)	39.3 (30.3)	29.3 (24.2)	30.7 (25.9)	0.703
Non-racing drivers	56.5 (23.7)	45.0 (26.7)	47.0 (27.5)	41.5 (16.7)	0.750
p value	0.0566	0.6867	0.1910	0.3106	

*Note: For the road departures the Spearman correlation was computed.

There was no significant difference in the number of road departures between the racing drivers and the non-racing drivers. On average, the racing drivers and the non-racing drivers had approximately 4.6 and 4.3 road departures per session, respectively. During the road departures, the averaged absolute vehicle yaw rate was significantly higher ($t(15) = 4.95$, $p < 0.0002$) for the non-racing drivers (272 deg/s, $SD = 172$ deg/s) compared to the racing drivers (124 deg/s, $SD = 67$ deg/s). A higher vehicle yaw rate during a road departure indicates a loss of control.

The racing drivers showed higher steering speeds and higher throttle variance while cornering when compared to the non-racing drivers, reaching statistical significance in all sessions except the first session for the steering speeds. No significant difference was found in the maximum brake position.

The subjective measures indicated a statistically significantly lower physical and lower temporal demand for the racing drivers as compared to the non-racing drivers. The mental demand, performance, and effort were also lower for the racing drivers than for the non-racing drivers, with each item reaching significance in at least one of the four sessions. The non-racing drivers reported significantly ($t(15) = 4.792$, $p = 0.0002$) better handling qualities of the vehicle, scoring the vehicle handling (from 0 to 5) on average with 3.8 ($SD = 0.58$) compared to 2.6 ($SD = 0.37$) for the racing drivers.

Fig 4 shows the vehicle speed, steering wheel angle, brake position, and throttle position, respectively as a function of travelled distance in the lap. On average, the racing drivers' vehicle speed in the corners was higher than for the non-racing drivers'. The figure also shows higher steering wheel angles for the racing drivers compared to the non-racing drivers. Moreover, in the first two corners, the racing drivers on average pressed the brake at a later position than the non-racing drivers did. Finally, the throttle position shows that racing drivers more often drove full (100%) throttle. It can also be seen that the racing drivers drove the fourth corner at 100% throttle, whereas some non-racing drivers released the throttle in this corner.

2.3.3 Vehicle control

The difference in vehicle control between the racing drivers and non-racing drivers is illustrated in Fig 5. It can be seen that the racing drivers drove the vehicle with higher steering speeds in all corners. Furthermore, the racing drivers drove a smaller amount of time with throttle positions between 20% and 60% than the non-racing drivers. This can be explained by a difference in throttle style: Compared to the non-racing drivers, the racing drivers held the throttle position longer at 100% and released to 0% at a later position in the corners (see Fig 4).

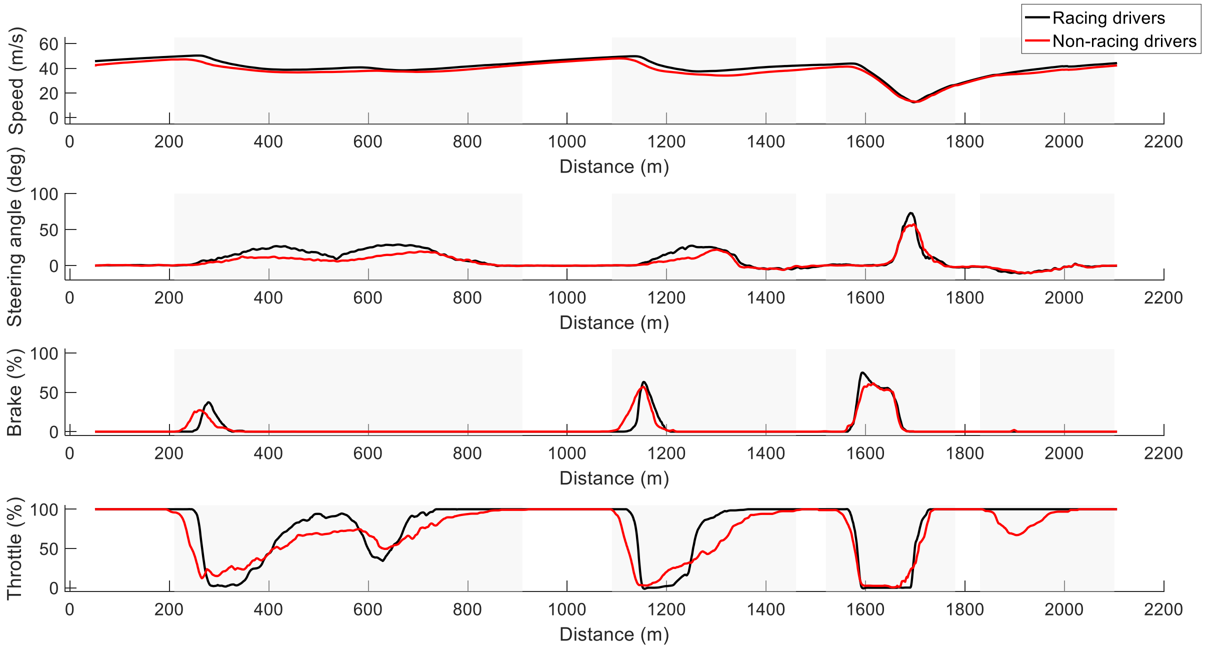

Fig 4. From top to bottom, overview of vehicle speed, steering angle, brake position, and throttle position as a function of traveled distance for the racing drivers and non-racing drivers averaged across both groups for the fastest laps of each of the four sessions. Grey shaded areas indicate the four corners.

Fig 5 also shows the brake pedal position for the third corner, illustrating the differences in brake pedal position build-up, modulation, and consistency between the racing drivers and the non-racing drivers. The racing drivers reached the maximum brake position after 0.38 s (*SD* = 0.15 s), which is significantly faster ($t(15) = 6.71$, $p < 0.001$) than the non-racing drivers, who reached the maximum brake pedal position after 1.12 s (*SD* = 0.26 s). Furthermore, the racing drivers showed a more distinct peak in the brake pedal position, whereas the non-racing drivers showed more variability among the participants.

The vehicle paths for the racing drivers and the non-racing drivers for the second and third corner are shown in Fig 6. It can be seen that compared to the non-racing drivers, the racing drivers adopted a traditional racing line in each of the corners, by approaching the corner from the outside (i.e., the left side of the circuit in case of a right-hand corner). At the middle or apex of the corner, the racing drivers drove more to the inside of the corner inside, and when exiting the corner, they consistently used the outside portion of the circuit. Compared to the racing drivers, the non-racing drivers adhered more to the centerline of the road and adopted a racing line to a lesser extent.

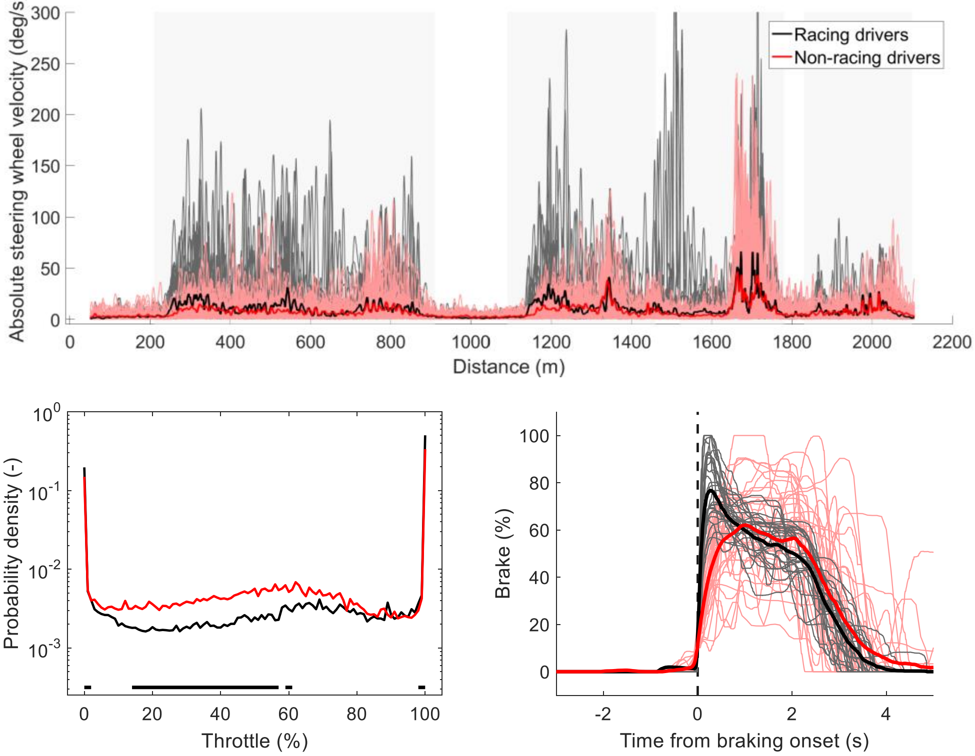

Fig 5. Top: absolute steering wheel velocity as a function of traveled distance of the fastest lap of each session (*N* = 28 for the racing drivers, *N* = 40 for the non-racing drivers). Individual lines are shown as well as the group means with a thick line type. Grey shaded areas indicate the four corners. Lower left: Probability density of the throttle position averaged across the fastest laps of each session, for the racing drivers and non-racing drivers. Significant differences ($p < 0.01$) are indicated by the black horizontal line at the bottom of the figure. Lower right: Brake position traces for the fastest lap of each session, for the racing drivers and non-racing drivers. A temporal shift was applied to the onset of braking (defined as brake position > 10). Individual participants' brake positions are shown, as well as the group means indicated by the thicker line. The vertical dashed line indicates the brake onset time, at t = 0 s.

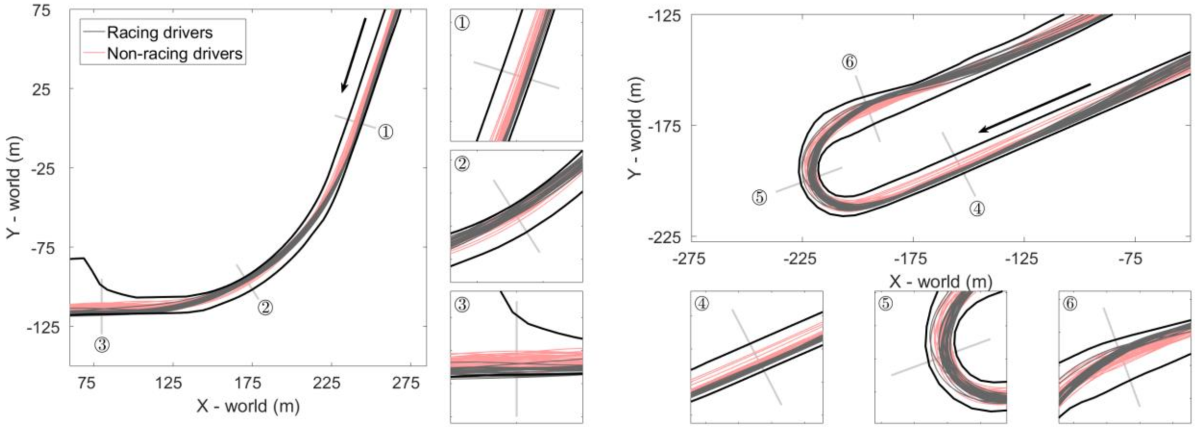

Fig 6. Individual paths of the vehicle center of the racing drivers (N = 28) and non-racing drivers (N = 40) for the fastest laps of each session for the second (left) and third (right) corner, the driving direction is indicated by the black arrow. The three panels indicate the start (1), middle (2), and the end of the corner (3) and correspond to an area of 40 by 40 m.

2.3.4 Eye and head movements

The individual and averaged gaze yaw angle, for both the racing drivers and the non-racing drivers, as a function of travelled distance per lap is illustrated in Fig 7. It can be seen that there were only small differences in the gaze yaw angle between the two groups. However, there were large differences in the head yaw angle for the racing drivers compared to the non-racing drivers (see also Table 1). The racing drivers turned their head nearly twice as much as the non-racing drivers while cornering.

This similar gaze yaw angle and difference in head yaw angle between the racing drivers and the non-racing drivers yields a difference in eye-to-head angle, which is illustrated in the lower pane of Fig 7. It can be seen that racing drivers showed slightly negative eye-in-head angles compared to the non-racing drivers, who predominantly have a near zero eye-to-head angle (except for the small corner radius corner at approximately 1700 m). In summary, the racing drivers steered their head more into the corners than the non-racing drivers.

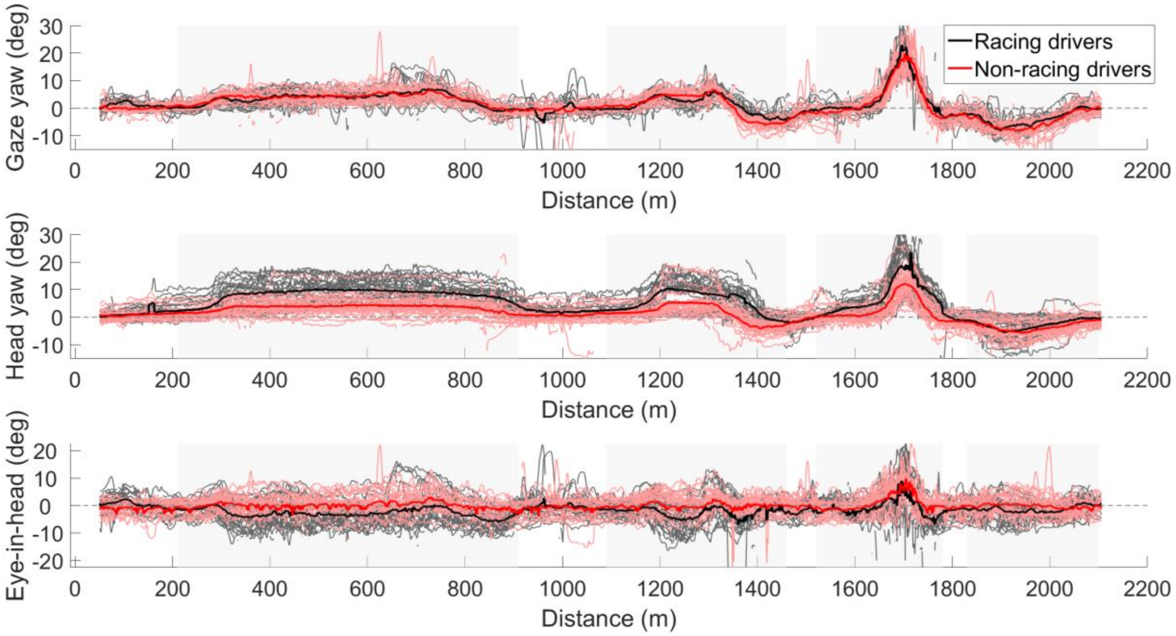

Fig 7. Gaze yaw angle (top), head yaw angle (middle), and eye-in-head angle (bottom) during the fastest overall lap of each session and racing drivers (*N* = 26) and non-racing drivers (*N* = 34). Individual lines are shown as well as the group means by the thick line. Positive values correspond to rotation to the right. The eye-in-head was determined as the difference between the gaze yaw angle and the head yaw angle and illustrates the orientation of the eye with respect to the head. Grey shaded areas indicate the four corners and a gray dashed line in the figures references to zero.

The tangent point analysis reveals a difference in gaze between the racing drivers and the non-racing drivers in the first corner. In Fig 8, the difference in the horizontal gaze angle and the angle between the vehicle and the tangent point is shown for both the racing drivers and the non-racing drivers. The figure shows that the racing drivers varied their gaze direction as a function of travelled distance, whereas the non-racing drivers kept a more constant gaze location, close to the vicinity of the tangent point. As the racing drivers entered the corner, they directed their gaze away from the tangent point towards the outside of the corner, and as they progressed through the corner they moved their gaze towards the tangent point and beyond the tangent point. As the racing drivers exited the corner, they directed their gaze again towards the outside of the corner and subsequently looked again towards the tangent point.

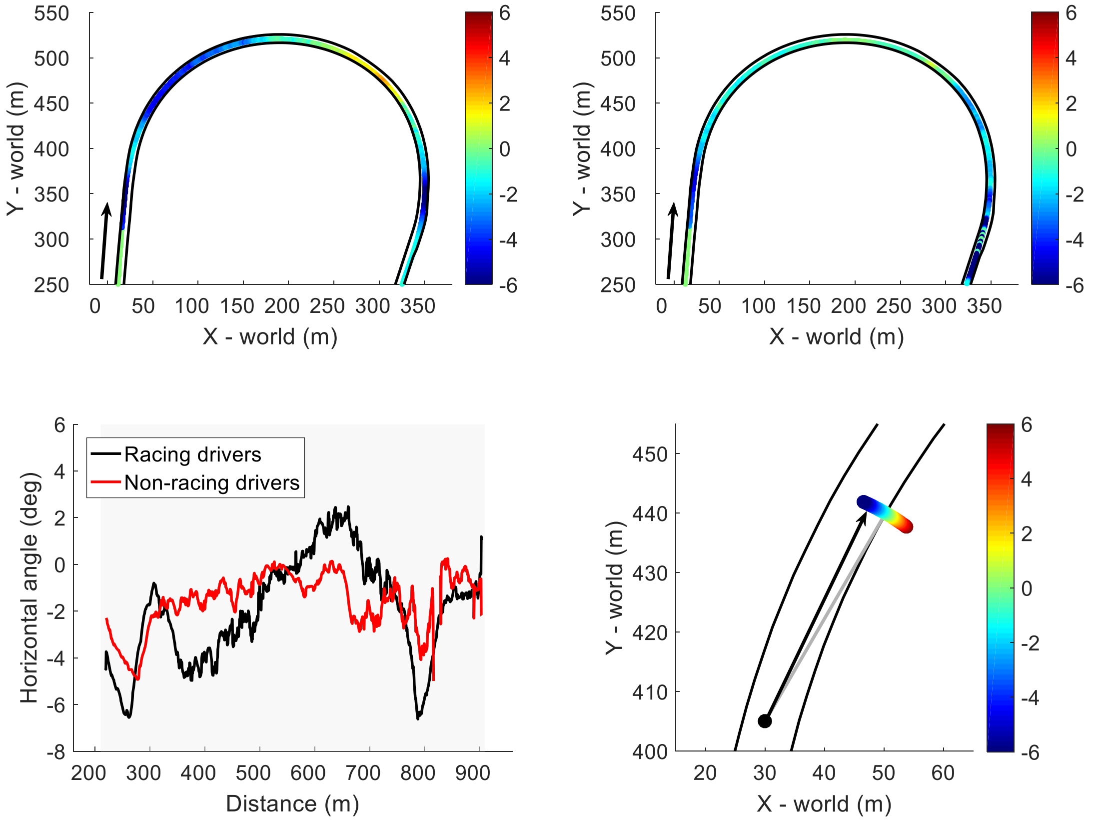

Fig 8. Difference between the horizontal gaze angle and the tangent point angle as a function of track position for the racing drivers (top left) and non-racing drivers (top right) averaged across all sessions and all laps. The black arrow indicates the driving direction. The lower left panel shows the horizontal gaze angle with respect to the tangent point, averaged across all sessions and fastest laps for the first corner for both the racing drivers and the non-racing drivers. The lower right panel shows a definition of the horizontal gaze angle, the tangent point, and the color scaling.

2.4 Discussion

In this paper, we studied the performance, control behavior, and visual behavior of seven young racing drivers in comparison with ten non-racing drivers when racing on a simulated circuit. We expected the racing drivers to perform better at racing-specific tasks (e.g., faster lap times) and based on Land and Tatler (2001) we expected the racing drivers to direct their gaze less at the tangent point while cornering.

Our results confirmed that the racing drivers drove faster lap times than the non-racing drivers. In fact, there was not a single non-racing driver who drove a personal best lap that was faster than the best lap of any of the racing drivers; in other words, there was no overlap in the overall performance of both groups. Both the racing drivers and non-racing drivers significantly improved their lap times from the first session to the last session, a finding which is similar to the performance of learner drivers in other driving simulator experiments (Van Leeuwen, Happee, & De Winter, 2015).

No significant differences were found in the non-domain specific choice reaction time task and tracking task. These results are consistent with the results of Bernardi et al. (2013) who found no differences in a reaction time task and visuospatial task between 11 racing drivers and 11 age-matched controls. These results are also in line with various team and individual sports, showing that experts do not differ in basic visual skills when compared to non-experts (Memmert et al., 2009).

Contrary to our expectation, the number of road departures did not differ between both groups from the second till the last session. This may be explained by both groups balancing their performance against the risk of having a road departure. The road departures of the racing drivers may be caused by leaving the circuit as a consequence of too much risk taking, without a loss of control. In case of the non-racing drivers, the road departures were more often a consequence of loss of control incidents, as indicated by the higher vehicle yaw rates due to the vehicle spinning.

Our results indicated a higher self-reported workload from the non-racing drivers as compared to the racing drivers, with the largest effects for the temporal demand and physical demand items. This latter finding may be explained by the physical effort required to operate the simulator. Compared to normal road cars, racing cars generate relatively high steering wheel and brake pedal forces (De Winter & De Groot, 2012), which pose physical demands that are comparable to physical demands experienced by normal athletes (Backman et al., 2005; Filho et al., 2015). In our experiment, however, the steering wheel force feedback and brake pedal stiffness were reduced to ensure that all participants were able to complete the experiment, as verified by the similar maximum brake pedal position achieved by the non-racing drivers and the racing drivers.

Because of their higher cornering speeds, the racing drivers drove closer to the physical limits than the non-racing drivers. Due to the nonlinear characteristics of racing tires (Milliken & Milliken, 1995), the vehicle could become unstable when driving close to the friction limits of the vehicle. To control the vehicle at higher cornering speeds, more steering corrections may be required (Braghin et al., 2008), which may explain why the racing drivers had higher steering activity than the non-racing drivers.

The racing drivers showed higher throttle variance during cornering and held the throttle at 0% and 100% for a larger fraction of time compared to the non-racing drivers. The racing drivers and the non-racing drivers reached comparable maximum brake pedal positions. However, compared to the non-racing drivers, the racing drivers achieved the maximum brake pedal position faster after the braking onset. These results can be explained from a time-optimality point of view: when the racing drivers decide to reduce their speed, they aim to achieve the maximum deceleration in a minimum amount of time by (1) swiftly releasing the throttle from 100% to 0%, by (2) pressing the brake pedal as fast as possible, and by (3) modulating the brake pedal position, to control the tires to their limit of adhesion to minimize the braking distance (Sharp, 2009). In the middle of the corner, the racing drivers keep 0% throttle to achieve the maximum lateral grip potential of the tires, see Milliken and Milliken (1995) for more details on the friction circle. From the middle to the exit of the corners, the racing drivers pressed the throttle slightly later, but reached full throttle earlier, aiming to reach maximum longitudinal acceleration out of the corners.

The racing drivers adopted a more traditional racing line compared to the non-racing drivers, a finding which can also be explained from a time-optimality point of view. The racing line is considered the fastest path around a circuit and is specific to each section of the circuit and the dynamics of the vehicle (Brayshaw & Harrison, 2005). Specifically, a racing line allows drivers to apply the brake pedal as late as possible and to maximize the acceleration potential of the vehicle coming out of the corners (Theodosis & Gerdes, 2011).

The racing drivers showed larger head rotations compared to the non-racing drivers while cornering. In other words, the racing drivers tended to turn their head more into the corner than did the non-racing drivers. These findings are consistent with Land and Tatler (2001) who found that a racing driver’s eye-in-head rotation remained within 5 degrees of the head axis. In our experiment, participants did not wear helmets. It is possible that racing drivers on real tracks adapt to the restricted field of view when viewing through a helmet. Gordon and Prince (1975) found up to a 22% reduction in horizontal field of view caused by full coverage helmets.

Our eye movement analysis showed a more variable gaze strategy for the racing drivers than for the non-racing drivers. The non-racing drivers adhered to a tangent point tracking strategy throughout the corner, whereas the racing drivers moved their gaze relative to the tangent point. These results are complementary to the results of a study on a real racetrack, which showed that a racing driver directed his gaze to the vicinity of the tangent point instead of at the tangent point (Land & Tatler, 2001). Contrary to models of visual control of steering (Land & Lee, 1994; Salvucci & Gray, 2004) in which reference points (e.g., the tangent point) are used to guide the steering input, our study shows that racing drivers vary their gaze while cornering, possibly to verify their path and to anticipate future control actions. Furthermore, the non-racing drivers may simply be looking at where they want to go (Wann & Swapp, 2000), whereas the racing drivers may be directing their eyes to task-relevant information (Gegenfurtner, Lehtinen, & Säljö, 2011).

The differences between the racing drivers and the non-racing drivers can be explained using the three-level behavioral taxonomy of Michon (1985). At the strategic level, the racing drivers risked having road departures against achieving the optimal racing line and high cornering speeds, whereas the non-racing drivers’ road departures were caused more often by an involuntary loss of control. At the tactical level, the racing drivers showed a different gaze strategy from that of the non-racing drivers, adjusting their gaze as they drove through the corner. Furthermore, the racing drivers chose different driving lines and optimized their driving lines to increase their corner exit speeds. At the operational level, the racing drivers operated the throttle pedal such that their corner exit speeds were optimized. Finally, a more time-optimal braking strategy and a higher steering activity differentiated the racing drivers from the non-racing drivers on the operational level.

In summary, our results illustrate better performance of all racing drivers when compared to non-racing drivers. However, no differences were found between the two groups in a generic motor control task or in a choice reaction-time task. Compared to non-racing drivers, the racing drivers selected tactical and operational control strategies that result in better performance (e.g., time-optimal braking, corner exit speed optimization) and adopted control strategies that allow the vehicle to operate closer to the friction limits. On the strategic level, the racing drivers balance their performance against the risk of road departures, whereas the non-racing drivers experienced road departures due to loss of control. Eye tracking results showed that racing drivers vary their gaze while negotiating a corner whereas non-racing drivers adhered more closely to a tangent point tracking strategy. Finally, the racing drivers showed greater head rotations while cornering. Our findings are consistent with the current consensus regarding expertise in sports; our expert racing drivers excelled in the task-specific aspects of race car driving but performed similarly to a non-expert sample in more generic motor and response task. Furthermore, our eye movement results indicate a difference in perceptual-cognitive skills between the racing drivers and the non-racing drivers, which is in line with the literature (Mann et al., 2007).

Our experiment was performed in a fixed-based racing simulator, and our results may benefit from higher fidelity motion-based simulator. For instance, drivers are known to use perceived lateral acceleration to determine their corner speed (Reymond, Kemeny, Droulez & Berthoz, 2001) and possibly, racing drivers differ with respect to non-racing drivers in terms of sensitivity to such motion cues. Furthermore, our non-racing driver sample was recruited from a technical university, and the generalizability of our results may benefit from a larger and more representative sample.

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Implications for driver assessment

This chapter examined the effect of driver expertise level on eye and head movements and steering behavior. The results showed substantial group differences even though all participants were given the same time-optimal driving task, that is, to drive as fast as possible. The presence of strong individual differences suggests that any driver-state assessment system should be person-specific, that is, calibrated with regards to the drivers´ level of skill.

Part II

Use of driving simulators for driver training

Chapter 3

Vertical field of view restriction in driver training: A simulator-based evaluation

Abstract

The young driver problem requires remedial measures against speeding and overconfidence. Previous research has shown that increasing the task difficulty during training can enhance subsequent retention performance and prevent overconfidence. In this driving simulator study, we evaluated the training effectiveness of vertical field of view restriction during a self-paced lane-keeping task. Sixty-two young, inexperienced drivers were divided into three groups: a near view (NV) group (upper part of the screen was blanked), a far view (FV) group (lower part of the screen was blanked), and a control group driving with full sight. All groups drove three training sessions lasting 8 min each on a curved rural road, followed by two retention sessions with full sight. The first retention session took place on the same rural road and the second session on a highway. Compared to the control group, the NV group drove with lower mean speed and had more road departures during training. Furthermore, NV drivers reported significantly lower confidence during the training sessions and the second retention session. NV drivers directed their eye gaze more closely to the vehicle during training and both retention sessions. FV drivers approached corners with lower speed compared to the control group during training and had a higher number of rapid steering wheel turns during training and both retention sessions. In conclusion, removing visual information resulted in lower reported self-confidence (NV) and altered steering behavior (FV) in retention sessions compared to driving with full sight. Furthermore, NV training caused drivers to direct their gaze closely to the vehicle during retention, which may be negative for road safety. Possible effects of simulator-based driver training on eye-scanning and safety are discussed.

Van Leeuwen, P. M., Happee, R., & De Winter, J. C. F. (2014). Vertical field of view restriction in driver training: A simulator-based evaluation. *Transportation research part F: traffic psychology and behaviour, 24*, 169–182 (adapted with minor changes).

3.1 Introduction

Worldwide, 1.2 million fatalities occur in traffic every year, and millions more individuals are injured (World Health Organization, 2009). Young drivers are vastly overrepresented, a public health concern also known as the young driver problem (Drummond, 1989; Organization for Economic Co-operation, 2006; Williams, 2006).

It is possible to classify the causes of the young driver problem using a three-level behavioral taxonomy developed by Michon (1985; see also Lee, 2007). At the strategic level, young drivers are overconfident in their own abilities and have an elevated acceptance to take risks and commit traffic violations (Brown & Groeger, 1988; Horswill, Waylen, & Tofield, 2004; Matthews & Moran, 1986). Loss of control due to speeding is a particularly frequent cause of accidents among young drivers (Laapotti & Keskinen, 1998; McGwin & Brown, 1999). At the tactical level, young drivers demonstrate inadequate hazard perception and inadequate 'calibration' of task demands with respect to their own abilities. The lowest level is the operational level, at which young drivers tend to have imperfectly learned skills for longitudinal and lateral vehicle control. Furthermore, young drivers tend to experience a high mental workload, particularly in environments that are new to them. There is growing consensus that driver training that focuses solely on the operational level (i.e., what the driver is able to do) is ineffective in reducing accident risk and that the higher levels (i.e., what the driver is willing to do) have to be targeted as well (Goode, Salmon, & Lenné, 2013; Hatakka, Keskinen, Gregersen, Glad, & Hernetkoski, 2002; Mayhew & Simpson, 2002).

For many decades, researchers have studied the effectiveness of training and enforcement methods, but the young driver problem has proven to be robust to interventions (Beanland, Goode, Salmon, & Lenné, 2013; Elvik, 2010). Based on a meta-analysis, Elvik and Vaa (2004) concluded that formal driver training is not an effective road-safety measure. Their analysis included 16 studies that compared formal driver training provided by driving schools with informal driver training, that is, self-training or training provided by family or friends. An analysis of the methodologically best studies (i.e., experiments that distributed participants randomly between formal and informal driver training) showed that formal driver training resulted in a 0% difference in the number of crashes per driver and 11% more accidents per kilometer driven compared to informal training. Elvik and Vaa (2004) also showed that the more lessons one had taken, the more the crash rate increased. Possible reasons for the lack of effectiveness may be that basic driver training increases self-confidence (Mayhew & Simpson, 2002) and normalizes risk-taking behavior.

Driving simulators are recognized as tools that may be effective for driver training and driver assessment, although much research still needs to be done in these areas (Beanland et al., 2013; Goode et al., 2013; Medeiros, Weinreb, Boer, & Rosen, 2012; Pollatsek, Vlakveld, Kappé, Pradhan, & Fisher, 2011). An advantage of using simulators for training relative to on-the-road training is the controllability of road infrastructure, weather, and traffic, as well as the fact that dangerous situations can be practiced without risk of collision. Such conditions open up possibilities for new types of driver training, such as learning from errors (Ivancic & Hesketh, 2000; Underwood, Crundall, & Chapman, 2011; Vlakveld, 2011) and exposing drivers to abstracted environments that depart from physical reality (Rizzo, Severson, Cremer, & Price, 2003).

Research in motor learning shows that by making the training task difficult—for example, by depriving the trainee of knowledge-of-results feedback—long-term retention and generalizability of skills can improve (Schmidt & Bjork, 1992). A driving-simulator study by Ivancic and Hesketh (2000) as well as a driving simulator study by De Groot, Centeno Ricote, and De Winter (2012) showed that by eliciting errors during training, performance in transfer-driving tests improved. Driving with reduced visibility, such as driving at night or driving in fog, reduces drivers' confidence and increases the perceived risk level (Saffarian, Happee, & De Winter, 2012; Stasson & Fishbein, 1990). Gregersen and Nyberg (2003) observed reduced accident rates in the first years of licensure for novice drivers who had completed a driver training course under dark driving conditions. Reduced visibility may cause drivers to become more vigilant, allowing them to react more accurately to hazardous events (Van der Hulst, Rothengatter, & Meijman, 1998). Additionally, emotional arousal promotes memory consolidation (Kleinsmith & Kaplan, 1963; McGaugh, 2000) and may therefore benefit driver training (Vlakveld, 2011).

Many studies have demonstrated the importance of visual information during driving (e.g., Mourant & Rockwell, 1972; Riemersma, 1979; Sivak, 1996; Wallis, Chatziastros, Tresilian, & Tomasevic, 2007). A number of studies have used visual occlusion (i.e., a technique whereby the driving scene is temporary occluded, typically by means of shutter glasses) to determine visual demand while driving (Backs, Lenneman, Wetzel, & Green, 2003; Senders, Kristofferson, Levison, Dietrich, & Ward, 1967; Van der Horst, 2004). Occlusion techniques have also been used to determine the effect of visual information on drivers' speed choice and curve driving performance (Cavallo, Bran-Dei, Laya, & Neboit, 1988; Godthelp, 1986; Hildreth, Beusmans, Boer, & Royden, 2000; Kondo & Ajimine, 1968; McLean & Hoffmann, 1973; Tsimhoni & Green, 1999).

Land and Horwood (1998) found that for low speeds (<12.5 m/s), a narrow horizontal visual aperture ranging from 7 to 8 deg below the horizon is sufficient for lateral vehicle control, as it yielded lane-keeping performance that is equivalent to the performance achieved with the whole scene visible. For higher speeds, Land and Horwood (1995) showed that with two narrow visible horizontal apertures displayed concurrently—one near the vehicle and one far from the vehicle—drivers achieved similar lane-keeping accuracy to that attained when driving with full sight. More recent studies (Chatziastros, Wallis, & Bülthoff, 1999; Cloete & Wallis, 2011; Neumann & Deml, 2011) with larger sample sizes and more sophisticated simulator technology have tried to replicate the experiments by Land and Horwood (1995). Using two narrow apertures placed 8.3 and 12.8 m in front of the vehicle, Neumann and Deml (2011) showed that steering precision was equivalent to that achieved under a condition with full sight, confirming the findings of Land and Horwood (1995). Cloete and Wallis (2011) did not find evidence of equivalent lane-keeping performance between driving with two narrow apertures and driving with full sight. The authors observed that lane-keeping accuracy was always substantially poorer when two narrow apertures were available compared to that under a control condition with full sight. These results suggest that drivers use more visual information (such as tangent points) than what can be perceived through only two narrow apertures and/or that the position of relevant visual features changes dynamically depending on road curvature and speed (Cloete &Wallis, 2011).

Eye-tracking studies (e.g., Gordon, 1966; Lappi, Lehtonen, Pekkanen, & Itkonen, 2013; Wilkie & Wann, 2003) have shown that drivers direct their visual attention to the near and far parts of the visual environment during straight-path driving and curve negotiation. Most researchers agree that the distant region is used by drivers to anticipate oncoming vehicles, obstacles, and road curvature (Lehtonen, Lappi, & Summala, 2012), whereas the near region of the road is used to estimate lateral position in the lane. This concept of preview vs. lateral position estimation is consistent with several models of driver steering behavior (Donges, 1978; Salvucci & Gray, 2004). These models distinguish between anticipatory open-loop control (steering actions based on curvature ahead) and compensatory closed-loop control (minimization of heading and lateral deviation errors with respect to the lane center); see Steen, Damveld, Happee, van Paassen, and Mulder (2011) for a review. Recently, Frissen and Mars (2014) used visual degradation of the near vs. far regions to investigate the robustness of these two visual processes. When the far visual region was blanked, lane-keeping accuracy was considerably worse and steering velocity considerably higher than with full vision, a finding that is consistent with the idea that lack of preview places increasing demands on compensatory control. Removing the visibility of the near region also resulted in deteriorated lane-keeping accuracy, but steering wheel velocity was virtually unaffected. Frissen and Mars (2014) concluded that these ‘‘observations add to Land and Horwood’s (1995) findings that an impairment of near vision allows smooth steering but yields large lateral position error’’ (p. 12).

In the present study, we evaluated a simulator-based training method that targeted young drivers’ risk awareness and speed choice by removing near or far visual road information using field of view (FOV) restriction. In the near view (NV) condition, the far part of the screen was blanked such that the driver could only see up to 5 deg below the horizon, corresponding to a distance of 8.5 m in front of the vehicle. Accordingly, the driver could correct lateral position errors but was unable to preview the curves farther ahead. Because of the lack of preview information, the driver would have to be continuously wary of upcoming curves that require braking. It was expected that the NV drivers would adopt a low speed to maintain acceptable task demands (cf. Fuller, 2005) and that the NV drivers would report lower levels of confidence and higher levels of risk compared to a control group driving with normal sight. We also evaluated a far view (FV) condition, achieved by blanking the bottom part of the screen up to 4 deg below the horizon, corresponding to 12.5 m ahead of the vehicle. This blanking was expected to make compensatory control difficult because the visual information about momentary lateral position error would be virtually absent. Training in the FV condition forces drivers to direct their gaze farther from the vehicle than they would when driving with full sight and may result in comparatively smooth steering wheel movements (cf., Frissen & Mars, 2014).

To summarize, in this study, three training groups were compared: NV and FV groups and a control (C) group driving with full sight. It was hypothesized that the NV group would drive with low speed and would report high risk and low confidence. Furthermore, it was hypothesized that the FV group would use smoother steering control compared to the C group. Finally, it was expected that these behaviors would be retained after training in retention sessions with full visibility.

3.2 Method

3.2.1 Participants

Sixty-two participants were recruited from the student community. Eligibility criteria were as follows: being in possession of driver's license, having limited driving experience (defined as having less than 3 years and less than 15,000 km of driving experience), and having normal or corrected-to-normal eyesight. Prior to the experiment, all participants completed an intake questionnaire with the following variables: (1) Number of half-years in possession of driver's license (1 to 6); (2) Total amount of driven kilometers (0–15,000, in steps of 3,000 km); (3) Experience with race/simulator games (never/sometimes/ occasionally/often); (4) Wearing glasses or lenses during the experiment (glasses/lenses/neither); (5) Experience in driving simulators (never/sometimes/occasionally/often); and (6) Experience with mopeds (never/sometimes/occasionally/ often). The mean age of the participants was 19.9 years (*SD* = 1.2). Of the 62 participants, 14 were female. Participants had their driver's license for 1.4 years on average (*SD* = 0.8) and reported an average total mileage of 4,065 km (*SD* = 3,207). Three participants reported more than occasional experience (two occasional, one often) with race/simulator games, six participants reported that they had sometimes driven in a simulator before, and one participant reported having driven in a simulator frequently. Thirty-two participants had no moped experience, and 19 participants had some-to-occasional experience with driving mopeds. Five participants wore their glasses, and 13 participants wore contact lenses. Using the results of the six questionnaire variables, participants were assigned to one of the three groups using the minimization method of Taves (1974). Twenty-one participants were included in the NV and FV groups and 20 in the control group. Participants received a compensation of ten euro and provided written informed consent. The research was approved by the Human Research Ethics Committee of the Delft University of Technology.

3.2.2 Apparatus

The simulator used for this study was a Green Dino driving simulator (classic model), which is also used for initial driver training in The Netherlands. This fixed-base simulator provided surround sound and a field of view spanning approximately 180 deg horizontally and 45 deg vertically. The vehicle dynamics represented those of a middle-class passenger vehicle. The seat, pedals, and steering wheel originated from a real car. Gear changing was automated; participants were only required to steer, accelerate, and brake. Steering force feedback was passive based on a spring system. Steering sensitivity was calibrated with respect to on-road vehicles (Katzourakis, De Winter, De Groot, & Happee, 2012). The virtual world was projected using three LCD projectors (front projector NEC VT676, brightness 2100 ANSI lumens, contrast ratio 400:1, resolution 1024 x

768 pixels; side projectors NEC VT470, brightness 2000 ANSI lumens, contrast ratio 400:1, resolution 800 x 600 pixels), and the dashboard, interior, and mirrors were integrated into the projected image. Head motion and gaze direction were measured with a SmartEye eye tracker (SmartEye, 2012, software version 5.6), which consisted of three Sony XC HR50 cameras (12- mm focal length, iris range: F1.4-closed) and two infrared illuminators. Two cameras were mounted above the steering wheel and below the virtual scenery, and the third camera was mounted behind the steering wheel, above the steering wheel center. The simulator model was updated at 100 Hz, and the visual update rate was 75 Hz. The screen frame rate was estimated to be a minimum of 30 Hz and was sufficiently high to guarantee a smooth visual projection. The driving simulator and eye tracker data were sampled and stored synchronously at 60 Hz.

3.2.3 Independent variable

The independent variable was the visual restriction. One group drove through the environment with full sight (control group). The second group (FV) drove the training sessions with the lower part of the screen blanked. No information was projected below a horizontal line 4 deg below the horizon, meaning that the driver could only see information that was farther than 12.5 m in front of the vehicle. The third group (NV) drove the training sessions with the upper part of the screen blanked. No information was projected above a horizontal line 5 deg below the horizon, and consequently, the driver could only see up to 8.5 m ahead. These thresholds were based on pilot testing with drivers that did not participate in the experiment, to ensure that it was possible to drive the vehicle in a reasonable manner. The 4-deg threshold in the FV condition gave participants sufficient sight to steer through the corners. Our chosen thresholds of 4 and 5 deg are in approximate agreement with the thresholds reported by Land and Horwood (1995) and Cloete and Wallis (2011), who both evaluated the effect of horizontal apertures ranging between 1 deg (extremely far) and 9 deg (extremely near) below the horizon. Our FOV restriction was independent of vehicle speed and blanked the visual scenery; the mirrors and car instruments remained always visible. For an illustration of the three conditions, see Fig. 1.

Fig. 1. Photos of the driving simulator; Top = control condition (C); Bottom left = near view (NV), all sight above 5 degrees below the horizon was blanked; Bottom right = far view (FV), all sight under 4 degrees below the horizon was blanked.

3.2.4 Procedure

First, participants completed the intake questionnaire and received a paper handout explaining the experimental procedure. After being seated in the simulator, the eye tracker was calibrated. Each participant drove three training sessions lasting 8 min each and two retention sessions lasting 8 and 6 min. Each session was followed by a break of no more than 5 min. During all breaks, the participants completed the NASA Task Load Index (TLX) questionnaire for measuring workload (Hart & Staveland, 1988) and a confidence questionnaire (De Groot, De Winter, López-García, Mulder, & Wieringa, 2011). After the three training sessions, participants completed the 8 min retention session, followed by the second retention session of 6 min in a different simulated driving environment. During the two retention sessions, the visual FOV restriction was disabled and participants drove with full sight. Table 1 provides an overview of the experimental sessions and the three groups.

Table 1. Experimental conditions during the training and retention sessions for the control, far view, and near view groups

	Rural environment (8 min sessions)				Highway environment (6 min session)
	Training 1	**Training 2**	**Training 3**	**Retention 1**	**Retention 2**
Control (C)	No restriction	No restriction	No restriction	No restriction	No restriction
Far view (FV)	Far visibility	Far visibility	Far visibility	No restriction	No restriction
Near view (NV)	Near visibility	Near visibility	Near visibility	No restriction	No restriction

3.2.5 Driving task

The three training sessions and the first retention session took place on a two-lane rural course 7.5 km length, with a 5-m lane width (De Groot et al., 2012). The course consisted of 25 curves: 22 90-deg corners, two smooth chicanes, and a 180-deg corner with a road-center radius of 40 m. Of the 22 90-deg corners, 14 corners (eight right corners and six left corners) had a road-center radius of 20 m or less. The course also included a tunnel and two hills with an elevation of 4 m. There was no other traffic, and no traffic signs were present in the virtual scenery, other than signs showing a 20-kph advised corner speed. The second retention session took place on a two-lane highway (3.6 m lane width) consisting of several slight bends and a 270-deg left curve with a 300-m radius. No other traffic and no traffic signs were present in the second retention session. All sessions commenced with the vehicle in the center of the right lane with zero speed, and participants started the session by turning the ignition key.

A paper handout explained that the experiment consisted of three training sessions followed by two testing sessions. It was further stated that the task was to keep the vehicle as accurately as possible in the center of the right lane, not to change lanes, drive safely, and follow Dutch traffic rules (Dutch traffic rules prescribe a speed limit of 80 kph on rural roads). Before starting the first training session, the driving task instructions were repeated in the simulator, with the following on-screen instructions (translated from Dutch): ‘‘Use only your right foot to operate the throttle and brake pedal; gear changes are automatic’’, ‘‘In case of a road departure, restart the car and continue driving’’, ‘‘Drive as accurately as possible in the center of the right line’’, and ‘‘Drive safely and according to Dutch traffic rules’’. Prior to the first training session, the NV and FV groups received the following additional instruction: ‘‘During the training sessions, part of your sight will be blanked. Before the first retention session, the NV and FV groups received the following instruction in the simulator: ‘‘In the following session, full sight will again be available’’.

3.2.6 Dependent measures

The following dependent measures were determined for each participant and each session. All measures (except for mean corner entry speed and standard deviation lane position) were calculated over the complete driven course including corners. The first 20 s of each session were regarded as lead-in and discarded from the analyses. The steering wheel angle was filtered using a 3-Hz low-pass filter before analysis.

3.2.6.1 Driving performance

Mean speed (m/s). The mean speed of the vehicle is a measure of driving style. Speed has been previously associated with crash involvement (Aarts & Van Schagen, 2006; Cooper, 1997; Elvik, Christensen, & Amundsen, 2004).

Mean corner entry speed (m/s). The corner entry speed was established at positions between 20 m before and 20 m after corner onset. A large reduction in speed before the corner may indicate that the driver anticipated the corner and was able to slow down before the start of the corner (cf., Comte & Jamson, 2000; Lee & Lishman, 1977). The measure was averaged across the first 12 sharp 90-deg corners (seven right-hand and five left-hand corners with a radius of 15 or 20 m).

Number of road departures. The number of times the vehicle crossed the lane boundaries with all edges of the vehicle represents the number of road departures. Road departures are usually the consequence of inadequate lane-keeping performance or high speed resulting in loss of control. After a road departure, the vehicle was reset in the center of the lane, and the participant was able to restart the vehicle using the ignition key. All data 10 s before and 20 s after a road departure were removed from the analysis of the other dependent measures.

Mean lane position (MLP) (m). The mean lateral position of the vehicle center represents the systematic deviation from the lane center (right = positive). Corner segments were excluded from this measure because smooth curve negotiation (e.g., corner cutting) could bias the MLP.

Standard deviation of lane position (SDLP) (m). The standard deviation of the lane position is a measure of lane-keeping precision, where a lower SDLP indicates less swerving on the road (e.g., Dijksterhuis, Brookhuis, & De Waard, 2011). SDLP was calculated by taking the standard deviation of the lateral position of the vehicle center and is thus insensitive to the mean lane position. Corner segments were excluded from this measure because smooth curve negotiation (e.g., corner cutting) results in lateral deviations biasing the SDLP.

3.2.6.2 Vehicle control

Steering reversal rate (SRR) (#/min). The SRR was defined as the number of clockwise to counterclockwise changes in steering wheel direction per minute. Only clockwise to counterclockwise reversals were counted if the counterclockwise steering velocity exceeded 3 deg/s (De Groot et al., 2011; He & McCarley, 2011; Theeuwes, Alferdinck, & Perel, 2002). Steering wheel reversal rate is a measure of control activity and correlates with other measures of control frequency (McLean & Hoffmann, 1975).

Rapid steering wheel turns (RSWT) (#/min). This measure was calculated as the number of instances per minute during which the steering wheel velocity exceeded 15 deg/s. RSWT may be indicative of driving in critical situations because drivers typically turn the steering wheel rapidly to avoid road departures (Johansson et al., 2004).

3.2.6.3 Gaze direction

Mean gaze pitch angle (deg). The mean vertical angle is the angle between the gaze vector and the horizon. A higher value indicates a larger angle down from the horizon. Data regarding gaze (including fixations and saccades) directed between the horizon and the dashboard were included, whereas data regarding gaze directed at the rear-view mirror and the dashboard dials were excluded. Eye fixations were determined via a dispersion-based method (Shic, Scassellati, & Chawarska, 2008) using a sliding window of 100 ms, a dispersion threshold of 2 deg, and a fixation duration threshold of at least 150 ms (Hornof & Halverson, 2002; Salvucci & Goldberg, 2000).

3.2.6.4 Subjective measures

NASA TLX (%). The NASA TLX is a subjective assessment of workload in the form a questionnaire (Hart & Staveland, 1988). The assessment is widely used in driving-behavior research (Hart, 2006) and includes the following six aspects of workload: mental demand, physical demand, temporal demand, performance, effort, and frustration. Scores were marked on a 21-tick horizontal bar with anchors on the left side (very low) and the right sides (very high). For the performance item, the anchors (perfect) and (failure) on the left and right side were used. A total score was calculated by averaging the six items and expressing the results on a scale from 0% (lowest rating on all items) to 100% (highest rating on all items).

Confidence questionnaire (%). The participant’s confidence was assessed using our confidence questionnaire, which contained the following three statements (translated from Dutch): (1) ‘‘I had a feeling of risk during driving’’, (2) ‘‘I think I drove safer compared to the average participant of this experiment’’, and (3) ‘‘I feel confident in my abilities to respond adequately’’. These items were inspired from previous questionnaires assessing drivers’ confidence (De Craen, 2010; De Groot et al., 2011; Ivancic & Hesketh, 2000; Wells, Tong, Genderton, Grayson, & Jones, 2008) and adapted to the present simulator- based lane-keeping task. Reactions to the statements could be given by marking a cross on a 21-tick horizontal bar identical to the bars used in the NASA TLX, with anchors on the left (strongly disagree) and right (strongly agree) sides. A total score was calculated by reversing the results from statement 1, averaging the three items, and expressing the results on a scale from 0% (lowest rating on all items) to 100% (highest rating on all items).

3.2.7 Statistical analyses

Loss of eye tracker data occurred due to the system’s inability to track relevant facial features, pupils, or corneal reflections. Loss of tracking can be caused by eye blinks, large head movements, or physical obstruction of the tracker cameras (e.g., by glasses). All eye tracker data captured 0.25 s before and after sequences of lost data were removed from the dataset. If more than 70% of eye tracker data were removed in a session, all eye tracker data were discarded for that particular session.

The results were statistically compared between the NV and C groups and between the FV and C groups, for each session, using an independent two-sample t test. Results between two sessions were compared using paired t tests. A result was declared statistically significant if $p < 0.05$ (or $p < 0.01$ in figures in which multiple tests were performed). Because the number of departures and the number of rapid steering wheel turns (RSWTs) had a skewed distribution (see also De Groot et al., 2012), these data were fractionally ranked (Conover & Iman, 1981) over all sessions and participants prior to conducting the statistical analyses.

3.3 Results

Two participants were excluded from the analysis. One participant from the NV group did not comply with the instructed driving task because he seemed to drive as fast as possible. The second participant (FV) was removed due to misinterpretation of the driving task and receiving additional instructions after the first driving session. Both excluded participants were removed from the Taves group assignment procedure as well and were replaced by two other participants. No participants ended the experiment due to simulator discomfort. Eye tracking data for 28 sessions were removed from the analysis; see Table 2 for further details about missing eye tracker data.

Table 2. Number of excluded eye tracker sessions and mean percentages of missing eye-tracker data across the included sessions (standards deviation across subjects in parentheses). *p* Values are shown for comparison between Control (C) versus Far View (FV) and Control versus Near View (NV)

		Excluded Sessions			Percentage of missing data			*p* value	
		Control	Far View	Near View	Control	Far View	Near View	C vs. FV	C vs. NV
	T1	1	1	2	25 (14)	26 (15)	36 (18)	0.958	0.086
Training	T2	2	2	1	27 (14)	24 (15)	33 (23)	0.608	0.353
	T3	2	2	2	32 (15)	28 (9)	31 (23)	0.416	0.972
Retention 1		3	2	3	32 (15)	29 (13)	34 (18)	0.631	0.729
Retention 2		2	1	2	28 (16)	30 (19)	22 (18)	0.763	0.236

3.3.1 Dependent measures

Table 3 presents the means and standard deviations of the dependent measures and includes the *p* values of comparisons between sessions and between groups.

Table 3. Results for the three training sessions and the two retention sessions. For each group the table shows mean values (standard deviations in parentheses) and *p* values for group comparisons between Far View (FV) and Control (C) and for Near View (NV) and C. *p* Values for session comparisons are indicated for the first versus last training session and the last training session versus first retention session

	Training			Retention		*p* value	
	T1	T2	T3	R1	R2	Training T1 vs. T3	Retention T3 vs. R1
Mean speed (m/s)							
FV	16.4 (1.5)	16.3 (1.5)	16.2 (1.8)	16.9 (2.1)	32.3 (2.4)	0.929	**0.018**
NV	15.1 (1.9)	14.0 (2.0)	13.7 (1.6)	16.6 (2.2)	30.9 (3.7)	**0.002**	**<0.001**
C	17.1 (1.7)	17.1 (1.7)	17.2 (1.8)	17.3 (1.8)	31.7 (2.2)	0.166	0.798
p value FV vs. C	0.147	0.115	0.098	0.606	0.449	-	-
p value NV vs. C	**<0.001**	**<0.001**	**<0.001**	0.382	0.413	-	-
Mean corner entry speed (m/s)							
FV	12.4 (1.5)	11.6 (1.3)	11.2 (1.3)	11.8 (1.4)	-	**0.007**	0.125
NV	13.8 (1.9)	13.6 (1.6)	13.3 (1.4)	12.2 (1.6)	-	0.122	0.064
C	12.4 (1.7)	12.3 (1.3)	12.3(1.2)	12.1 (1.5)	-	0.932	0.454
p value FV vs. C	0.930	0.135	**0.016**	0.755	-	-	-
p value NV vs. C	**0.015**	**0.006**	**0.021**	0.762	-	-	-
Road departures (#)							
FV	1.6 (2.4)	1.7 (2.7)	1.5 (2.6)	0.8 (1.3)	0.0 (0.0)	0.796	0.256
NV	13.9 (8.4)	9.2 (9.7)	6.4 (5.9)	0.7 (1.6)	0.0 (0.0)	0.087	**0.017**
C	1.8 (3.2)	0.5 (1.2)	0.4 (1.3)	0.3 (1.0)	0.0 (0.0)	0.159	0.079
p value FV vs. C	0.811	0.105	0.103	0.364	-	-	-
p value NV vs. C	**<0.001**	**<0.001**	**<0.001**	0.722	-	-	-
MLP straights (m)							
FV	-0.06 (0.27)	-0.09 (0.27)	-0.07 (0.17)	-0.12 (0.15)	0.18 (0.17)	0.876	0.441
NV	0.13 (0.23)	0.09 (0.27)	0.02 (0.26)	-0.16 (0.28)	0.20 (0.18)	**0.004**	**<0.001**
C	-0.06 (0.23)	-0.12 (0.25)	-0.12 (0.26)	-0.16 (0.22)	0.22 (0.23)	0.115	0.514
p value FV vs. C	0.924	0.678	0.465	0.546	0.579	-	-
p value NV vs. C	**0.015**	**0.011**	0.079	0.980	0.774	-	-
SDLP straights (m)							
FV	0.72 (0.21)	0.58 (0.14)	0.48 (0.13)	0.38 (0.11)	0.42 (0.08)	**<0.001**	**0.003**
NV	0.53 (0.16)	0.48 (0.13)	0.49 (0.16)	0.37 (0.13)	0.40 (0.11)	0.914	**0.002**
C	0.37 (0.12)	0.38 (0.14)	0.35 (0.12)	0.34 (0.11)	0.39 (0.11)	0.342	0.926
p value FV vs. C	**<0.001**	**<0.001**	**0.002**	0.285	0.280	-	-
p value NV vs. C	**0.003**	**0.046**	**0.004**	0.573	0.665	-	-
Steering reversal rate (#/min)							
FV	39.6 (3.8)	36.2 (3.8)	34.9 (4.6)	42.3 (3.4)	55.4 (4.5)	**<0.001**	**<0.001**
NV	42.0 (6.9)	39.5 (6.8)	39.6 (9.6)	41.8 (3.5)	55.0 (5.0)	0.137	0.177
C	43.0 (3.7)	40.3 (3.8)	39.3 (3.6)	39.7 (3.8)	53.9 (5.4)	**<0.001**	0.842
p value FV vs. C	**0.008**	**0.002**	**0.003**	**0.044**	0.343	-	-
p value NV vs. C	0.604	0.632	0.885	0.111	0.522	-	-
Rapid steer wheel turns (#/min)							
FV	36.5 (10.6)	29.5 (7.2)	27.5 (6.9)	26.3 (6.6)	3.42 (2.2)	**<0.001**	0.065
NV	35.3 (12.6)	27.6 (11.5)	28.6 (16.5)	25.5 (8.9)	2.85 (2.9)	**0.024**	0.541
C	30.6 (9.1)	22.0 (6.1)	22.1 (6.4)	22.6 (7.1)	3.19 (6.1)	**<0.001**	0.319
p value FV vs. C	**0.042**	**0.001**	**0.005**	**0.037**	**0.047**	-	-
p value NV vs. C	0.127	0.070	0.141	0.180	0.615	-	-
Mean gaze pitch angle (deg)							
FV	3.50 (1.2)	3.54 (1.3)	3.42 (1.4)	4.44 (1.8)	3.59 (2.1)	0.515	**0.001**
NV	7.89 (1.9)	7.47 (1.4)	7.72 (1.6)	4.70 (1.5)	4.05 (1.7)	0.714	**<0.001**
C	4.19 (1.2)	4.39 (1.4)	4.08 (1.5)	3.68 (1.2)	2.87 (1.0)	0.169	0.163
p value FV vs. C	0.079	0.065	0.164	0.137	0.188	-	-
p value NV vs. C	**<0.001**	**<0.001**	**<0.001**	**0.039**	**0.016**	-	-

Note: The sample sizes for the FV, NV, and C groups were 21, 21, and 20, respectively. For the eye-tracking data, the number of excluded sessions are reported in Table 2.

3.3.1.1 Driving performance

Mean speed. NV drivers drove significantly slower than the C drivers in all training sessions and reduced their mean speed from Training 1 to Training 3. The three groups drove with similar mean speeds in both retention sessions. Both FV and NV drivers increased their mean speed after training.

Mean corner entry speed. NV drivers drove significantly faster into the corners than drivers in the C group. FV drivers significantly reduced their corner entry speed during training and drove significantly more slowly into the corners than drivers in the C group during the last training session.

Number of road departures. NV drivers showed significantly more road departures than drivers in the C group and a significant reduction in road departures between Training 3 and Retention 1. There was no significant difference in road departures between the FV and C groups in any of the training and retention sessions. During the highway retention drive, no road departures occurred for any of the three groups.

Lane-keeping performance (SDLP). Significant differences were found in the training sessions between drivers in the C and FV groups and between drivers in the C and NV groups, with those in the C group exhibiting the best lane-keeping performance of the three groups. Both the NV and FV groups improved significantly from training to the first retention.

Mean lane position (MLP). The NV group drove closer to the right of the lane compared to the C group (significant in the first and second training sessions). The NV group drove significantly closer to the center of the lane in the third training session than in the first training session. No significant differences were found between the NV and C groups in the first and second retention sessions. No differences were found between the FV and C groups with respect to the MLP measure.

3.3.1.2 Vehicle control

Steering reversal rate (SRR). The FV group showed a significantly lower steering reversal rate than the C group during training but a significantly higher steering reversal rate during the first retention session. Both the FV and C groups showed a reduction in steering activity from Training 1 to Training 3, whereas the steering activity of the NV group remained at approximately the same level across the three training sessions.

Rapid steering wheel turns (RSWTs). The FV group showed significantly more RSWTs compared to the C group in all five sessions. The number of RSWTs decreased among all groups from Training 1 to Training 3.

Fig. 2 (left) shows the steering wheel angular position for the NV and FV groups during all three training sessions for a typical right-hand corner. The NV group steered into the corner later and more abruptly compared to the C group. The FV group can be observed to have steered earlier into the corner and turned less after the initial steering movement compared to the C group, resulting in a wider vehicle path, as shown in Fig. 2 (right).

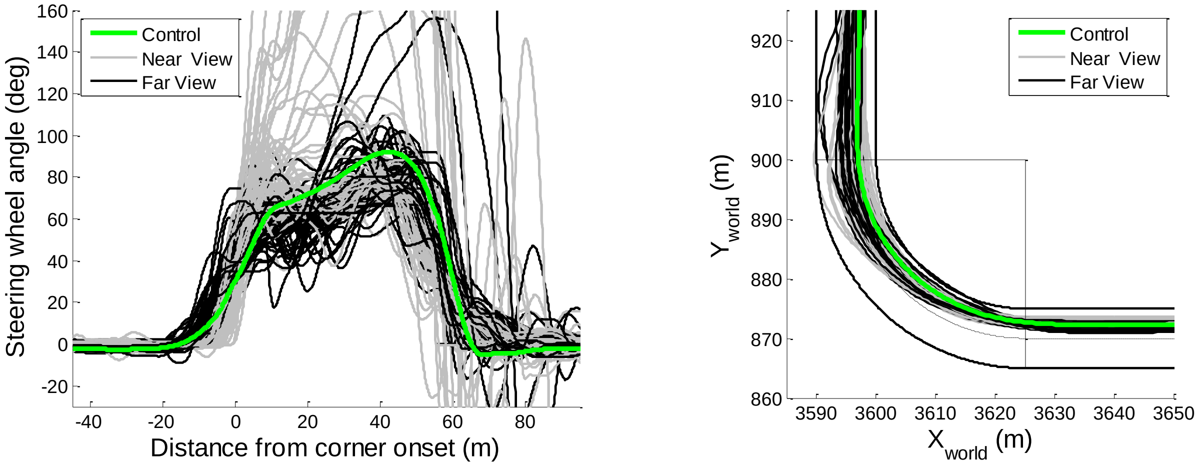

Fig. 2. Left: Individual steering wheel angle for the near view (*n* = 52) and far view (*n* = 60) groups during a typical 30 m road-center radius right-hand corner for all three training sessions. The green line indicates the mean steering wheel angle of the control group (*n* = 59), averaged across Training 1 to 3. Right: Individual paths of the center of the car of the near view (*n* = 52) and far view (*n* = 60) groups during a typical 30 m road-center radius right-hand corner for all three training sessions. The green line indicates the mean path of the control group (*n* = 59), averaged across Training 1 to 3. Road departures were removed from the figure for clarity. The participants approached the corner from the right of the figure.

Fig. 3 (left) shows the probability density function of the steering wheel speed for the three groups cornering in the training sessions. The NV group showed significantly fewer lower-speed (<135 deg/s) steering wheel movements and significantly more high-speed (>270 deg/s) wheel movements compared to the C group. The higher steering wheel speeds of the NV group represent abrupt steering movements when entering corners and the corrective steering movements performed to prevent road departures (cf. Fig. 2 left). The FV group showed significantly more steering movements at speeds between 26 and 38 deg/s compared to the C grouping the corner segments. On the straight road segments (right figure), the NV group showed significantly more movements at lower speeds (10–18 deg/s) and fewer at higher speeds (>35 deg/ s) compared to the C group. This finding suggests that the NV group was more inclined to make small corrective steering movements on the straight road segments than the C group.

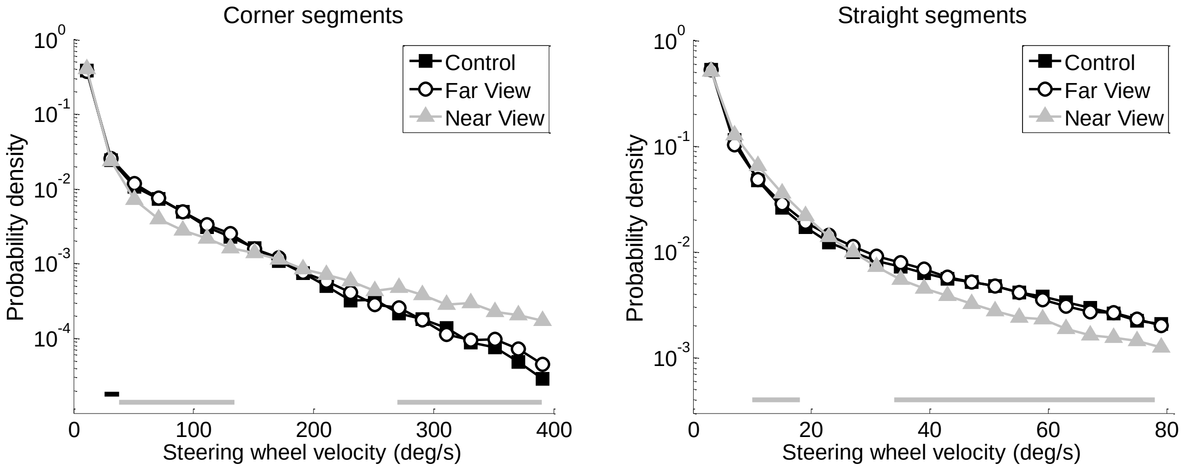

Fig. 3. Probability density function of steering wheel speed during corners (left) and straight road segments (right) for Training 1 to 3 combined. The distribution was determined by aggregating the steering wheel speeds of all participants into 4 deg/s bins. Significant differences ($p < 0.01$) between far view and control are indicated by black horizontal lines. Significant differences ($p < 0.01$) between near view and control are indicated by grey horizontal lines.

3.3.1.3 Gaze direction

The effect of the FOV restriction during training on the participants' vertical gaze distribution is shown in Fig. 4. Participants from the FV and NV groups directed their gaze above and below the FOV restriction border, respectively. The FV group directed their gaze between the FOV restriction border and the horizon, whereas the NV group directed their gaze close to the FOV restriction border, presumably in an attempt to maximize their preview distance. The NV group gazed significantly closer to the vehicle in both retention sessions compared to the C group. Fig. 5 illustrates fixations for three representative participants from each group in the second retention session. The figure illustrates that the selected NV participant fixated more closely to the vehicle than the other two participants.

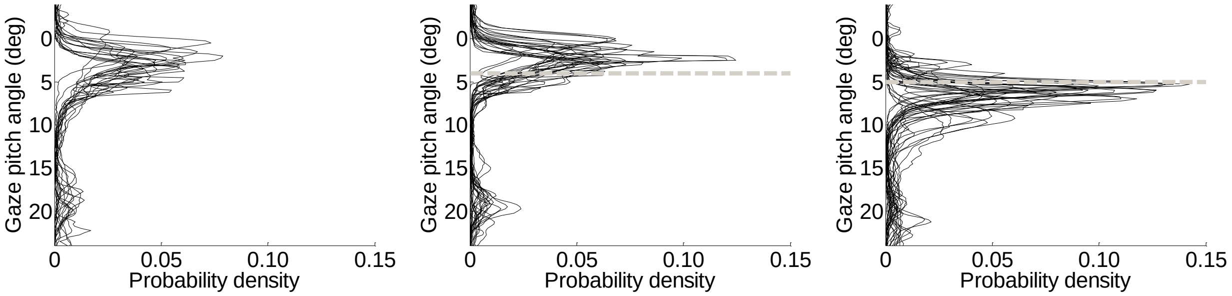

Fig. 4. Vertical gaze pitch distributions for all groups in the third training session. Control (C; left, N=18), far view (FV; centre, N=19), and near view (NV; right, N=19). The distribution is derived over 0.25 deg bins. The grey dashed horizontal lines represent the restriction borders. Each black line represents one subject. Note that the speedometer is located at 18 degrees.

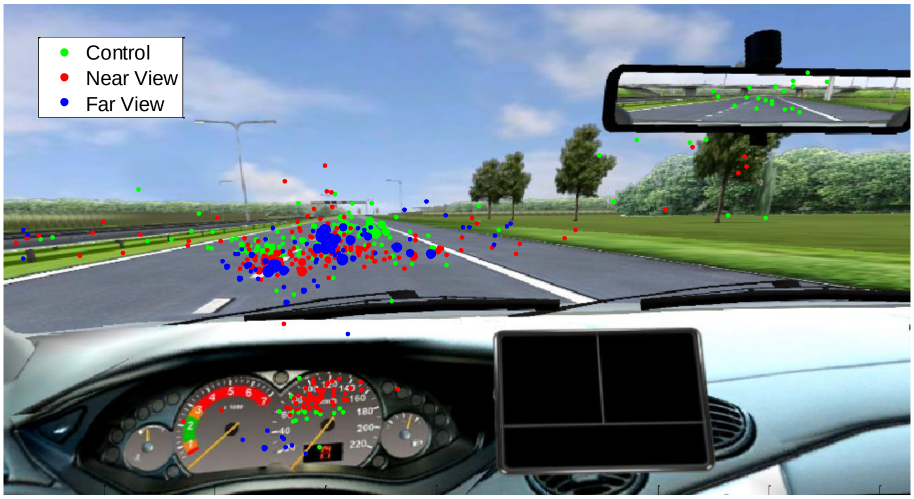

Fig. 5. Fixation distribution during the second retention session for one participant from the control group (C), one participant from the near view group (NV), and one participant from the far view (FV) group. Their mean gaze pitch angles were 2.9, 3.9, and 3.5 degrees respectively. Fixation duration is indicated by the circle radius (the radius in the legend corresponds to approximately 3.5 seconds). Fixations during cornering were omitted from the figure.

3.3.1.4 Subjective measures

NASA TLX. Fig. 6 (left) shows the means for all TLX items as a function of session and group. A significantly higher workload was reported by the NV group for each of the three training sessions ($t(39) = 4.04$, $p < 0.001$, $t(39) = 3.02$, $p = 0.005$, and $t(39) = 4.60$, $p < 0.001$ for session 1, 2, and 3, respectively). Additional analysis showed that these effects were most pronounced for the physical demand, effort, and frustration scales. Both the NV and FV group reported significantly reduced workload from Training 1 to Training 3 ($t(20) = 3.51$, $p = 0.002$ and $t(20) = 3.10$, $p = 0.006$ for NV and FV, respectively). The workload for the NV group significantly decreased ($t(20) = 7.24$, $p < 0.001$) from Training 3 to the first retention session. No differences between groups were observed in the retention sessions with respect to the workload measure.

Confidence questionnaire. Fig. 6 (right) shows lower confidence levels for the NV group than for the C group during all training sessions ($t(39) = 4.18$, $p < 0.001$, $t(39) = 2.82$, $p = 0.008$, and $t(39) = 3.80$, $p < 0.001$ for Training sessions 1, 2, and 3, respectively). Significantly higher levels of self-reported risk ($t(39) = 2.25$, $p = 0.028$) and lower levels of safety ($t(39) = 2.09$, $p = 0.049$) and confidence ($t(39) = 2.52$, $p = 0.016$) were reported in the second retention session by the NV group compared to the levels reported by the C group. There were no significant differences between the C and FV groups with respect to the total confidence score. All three groups showed an increase in confidence from Training 1 to 3 ($t(20) = 3.23$, $p = 0.004$, $t(20) = 2.99$, $p = 0.008$, and $t(19) = 2.60$, $p = 0.017$ for FV, NV, and C, respectively).

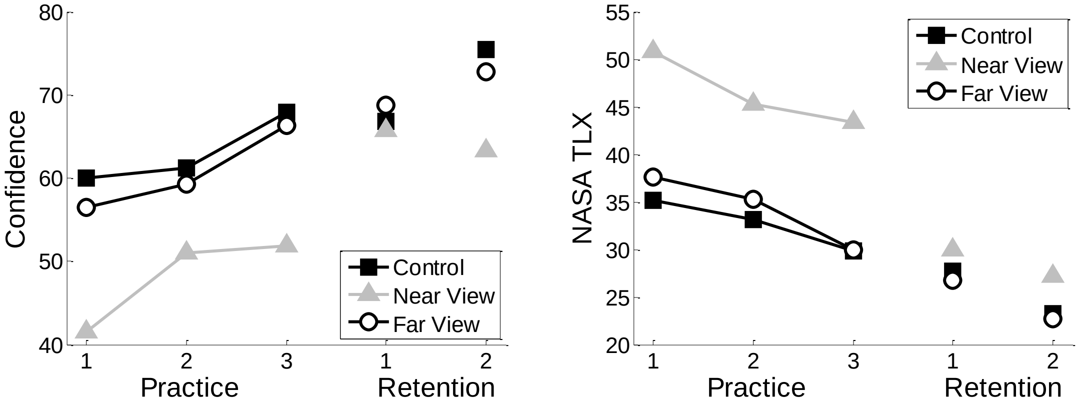

Fig. 6. Self-reported workload (NASA TLX; left) and self-reported confidence (right) for the training and retention sessions (mean over subjects).

3.3.2 Corner entry analysis

Fig. 7 shows the mean corner entry speed for the 90-deg corners in the case of no road departures (left figure) and road departures (right figure). The corner starts at 0 m and -20 and -10 m indicate 20 and 10 m before the start of the corner, respectively. The NV group drove more slowly 20 m before the corners compared to the FV and C groups when no road departures occurred and drove faster 20 m before the corners when road departures did occur. In both cases, the NV group took the corners at higher speeds than the FV and C groups did. The speed pattern through the curve was roughly similar between the FV and C groups. However, the FV group approached the corners significantly more slowly than the C group in Training 3 (see also Table 2). During Retention 1, there were no significant differences in corner entry speeds between the three groups.

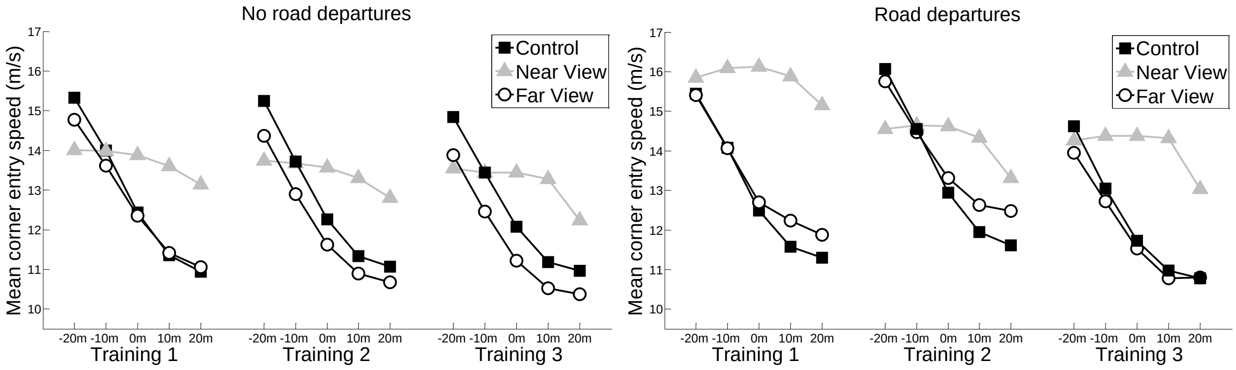

Fig. 7. Mean corner entry speed from 20 meter before corner onset (-20) to 20 meter after corner onset (+20), for corners without (left) and with road departures (right).

3.4 Discussion

This study investigated a simulator-based training method targeting speed choice and risk awareness. We hypothesized that by removing visual information during training, participants would drive with lower speed and report lower levels of confidence than a control group driving with full sight in both the training and retention sessions.

Consistent with our hypotheses, the NV group drove with significantly lower speed and had more road departures and poorer lane-keeping performance than the C group. Most of these training effects did not transfer to post-training retention sessions, with the driving performance of the NV and C groups being statistically indistinguishable in this phase. The confidence was retained, however: NV reported the lowest confidence during training, and this low confidence was still detected in the second retention session in a highway environment.

The mean speeds of the FV and C groups were similar during both training and retention sessions. However, during training, the FV group approached and negotiated the corners at a lower speed and started steering into the corners earlier than the C group. Training with far view required the participants to control the vehicle with information from far ahead. However, compensatory control was more difficult for the FV group and consequently resulted in impaired lane-keeping precision compared to the C group during training. This difficulty in exerting compensatory control may have caused drivers in the FV group to be more cautious when approaching and negotiating corners.

Generally, the FV and NV groups' training did not result in improved driving performance or driving behavior in the retention sessions compared to training with full sight. This result demonstrates the ineffectiveness of the visual FOV restriction training method compared to the self-training of the C group drivers. The restriction of visual information possibly causes trainees to over-rely on one region of the visual field, resulting in sub-optimal performance in the retention sessions. Previous research has demonstrated the ineffectiveness of basic driver training compared to self-training or informal training (Beanland et al., 2013; Lund, Williams, & Zador, 1986; Vernick et al., 1999). Driver training may promote overconfidence in one's own skills (Lee, 2007; Mayhew & Simpson, 2002), which suggests that reducing self-confidence can be beneficial in reducing the crash risk for newly trained drivers. Training with near visibility reduced the overall confidence level and increased workload during training. One cause of the reduced confidence of the NV group may be the large number of road departures. The NV group, unable to anticipate oncoming corners, approached corners faster and braked later, resulting in more road departures than the other two groups. Ivancic and Hesketh (2000) previously showed that making errors during training is an effective learning strategy for reducing confidence during simulator-based training. Second, the inability to see information far ahead may be a cause of the observed low confidence and increased perception of risk, similar to driving in fog (Saffarian et al., 2012; Stanton & Pinto, 2000).

The visual behavior of the NV group transferred to the retention sessions. In both retention sessions, NV drivers directed their gaze more closely to the vehicle compared to drivers in the C group. It is known that inexperienced drivers fixate more closely to the vehicle (Falkmer & Gregersen, 2005; Mourant & Rockwell, 1972) and have poorer anticipation of future events compared to experienced drivers. This study showed that removing visual information during training can have post-training effects on visual behavior with respect to a control group, a finding that must be applied cautiously. Training drivers to reallocate their visual attention during a lane-keeping task may reduce their attention to other vital visual tasks. Driving consists of many combined visual tasks, and looking close ahead reduces attention to information further ahead, potentially reducing the time to anticipate future events; this behavior may cause drivers to fail to respond to hazards farther down the road (e.g., corners, traffic).

During training, FV drivers controlled the vehicle with a lower steering reversal rate compared to C drivers and showed more (jerky) rapid steering movements. The latter finding may have been caused by the lack of immediate lateral position information: FV trainees made rapid corrections when the lateral error was perceived as too large but had no visual incentive to correct minor errors. The higher number of rapid steering wheel turns was retained in both retention sessions, which is in line with our earlier research showing that steering behavior is more easily retained than observable metrics of driving performance such as lane-keeping accuracy or mean speed (De Groot et al., 2011; Van Leeuwen, De Groot, Happee, & De Winter, 2011). Previous research in motor learning concurs that subjects tend to repeat previously learned error-correcting behavior (Schmidt, 1991).

The NV group had steering reversal rates comparable to those of the C group during the training sessions, but showed more high-speed steering movements during cornering and greater active steering control on the straight road segments compared to the C group. These findings are consistent with those of Frissen and Mars (2014), who found higher steering activity when driving with blanked far sight compared to driving with full sight during a forced-paced condition in which speed was constant. In our self-paced experiment, NV drivers' mean speed was found to be significantly correlated with the steering reversal rate ($r = .56$, $p < 0.001$, $n = 63$). In other words, the speed of the drivers was an important factor in explaining the drivers' steering activity. In the training sessions, the NV drivers adopted lower speeds than those observed for the C drivers, most likely as a compensatory strategy to maintain acceptable performance while driving with the impoverished visual scene. However, the lane-keeping performance and number of road departures of the NV group were still substantially worse than those of the control group driving with full sight. Furthermore, the NV group reported higher levels of risk and workload compared to the C and FV groups during training. Presumably, the NV group insufficiently regulated their speed and consequently their time to react to oncoming curvature. These findings are not in agreement with the task difficulty homeostasis and risk homeostasis theories (Fuller, 2005; Wilde, 1982), which predict that perceived task difficulty and perceived risk, respectively, are used as normalizing mechanisms while driving. In other words, although drivers compensated for the reduced visual information by slowing down, they did not compensate sufficiently to maintain their nominal lane-keeping accuracy.

To summarize, there are clear differences between the steering behavior of the NV and the FV groups. These differences appear to be consistent with two-level models of steering, which state that far visual information is used for smooth steering control and near visual information is used for lateral error correction (e.g., Salvucci & Gray, 2004). NV drivers showed active steering behavior (Fig. 3 right) with similar SRR and RSWTs as C drivers but were unable to keep the vehicle as precisely in the center of the lane as C drivers. The sharp corners were particularly problematic for the NV group. The lack of preview prevented the trainees from anticipating upcoming corners, resulting in high corner entry speeds, abrupt and high-speed steering corrections (Fig. 3 left), and many road departures. Drivers in the NV group drove with a lower mean speed than drivers in the C group and thereby moderated their own steering demands. Similarly to the NV group, the FV group also showed deficient lane-keeping precision. However, in contrast to the NV group (which showed active steering behavior), the FV group had a relatively low steering reversal rate. The low reversal rate can be explained by the fact that the FV drivers had no visual incentive to correct minor lane center errors. Furthermore, the FV group entered the corners more carefully and steered earlier into these corners compared to the C group, consistent with a preview strategy.

This study consisted of three sessions with 24 min of practice per participant, whereas driving skill and driving style are usually developed over years of driving experience (Mayhew, Simpson, & Pak, 2003; Pradhan et al., 2005). Transfer of training was assessed in a new simulated environment but in the same simulator, in the same virtual vehicle, and with the same driving task instruction to keep the vehicle centered in the right lane. Groeger and Banks (2007) argued that for driver training to be effective, skills learned during driver training will have to transfer positively under new and more demanding traffic circumstances. Groeger and Banks further argued that transfer needs to occur along several dimensions (knowledge domain, physical context, temporal context, functional context, modality, and state/task/situation demand). For future work, it is recommended to investigate longer training periods, long-term retention, and far transfer effects of FOV restriction on a driving task. Driving simulators are known to be able to provide metrics that are predictive of real-world driving (e.g., Lee, Cameron, & Lee, 2003). However, several relevant perceptual cues (e.g., sustained g forces, tactile road rumble, photorealism) and environmental aspects (e.g., other cars) were not provided in our driving simulator experiment. More research regarding the transfer of learning from simulated tasks to real vehicle tasks is therefore recommended. Another limitation is that our study was conducted with participants recruited from a technical university. Engineering students tend to have above-average intelligence (Wai, Lubinski, & Benbow, 2009), and intelligence is known to be predictive of driving safety (Whitley et al., 2010). Furthermore, engineering students tend to be specifically interested in (simulator) technology. Hence, the present results may not be readily generalized to the entire population of young drivers.

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Implications for use of driving simulators for driver training

This chapter investigated the effect of removing visual information aimed at improving novice driver´s speed choice and risk awareness. The result illustrate that the removal of visual information altered driver´s eye-movements, steering control, and speed choice. However, retention of the learned skills was low, pointing to limited training effectiveness.

Chapter 4

Effects of concurrent continuous visual feedback on learning the lane keeping task

Abstract

This study investigated the training effectiveness of continuous visual feedback in a simulator-based lane keeping task. Two groups of student drivers (total of 30 participants) were instructed to drive as accurately as possible in the center of the right lane in a self-paced driving task during five 8-min sessions. One group received visual feedback using a horizontal compensatory display positioned on the dashboard, which provided an indication of the momentary distance to the lane center during the three training sessions. During two retention sessions (immediate and one day delayed) both groups drove without the augmented feedback. The augmented feedback resulted in improved performance on a measure lane keeping accuracy, but this effect disappeared during retention. Furthermore, the augmented feedback resulted in increased steering wheel activity during all sessions, and increased driver workload in the delayed retention session. These results provide support for the guidance hypothesis and have possible implications for the use of continuous concurrent feedback in simulator-based driver training.

Van Leeuwen, P. M., De Groot, S, Happee, R, & De Winter, J. C. F. (2011). Effects of concurrent continuous visual feedback on learning the lane keeping task. *Proceedings of the 6th International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, Lake Tahoe, CA, 482–488.

4.1 Introduction

Nowadays, driving simulators are increasingly used in driver training programs (Allen, Park, Cook, & Fiorentino, 2009; De Winter, De Groot, Mulder, Wieringa, Dankelman, & Mulder, 2009). Driving simulators offer important advantages compared to on-the-road training, such as control and repeatability of training conditions, objective performance assessment, and guaranteed safety in difficult driving situations. Furthermore, with simulators it is possible to enhance the task intrinsic information by means of visual, auditory, or tactile augmented feedback.

Augmented feedback is information provided in addition to the task-intrinsic feedback and can be used to guide the learner to higher task performance during the training phase of skill acquisition. Augmented feedback can help to speed up the learning process, but is also known to lead to potential degradation of task performance when the augmented feedback is withdrawn in post-training retention tests (Schmidt & Wulf, 1997). This phenomenon is described by the guidance hypothesis (Salmoni, Schmidt, & Walter, 1984). Too much guidance can result in learners not developing the information processing activity required to perform the task without augmented feedback, and to a development of over-corrective behavior (Young, Schmidt, & Lee, 2001). Such maladaptive corrections occur if the augmented feedback evokes corrective actions that are trivially small or beyond the precision of the motor system (Lee & Carnahan, 1990). Swinnen (1996) stated that augmented feedback can benefit learning when it is presented in such a way that learners do not become dependent on it. For simple motor tasks, continuous concurrent augmented feedback is known to be ineffective (Schmidt & Wulf, 1997). However, for more complicated tasks, studies have shown that continuous concurrent feedback can improve performance during retention (Wulf & Shea, 2002). A recent study concerning driver training using simulators has shown that training with augmented vibratory feedback results in faster learning and higher retention performance of the lane keeping task than training without augmented feedback (De Groot, De Winter, López-García, Mulder, & Wieringa, 2011). In that study, the augmented feedback was designed such that the learner could not become dependent on it, using a bandwidth scheme, and by using binary (on/off) non-directional feedback.

The aim of this study was to investigate the effect of continuous concurrent visual feedback in simulator-based driver training. Lane keeping accuracy has been used as a measure to describe road safety in several studies (Brookhuis & De Waard, 1993; Östlund et al., 2004) and is also the primary performance measure in this study. Continuous visual feedback on the momentary lane center deviation was presented on the dashboard of the virtual car. Learning performance was assessed during an immediate and a delayed retention session. Taking into account the effect of sleep on learning behavior (Walker, Brakefield, Morgan, Hobson, & Stickgold, 2002) the second retention session took place one day after the training and immediate retention sessions.

4.2 Method

4.2.1 Participants

Thirty participants (21 men, 9 women) were tested in two groups. One group received augmented feedback (FB, 14 participants) during training and a control group drove without augmented feedback (NFB, 16 participants). Participants had no driver's license (13 participants were already taking driving lessons) and all participants were recruited from the student community. The mean age was 19.5 years (*SD* = 2.2) and all participants completed an intake questionnaire prior to participation in the experiment with the following variables: 1) Gender (male/female); 2) Possession of a motorcycle or moped drivers licence (yes/no); 3) Experience in driving simulators (yes/no) and 4) Playing (minimum 1 hour per week) of video games (yes/no). Using the results of these variables the participants were assigned to one of the two groups using the minimization method of Taves (1974).

4.2.2 Apparatus

The simulator used for this study was the Green Dino driving simulator (Green Dino, 2010) which is used for initial driver training in The Netherlands. This fixed-base simulator, with 180- degree field of view and surround sound simulates a middle-class passenger vehicle. The simulator was equipped with realistic controls; the seat, pedals, and steering wheel originated from a real car. Steering force feedback was passive and the engine model represented that of a realistic car with automatic transmission.

The virtual world was projected using three LCD projectors with 1024 x 768 pixels for the center display and 800 x 600 pixels for the two side displays. The feedback (a horizontal compensatory display) was projected on the simulated dashboard. Instruments and mirrors were integrated in the simulation visualisation.

To measure the number of fixations and time drivers spent looking at the feedback area, a remote mounted Facelab eye tracker was used with two cameras mounted above the steering wheel and below the virtual scenery. See Figure 1 for an overview of the simulator, the eye tracker, and the feedback.

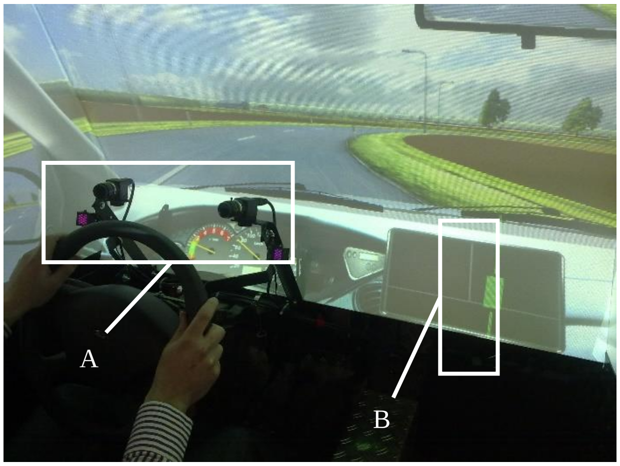

Fig. 1. Simulator during the experiment (A = eye tracker, B = augmented feedback) The vertical lines of the augmented feedback represent the lane center, while the rectangle indicates the vehicle position with respect to the lane center).

4.2.3 Procedure and task

Before participating in the experiment, participants completed an intake questionnaire for group assignment and were informed of the driving task. All participants provided written informed consent and the research was approved by the Human Research Ethics Committee of the Delft University of Technology. All sessions took place on a two-lane rural road of 7.5 km length, with varying curvature and without other traffic. The instructed task was to keep the vehicle as accurately as possible in the center of the right lane, while maintaining a realistic speed within the 80 kph speed limit. Gear selection was automated; participants were required to steer, accelerate, and brake. Participants were informed of the presence of the eye tracker and, if applicable, the presence of the augmented feedback, explaining the visualization of the lane center error. Participants were not informed of the absence of the augmented feedback during the retention sessions. After being seated in the simulator the eye tracker was calibrated to each participant and the instructions were repeated on the screen.

Each participant drove three training sessions of eight minutes followed by a maximum three-minute break, in which they completed the NASA TLX questionnaire for measuring workload (Hart & Staveland, 1988). After the three training sessions an immediate retention session took place and a second retention session was driven one day later. During the retention sessions the augmented feedback was disabled. The eye tracker was recalibrated before the start of the last retention session.

4.2.4 Dependent measures

To determine the effect of the augmented feedback on the lane keeping task the following dependent measures were determined for each training and retention session.

1) Root mean square error (RMSE) with respect to the lane center (m), describing the lane keeping accuracy.

2) Lane center error band; the time-percentage of total driving time that drivers kept the absolute lane center error smaller than 0.10 meters. This measure represents the amount of near-perfect lane keeping accuracy.
3) Average speed (m/s) was included in this study as a measure of the participants’ efficiency of completing the driving task. The speed over the complete course (including corners) was used in this study.
4) Steering wheel steadiness (%); this measure was calculated as the percentage of the time the steering wheel’s angular velocity was smaller than one degree per second. Reduced steering wheel steadiness is related to the increased amount of steering corrections.
5) Number of fixations on the feedback area, describing the number of times participants fixated on the feedback area. A single fixation was determined as a consecutive sequence of individual gaze points in the feedback area of 150 ms or longer (Salvucci & Goldberg, 2000; Hornof & Halverson, 2002).
6) NASA TLX, a subjective workload assessment tool in the form of a questionnaire.

The results were statistically compared per session between the FB and NFB groups using an independent two-sample t test with $\alpha = 0.05$. Missing eye tracker data (e.g., temporary loss of gaze tracking due to rapid head movements) were discarded from the analysis.

4.3 Results

In Table 1, the mean values for the dependent measures are presented and the statistical significance between the NFB and FB groups per session is indicated with the p-values.

No significant difference was found in the RMSE lane center and average speed between the NFB and FB groups in both the training and retention sessions. The time participants kept the vehicle at a small lateral error was higher for the FB group during training session (significant in the third session), but this was not transferred to the retention session. Steering wheel steadiness was significantly higher for NFB in the training sessions, and this result was transferred to the retention sessions. The lane center error band and the steering wheel steadiness are illustrated in Figure 2. Steering wheel steadiness increased from the first training session to the second and remained relatively constant afterward.

The number of fixations indicates that the FB group looked at the augmented feedback during training sessions. In the retention sessions, the FB group did not look significantly more to the augmented feedback area compared to the NFB group. A higher workload was reported by the FB group and this was significant (p=.049) for the temporal demand item in the second retention session. The temporal demand item represents the time pressure felt due to the rate or pace at which the task or task elements occurred (Hart & Staveland, 1988).

Table 1. Averaged group results and corresponding *p*-values for NFB (*n* = 16) and FB (*n* = 14) groups in training and retention sessions (standard deviation in parentheses)

	Training			Retention	
	1	2	3	Immediate	After 1 day
1. RMSE position in lane (m)					
No Feedback	1.01 (0.45)	0.86 (0.43)	0.77 (0.45)	0.64 (0.14)	0.65 (0.21)
Feedback	0.90 (0.27)	0.76 (0.28)	0.65 (0.24)	0.67 (0.26)	0.71 (0.26)
p	.401	.455	.367	.652	.500
2. Lane center error band* (% of total time)					
No Feedback	11.2 (5.6)	12.8 (5.1)	13.2 (4.8)	15.0 (3.9)	14.5 (4.6)
Feedback	13.2 (5.8)	16.3 (6.0)	18.0 (6.5)	16.5 (5.2)	14.1 (4.8)
p	.349	.090	**.029**	.373	.805
3. Average speed (m/s)					
No Feedback	16.6 (1.6)	16.5 (1.6)	16.8 (1.5)	16.8 (1.5)	16.9 (1.4)
Feedback	17.5 (1.4)	17.0 (1.6)	17.0 (1.4)	17.0 (1.4)	17.6 (1.4)
p	.141	.404	.603	.738	.187
4. Steering wheel steadiness* (% of total time)					
No Feedback	27.7 (3.9)	32.3 (2.6)	32.6 (2.8)	33.2 (2.8)	33.3 (2.5)
Feedback	24.1 (4.9)	28.5 (4.3)	28.2 (4.2)	29.4 (4.5)	28.6 (4.5)
p	**.032**	**.006**	**.002**	**.009**	**.002**
5. Number of fixations on feedback area**					
No Feedback	8.6 (4.8)	9.0 (6.5)	7.5 (4.7)	8.2 (3.5)	6.4 (4.1)
Feedback	46.2 (40.7)	64.5 (49.0)	69.7 (55.1)	6.3 (4.0)	6.0 (5.8)
p	**.001**	**.001**	**.001**	.256	.870
6. NASA TLX total score (%)					
No Feedback	43 (12)	41 (13)	36 (13)	35 (13)	26 (12)
Feedback	46 (15)	43 (14)	42 (17)	36 (12)	34 (12)
p	.637	.643	.255	.786	.081

* Several other measures with various thresholds have been evaluated, providing similar results.

** Not all data was valid, 64.5% of the data were included in the analysis.

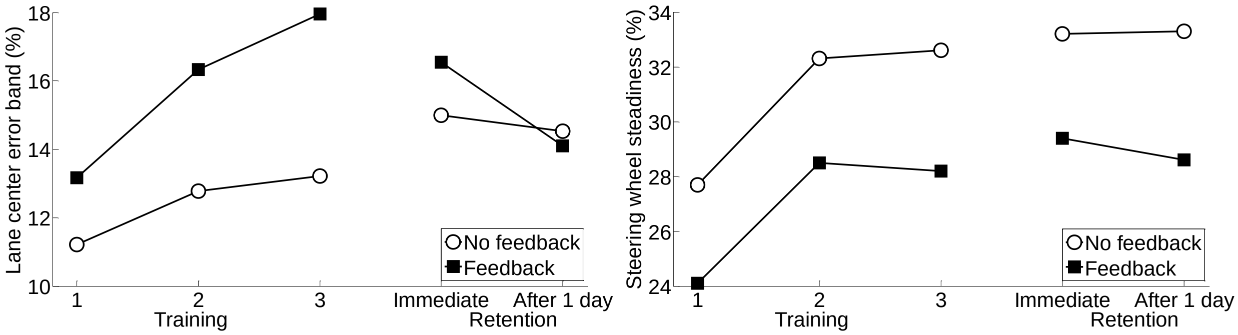

Fig. 2. Lane center error band (left) and steering wheel steadiness (right) for both groups during training and retention sessions.

4.4 Discussion

In this study, we investigated the training effectiveness of continuous concurrent visual feedback in a simulator-based lane keeping task. Consistent with the guidance hypothesis, the total time participants drove very near to the lane center was higher for the FB group in training and these effects disappeared in the retention phase. The RMSE lateral error showed similar trends in both training and retention but these were not significant.

The FB group had a significantly reduced steering wheel steadiness during training as compared to the NFB group. This over-corrective steering behavior is related to the maladaptive correction hypothesis of augmented feedback (Lee & Carnahan, 1990; Young et al., 2001). The FB group used more steering actions to keep a near-perfect lane keeping accuracy during training, and this effect persisted in retention when the augmented feedback was absent for both groups.

The concurrent augmented feedback might have overemphasized the trivially small momentary lane center errors. In contrast to the augmented feedback, the task-intrinsic visual feedback represents a combination of current and future lane center error as well as heading information (Donges, 1978; Land & Horwood, 1995). The reduced perception of future error for the FB group may have led to reduced “anticipatory” driving behavior, resulting in a lower steering wheel steadiness and increased temporal demands.

The mean fixation time for the FB group was 0.64 seconds, indicating that participants used the augmented feedback as a short verification of the perceived lane center error; participants discretely sampled the augmented feedback as opposed to looking at the augmented feedback for longer subsequent periods.

In this study, the augmented feedback did not result in improved retention of lane keeping accuracy and the augmented feedback negatively influenced the steering control behavior and workload (temporal demands) of the participants. Because of these results, we recommend being cautious with applying continuous concurrent visual feedback in driver training. For future work, different types of visual feedback could be considered, which reduce the dependency of the participant like bandwidth feedback (Lee & Carnahan, 1990; De Groot et al., 2011), or which include the predicted future lane center error.

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Implications for use of driving simulators for driver training

The study in Chapter 4 investigated the lateral control skill of novice drivers by adding concurrent visual feedback on the lateral lane position. Novice drivers benefited from visual feedback, and improved their lane keeping and steering performance. Similar to the results in Chapter 3, the retention of the learned skills was low. That is, performance differences diminished in the post-training sessions.

Chapter 5

Investigating the effect of a visual search task for simulator-based driver training

Abstract

Novice drivers tend to direct their gaze to the road ahead and not scan the environment properly. This study investigated the training effectiveness of a visual search task in a driving simulator, aimed at increasing young drivers' spread of visual search. Two groups of inexperienced drivers were instructed to drive as accurately as possible in the center of the right lane in a self-paced driving task of four 6-min sessions in a rural environment. While driving, one group performed a visual search task, consisting of detecting and fixating on visual stimuli in the peripheral area. The stimuli were purple dots that faded in slowly and disappeared when fixated by the participant. After training, both groups drove a transfer session in an urban environment, in which various hazardous situations occurred. Results showed that both groups improved their lane keeping performance, whereas the training group became more proficient in the visual search task. However, in the transfer session no group differences were detected. In conclusion, despite improvements in visual search performance during a relatively short training period, the visual search training did not detectably influence the spread of visual search of novice drivers during a post-training transfer session.

Van Leeuwen, P. M., Happee, R., & De Winter, J. C. F. (2013). Investigating the Effect of a Visual Search Task for Simulator-Based Driver Training. *Proceedings of the 7th International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, Bolton Landing, NY, 425–431

5.1 Introduction

Young drivers are overrepresented in road traffic crashes. Crash rates are highest in the first months of independent driving and decline as drivers gain experience (Mayhew, Simpson, & Pak, 2003). Many studies have shown differences in visual search behavior between experienced and novice drivers (e.g., Underwood, Chapman, Brocklehurst, Underwood, & Crundall, 2003). One factor that has been associated with the high crash rates among novice drivers is their poor ability to identify and anticipate hazards (e.g., Fisher, Pollatsek, & Pradhan, 2006). McKnight and McKnight (2003) reviewed 2,000 police accident reports, and showed that failure to search ahead, to the side, or the rear was a factor in 43% of young drivers' crashes.

Several studies have shown that novice drivers have an elevated mental workload (Lee, 2007), a phenomenon which has been associated with spatial gaze concentration (Recarte & Nunes, 2003). Crundall and Underwood (1998) found that inexperienced drivers are less inclined than experienced drivers to adjust their visual search to the complexity of the environment and to changing task demands. Novices tend to allocate their visual attention to information close to the vehicle, which may be caused by their limited steering control skills compared to experienced drivers (Mourant & Rockwell, 1972). Summala, Nieminen, and Punto (1996) showed that inexperienced drivers rely less on peripheral vision for lateral vehicle control, and fixate more on lane markers and areas close to the vehicle. An effect of driving experience on peripheral vision was also found by Crundall, Underwood, and Chapman (1999). They reported decreased peripheral detection rates for non-drivers versus experienced drivers while watching video clips of driving scenes. Underwood, Chapman, Bowden & Crundall (2002) showed that novices' reduced visual search on divided highways is caused by an impoverished mental model of likely events to occur, instead of being caused by cognitive demands due to lack of driving experience.

In this study, we investigated the effectiveness of a visual search task aimed at increasing inexperienced drivers' spread of search in a driving simulator. Inexperienced drivers were instructed to perform a lane keeping task while peripheral visual cues were to be detected and fixated. Low saliency and random appearance of these stimuli prevented bottom-up (i.e., stimulus-driven) responses, resulting in active visual search.

5.2 Method

Two groups of inexperienced drivers were tested; see Table 1 for an overview. One group received a visual search training (14 participants) and a control group (16 participants) drove without visual search training. Groups were assigned balancing age, gender, driving simulator experience, total mileage, and months since obtaining the driving license, using the minimization method of Taves (1974). All participants received compensation of 5 euro and provided written informed consent.

Table 1. Mean demographic and driving experience data (standard deviations in parentheses)

	Control	Training
Age (years)	19.1 (1.3)	19.1 (0.8)
Gender (male / female)	14 / 2	13 / 1
Driving simulator experience (number of participants)	2	1
Driving license (months)	6.6 (3.8)	6.8 (3.5)
Total mileage (km)		
0–10,000	15	14
10,000–20,000	1	0

This study used a fixed-base simulator (Green Dino BV), with 180-degree horizontal and 45-degree vertical field of view and surround sound simulating a middle-class passenger vehicle. The virtual world was projected using three LCD projectors with 1024 x 768 pixels for the center display and 800 x 600 pixels for the two side displays. Instruments and mirrors were integrated into the simulation visualisation.

The visual search training consisted of randomly appearing purple dots left and right of the road, above the virtual hood, and below the rearview mirror (Figure 1). The dots were 20 mm in diameter and were composed of the following RGB color components: 255, 87, 213. The dots faded in, in 7.6 s. On average 29 (*SD* = 4.0) dots appeared per training session. When subjects fixated on a dot for 350 ms the dot would disappear and a next dot would randomly appear within 5 to 9 seconds. Non-fixated dots remained visible for 5 to 9 seconds, after which they disappeared and a new dot appeared. A two-degree fixation tolerance was used to account for eye tracker inaccuracy. Gaze was recorded at 60 Hz using a three-camera remote mounted Smart Eye (version 5.6) eye tracker.

Participants drove four training sessions and one transfer session of six minutes, each followed by approximately 5 min breaks, in which subjects completed the NASA TLX questionnaire for measuring workload (NASA, 1986). After each training session the training group received oral feedback on the number of detected dots, motivating them to improve their search performance. During the transfer session the visual search task was disabled.

All training sessions took place on a two-lane rural road, with various sharp curves, and without other traffic, see Figure 1. The instructed task was to keep the vehicle as accurately as possible in the center of the right lane. Furthermore, participants were instructed to follow the Dutch traffic rules and drive within the 80 kph speed limit. The transfer session took place in an urban environment with short rural road sections. The urban environment consisted of 30, 50 and 80 kph speed limit zones with other traffic (cars, cyclists, and pedestrians). During the transfer session various hazardous situations occurred (e.g., crossing pedestrian) triggered after passing fixed locations in the virtual world.

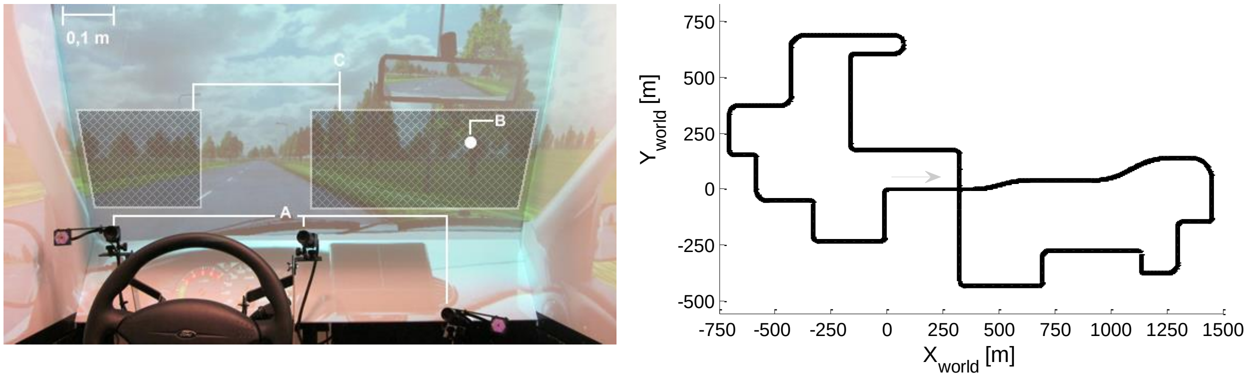

Fig. 1. Left: Simulator during the experiment (A = eye tracker, B = example of an appearing dot, C = areas where the dots appeared). Right: Top view of the course; arrow indicates starting point and driving direction.

Gear selection was automated; participants were required to steer, accelerate, and brake. Participants were informed in writing of the presence of the eye tracker and, if applicable, the visual search training during the training sessions. After taking place in the simulator the eye tracker was calibrated and the instructions were repeated on the screen. After the fourth training session, the participants received on-screen information regarding the changed driving scenario in the transfer phase.

The following dependent measures were determined per session:

1) Mean speed (m/s).

2) Standard deviation lateral position (SDLP) (m).

3) Gaze road center (GRC) (%), the percentage of time gazed within an 8 degree radius around the road center.

4) Horizontal gaze variance (HGV) (deg2) was calculated on the straight road segments and was used as measure of spread of search.

5) Steering reversal rate, (#/min) defined as the number of changes in steering wheel direction per minute with the steering velocity exceeding 3 degrees per second. This measure was calculated from the 3 Hz low pass filtered steering wheel angle.

6) Targets missed (#).

7) Mean target response time (s). Missed targets were excluded from the analysis.

8) NASA TLX (%), a workload assessment tool in the form of a questionnaire.

The results were compared per session between the training and control group using a two-sample t test. The NASA TLX results were fractionally ranked prior to statistical analysis because of their skewed distribution. Eye tracker data from 0.5 s before until 0.5 s after sequences of lost data (e.g., due to blinks) were removed. If more than 60% of eye tracker data was removed from a session, the corresponding session was removed from the analysis.

5.3 Results

One participant ended the experiment due to simulator discomfort and was replaced by another participant. Dependent measures per group and session are shown in Table 2. None of the training group participants reported targets failing to disappear after being fixated as a result of eye tracker inaccuracy or loss of tracking.

Table 2. Averaged group results and corresponding *p* values for the control group (*n* = 16) and training group (*n* = 14) in training and transfer sessions (standard deviations in parentheses)

		Training				Transfer
		1	2	3	4	5
Mean speed (m/s)	Control	17.2 (1.5)	17.0 (1.8)	16.7 (1.8)	17.1 (1.8)	13.0 (0.83)
	Training	17.3 (1.4)	17.1 (1.7)	17.0 (1.5)	17.4 (1.4)	12.9 (0.79)
	p	.787	.833	.657	.590	.823
Standard deviation lateral position (m)	Control	0.73 (0.20)	0.52 (0.16)	0.46 (0.07)	0.46 (0.13)	0.59 (0.16)
	Training	0.75 (0.21)	0.67 (0.15)	0.52 (0.09)	0.55 (0.13)	0.58 (0.15)
	p	.725	**.021**	.105	.146	.858
Gaze road center* (%)	Control	62 (6.8)	58 (7.0)	59 (7.2)	57 (8.3)	39 (5.0)
	Training	54 (10.3)	50 (11.3)	49 (7.3)	46 (8.2)	37 (7.8)
	p	**.027**	**.029**	**.001**	**<.001**	.411
Horizontal gaze variance* (deg^2)	Control	51.8 (27.4)	76.4 (38.1)	86.7 (51.5)	96.9 (51.0)	162.2 (48.3)
	Training	90.7 (30.8)	137.7 (47.7)	133.1 (53.2)	170.0 (57.6)	176.5 (98.2)
	p	**.002**	**.001**	**.034**	**.002**	.639
Steering reversal rate (#/min)	Control	20.1 (5.3)	15.8 (3.0)	14.1 (3.3)	13.8 (3.2)	15.5 (3.3)
	Training	20.2 (3.0)	16.4 (3.3)	16.6 (3.5)	17.3 (3.3)	15.1 (3.6)
	p	.973	.630	.086	**.016**	.760
Targets missed (#)	Training	6.93 (2.64)	4.07 (2.81)	2.57 (1.91)	2.14 (2.07)	-
Mean target response time (s)	Training	5.09 (0.74)	3.92 (0.47)	3.73 (0.61)	3.34 (0.66)	-
NASA TLX (%)	Control	47 (14)	44 (15)	37 (16)	38 (17)	49 (18)
	Training	57 (16)	49 (17)	41 (17)	41 (14)	49 (19)
	p	.081	.397	.489	.601	.989

* on average 25% of eye tracker data was discarded per session. In total 14 sessions were removed from the analysis.

During the training sessions, a significantly higher visual search (i.e., lower GRC, higher HGV) was observed for the training group compared to the control group, illustrated in Figure 2.

The SDLP for the training group was significantly higher than the SDLP of the control group in the second training session only. Steering reversal rate was significantly higher for the training group in the last training session only. No significant group differences were found regarding mean speed and self-reported workload. No significant differences between the training and control group were found in the transfer session for any of the driving behavior, eye-scanning, or workload measures.

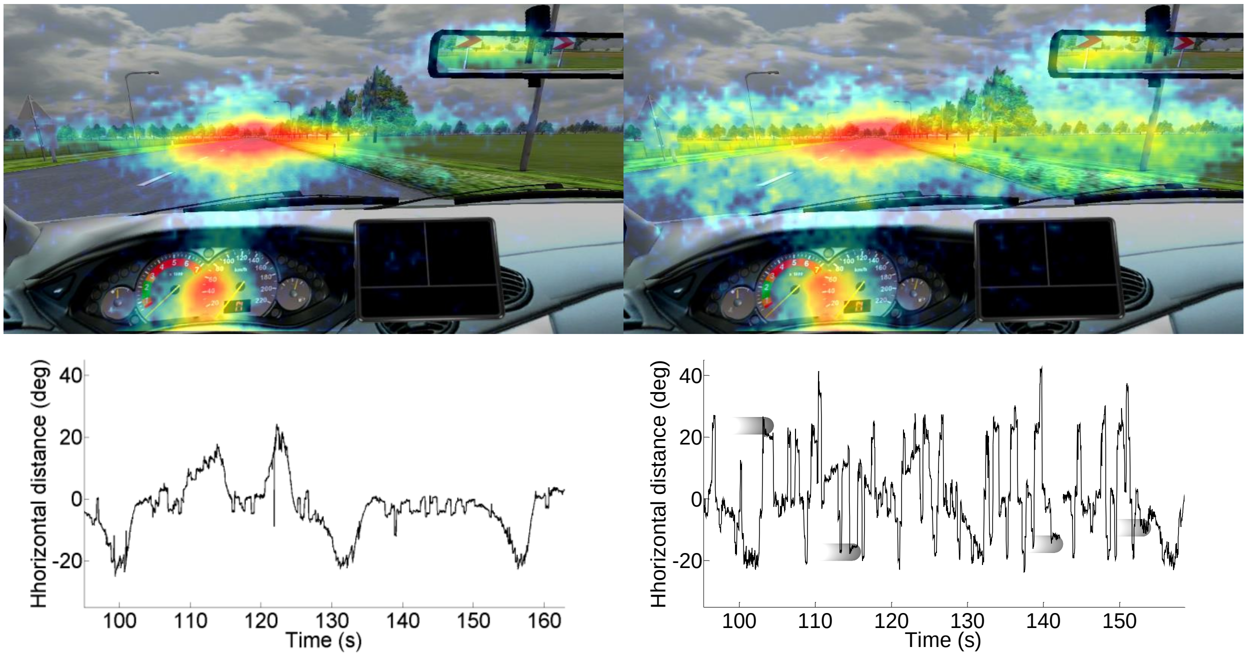

Fig. 2. Gaze distribution for the control (top left) and training group (top right) for all participants in the 4th session. Distributions were generated after converting to a logarithmic scale. Horizontal gaze angle for two selected participants; control group (bottom left) and training group (bottom right). Fading in of the targets is illustrated by the increasing grayscale intensity (bottom right only).

The HGV significantly increased from the first session to the last training session for the training group ($t(13) = 4.52$, $p < .001$) and for the control group ($t(14) = 3.29$, $p = .006$). A significant performance improvement from the first training session to the last training session was found for missed targets ($t(13) = 7.81$, $p < .001$) and target response time ($t(13) = 7.20$, $p < .001$). Figure 3 shows that response time and target miss rate are higher for more peripheral targets, and that gaze variance differs strongly between participants and is consistent between sessions 3 and 4.

5.4 Discussion

In this study, we investigated the training effectiveness of a visual search task. The group who performed the visual search task while driving became gradually better at detecting the visual stimuli, as demonstrated by a diminished number of object misses and significantly improved response time. In the transfer session, no differences in eye-scanning and driving behavior were detected between the two groups, indicating that the training effects did not detectibly generalize to the new condition.

The ineffectiveness of the visual search training may be explained by the absence of hazardous information in the visual stimuli. The stimuli were designed to prevent bottom-up responses during driving, aimed at improving the spread of visual search. The 'meaningless' visual search however, may not have improved drivers' mental model of hazardous situations. Improving the novices' mental model of hazardous situations could result in improved recognition and processing of hazards (Chapman, Underwood, & Roberts, 2002). Furthermore, due to the lack of hazardous information in the visual stimuli the inexperienced drivers were not trained in generating appropriate responses after detecting hazardous situations.

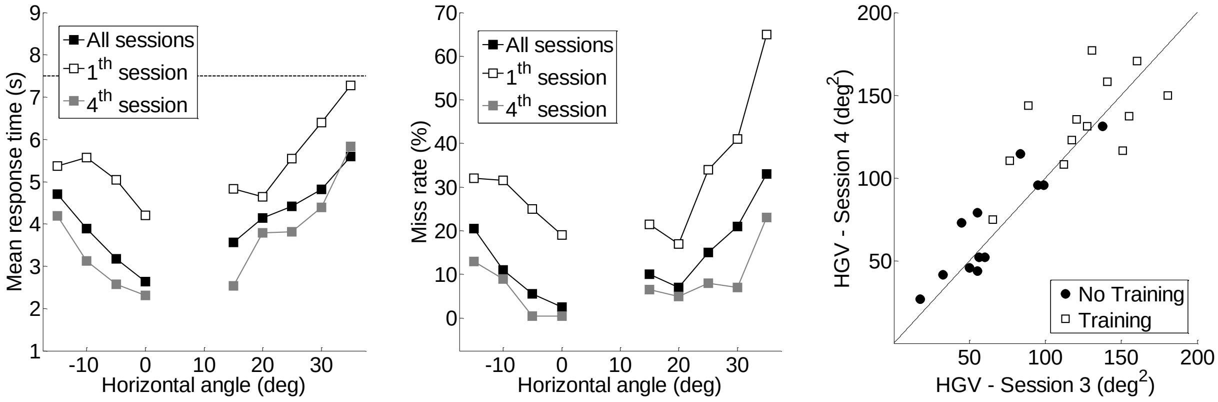

Fig. 3. Left: Distribution of mean response time as a function of the horizontal view angle for session 1, session 4, and averaged across all four sessions. The dashed line indicates the time at which the target dot had completely faded in. Center: Percentage of missed targets as a function of horizontal view angle for session 1, session 4 and averaged across all four sessions. Right: Horizontal gaze variance for participants of both groups in sessions 3 and 4. Five participants are missing from the figure due to missing eye tracker values.

Driving performance and visual search showed strong performance improvement for the visual training group during training, indicating increasingly effective timesharing between both tasks. Schneider and Fisk (1982) found that two visual search tasks can be more easily time-shared when both tasks are cognitively automated, or when one task is automated and the other is a controlled search task. Possibly, the visual attention required for vehicle control in the training sessions was an automated task, which therefore could easily be time-shared with the visual search task.

The sample tested in this study consisted mainly of male students, limiting the generalizability of the results. Furthermore, the training lasted only 24 minutes per participant, whereas driving skill is developed during years of driving experience (Mayhew et al., 2003). Other training interventions aimed at improving young drivers' mental model of hazards (e.g., Fisher et al., 2006) seem effective in improving novices' visual search in hazardous situations. Training of visual search by manipulating drivers' eye-scanning must be addressed carefully, however. Training visual search during a driving task for which trainees lack attentional resources may well decrease driving safety (Crundall et al., 2012), as redirecting their visual attention may reduce their attention to other vital visual tasks.

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Implications for use of driving simulators for driver training

In this chapter a visual search task was added to a self-paced lane keeping task, aimed at improving the visual search skills of novice drivers. The novice drivers improved their visual search during the practice sessions, but their visual search skills did not transfer to a different driving scenario. Similar to the results of Chapters 3 and 4, the visual search skills of drivers improved on the short term, but were not transferred to a post-training evaluation session.

Chapter 6

Changes in driving performance and gaze behavior of novice drivers during a 30-min simulator-based training

Abstract

Previous research has shown that novice drivers have underdeveloped vehicle control skills and visual search strategies that differ from those of experienced drivers. However, little is known about how novices' driving performance and gaze behavior jointly change over the course of practice. In this paper, we investigated changes in driving performance and gaze behavior of 52 novice drivers while gaining experience in the simulator. The participants completed four sessions of 6 to 8 minutes on a rural road containing multiple 90-degree curves, and their task was to drive as close as possible to the center of the right lane. The results showed that the standard deviation of lateral position (SDLP) and steering activity significantly reduced from the first to the fourth session. The eye-tracking data showed that participants increased their spread of visual search and reduced gaze tunneling. Participants' self-reported workload decreased from the first to the fourth session. Additionally, our results demonstrate that participants increased their gaze tunneling as a function of driving speed. In conclusion, during the first approximately 30 minutes of driving experience in a driving simulator, SDLP decreases, gaze variance increases, and self-reported workload decreases. These results indicate that short-term changes in driver skill and visual behavior of novice drivers can be detected using driving simulators.

Van Leeuwen, P. M., Happee, R., & De Winter, J. C. F. (2015). Changes of driving performance and gaze behavior of novice drivers during a 30-min simulator-based training. *Procedia Manufacturing, 3*, 3325–3332 (adapted with minor changes).

6.1 Introduction

Novice drivers are overrepresented in road traffic crashes (Lee, 2007). Accident rates are particularly high in the first few months after obtaining a driver's license and decline as drivers gain experience (Mayhew, Simpson, & Pak, 2003; McGwin & D.B. Brown, 1999). It is important to understand how novice drivers differ from experienced drivers, and how novice drivers learn from experience, in order to develop effective crash countermeasures.

Prior research has shown that novice and experienced drivers differ in various ways. Novice drivers generally have underdeveloped vehicle control skills and less spare attentional capacity than experienced drivers (Duncan, Williams, & Brown, 1991; Lee, 2007). Furthermore, novice drivers have a relatively poor ability to identify and anticipate traffic hazards (McKnight & McKnight, 2003; Pradhan, Hammel, DeRamus, Pollatsek, Noyce, & Fisher, 2005) compared to their experienced counterparts. Also, novice drivers adjust their visual search less effectively to the environmental situation (Crundall & Underwood, 1998), tend to direct their gaze more often to the immediate vicinity (Mourant & Rockwell, 1972), rely less on peripheral vision for vehicle control (Summala, Nieminen, & Punto, 1996), and show less variability in fixation patterns (Underwood, Chapman, Brocklehurst, Underwood, & Crundall, 2003). Additionally, novice drivers differ from experienced drivers when it comes to the use of in-vehicle technology (Lee, 2007). For example, Wikman, Nieminen, and Summala (1998) found that novice drivers had longer glance durations to in-vehicle tasks than experienced drivers in an instrumented vehicle.

In addition to studying how novice drivers and experienced drivers differ in a cross-sectional sample, it is also possible to study how the behavior of novices' changes as a function of driving experience. In order to obtain such knowledge, the behavior of novice drivers has to be observed at different moments in time.

The learning curve is a classical finding in studies of skill acquisition and occurs because skills become 'automatic' (i.e., more unconscious and efficient) with experience (Ranney, 1994). Various driving simulator studies on the training of novices have shown a learning curve effect, in terms of improved driving performance, reduced workload, and increased self-confidence (De Groot, De Winter, López-García, Mulder, & Wieringa, 2011; Shinar, Tractinsky, & Compton, 2005). Charlton and Starkey (2011), for example, found that participants decreased driving performance variability, improved secondary task performance, and reported less difficulty in their driving task after practicing in a driving simulator for a 12-week period.

Several longitudinal studies have found that self-reported violations increase with driving experience (De Craen, 2010; Wells, Tong, Sexton, Grayson, & Jones, 2008). These findings are corroborated by driver-training data documented by De Winter, Wieringa, Kuipers, Mulder, and Mulder (2007). These authors found that although errors decreased during driving lessons in a driving simulator, the speed of task execution and violations increased. Similarly, Underwood (2013) found that during the first six months of driving, novices increased their mean road speed and tendency to cut corners when tested on three test occasions using an instrumented vehicle.

These findings point to the paradoxical nature of skill acquisition in car driving: if drivers use their learned skills in order to drive faster, the net effect on road safety is attenuated or even negative (Hatakka, Keskinen, Gregersen, Glad, & Hernetkoski, 2002).

Although ample studies have investigated differences between novice and experienced drivers, and have reported learning curves of driver behavior data, only a few studies have measured the changes in gaze behavior over the course of practice. We combined the datasets of three previously published studies (Van Leeuwen, De Groot, Happee, & De Winter, 2011; Van Leeuwen, Happee, & De Winter, 2013; Van Leeuwen, Happee, & De Winter, 2014), in each of which novice drivers were practicing a lane-keeping task while their eye-gaze patterns were measured using an eye-tracker. The experimental protocols were highly similar for the three experiments, yielding a fairly large sample (N = 52). Our aim was to explore whether and how drivers' gaze patterns change as a function of a 30 min driving experience.

6.2 Methods

6.2.1 Participants

Participants were recruited from the Delft University of Technology campus and were mainly undergraduate students. Participants were not in possession of a driver's license (Experiment 1 (Van Leeuwen, De Groot, Happee, & De Winter, 2011)) or in possession of a driver's license for less than 3 years (Experiments 2 (Van Leeuwen, Happee, & De Winter, 2013) and 3 (Van Leeuwen, Happee, & De Winter, 2014)). Table 1 shows an overview of the participant data.

Table 1. Mean demographic and driving experience data (standard deviation in parentheses)

	Experiment 1	Experiment 2	Experiment 3
Age (years)	19.2 (2.3)	19.1 (1.3)	19.9 (1.1)
Gender (males / females)	11 / 5	12 / 4	16 / 4
Driving simulator experience (number of participants)	-	2	2
Driving license (months)	-	6.6 (3.8)	8.4 (4.9)
Total mileage (0-10,000 km / 10,000-20,000 km)	-	15 / 1	16 / 4

6.2.2 Apparatus

The experiments were conducted in a Green Dino fixed-base driving simulator, which is also used at driving schools in The Netherlands for initial driver training. The simulator consisted of a cabin with a seat, pedals, and steering wheel originated from a real car. The steering force feedback was provided by a passive spring system, and steering sensitivity had been calibrated with respect to typical on-road cars (Katzourakis, De Winter, De Groot, & Happee, 2012). Surround sound was provided by a four-speaker system, and the virtual world was projected using three LCD projectors spanning a field of view of approximately 180 deg horizontally and 45 deg vertically (Van Leeuwen, Happee, & De Winter, 2014; Van Leeuwen, Gómez i Subils, Ramon Jimenez, Happee, & De Winter, 2015). The dashboard, interior, and mirrors were integrated into the projected image. The simulator model was updated at 100 Hz, and the visual update rate was 75 Hz. The frame rate was estimated to be at least 30 Hz, sufficiently high to guarantee a smooth visual projection.

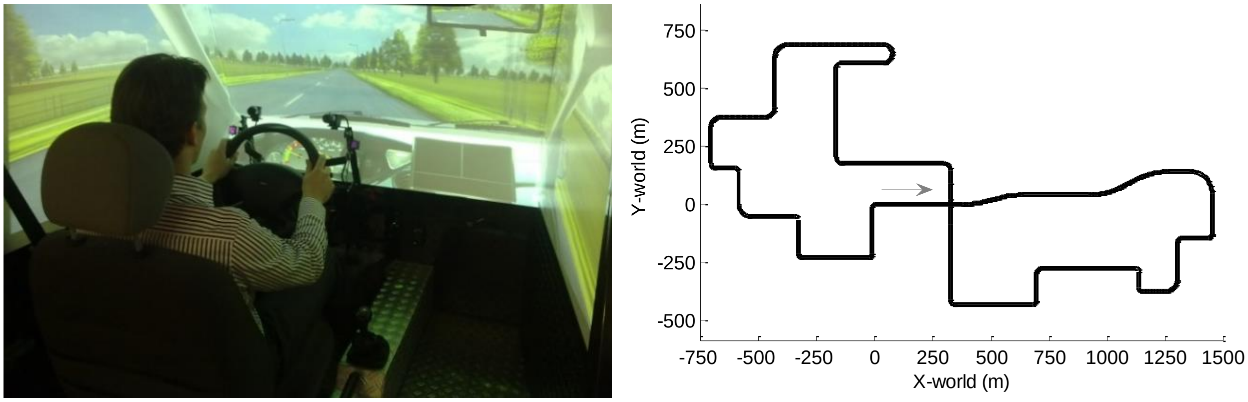

Fig. 1. Left = Photo of driving simulator (Experiment 1). Right = Top view of the course; the arrow indicates the starting location and direction.

Head and eye movements were measured with a remote eye tracker of Seeing Machines (faceLAB) or SmartEye. For each experiment, two cameras were mounted to the left and the right of the steering wheel, below the virtual scenery. For the three-camera SmartEye system, the third camera was placed near the right side mirror (Experiment 2) or behind the steering wheel and above the steering axis (Experiment 3).

Table 2. Overview of experiment dates, number of participants, experimental sessions, and eye tracker equipment

Experiment	Date	*N*	Training sessions (duration)	Retention session (duration)	Eye tracker (software version)	Cameras (#)
1	Nov 11 – Nov 30, 2010	16	3 (8 min)	1 (8 min)	faceLAB (4.3)	2
2	May 12 – May 18, 2011	16	4 (6 min)	–	SmartEye (5.6)	3
3	Dec 1, 2011 – Jan 19, 2012	20	3 (8 min)	1 (8 min)	SmartEye (5.6)	3

6.2.3 Procedures

The three experiments were conducted independently. Each experiment evaluated a particular training method using a between-subjects design with a control group and a treatment group. The analyses in this paper are based on the control group data for each experiment and consist of the first four driving sessions. The included four sessions of each participant were all driven on the same day.

Participants completed an intake questionnaire and received written information explaining the experimental procedures. Next, participants were assigned to the control or treatment group using the minimization method of Taves (1974). Afterward, the eye-tracker was calibrated and participants commenced the training sessions. Each training session was followed by a 5 min break, during which participants completed the NASA TLX questionnaire (Hart & Staveland, 1988). After completing the three training sessions in Experiment 1 and 3, participants drove an immediate retention session with the same instructions as provided for these training sessions. The participants from Experiment 2 drove four training sessions (Table 2). The total experiment duration was 40–50 min for all participants.

6.2.4 Driving task

All sessions were conducted on the same two-lane rural road of 7.5 km length and 5 m lane width. The course consisted of 25 curves of varying curvature (see Van Leeuwen et al. (2015) for details). No traffic was present on either lane and no traffic signs were present, except for signs indicating a 20 km/h advised corner speed. All sessions started at the same location in the virtual environment and with the vehicle stationary in the center of the right lane. Figure 1 (left) shows a photo of the simulator and virtual environment, and Figure 1 (right) shows a top view of the course.

Participants received written instructions to drive as close as possible to the center of the right lane, to drive safely, and to adhere to the Dutch traffic rules. Participants were instructed to use the accelerator, the brake, and the steering wheel to operate the vehicle, and they were informed that gear changing was automated. Furthermore, participants were informed of the session duration. Before commencing with the first training session, the instructions were repeated on the front projection of the simulator.

6.2.5 Dependent measures

The first 20 s of each session were removed from the analysis. Also, intervals from 10 s before to 20 s after road departures (resulting in vehicle reset on the middle of the right lane) were removed from the analysis. The steering signal was filtered with a 2nd-order 3-Hz low-pass Butterworth filter, to remove noise from the signal.

Eye blinks and other missing data were removed from the eye tracker data (including a 0.5-s margin before and after, (Van Leeuwen et al., 2014; Van Leeuwen et al., 2015)). If more than 60% of eye tracker data were removed from a session, the entire session was excluded from the analysis.

The following dependent measures were determined for each participant and session:

1) Mean speed (m/s).

2) Mean lateral position (MLP) (m) was used as a measure of lane keeping bias.

3) Standard deviation lateral position (SDLP) (m) was used as a measure of lane keeping precision.

4) Steer speed (deg/s) was defined as the averaged steering wheel velocity.

5) Steer steady (0-1), defined as the fraction of time the absolute steering wheel velocity was below 1 deg/s. A low steer steady signals a high steering activity.

6) Throttle variance (0-1) was calculated as a measure of throttle activity.

7) Horizontal gaze variance (HGV) (deg2) was calculated on the straight road segments (Van Leeuwen et al., 2013).

8) Gaze road center (GRC) (%) was calculated as the percentage of gaze within an 8-deg cone around the road center on the straight road segments (Van Leeuwen et al., 2013; Victor, Harbluk, & Engström, 2005).

9) Percentage dials (%) and percentage mirror (%). Percentage of time participants gazed at the dials and rear-view mirror, respectively.

10) NASA TLX (%). Subjective workload, with scores marked from very high to very low.

6.3 Results

Five sessions of driving simulator data were lost due to data recorder malfunctioning. The eye-tracker data of 16 driving sessions were discarded. Overall data loss (excluding the 16 discarded sessions) from the eye tracker measurements was 30.9%. The TLX results for Session 1 of one participant were missing because the participant did not complete the form.

In Table 3, the means, standard deviations, and statistical test results are shown for each of the dependent measures. It can be seen that SDLP and steering activity reduced from Session 1 to 4. No significant differences occurred between Sessions 1 and 4 for the driving speed and throttle variance. Participants increased their visual search (HGV) and reduced their attention to the roadway (GRC) on the straight road sections from Session 1 to 4. No significant differences were found between Sessions 1 and 4 regarding the time spent gazing at the dials or rear-view mirror. Participants spent considerably more time directing their gaze at the dials compared to the time directed at the rearview mirror. Self-reported overall workload decreased from 39.5% in Session 1 to 33.1% in Session 4. The largest decrease was observed for the Mental demand, Temporal demand, and Frustration items of the TLX.

Table 4 shows significant correlations between the mean speed, steer speed, and throttle variance. Table 4 also shows a significant correlation between the mean speed, GRC, and the percentage dials. This indicates that driver who drove faster directed a larger percentage of their gaze at the road center and focused less on the dials.

Table 3. Means with standard deviations in parentheses of the dependent measures for the four driving sessions. The *p* values and effect sizes are shown for comparisons between Sessions 1 and 4. The Pearson correlation coefficient for comparisons between Sessions 1 and 4 and Sessions 3 and 4 are shown

	Session				Significance S1 vs. S4		Correlation (r)	
	1	2	3	4	p value	d_z	S1/S4	S3/S4
Mean speed (m/s)	16.9 (1.47)	16.8 (1.71)	16.8 (1.75)	17.0 (1.65)	.816	0.03	.49	.93
MLP (m)	0.09 (0.21)	0.15 (0.23)	0.18 (0.23)	0.18 (0.23)	**< .001**	0.48	.56	.89
SDLP (m)	0.71 (0.26)	0.60 (0.21)	0.54 (0.18)	0.52 (0.13)	**< .001**	-0.89	.57	.76
Steer speed (deg/s)	18.7 (5.7)	15.9 (4.15)	15.5 (4.56)	15.1 (3.03)	**< .001**	-0.80	.63	.77
Steer steady (0-1)	0.17 (0.04)	0.19 (0.04)	0.20 (0.04)	0.20 (0.04)	**< .001**	0.93	.51	.87
Throttle variance (0-1)	0.071 (0.039)	0.068 (0.038)	0.075 (0.043)	0.081 (0.045)	.173	0.20	.35	.94
HGV (deg^2)	52.0 (25.2)	59.2 (33.5)	63.0 (31.8)	63.3 (33.3)	**.002**	0.51	.68	.82
GRC (%)	72.3 (7.92)	69.9 (9.25)	68.8 (10.58)	68.4 (9.16)	**< .001**	-0.55	.51	.81
Percentage dials (%)	11.8 (5.18)	12.9 (5.62)	12.7 (6.01)	13.8 (6.51)	.051	0.30	.58	.92
Percentage mirror (%)	0.45 (0.75)	0.56 (1.38)	0.57 (1.3)	0.46 (0.96)	.480	0.11	.46	.78
Data loss eye tracker (%)	27.9 (19.0)	29.6 (17.9)	32.7 (22.6)	33.3 (22.4)	**.017**	-0.18	.77	.96
TLX Mental (%)	44.7 (20.8)	39.0 (21.8)	34.5 (19.4)	33.4 (21.0)	**.001**	-0.47	.32	.78
TLX Physical (%)	28.2 (17.8)	27.4 (17.0)	25.0 (17.2)	26.2 (18.2)	.322	-0.14	.60	.83
TLX Temporal (%)	36.5 (18.3)	35.2 (17.1)	29.6 (16.4)	27.7 (18.0)	**.002**	-0.46	.39	.73
TLX Performance (%)	50.1 (18.8)	52.6 (20.0)	48.0 (25.3)	46.4 (27.7)	.342	-0.13	.35	.64
TLX Effort (%)	42.5 (17.7)	40.3 (18.1)	38.4 (17.5)	38.8 (18.8)	.149	-0.21	.39	.57
TLX Frustration (%)	35.1 (21.1)	32.0 (20.3)	29.8 (19.2)	26.3 (16.9)	**.005**	-0.41	.22	.70
TLX Total (%)	39.5 (10.4)	37.8 (11.6)	34.2 (10.9)	33.1 (11.3)	**< .001**	-0.54	.36	.76

Note: Differences were declared statistically significant if $p < .05$ using a paired t test. Effect sizes were reported as Cohen's d_z, $d_z = t/N^{0.5}$. Due to data loss and excluded sessions in Session 1 and Session 4, $N = 50$ for the driving simulator results, $N = 46$ for the gaze results, and $N = 51$ for the NASA TLX results.

Figure 2 illustrates the correlation between sessions for three selected variables. It shows a reduction of GRC (left) and SDLP (right), and the increase in HGV (middle) from Session 1 to 4. The figure also shows the large individual differences for the selected measures and the stronger correlation between Session 3 and 4 as compared to the correlation between Session 1 and 4.

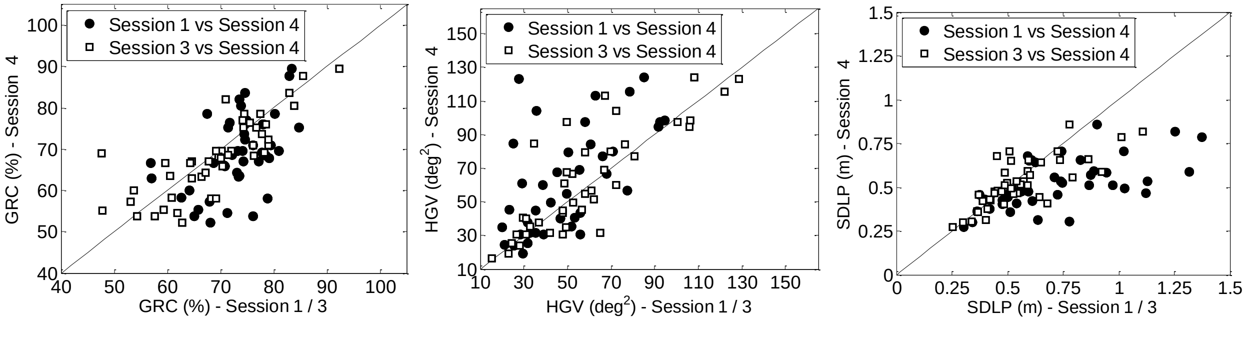

Fig. 2. Associations between selected dependent measures (Session 4 vs. Session 1 / 3). From left to right are shown the Gaze Road Center (GRC; $N = 46$), Horizontal Gaze Variance (HGV; $N = 46$), and the Standard Deviation Lane Position (SDLP; $N = 50$). The corresponding correlation coefficients are shown in Table 3.

Figure 3 (Left) illustrates the reduction in steering activity from Session 1 to 4. Figure 3 (Right) shows a heatmap of the gaze distribution on the straight road segments. This figure makes clear that a large portion of drivers' visual attention was directed to the forward roadway and speedometer.

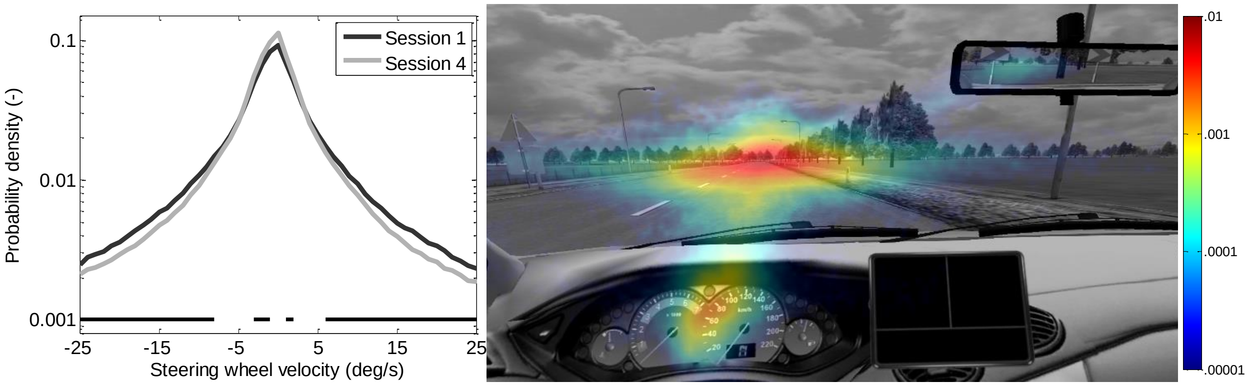

Fig. 3. Left = Distribution of the participant averaged steering wheel velocity for Session 1 and 4. The distributions were calculated for 1 deg bins. Significant differences (p < .001) are indicated by horizontal black lines. Right = Heatmap showing the gaze distribution on straight road segments. The distribution was determined by aggregating gaze data from all sessions and participants in one-by-one degree bins.

The gaze pitch (downward) angle below the horizon and the HGV as a function of driving speed are shown in Figure 4 (Left) and (Center). As drivers increase their driving speed, they direct their attention closer to the horizon (further ahead of the vehicle) and reduce their horizontal spread of visual search. Figure 4 (Center) illustrates the significant increase in HGV from Session 1 to Session 4. The decrease in visual search as a function of driving speed is further illustrated in Figure 4 (Right). This figure shows that, as the driving speed increases, drivers focused more at the road center and less at other areas, such as the dials.

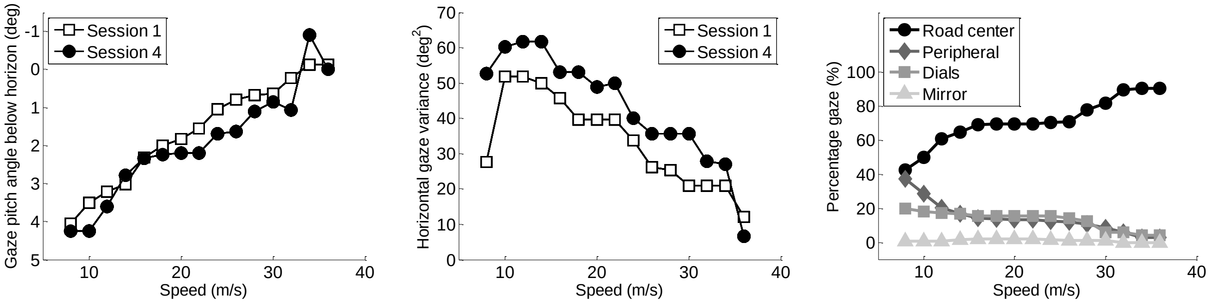

Fig. 4. Gaze pitch angle below the horizon (Left) and Horizontal Gaze Variance (HGV; Center) as a function of driving speed for Session 1 and 4. Right = Gaze distribution between Road center, Peripheral area, Dials, and Mirror, as a function of driving speed, averaged across all sessions. Distributions were calculated for 1 m/s bins and averaged per bin across all participants.

Table 4. Correlation matrix of the dependent measures. Correlations were determined from the average of the four sessions

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Mean speed (m/s)														
2. MLP (m)	.10													
3. SDLP (m)	.24	**-.38**												
4. Steer speed (deg/s)	**.29**	-.12	**.49**											
5. Steer steady (0-1)	-.25	-.17	-.18	**-.38**										
6. Throttle variance (0-1)	**.71**	.10	.26	**.44**	**-.31**									
7. HGV (deg^2)	-.17	-.20	**-.29**	-.03	.07	-.22								
8. GRC (%)	**.36**	**.38**	-.27	-.22	.08	.23	**-.43**							
9. Percentage dials (%)	**-.34**	-.10	.26	.01	-.02	-.21	-.21	**-.55**						
10. Percentage mirror (%)	-.01	.06	-.14	-.03	-.25	.05	**.30**	**-.29**	.11					
11. Data loss eye tracker (%)	.09	.17	**.36**	**.28**	-.16	.08	**-.44**	.06	.22	-.08				
12. NASA TLX (%)	-.28	.03	-.17	-.13	.02	**-.40**	.10	-.06	-.18	.00	-.18			
13. Participant age (years)	.17	.01	-.05	.07	.20	.02	-.07	.14	.01	-.15	.01	-.04		
14. Participant gender (female/male)	.13	.22	-.17	-.22	.19	**.28**	-.09	.05	-.09	.02	-.02	.09	-.03	

Note: *N* = 52 for variables 1 – 6, 13 – 14, *N* = 50 for variables 7 – 11, and *N* = 32 for variable 12. For the NASA TLX, the results of Experiment 3 (*N* = 20) could not be included from the correlation matrix. Correlations that are statistically significant ($p < .05$) are in boldface.

6.4 Discussion

In this paper, we investigated changes in driving and gaze behavior of novices while they were gaining experience in a driving simulator. We observed statistically significant changes in several performance and gaze measures during an approximately 30-minute period of driving practice.

The standard deviation of lateral position, a measure of driving precision, improved from Session 1 to 4. Improved driving precision was also found by Shinar et al. (2005), among others, and is consistent with general learning effects in perceptual and motor tasks (Newell & Rosenbloom, 1981). Interestingly, we found no statistically significant differences in driving speeds between the first and last session. This lack of effect may be because participants could not gain time (i.e., the session durations were fixed at 6 or 8 min) and because the participants were instructed to drive as accurately as possible. Thus, the participants had no incentive to increase their driving pace.

Our results showed a significant increase in HGV and a decrease in GRC from Session 1 to 4. Furthermore, we observed a reduction in self-reported workload from Session 1 to 4. These finding can be interpreted in light of the literature showing that when humans are put under stress, they focus on cues that are most immediate and familiar (Hanckock, 1989). We argue that as drivers gain experience, their mental workload and stress levels drop, and hence their ‘tunnel vision’ reduces. Cognitive tunneling has been demonstrated in various previous simulator-based and video-based driving studies (Crundall, Underwood, & Chapman, 1999; Engström, Johansson, & Östlund, 2005). Reimer (2009), for example, found a reduction in gaze distributions and a reduced peripheral vision when drivers performed a secondary cognitive task in an instrumented vehicle.

Our results further showed that as driving speeds increase, HGV decreases and GRC increases. This finding is consistent with the literature. For example, in one driving simulator study (Rogers, Kadar, & Costall, 2005), it was found that as driving speeds increased (hence, the task became more demanding), the gaze distribution progressively narrowed. Our results also showed that as drivers drove faster, they directed their gaze further ahead of the vehicle and spent less time gazing at the dials and peripheral areas. The reduction in gaze directed at the dials with increasing driving speeds is consistent with Denton (1969), who discussed that the use of the speedometer might be determined to some extent by the spare amount of mental capacity.

In conclusion, our results demonstrate a clear effect of practice on the driving precision and gaze tunneling of novice drivers in a driving simulator. These results indicate that short-term changes of driving performance and gaze behavior of novice drivers can be detected using state-of-the-art eye-tracking equipment. The main limitation of our work is that we cannot prove whether drivers learned to drive a real vehicle, or whether the observed effects are merely the result of short-term adaptation to the driving simulator. Furthermore, 30 min of experience can reflect only the initial stages of learning and does not necessarily correlate with long-term effects.

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Implications for driver assessment

The study in Chapter 6 demonstrated the effect of a short simulator training session on eye movements, driving performance and mental demands in novice drivers. The results illustrate the effect of driving experience on measures of eye-movements and steering behavior. Whereas Chapter 2 was concerned with group differences in driving expertise, the present chapter demonstrated within-subject changes of eye-movements and steering behavior. The combined results suggest that driver-state assessment algorithms should be attuned to between- and within-subject reference values.

Part III

Towards real-world applications:
Real-time driver assessment

Chapter 7

The effects of time pressure on driver performance and physiological activity: A driving simulator study

Abstract

Speeding because of time pressure is a leading contributor to traffic accidents. Previous research indicates that people respond to time pressure through increased physiological activity and by adapting their task strategy in order to mitigate task demands. In the present driving simulator study, we investigated effects of time pressure on measures of eye movement, pupil diameter, cardiovascular and respiratory activity, driving performance, vehicle control, limb movement, head position, and self-reported state. Based on existing theories of human behavior under time pressure, we distinguished three categories of results: (1) driving speed, (2) physiological measures, and (3) driving strategies. Fifty-four participants drove a 6.9-km urban track with overtaking, car following, and intersection scenarios, first with no time pressure (NTP) and subsequently with time pressure (TP) induced by a time constraint and a virtual passenger urging to hurry up. The results showed that under TP in comparison to NTP, participants (1) drove significantly faster, an effect that was also reflected in auxiliary measures such as maximum brake position, throttle activity, and lane keeping precision, (2) exhibited increased physiological activity, such as increased heart rate, increased respiration rate, increased pupil diameter, and reduced blink rate, and (3) adopted scenario-specific strategies for effective task completion, such as driving to the left of the lane during car following, and early visual lookout when approaching intersections. The effects of TP relative to NTP were generally large and statistically significant. However, individual differences in absolute values were large. Hence, we recommend that real-time driver feedback technologies use relative instead of absolute criteria for assessing the driver's state.

Rendon-Velez*, E., Van Leeuwen*, P. M., Happee, R., Horváth, I., Van der Vegte, W. F., & De Winter, J. C. F. (2016). The effects of time pressure on driver performance and physiological activity: a driving simulator study. *Transportation research part F: traffic psychology and behaviour, 41*, 150–169. **joint first authors*

7.1 Introduction

7.1.1 The dangers of ‘time pressure’

A large portion of road traffic crashes occurs because drivers have been speeding or committing other types of traffic violations, such as tailgating and dangerous overtaking (Elander, West, & French, 1993; Elvik, Christensen, & Amundsen, 2004; Evans & Wasielewski, 1982; Organisation for Economic Co-operation & Development, 2006; Parker, Reason, Manstead, & Stradling, 1995). Speeding is a factor in between 10% and 40% of accidents on European roads (Organisation for Economic Co-operation & Development, 2006; Treat et al., 1979). McKenna (2005) reported that 33% of 9470 surveyed speeding offenders indicated that they were in a hurry at the time of their speeding offence. Another survey study by Collinson (2014) indicated that 77% of 150 people who were caught speeding did so because they lacked time to make the journey.

Several factors may explain why drivers decide to speed and violate the traffic rules. This includes personality factors, such as thrill seeking, pleasure in fast driving, and aggressiveness, as well as environmental factors, such as peer pressure, and perhaps most importantly, a shortage of available time (e.g., Beck, Daughters, & Ali, 2013; Beck, Wang, & Yan, 2012; Coeugnet, Miller, Anceaux, & Naveteur, 2013; Coeugnet, Naveteur, Antoine, & Anceaux, 2013; Matthews, 2002; Rendon-Velez, Horvath, & Van der Vegte, 2012; Rothengatter, 1988). Note, however, that a time constraint alone is not a necessary condition for speeding; the driver also has to believe it is important to complete the task in time (Benson & Beach, 1996; Coeugnet et al., 2013).

7.1.2 Models that describe how time pressure influences (driver) performance

A model of Wickens, Lee, Liu, and Gordon-Becker (2004) describes how (1) information input, (2) information-processing efficiency, and (3) task performance are influenced by external ‘stressors’ (such as pressure to complete a task in time). Specifically, Wickens et al.’s model illustrates that external stressors have direct influences on the quality of the information input and task performance (e.g., through increased levels of noise, lighting, or vibrations). The direct consequence of driving faster is that a higher amount of information has to be processed per unit of time. Thus, driving speed has a direct influence on the information input rate. Stress also has indirect psychological influences. For example, having to complete a task in a short amount of time could lead to high mental workload, anxiety, frustration, and anger, which in turn reduces information processing efficiency.

Maule and Hockey (1993) describe the effects of time pressure by means of a two-level control model. According to this model, the human cognitive system is self-regulatory. On the lower control level, small discrepancies between the current and target mental state are regulated by subconscious corrective actions (e.g., changes in speed, memory use, timing). When the discrepancy between the current and target state is large and subconscious control strategies are inadequate, control temporarily shifts to a higher level of cognitive (conscious) control (Maule & Hockey, 1993; see also Robert & Hockey, 1997). At this higher level, four modes are available to cope with high task demands: (1) increasing effort (trying harder) and accelerating control actions, (2) adopting a strategy that requires less effort, (3) changing the environment by removing stressors (e.g., re-negotiating the time deadline), or (4) doing nothing to reduce task demands (for further studies, see Edland & Svenson, 1993; Miller, 1960; Wright, 1974). When a driver adopts mode 1, this will be reflected in measures of speed as well as physiological measures associated with the activity of the sympathetic nervous system (Maule & Hockey, 1993). Modes 3 and 4 are usually not feasible when having to drive to a destination in a fixed amount of time, as the driver can control the state of his own vehicle in the environment but can hardly modify the environment itself. In this paper, our focus is on modes 1 and 2. That is, in the present study, we evaluated whether drivers modify their lateral/longitudinal driving behavior, posture, and gaze patterns by increasing their effort (mode 1) or by modifying their behavior in such a way that the driving task becomes easier to carry out (mode 2) while maintaining a high average driving speed in order to arrive at the destination in time.

7.1.3 Previous research that investigated the effects of time pressure on driving performance

Several previous studies have demonstrated the effects of time pressure on measures of driving performance. Van der Hulst, Rothengatter, and Meijman (1998) studied car following behavior in fog conditions using a driving simulator. Participants who were instructed to drive on a fixed time schedule showed less variability in their time headway due to decelerations of lead vehicles compared to a control group instructed to drive as they would normally do. The improved precision in the control of the vehicle suggests that the drivers adapted to the time constraint by increasing their level of alertness (Van der Hulst et al., 1998), an effect that corresponds to mode 1 (trying harder) in the model of Maule and Hockey (1993). Cnossen, Rothengatter, and Meijman (2000) instructed drivers to drive as fast as possible in a simulated environment. The results showed that participants had poorer lane keeping accuracy when they drove as fast as possible compared to when asked to adhere to the speed limits as if they were taking a driving test. In another driving simulator study, Zhai, Accot, and Woltjer (2004) found that drivers slowed down when they were required to maintain lane position accurately. Conversely, when the lane width increased, drivers were able to drive faster. These latter two studies suggest that the effects of time pressure can be described as a speed-accuracy tradeoff (see also Szalma, Hancock, & Quinn, 2008, for a meta-analysis on the effects of time pressure on measures of speed and accuracy).

Performance measures of speed and accuracy are advantageous for driver assessment applications because they represent an objective and observable state of the vehicle in its environment. Another advantage of these measures is that they are closely related to safety and accidents (Aarts & Van Schagen, 2006; Cooper, 1997; Lajunen, Karola, & Summala, 1997). A disadvantage of performance measures of speed and accuracy is that they cannot readily be used to identify whether a driver is subjected to time pressure or not, because these measures are highly situation-dependent (e.g., Cantin, Lavallière, Simoneau, & Teasdale, 2009). For example, a driver under time pressure may be stuck in a traffic jam, as a result of which speed/accuracy measures of driving performance are not informative at all. Similarly, a measure of lane keeping accuracy will be meaningless when a time-pressurized driver is frequently overtaking other road users.

7.1.4 The potential of psychophysiology for studying the effects of time pressure on car driving

When humans are subjected to stressors (such as time pressure), they tend to show a variety of physiological responses such as pupil dilation, increased heart rate, slowed digestion, and a constriction of blood vessels, mechanisms that are collectively known as the 'fight-or-flight' response (e.g., Cain, 2007; Kramer, 1991; Wickens et al., 2004). Furthermore, visual and cognitive tunneling occurs, referring to the fact that a stressed person stops carrying out secondary tasks and processes the cues that are most immediate and familiar (Hancock, 1989; Hancock & Szalma, 2008).

Various experimental studies in flight/driving simulators and real vehicles (e.g., Backs, Lenneman, Wetzel, & Green, 2003; Brookhuis & De Waard, 2010; Veltman & Gaillard, 1996) have measured physiological responses as a function of task demands. Examples include physiological measurements during the presence/absence of a secondary task (Mehler, Reimer, Coughlin, & Dusek, 2009), as a function of road infrastructure (Dijksterhuis, Brookhuis, & De Waard, 2011), or for different levels of automated driving (De Winter, Happee, Martens, & Stanton, 2014). An experiment by Cnossen et al. (2000) showed increased heart rates when participants drove as fast as possible compared to driving as accurately as possible.

Car driving is predominantly a visual task (e.g., Sivak, 1996), and a large body of research has evaluated the effects of task demands on drivers' visual scanning behavior (e.g., Crundall & Underwood, 1998; Recarte & Nunes, 2000; Reimer, 2009; Wikman, Nieminen, & Summala, 1998). In a driving simulator study, Rogers, Kadar, and Costall (2005) increased the task demands by increasing the driving speed during a straight-lane driving task. Their findings showed that participants, regardless of their level of driving experience, narrowed their gaze distribution when the driving speed was increased. Recently, remote eye trackers have shown to be promising tools for measuring the pupil dilation response as a function of cognitive task demands in low-cost measurement setups (Klingner, Kumar, & Hanrahan, 2008; Marquart & De Winter, 2015) as well as in driving simulators (Palinko, Kun, Shyrokov, & Heeman, 2010).

In addition to the human physiological response, time pressure also influences bodily posture and kinetics (Birch, Juul- Kristensen, Jensen, Finsen, & Christensen, 2000; Bongers, De Winter, Kompier, & Hildebrandt, 1993; Van Galen & Van Huygevoort, 2000). Using pressure sensors in the seat, Riener, Ferscha, and Matscheko (2008) found that drivers adjusted their posture in curves as a function of curve radius and driving speed. Tran and Trivedi (2010) showed using a vision-based motion tracking system that relaxed drivers took a more 'leaned back' posture, whereas concentrated drivers showed a more 'forward leaning' posture during a highway-driving task in a simulator.

7.1.5 The present study

In a driving simulator experiment, we evaluated two levels of time pressure: a baseline condition with no time pressure (NTP) and a time pressure (TP) condition in which drivers drove with a time constraint imposed on their driving task. Participants drove along an urban road in which various scenarios occurred: car following, overtaking an obstacle, and crossing intersections. We evaluated the effects of time pressure on a large number of dependent measures (including measures of eye movement, pupil diameter, cardiovascular and respiratory activity, driving performance, vehicle control, limb movement, head position, and self-reported status) to explore which of these measures are indicative of driving under time pressure.

Based on the models of Wickens et al. (2004) and Maule and Hockey (1993), we derived three broad hypotheses. Our first hypothesis was that drivers under time pressure drive at a higher speed and execute their tasks at a higher rate. This first hypothesis provides what is essentially a manipulation check as to whether, and to what extent, the task instructions cause participants to arrive at the destination in a shorter amount of time compared to driving without time pressure. We also investigated auxiliary measures of driving speed, such as braking and throttling activity, as well as lane keeping accuracy (accuracy was expected to decrease when driving faster, as predicted by the speed-accuracy tradeoff). The second hypothesis was that drivers react physiologically to the presence of the time pressure stressor. Although it is well established that stress causes signs of sympathetic arousal, what is less well known is which of the physiological measures are most sensitive to time pressure instructions in a car driving task. Furthermore, the present study exhibits several features that allowed us to test this hypothesis with a high level of spatiotemporal detail. Specifically, we synchronized the driving performance and physiological signals, allowing us to explore which of the measures are indicative of driving under time pressure at the different scenarios along the route. The third hypothesis was that drivers adapt their behavior by means of adjusting their driving strategy. As described above, we defined a change in strategy as a change in driving or visual behavior (other than simply driving faster) that allowed the driver to achieve the goal of arriving at the destination with greater effectiveness.

In the analysis, we put special emphasis on physiological data, because physiological data can provide a real-time assessment of the driver’s state without requiring an overt reaction from the driver (De Waard, 1996; Kramer, 1991). For example, it might be possible to detect an altered physiological state of a driver when the driving speed is restricted or when the driver does not physically move the wheel or pedals. Compared to vehicle-centered performance measures, measures based on human physiology can provide person-centered indicators of time pressure that may be of value in the development of driver monitoring and feedback applications (cf. Mehler et al., 2009; Reimer, 2009).

7.2 Methods

7.2.1 Participants

Fifty-six participants (48 males and 8 females) were recruited from the Delft University of Technology student and employee community. Participants were in possession of a valid driver's license and had normal or corrected-to-normal eyesight. Prior to the experiment participants filled out an 18-item intake questionnaire consisting of general items (age, gender, wearing glasses or contact lenses, medication, educational qualification, occupation), simulation-related items (playing computer games, prior experience in driving simulation, number of participated simulator experiments in the past), and driving experience items (e.g., driving frequency and mileage in the past 12 months, and accident involvement and traffic violations in the past 36 months). Some of these items were derived from the Driving Habits Questionnaire (Owsley, Stalvey, Wells, & Sloane, 1999).

Of the 54 participants who completed the experiment, there were 46 males (mean age = 28.5, *SD* = 4.3) and 8 females (mean age = 27.0, *SD* = 2.9). On average participants had their driving license for 9.1 (*SD* = 4.5) years, with a mean annual mileage of 6350 (*SD* = 8116) km. Three participants reported the use of medication (insulin, Aerius and folate, and paracetamol, respectively) and 18 participants wore contact lenses or glasses during driving. Twenty participants reported prior experience in a driving simulator, with a mean of 0.59 (*SD* = 1.12, N = 54) experiments per participant. For an overview of the results of the intake questionnaire, see Table 1. Before commencing the experiment, all participants provided written informed consent. The research was approved by the Human Research Ethics Committee of the Delft University of Technology.

Table 1. Distribution of participants (N = 54), for the frequency of playing computer games, driving frequency, and educational qualification

On average how often did you play computer or video games in the last 12 months?		On average, how often did you drive a car in the last 12 months?		What is your highest educational qualification?	
Every day	0	Every day	7	Primary / elementary school	1
4–6 days/week	3	4–6 days/week	5	Secondary / high school	0
1–3 days/week	3	1–3 days/week	14	Bachelor degree	15
About once a week	12	About once every two weeks	13	Postgraduate degree	38
Less than once a month	14	About once a month	7		
Never	22	Less than once a month	5		
		Never	3		

7.2.2 Apparatus

A fixed-base driving simulator (Green Dino, Wageningen, the Netherlands) was used in this experiment. The simulator cabin was equipped with the following components: steering wheel, ignition key, gear lever, single seat, and pedals. The steering wheel, pedals, gear lever, and indicators were obtained from a regular passenger car, and the dashboard, interior, and mirrors were integrated into the projected visuals, as shown in Fig. 1. Steering wheel force feedback was provided by a passive spring system. Surround sound was used to provide auditory wind, tire, and engine feedback. The simulator provided a horizontal field of view of 180 degrees by means of three projectors. The front view projection (front projector: NEC VT676) had a resolution of 1024 x 768 pixels, and the side views (side projectors: NEC VT470) featured a resolution of 800 x 600 pixels. The simulation ran at a frequency of 100 Hz, and the frame rate of the visual projection was estimated to be greater than 25 Hz (i.e., high enough to guarantee a smooth visual experience throughout the experiment).

Fig. 1. One of the experimenters in the driving simulator, with inertial sensors and eye tracker.

Eye and head movements were recorded using a Smart Eye eye-tracking system (software version 5.9), consisting of three remote mounted cameras (Sony XC-HR50) and two infrared illuminators. The data from the simulator and eye tracker were sampled and stored synchronously at 60 Hz. The participant's electrocardiogram (ECG) was obtained using a lead II configuration with three disposable snap electrodes and was recorded on a portable Mobi8 device (Twente Medical Systems International). The expansion of the thorax during inhalation and exhalation was measured using an inductive effort belt (Sleep Sense) worn around the chest. This belt was connected to a respiration effort sensor (RespiV6) which in turn was connected to the Mobi8 device. Both ECG and respiration data were received wireless and stored at 256 Hz. Limb movements were measured using four wireless inertial 3D motion trackers (Xsens MTw) placed at the ankles and wrists. The limb movement data were received wirelessly and stored at 75 Hz.

A trigger signal was sent when the clutch was pressed as the participant started the driving session. Using this trigger signal, data from the peripheral hardware were synchronized with the driving simulator data during post-processing.

7.2.3 Independent variable

The independent variable was the time constraint imposed on the driving task. In the no time pressure (NTP) session, the participant had sufficient time to complete the driving task. In the second session, time pressure (TP) was imposed by requesting the participants to complete the driving task within 80% of their NTP completion time, with a minimum of 7 min 20 s (defined as an absolute minimum according to pilot tests by the authors). Thus, the time constraint was different for each individual. In both sessions, the elapsed time was displayed on the virtual dashboard. Furthermore, during the NTP and TP sessions, auditory information was provided: the voice of a previously recorded fictitious ‘passenger’ was played back during both sessions. In the NTP session, the passenger was talking about casual things, while in the TP session, the passenger was complaining about being late and was motivating the participant to hurry up. In both sessions, the passenger sentences were uttered every 15 s.

7.2.4 Procedures

Prior to the simulator drives, participants received a paper handout explaining the experiment and procedures, and filled out the 18-item intake questionnaire. Additionally, participants filled out the Mini Driver Behavior Questionnaire (Mini-DBQ) to measure aberrant driving behaviors (Martinussen, Lajunen, Møller, & Özkan, 2013) and the Multidimensional Driving Style Inventory (MDSI) for assessing driving style (Taubman-Ben-Ari, Mikulincer, & Gillath, 2004). Next, participants watched a 5-min instruction video, explaining the driving simulator operation, the sensor instrumentation procedures, and the instructions for the training and NTP sessions. The video informed the participants only about the upcoming training and the NTP sessions, in order to ensure that participants were naïve to the specific instructions of the TP session while driving the training and NTP sessions. After watching the instruction video, the inertial motion trackers were attached to the ankles and wrists of the participants, and the three ECG electrodes were placed below the left and right clavicle and below the left pectoral muscle in a lead II configuration. The respiration belt was placed at the diaphragm level of the sternum and tightened sufficiently without causing discomfort.

Participants then seated themselves inside the driving simulator. Next, participants carried out a series of head movements and eye movements to calibrate the eye tracker. Participants completed three sessions in the following order: training session (T), no time pressure session (NTP), and time pressure session (TP). Before commencing with the training session, participants were told to relax, and the instructions regarding the training and NTP sessions were repeated orally by the experimenter. After having completed the NTP session, participants received a tablet showing the video instructions for the TP session. After each session, a 5-min break took place during which participants remained seated in the driving simulator. During these breaks, participants filled out the NASA task load index (TLX) for measuring workload (Hart & Staveland, 1988). Furthermore, participants filled out a questionnaire measuring their perceived time pressure, as well as a 6-item confidence questionnaire measuring their confidence in the driving task (see Section 7.2.8.5). The order of the driving sessions was not counterbalanced, to facilitate the individually adapted time constraint in the TP condition.

7.2.5 Driving task

Prior to the training session, participants received video instructions to drive straight ahead, to cross the intersections, and to overtake the obstacles when required. Participants were instructed to obey traffic rules and were informed that their lane was not a priority lane. For the NTP session, participants received instructions to drive safely and in a relaxed manner, as if they drove a fictitious friend to the airport without any time constraints. After the NTP session participants received oral and video instructions to drive to the airport with a time constraint. All sessions started with the vehicle from standstill at the center of the lane, and participants were requested to start the vehicle by pressing the clutch pedal. Participants were required to accelerate, brake, steer, and use the clutch and gear lever to operate the manual gearbox.

7.2.6 Driving environment

The driving environment consisted of an urban area with regular traffic conditions, identical in both the NTP and the TP sessions. The two-way road had a length of 6970 m and a lane width of 4 m. The road consisted of 17 segments and 16 intersections with stop signs and without traffic lights. Several traffic situations were triggered on passing specific positions in the virtual scenery. The traffic situations included: (1) free driving, (2) car following with traffic in the opposing lane, (3) obstacle overtaking with and without traffic in the opposing lane, and (4) intersections with and without approaching traffic. During the car following scenarios, traffic in the opposing lane prevented participants from overtaking the lead car. Traffic in the opposing lane during the obstacle overtaking events required participants to decelerate before the obstacle until the traffic in the opposing lane had passed the obstacle. During the intersection scenarios with traffic, participants were unable to cross the intersection until the traffic had cleared from the intersection. During the training session the environment was identical to the TP and NTP sessions, but included three additional obstacle overtaking scenarios. See Table 2 for an overview of the traffic scenarios during the three sessions and Fig. 2 for screenshots of the four scenarios.

Table 2. Overview of traffic scenarios

Scenario	Traffic condition	Starting positions (m)
Free driving	without traffic in opposing lane	1710, 2875
Intersection crossing	without traffic in intersection lane	810, 2635, 3775, 4100, 4935, 5260, 6100
	with traffic in intersection lane	180, 1135, 1680, 2005, 2845, 3150, 4305, 5470, 6425
Car following	with traffic in opposing lane	210, 2035, 3850, 4965, 5500
Obstacle overtaking	without traffic in opposing lane	1495, 3320*, 3980*, 4665, 6635
	with traffic in opposing lane	960, 2785, 3510, 4250, 4500*, 5410, 6250

*****Only during the training session.

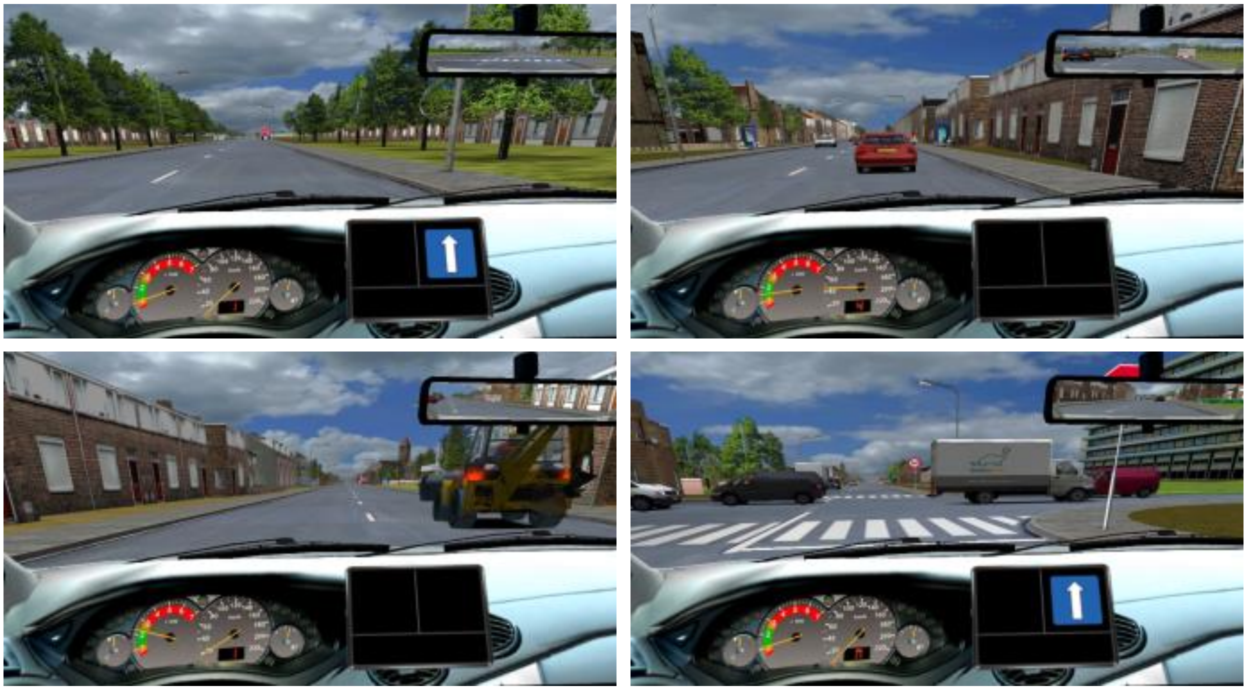

Fig. 2. Screenshots of the four traffic scenarios; free driving (top left), car following with traffic in the opposing lane (top right), obstacle overtaking without traffic in the opposing lane (bottom left), and intersection crossing with traffic in the intersection lane (bottom right). *Note*. The route guidance arrow was shown at each intersection.

7.2.7 Data processing

The driving simulator, eye-tracker, physiological, inertial, and force data were synchronized and re-sampled to 100 Hz prior to post-processing. Data were analyzed from the start of each session to the point where participants were 380 m past the final intersection (i.e., after having traversed 6835 m). At this location the end of the road was visible. The following postprocessing was performed on the recorded signals:

7.2.7.1 Steering signal

Steering signal data were low-pass filtered with a 3 Hz cut-off frequency, to remove the high frequency noise.

7.2.7.2 Eye movements and head movements

Eye movements and head movements were low-pass filtered with cut-off frequencies of 10 Hz and 5 Hz, respectively. Data loss with remote mounted eye trackers occurs when the system is unable to detect a participant's facial features, pupil, or corneal reflections due to an obstruction of the eye-tracker cameras or due to large head movements (e.g., Prado Vega, Van Leeuwen, Vélez, Lemij, & De Winter, 2013; Van Leeuwen, Gòmez i Subils, Ramon Jimenez, Happee, & De Winter, 2015; Van Leeuwen, Happee, & DeWinter, 2014). Eye closures were classified as a blink when the eye-opening was smaller than 50% of the participant's median eye-opening. Gaze data during blinks as well as data from 0.2 s before to 0.2 s after segments of missing data were removed. When more than 60% of data had to be removed, all the eye-tracker data of the respective session were removed from the analysis.

7.2.7.3 The pupil diameter

The pupil diameter is highly sensitive to illumination (Watson & Yellott, 2012). During the simulation, the illumination intensity was a function of the virtual environment and varied with the participant's location in the virtual world. The pupil diameter measurements were corrected for illuminance intensity at each traveled distance in the virtual scenery using measured illumination intensity data (see supplementary material).

7.2.7.4 Physiological data

Physiological data were filtered before further processing. Specifically, the ECG signal was high-pass filtered at 10 Hz, to remove low frequency drift from the signal. The resulting QRS complex of the ECG signal was de-noised using wavelets (Addison, 2005), and inter-beat intervals were extracted from the clean R-peak signal. The respiration rate signal was bandpass filtered (0.05–1 Hz) to remove the low frequency drift and high frequency noise from the signal. The resulting signal was used to calculate the inter-breath frequency from the time between two subsequent inhalation peaks.

7.2.7.5 Inertial sensor

Inertial sensor data were low-pass filtered with a 10 Hz cut-off frequency to remove the high frequency noise component.

7.2.8 Dependent measures

A number of dependent measures were calculated per session and per participant. The dependent measures were divided into the following categories:

7.2.8.1 Driving performance

Lane keeping accuracy and precision were defined as the mean lateral position (m) (left = positive) and the standard deviation of the lateral position (SDLP) (m), respectively (cf. Van Leeuwen et al., 2014). Obstacle overtaking maneuvers were excluded from these measures. Measures of vehicle speed (mean speed and maximum speed) (m/s) were used to capture driving style and task performance. During car following situations, the time headway (s) was determined (for headways smaller than 300 m with respect to the lead car), a measure which is indicative of tailgating behavior (Vogel, 2003).

7.2.8.2 Vehicle control

Mean absolute steering speed (deg/s) and throttle variance (minimum possible = 0, maximum possible = 0.25) were calculated as measures of steering and throttle activity. Furthermore, the mean number of gear changes and the mean number of brake applications were determined to represent the amount of control actions performed during the session. Finally, the maximum brake pedal position, on a scale of 0 (minimum) to 1 (maximum), was determined as a measure of braking performance (De Groot, De Winter, Wieringa, & Mulder, 2009). Mean limb accelerations (m/s^2) were determined by taking the mean of the square root of the sum of the squared x, y, and z components of the measured wrist/ankle accelerations. The limb acceleration measure is indicative of the driver’s control activity.

7.2.8.3 Eye movements and head movements

Gaze road center (GRC) (%) was calculated as the percentage of time that participants gazed within an approximately 8 deg radius from the road center. This measure is representative of the amount of gaze tunneling and has been demonstrated to be sensitive to secondary task demands (Van Leeuwen, Happee, & De Winter, 2013; Victor, Harbluk, & Engström, 2005). Additionally, we calculated the horizontal gaze variance (HGV; deg^2), representing the spread of visual search. The percentages of time that the participants were glancing at the dials and clock were calculated from the gaze vector with respect to predefined regions on the screen. These measures were used to verify the use of the simulated dashboard instruments and the clock showing the elapsed time in the session. The mean head position (m) was defined as the longitudinal component of the distance from the participants head to the top of the steering wheel (as determined by the eye-tracker system), and was regarded as a measure of driver posture.

7.2.8.4 Physiological responses

The mean eye blink frequency (Hz) and the mean pupil diameter (mm) were extracted from the eye-tracker data, as these measures are known to be sensitive to task demands (Beatty, 1982; Recarte, Pérez, Conchillo, & Nunes, 2008). From the respiratory measurements, the mean respiration rate (1/min) and the respiration amplitude (mm) were calculated. These measures have also been shown to be sensitive to emotions and task demands (Boiten, Frijda, & Wientjes, 1994; Wientjes, Grossman, & Gaillard, 1998). The mean heart rate (1/min) and the mean heart rate variability (HRV) were determined from the inter-beat intervals in the ECG signal. The HRV was calculated by dividing the standard deviation of the inter-beat interval by the mean inter-beat interval (De Waard, 1996). Measures of cardiac response are indicative of task demands (Backs et al., 2003; Cain, 2007).

7.2.8.5 Self-report measures

NASA TLX (0–100). The participants' self-reported workload was assessed with the NASA TLX questionnaire (Hart & Staveland, 1988) consisting of the following six items: mental demand, physical demand, temporal demand, performance, effort, and frustration. The response scale for each of the six items consisted of 21 checkboxes with anchors on the left (low), center (med), and right (high). For the performance item, the anchors good, med, and poor were used from the left to right.

Confidence (0–100). The participants' confidence was assessed using a confidence questionnaire consisting of the following six items: (1) ''I understood how to negotiate the driving situations presented in the simulation", (2) ''Driving in this environment was easy", (3) ''I performed well on driving the car (I was confident about my driving skills)", (4) ''I think I performed better than the average participant in driving to the airport", (5) ''I had a feeling of risk during driving", and (6) ''I feel confident to drive in similar conditions in the real world". These items were inspired from previous questionnaires assessing driver's confidence (De Craen, 2010; De Groot, De Winter, López-García, Mulder, & Wieringa, 2011; Ivancic & Hesketh, 2000; Wells, Tong, Genderton, Grayson, & Jones, 2008). The corresponding response scale consisted of 21 checkboxes with anchors on the left (strongly disagree), center (neither agree nor disagree), and right (strongly agree).

Simulator discomfort and time pressure. The simulator discomfort experienced by the participants was assessed by the following question: ''I have experienced motion sickness in this experiment (general discomfort felt, in cars or boats, during long trips)" on a five-point scale (1 = never, 2 = little, 3 = somewhat, 4 = much, 5 = very much). Furthermore, the sensation of time pressure during the experiment was assessed with three questions: (1) ''During driving I felt there WAS NOT enough time to drive and arrive to the airport", (2) ''During driving I felt that I have to hurry up", and (3) ''How much time pressure did you feel when driving?" on a five-point scale (1 = no pressure at all, 2 = a little pressure, 3 = moderate pressure, 4 = high pressure, 5 = very high pressure). Finally, to assess the participant's self-reported driving speed, participants were asked the following question: ''How fast did you drive in order to arrive at the airport?" (1 = not at all fast, 2 = a little fast, 3 = moderately fast, 4 = fast, 5 = very fast).

7.2.9 Statistical analysis

Means and standard deviations were computed over the complete session, as well as for individual scenarios (e.g., car following). Differences between sessions were statistically analyzed with paired t tests. The questionnaire results were fractionally ranked (Conover & Iman, 1981) over all sessions and participants, because of their skewed distributions. Results were declared significant if $p <$ 0.001. This conservative alpha value was used to reduce the probability of Type I error, in light of the large number of dependent measures. Correlations between the NTP and TP sessions were determined with the Pearson's correlation coefficient. Additionally, because data may be sensitive to outliers, Spearman's rank correlation coefficients were calculated.

7.3 Results

Two of the 56 participants aborted the experiment because of simulator discomfort; these participants were excluded from the analyses. For the remaining 54 participants (i.e., 54 NTP sessions and 54 TP sessions), 28.6% of the eye-tracking data were removed because of data loss. For 7 of these 108 sessions (3 NTP sessions and 4 TP sessions), the data loss exceeded 60%. Therefore, the eye-tracking data for these 7 sessions were removed entirely.

7.3.1 The effects of time pressure on the dependent measures

Table 3 shows the results for the training, NTP, and TP sessions for all driving performance, vehicle control, physiology, gaze, and self-report measures. Furthermore, *p* values and effect sizes are tabulated for comparisons between T and NTP, T and TP, and NTP and TP. Statistically significant differences between the NTP and TP sessions can be observed for all driving performance measures. That is, consistent with Hypothesis 1 (i.e., the manipulation check of the effects of time pressure), participants increased their speed during the TP session compared to the NTP session. Furthermore, drivers in the TP session drove significantly closer to the lead car during car following, had lower driving precision (i.e., a higher SDLP), and had faster control actions (i.e., an increase of steering speed, throttle variance, and number of brake operations). Specifically, in the TP session, drivers moved their limbs more rapidly, especially their right foot (which is used for operating the throttle) and their right hand (which is used for changing gears). No statistically significant differences were observed regarding the activity of the left hand, which is interpretable because the left hand serves no specific purpose on a road without curves.

Table 3. Means and standard deviations of the dependent measures for the training (T), no time pressure (NTP), and time pressure (TP) sessions. *p* values and effect sizes (in parentheses) are shown. The Pearson (r) and Spearman (ρ) correlation coefficients are indicated for comparisons between the NTP vs TP session (N = 54, but N = 50 for the gaze and pupil diameter measures). Effect sizes were determined as Cohen's $d_z = t/N^{0.5}$

Dependent measures	Session mean (*SD*)			*p* value (d_z)			Correlation	
	Training (T)	NTP	TP	T - NTP	T – TP	NTP -TP	*r*	*ρ*
Driving performance								
Completion time (s)	551.7 (51.9)	548.1 (38.3)	462.8 (34.6)	n/a	n/a	**<0.001** (2.83)	0.656	0.628
SDLP (m)	0.26 (0.09)	0.24 (0.08)	0.30 (0.14)	0.033 (0.30)	0.021 (-0.33)	**<0.001** (-0.49)	0.527	0.465
Mean lateral position (m)	-0.22 (0.2)	-0.16 (0.21)	-0.05 (0.25)	**<0.001** (-0.53)	**<0.001** (-0.90)	**<0.001** (-0.70)	0.764	0.763
Mean speed (m/s)	12.3 (1.2)	12.3 (0.9)	14.7 (1.1)	0.782 (-0.04)	**<0.001** (-1.98)	**<0.001** (-2.74)	0.669	0.631
Max speed (m/s)	26.6 (3.3)	24.7 (2.4)	30.5 (3.6)	**<0.001** (0.65)	**<0.001** (-1.07)	**<0.001** (-1.83)	0.490	0.500
Minimum time headway (s)	n/a	4.1 (2.9)	1.0 (0.6)	n/a	n/a	**<0.001** (-1.09)	0.215	0.293
Vehicle control								
Mean steering speed (deg/s)	8.02 (1.71)	7.63 (0.99)	8.36 (1.26)	0.070 (0.25)	0.116 (-0.22)	**<0.001** (-0.80)	0.684	0.755
Throttle variance (0–1)	0.051 (0.03)	0.043 (0.03)	0.107 (0.04)	0.009 (0.37)	**<0.001** (-1.91)	**<0.001** (-1.97)	0.669	0.664
Mean number of gear shifts (#)	65.3 (11.9)	63.9 (11.5)	59.4 (11.5)	0.142 (0.20)	**<0.001** (0.53)	0.002 (0.44)	0.602	0.617
Mean brake operations (#)	27.7 (5.2)	24.3 (5.4)	26.4 (5.2)	**<0.001** (0.59)	0.153 (0.20)	**0.001** (-0.47)	0.645	0.588
Max brake (0–1)	0.90 (0.04)	0.88 (0.07)	0.91 (0.02)	0.011 (0.36)	0.024 (-0.32)	**<0.001** (-0.57)	0.505	0.530
Mean acc. right hand (m/s^2)	0.059 (0.07)	0.041 (0.07)	0.068 (0.08)	0.005 (0.42)	0.037 (-0.30)	**<0.001** (-0.63)	0.850	0.807
Mean acc. right foot (m/s^2)	0.133 (0.04)	0.130 (0.04)	0.149 (0.04)	0.215 (0.18)	**<0.001** (-0.76)	**<0.001** (-0.91)	0.880	0.842
Mean acc. left hand (m/s^2)	0.065 (0.05)	0.061 (0.05)	0.066 (0.05)	0.374 (0.13)	0.533 (-0.09)	0.071 (-0.25)	0.947	0.919
Mean acc. left foot (m/s^2)	0.154 (0.06)	0.148 (0.06)	0.163 (0.07)	0.249 (0.17)	0.004 (-0.42)	0.002 (-0.45)	0.881	0.845
Gaze								
Gaze road center (%)	55.4 (12.5)	52.5 (12.5)	55.8 (11.2)	**<0.001** (0.52)	0.738 (-0.05)	0.056 (-0.28)	0.696	0.777
Horizontal gaze variance (deg^2)	60.8 (16.7)	68.8 (23.6)	76.9 (23.6)	**<0.001** (-0.67)	**<0.001** (-0.85)	0.003 (-0.44)	0.723	0.778
Percentage dials (%)	11.0 (11.2)	11.5 (10.9)	10.1 (11.5)	0.428 (-0.11)	0.143 (0.20)	0.035 (0.30)	0.906	0.742
Percentage clock (%)	1.48 (1.01)	1.31 (1.00)	2.25 (1.06)	0.120 (0.22)	**<0.001** (-0.67)	**<0.001** (-0.86)	0.423	0.346
Missing eye-tracker data (%)	26.7 (16.4)	29.1 (15.3)	28.4 (16.7)	0.039 (-0.29)	0.152 (-0.20)	0.674 (0.06)	0.849	0.787

(table continues)

Table 3. Continued

Physiology								
Mean blink rate (Hz)	0.24 (0.15)	0.29 (0.15)	0.24 (0.11)	**<0.001** (-1.09)	0.077 (-0.26)	**0.001** (0.50)	0.852	0.833
Mean pupil diameter (mm)	5.38 (0.69)	5.19 (0.68)	5.37 (0.66)	**<0.001** (1.47)	0.565 (0.08)	**<0.001** (-0.94)	0.956	0.951
Mean respiration rate (1/min)	20.6 (2.07)	19.0 (2.65)	20.3 (2.70)	**<0.001** (1.08)	0.097 (0.23)	**<0.001** (-0.81)	0.840	0.847
Mean respiration amplitude	12.7 (3.18)	12.0 (2.73)	12.2 (2.71)	0.014 (0.35)	0.243 (0.16)	0.292 (-0.15)	0.876	0.856
Mean heart rate (1/min)	82.1 (12.8)	79.2 (12.3)	82.1 (12.9)	**<0.001** (1.01)	0.924 (-0.01)	**<0.001** (-0.78)	0.956	0.954
Mean HRV (-)	0.069 (0.02)	0.068 (0.02)	0.071 (0.02)	0.391 (0.12)	0.249 (-0.16)	0.021 (-0.33)	0.844	0.803
Mean head position (m)	0.764 (0.05)	0.767 (0.05)	0.764 (0.05)	0.023 (-0.33)	0.918 (0.01)	**<0.001** (0.50)	0.993	0.987
Subjective measures								
Motion sickness (1–5)	1.89 (0.98)	1.70 (0.96)	1.70 (0.98)	0.032 (0.30)	0.077 (0.25)	1.000 (0.00)	0.921	0.894
Not enough Time (1–5)	1.76 (0.87)	1.37 (0.56)	3.98 (0.79)	**<0.001** (0.50)	**<0.001** (-1.88)	**<0.001** (-2.42)	-0.283	-0.245
Hurry feeling (1–5)	2.09 (0.92)	1.61 (0.74)	4.28 (0.76)	**<0.001** (0.56)	**<0.001** (-1.84)	**<0.001** (-2.41)	-0.106	-0.019
Fast arrival (1–5)	1.67 (0.87)	1.70 (0.74)	3.74 (0.85)	0.766 (-0.04)	**<0.001** (-1.69)	**<0.001** (-1.93)	0.115	0.159
Time pressure (1–5)	1.50 (0.64)	1.35 (0.55)	3.69 (0.91)	0.146 (0.20)	**<0.001** (-2.36)	**<0.001** (-2.53)	0.262	0.234
Understanding (0–100)	84 (15)	87 (12)	78 (20)	0.115 (-0.22)	0.054 (0.27)	**<0.001** (0.49)	0.466	0.604
Was easy (0–100)	66 (26)	78 (19)	63 (23)	**<0.001** (-0.60)	0.320 (0.14)	**<0.001** (0.70)	0.417	0.477
Performed well (0–100)	61 (25)	72 (20)	61 (26)	**<0.001** (-0.57)	0.936 (0.01)	**0.001** (0.47)	0.478	0.441
Performed above average (0–	46 (17)	53 (18)	46 (23)	**<0.001** (-0.53)	0.943 (-0.01)	0.005 (0.41)	0.656	0.603
Feeling of risk (0–100)	36 (27)	23 (21)	53 (28)	**<0.001** (0.67)	**<0.001** (-0.64)	**<0.001** (-1.08)	0.370	0.366
Confident (0–100)	84 (21)	85 (18)	65 (26)	0.817 (-0.03)	**<0.001** (0.80)	**<0.001** (0.94)	0.580	0.626
Mental demand (0–100)	52 (21)	39 (23)	59 (20)	**<0.001** (0.71)	0.008 (-0.38)	**<0.001** (-1.22)	0.690	0.650
Physical demand (0–100)	27 (18)	23 (16)	38 (22)	0.033 (0.30)	**<0.001** (-0.76)	**<0.001** (-0.89)	0.613	0.672
Temporal demand (0–100)	28 (22)	20 (16)	71 (16)	0.012 (0.36)	**<0.001** (-2.17)	**<0.001** (-2.68)	0.290	0.220
Performance (0–100)	62 (26)	68 (25)	47 (25)	0.036 (0.30)	0.002 (-0.45)	**<0.001** (-0.62)	0.154	0.183
Effort (0–100)	44 (25)	33 (19)	64 (16)	**<0.001** (0.64)	**<0.001** (-0.87)	**<0.001** (-1.54)	0.341	0.304
Frustration (0–100)	30 (23)	21 (20)	49 (27)	**<0.001** (0.59)	**<0.001** (-0.75)	**<0.001** (-1.16)	0.503	0.474

The results show a significantly higher workload on each of the six items of the NASA TLX for the TP versus the NTP session. Among the 17 self-report measures, the largest effects (|dz| > 2.0) of NTP versus TP were observed for the time-related measures (i.e., not enough time, feeling of hurry, time pressure, and temporal demand). Thus, our time pressure manipulation was successful in the sense that participants in the TP condition drove faster and experienced a greater feeling of hurry, time pressure, and temporal demand than in the NTP condition.

Consistent with Hypothesis 2, participants exhibited physiological reactions that represent an increase of sympathetic arousal. Statistically significant differences were observed for each of the physiological measures, except for the mean respiration amplitude and the mean HRV. The mean blink rate decreased, while the mean pupil diameter, mean respiration rate, and mean heart rate increased from the NTP to the TP session. Additionally, drivers sat slightly (but statistically significantly) closer to the steering wheel in the TP session compared to the NTP session. Table 3 further shows that the session-averaged horizontal gaze variance and percentage road center were not significantly different for the TP session compared to the NTP session. The time spent gazing at the in-vehicle clock increased when participants drove in the TP session compared to the NTP session, most likely because the clock contained task-relevant information in TP condition.

The comparisons of physiological responses between the NTP and TP session had a medium effect size ($d_z = 0.5$) for the mean blink rate and a large effect size for the mean pupil diameter ($d_z = 0.9$). These effect sizes were comparable to the effect sizes of the vehicle control measures shown in Table 3.

Correlation coefficients between the NTP and TP sessions are shown in Table 3. Correlations were about 0.5–0.6 for the vehicle control measures and about 0.8–0.9 for the physiological measures. Fig. 3 illustrates the correlation coefficient between the NTP and TP sessions for the mean speed (left), mean blink rate (center), and mean pupil diameter (right). Statistically significant effects of the time pressure manipulation are visible in all three figures. Furthermore, Fig. 3 signifies that the differences between individuals are substantially larger than the effects within individuals due to time pressure.

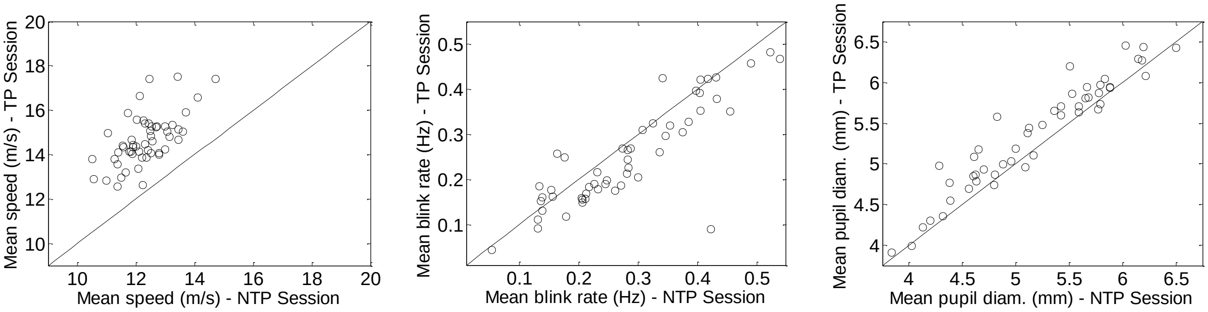

Fig. 3. Correlation between mean speed (left, *N* = 54), blink rate (center, *N* = 54), and pupil diameter (right, *N* = 50) between the No time pressure (NTP) and Time pressure (TP) sessions. The correlation coefficients are shown in Table 3.

Table 4. Pearson correlation matrix (N = 54) for driving performance, physiological, and self-reported workload measures. Correlations per measure were determined by taking the difference between the time pressure (TP) and no time pressure (NTP) sessions

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Mean speed (m/s)															
Max speed (m/s)	**.39**														
SDLP (m)	**.43**	.13													
Mean steering speed (deg/s)	**.56**	**.39**	**.66**												
Throttle variance (0–1)	**.60**	**.57**	**.32**	**.51**											
Mean acc. right hand (m/s^2)	**.29**	**.33**	**.31**	**.48**	**.35**										
Mean acc. right foot (m/s^2)	**.45**	**.36**	**.35**	**.48**	**.55**	**.48**									
Mean pupil diameter (mm)	**.36**	.26	**.37**	**.39**	**.29**	.14	.20								
Mean blink rate (1/s)	-.06	.07	.21	.06	-.05	.09	.01	**-.34**							
Percentage clock (%)	-.15	-.02	-.04	.10	-.13	.06	-.06	.00	-.23						
Percentage dials (%)	-.23	**-.47**	-.22	**-.28**	**-.36**	-.11	**-.27**	.13	**-.49**	.26					
Hor. gaze variance (deg^2)	.04	.01	**.37**	**.34**	.02	.15	.06	-.05	**.30**	.17	-.10				
Mean heart rate (1/min)	.04	**.34**	.06	.18	.26	.15	.18	**.41**	-.01	-.01	-.13	.10			
Mean respiration rate (1/min)	.21	**.28**	.03	.15	**.29**	.10	.04	**.40**	-.11	-.02	.13	.05	.21		
TLX mental demand (0–100)	.23	.19	**.28**	**.40**	**.28**	-.11	.15	**.49**	-.09	.00	-.05	.10	.12	.18	

Note: Correlations of magnitude greater than .27 correspond to $p < 0.05$ and are in boldface.

7.3.2 The relative validities of the physiological measures

A correlation matrix for the within-subject difference between the NTP and TP sessions is shown in Table 4 and Table S.1. This correlation matrix shows a positive manifold among the mean speed, maximum speed, SDLP, mean steering speed, throttle variance, mean pupil diameter, and the mental demands item from the NASA TLX. Thus, the mean pupil diameter exhibits relative validity with respect to driving performance measures and self-reported mental workload.

Several of the correlations listed in Table 4 are illustrated in Fig. 4. The correlations of the pupil diameter and mean speed (left), pupil diameter and mental demands (NASA TLX) (center), and pupil diameter and heart rate (right) are depicted. The figures show that an increase in pupil diameter was moderately associated with an increase in driving speed, heart rate, and mental demands (NASA TLX). For example, Fig. 4 (right) shows that people who showed a large increase in mean heart rate generally also showed a large increase in mean pupil diameter.

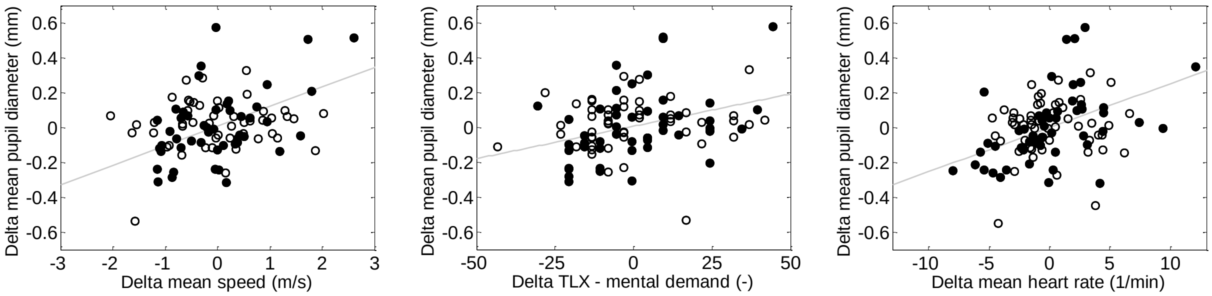

Fig. 4. Correlation between session differences of pupil diameter and mean speed (left, *N* = 50), pupil diameter and mental demand (NASA TLX) (center, *N* = 50), and pupil diameter and heart rate (right, *N* = 50). Session differences between the Training (T) and No time pressure (NTP) sessions are indicated by unfilled markers and session differences between the Time pressure (TP) and NTP session are indicated by filled markers. Session differences were determined with respect to the session mean. Linear fits calculated from session differences between the TP and NTP session are shown as gray lines.

7.3.3 The effects of time pressure during traffic scenarios

7.3.3.1 Physiological signals versus traversed distance along the route

Fig. 5 shows an overview of 11 selected measures as a function of traveled distance in the NTP and TP sessions. This figure illustrates the difference between the NTP and TP session for the various types of scenarios along the route (see Table 2, for an overview of the traffic scenarios).

Consistent with Table 3 and Hypothesis 1, drivers in the TP session drove with higher average speeds and throttle positions than they did in the NTP session. However, this was not the case during the car following scenarios, where the participants were held up by a lead car that was driving at constant speed. It can also be seen that participants braked harder before intersections during the TP session than during the NTP session, which can be explained by their higher approach speed and their attempt to brake late in order to prevent time loss. Fig. 5 also shows that limb movement occurred particularly when approaching and leaving intersections, associated with accelerating, braking, and gear changing.

Consistent with Hypothesis 2 (effects on physiological measures), Fig. 5 shows an overall increase in pupil diameter, respiration rate, and heart rate during the TP session compared to the NTP session. Fig. 5 also shows a slightly more forward posture (indicated by a lower longitudinal head position). It can also be seen that the participants moved the head forward, on average about 1 cm, when approaching an intersection.

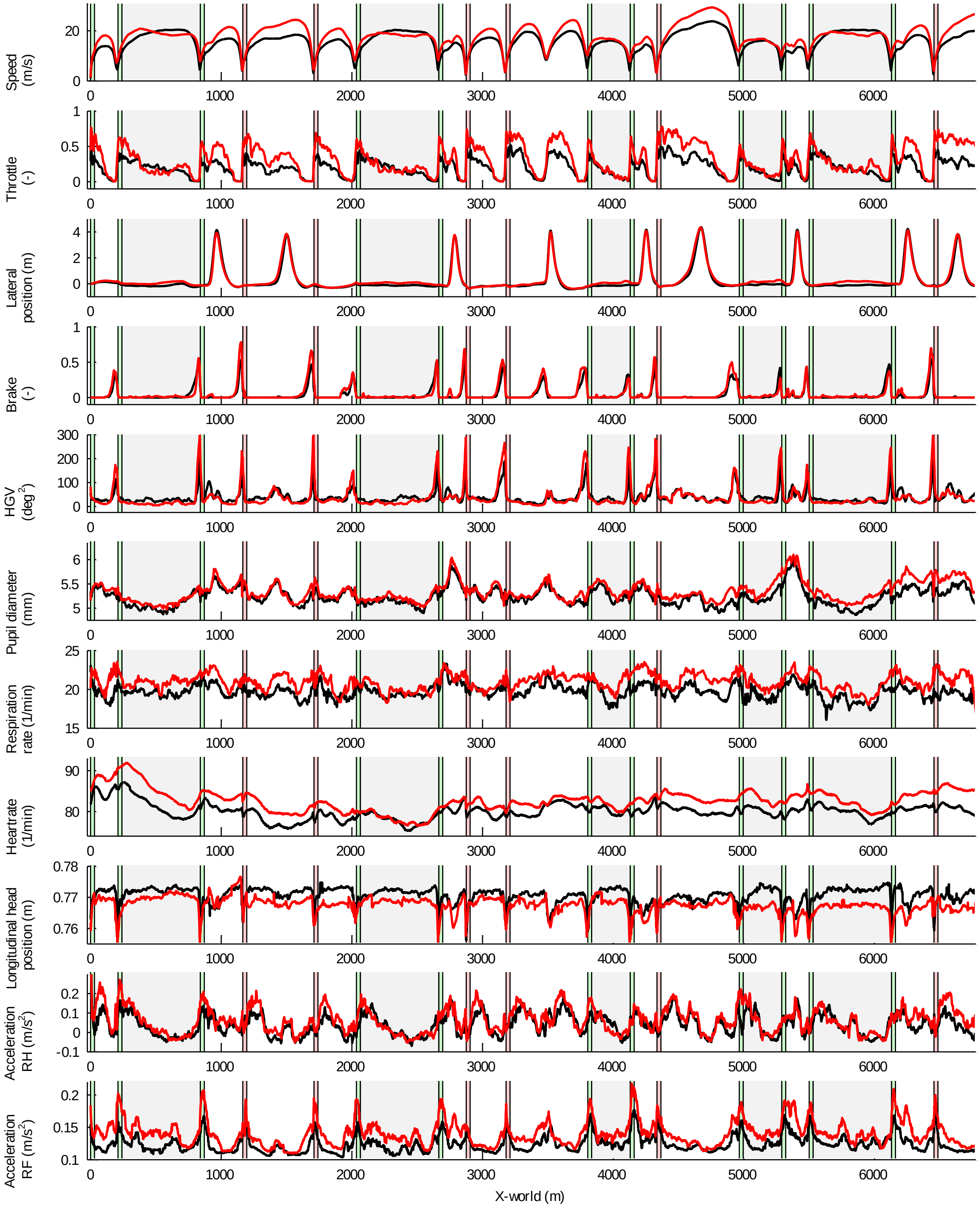

Fig. 5. Means of 11 signals as a function of travelled distance for the No time pressure (NTP; black) and Time pressure (TP; red) sessions. The speed, lateral position, throttle position, and brake position were determined using a spatial sliding window of 4 m. The horizontal gaze variance (HGV), pupil diameter, respiration rate, heart rate, head position, and limb accelerations were determined using a temporal sliding window of 3 s. The intersections with and without traffic are indicated by green and red shading, respectively. Car following situations are indicated by gray shading and the overtaking maneuvers can be identified by lateral positions exceeding 2 m.

Regarding Hypothesis 3, several strategies can be observed. First, participants showed a higher (i.e., more to the left of the road) lateral position during car following for the TP session compared to the NTP session. This might represent a useful strategy to be able to change lanes quickly as soon as the left lane is free from traffic, or a previously learned strategy to signal to other road users that one is in a rush and wants to overtake the lead car (see e.g., Portouli, Nathanael, & Marmaras, 2014, for the communicative strategies that drivers use in traffic). Second, the increase in horizontal gaze variance (HGV) when approaching the intersections, which was most pronounced during the TP session, indicates that participants widened or accelerated their visual search. This behavior might represent an increased lookout, similar to the fact that participants adopted a more forward posture when approaching intersections.

In the following sections, we zoom in and describe the distance-based effects for three scenarios: obstacle overtaking, intersection crossing, and car following.

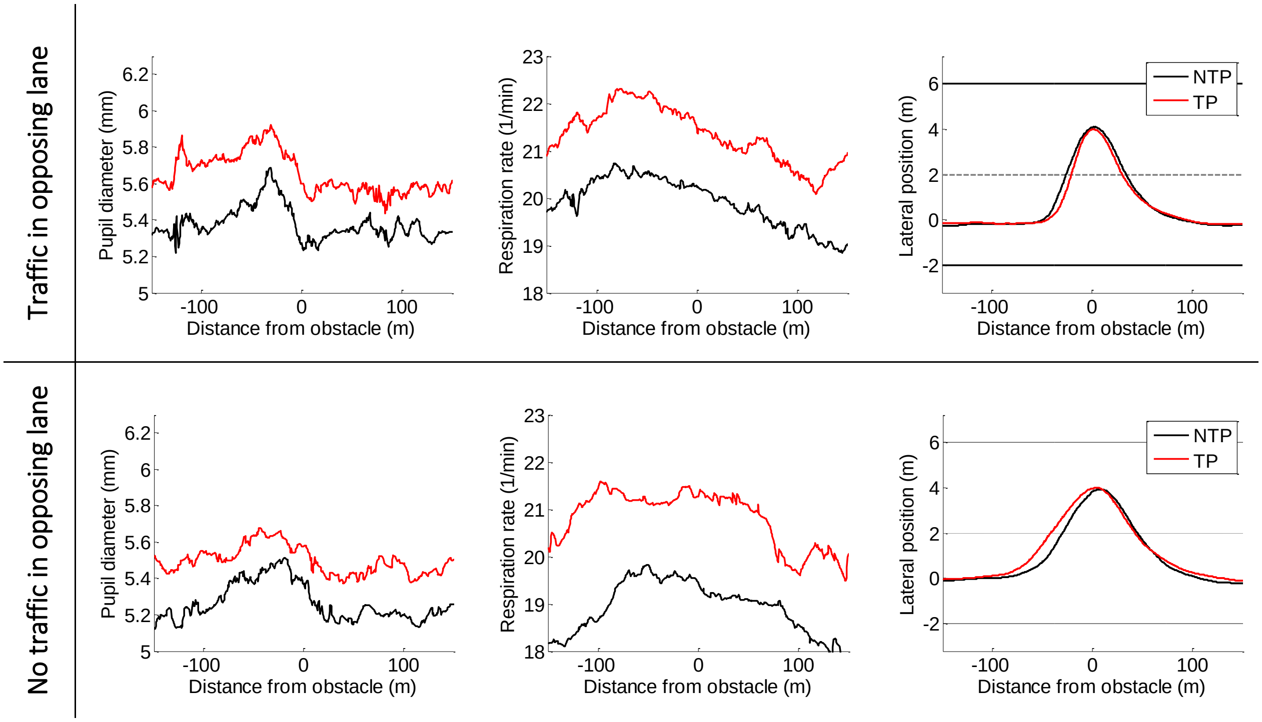

Fig. 6. Mean pupil diameter (left), mean respiration rate (center), and mean lateral position (right) for NTP (black) and TP (red) during overtaking maneuvers with traffic approaching in the opposing lane (top) and without traffic in the opposing lane (bottom). In the right two figures, the black lines indicate the lane boundaries and the dashed gray line indicates the road center line. The measures were averaged across all obstacle overtake maneuvers and participants. The measures were determined using a spatial sliding window of 0.5 m.

7.3.3.2 Obstacle overtaking

Fig. 6 shows the pupil diameter, respiration rate, and lateral position for both the NTP and TP sessions during the obstacle overtaking scenarios. Consistent with Hypothesis 2, participants showed an increased mean pupil diameter when approaching the obstacle, both in the overtaking scenario with traffic in the opposing lane (top left figure) as well as in the scenario without traffic in the opposing lane (bottom left figure). The respiration rate shows an increase prior to the overtaking maneuver and a decrease thereafter (middle two figures).

The lateral position shows that when traffic was present in the opposing lane, participants in the TP session initiated their overtaking maneuver later compared to the NTP session (right top figure). However, when no traffic was present in the opposing lane, the participants in the TP session initiated their overtake maneuver earlier compared to the NTP session (right bottom figure). In the context of Hypothesis 3, this can be interpreted as a strategy to complete the task as quickly as possible in a safe manner. That is, without traffic, it makes sense to change lanes early in order to minimize the traveled distance and to maximize the smoothness of travel.

7.3.3.3 Intersection crossing

Fig. 7 shows the mean speed, mean brake position, mean horizontal gaze variance, and mean respiration rate for both the NTP and TP sessions during the intersection-crossing scenarios. Consistent with Hypothesis 1 (manipulation check), TP resulted in an increased driving speed, increased intersection approach speed, and faster acceleration after crossing the intersection compared to the NTP session, both for the intersections with and without traffic. Consistent with Hypothesis 2 (physiological effects of time pressure), for both intersection types, the respiration rate was higher for the TP session than for the NTP session. A distinct pattern can be observed here, with the respiration rate rising upon approaching the intersection (see also Fig. 5, demonstrating a distance-based synchrony of the TP and NTP sessions for several of the physiological measures).

Drivers in the TP session braked later when there was no traffic on the intersection, and earlier when traffic was present on the intersection, compared to the NTP session. This strategy can be explained as follows: If the approach speed is higher and there is crossing traffic at the intersection, it makes sense to brake early, because one has to stop before the crossing traffic. However, if there is no traffic, then braking is not required and deceleration has a negative effect on the overall mean speed. The horizontal gaze variance increases in both intersection types during both the NTP and TP sessions, which indicates that participants scanned the intersection before crossing the intersection. Furthermore, participants in the TP session initiated their visual search earlier while approaching the intersection compared to the NTP session, as can be seen in the increasing horizontal gaze variance before the intersection for both intersection types. This altered visual scanning behavior when approaching intersections may be a strategy (Hypothesis 3) to acquire a maximal amount of visual information, in an attempt to minimize risk when crossing intersections with high speed.

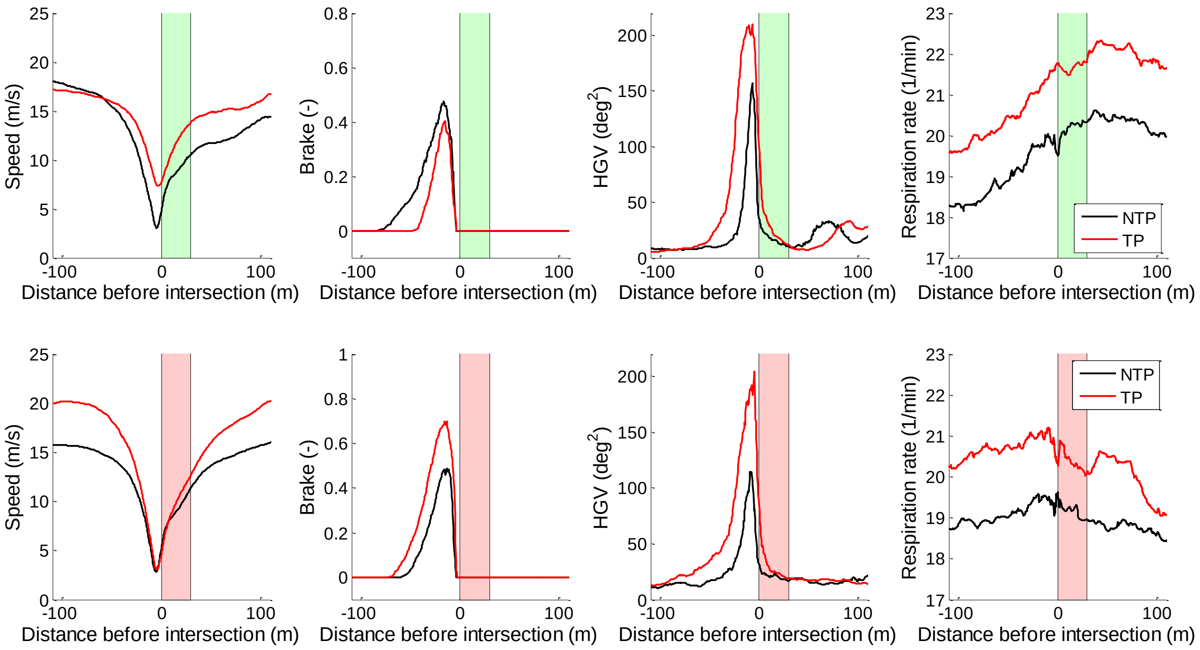

Fig. 7. Speed (far left), brake (left), horizontal gaze variance (right), and respiration rate (far right) before intersections without (top) and with traffic (bottom) on the intersection. Color shaded regions indicate the intersecting lane, with green and red corresponding to intersections without and with traffic, respectively. The measures were determined using a spatial sliding window of 0.5 m. Additionally, for each 0.5 m, the horizontal gaze variance was determined using a temporal window of 3 s.

7.3.3.4 Car following

Fig. 8 shows the distribution of the lateral position, time headway, and throttle position for the NTP and TP sessions during the car following scenarios. During these scenarios, participants followed a lead car that had a constant speed. Fig. 8 (left) shows a probability distribution function indicating that, during the TP session, participants drove more toward the left of the lane than during the NTP session, possibly representing a strategy that prepares for overtaking or that signals to other road users that he/she is in rush (see also above). Fig. 8 (center) illustrates the smaller time headway adopted by participants in the TP session compared to participants in the NTP session. Fig. 8 (right) shows the throttle position for participants in both sessions. Participants in the TP session more often applied full throttle than participants in the NTP session. At first sight, this behavior seems to serve no functional purpose as the lead car’s speed was constant, but it may be a preparatory strategy allowing participants to overtake as soon as the traffic in the adjacent lane is free.

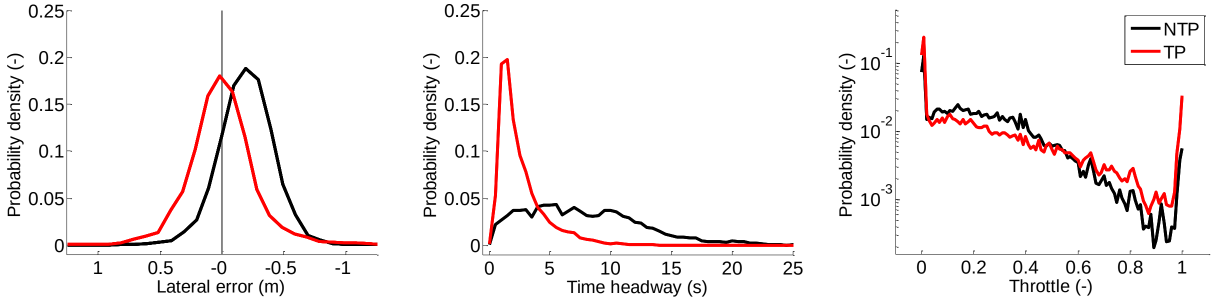

Fig. 8. Distributions of the lateral position (left), time headway (center), and throttle position (right, displayed on a logarithmic scale) during the car following scenarios. The distributions were determined by grouping the data across all participants in 0.1 m, 0.5 s, and 1% bins for the lateral position, time headway, and throttle, respectively.

In Fig. 9, a heat map showing the gaze distribution during car following illustrates the increased gaze tunnelling of drivers' gaze. A significant difference in percentage road center ($t(49) = 4.25$, $p < 0.001$) was found during the car following scenario between the NTP session (M = 57.9%, *SD* = 14.3%) and the TP session (M = 66.7%, *SD* = 16.9%). The reduced gaze variance during the car following scenarios is indicative of increased gaze tunnelling during the TP session compared to the NTP session.

Fig. 9. Heat map of gaze probability density during car following in the No time pressure (NTP; left) and Time pressure (TP; right) sessions, overlaid on a screenshot of the simulator display. Gaze distributions were determined by aggregating gaze data from car following sections of all participants in one-by-one degree bins and are shown on a logarithmic scale.

7.4 Discussion

This study explored the effects of time pressure on measures of driver physiology, driving performance, and vehicle control. We formulated three broad hypotheses: (1) When under time pressure, drivers show an increase of speed and an acceleration of control actions, (2) When under time pressure, drivers show increased signs of sympathetic arousal, that is, increased physiological activity, and (3) When under time pressure, drivers demonstrate various strategic behaviors that allow them to complete the driving task more effectively while minimizing the risk of crashing.

7.4.1 Hypothesis 1: Effects of time pressure on speed

Regarding the first hypothesis, it is concluded that the time pressure instructions clearly had the expected effect. Looking at Table 3, the four largest effect sizes between NTP and TP ($|d_z| > 2.5$) among the 44 dependent variables were observed for (1) the task completion time itself, (2) the mean speed (which is highly correlated with the reciprocal of task completion time), (3) the self-reported time pressure, and (4) the self-reported temporal demand. These observations indicate that a driving simulator setup can elicit strong behavioral effects when drivers are exposed to a temporal constraint.

Various measures that are causally related to driving speed, such as throttle variance, activity of the right foot, maximum brake position, and mean absolute steering speed, were also higher for TP compared to NTP. These effects can be explained through classical mechanics. For example, when approaching an intersection with high speed and having to come to a standstill, a greater brake pedal pressure is required compared to when approaching with low speed. Similarly, when accelerating to high speed, a high throttle position is a prerequisite.

Another expected finding was that the lane keeping precision was poorer in the TP session compared to the NTP session. This indicates that a speed-accuracy tradeoff existed (cf. Szalma et al., 2008; Zhai et al., 2004). A reduction of lane keeping precision is also consistent with results from, for example, Engström, Johansson, and Östlund (2005), who found increased SDLP values when visual demands were increased by a secondary visual task.

7.4.2 Hypothesis 2: Effects of time pressure on physiological measures

Consistent with Hypothesis 2 and the stress model of Wickens et al. (2004), the time pressure ‘stressor’ resulted in increased physiological activity such as increased heart rate, increased respiration rate, increased pupil diameter, and decreased blink rate for participants in the TP session versus the NTP session. The strongest effects were observed for the pupil diameter, the respiration rate, and the heart rate. Our findings of heart rate and respiratory rate are in line with previous transportation research on the effects of secondary tasks during driving. For example, Mehler et al. (2009) found increased heart rates and respiration rates in 121 participants when performing an n-back mental task in a driving simulator compared to a control condition without secondary task. Our results regarding the pupillary response and blink rates are similar to the literature as well. For example, Recarte et al. (2008) found an increase in pupil diameter and a reduction of blink rate when drivers performed a secondary visual task.

Participants directed their gaze more at the lead car during the TP session than during the NTP session. Such gaze tunneling occurs when participants attend to their primary task and disregard secondary tasks (Crundall, Shenton, & Underwood, 2004; Hancock, 1989; Recarte & Nunes, 2003; Williams, 1988). In the present experiment, gaze tunnelling might signal a strategy in which the participant focuses acutely on the car in front, explained by the closer following distance which required drivers to be more alert on the behavior of the lead vehicle.

Although the effects for the different physiological measures were mostly similar to each other and in the expected direction, each of these measures has unique strengths and weaknesses. For example, consistent with previous research in memory tasks and arithmetic tasks (e.g., Beatty, 1982; Klingner, 2010; Marquart & De Winter, 2015), pupil diameter has the advantage that it responds within a few tenths of second to changes in task demands, and that it can reach a peak dilation of 0.5 mm in as little as 1 s. It should be noted, however, that fluctuations in pupil diameter might be confounded by environmental lighting and gaze direction (e.g., Beatty, 1982; Klingner, 2010). The heart rate has lower temporal sensitivity, and therefore is less suitable for assessing the effect of scenarios. Specifically, the mean inter-beat interval is 0.75 s, and it takes at least several beats to detect a change in heart rate (Jorna, 1992; Rowe, Sibert, & Irwin, 1998).

It is interesting that HRV, which has been said to be a valid index of time pressure (Nickel & Nachreiner, 2003), did not decline under TP. We believe that there are two main issues with the use of HRV. First, many different operationalizations of HRV exist (Task Force of the European Society of Cardiology & the North American Society of Pacing & Electrophysiology, 1996), such as frequency domain approaches, successive differences of inter-beat intervals, or average variability of inter-beat intervals (as employed in the present study). Second, HRV is difficult to interpret unless the task is constant with time. In our study, the task was dynamic, featuring various points along the route where the situation changed (e.g., car following, coming to a standstill). Thus, using heart rate variability for a task that itself varies as a function of time creates difficulties in interpretation.

One may argue that it is not surprising that time pressure elicited signs of sympathetic arousal. While this may be true, what is unique in our research is that we synchronized a large number of physiological measures with measures of driving performance and vehicle control. This allowed us to compare the differences between the NTP and TP sessions as a function of traveled distance along the route. Furthermore, we assessed the magnitude of inter-individual and found strong correlations between the two sessions ($r > 0.8$, see Table 3 and Fig. 3), indicating that the effects of time pressure should be interpreted as relative changes within individuals rather than changes on an absolute scale. Furthermore, we demonstrated the relative validities of the physiological measures. For example, people who showed a greater increase in mean speed were generally also those people who showed the greater increase in pupil diameter (Table 4).

7.4.3 Hypothesis 3: Effects of time pressure on driving strategy

Consistent with Hypothesis 3 and the model of Maule and Hockey (1993), drivers adapted their driving strategies to the time constraint. For example, in the TP session, drivers drove more to the left of the right lane than in the NTP session, an effect that was particularly pronounced during car following. Presumably, drivers were maintaining a lateral position closer to the left lane in order to prepare for an overtaking maneuver. Another explanation is that participants drove to the left to signal to the lead car that they were in a rush.

A second change in strategy was observed when participants overtook obstacles and when crossing intersections. Specifically, in the TP session when no traffic was present in the opposing lane, participants made the overtaking maneuver earlier than in the NTP session. A similar effect could be seen in the intersection scenario, where participants in the TP session braked later compared to the NTP session when no traffic was present on the intersection, and braked earlier compared to the NTP session when traffic was present on the intersection. Presumably, participants in the TP session used these strategies to minimize the overall time to complete the session. Furthermore, at intersections, participants in the TP session adopted a more forward seating posture and showed greater gaze variance, possibly in an attempt to scan the intersection for oncoming traffic more rapidly before crossing it.

A third strategy was identified during car following, during which participants in the TP session showed a high throttle activity despite the fact that the lead car speed was constant. Note that some of these behaviors are nonfunctional in the driving simulator. For example, the other traffic did not adapt to the participant’s behavior in any way (and so gestures or signaling did not have an effect). Collectively, these strategies under time pressure represent behaviors that may seem irrational, but serve the higher-order purpose to complete the task quickly yet safely.

7.4.4 Implications of our research for driver assessment applications

The results of our experiment showed strong and statistically significant changes in physiological measures when drivers experienced time pressure. These findings provide support for the potential implementation of physiological measurements as estimators of driver’s task demands (see also Brookhuis & DeWaard, 2010; Mehler et al., 2009). The mean pupil diameter, mean heart rate, and mean respiration rate demonstrated a particularly strong effect as a function of time pressure. The vehicle-derived performance measures also showed strong effects of time pressure, but exhibited a strong context dependency. For example, during car following the participants’ driving speeds were about equal to the speed of the lead car. Furthermore, our experiment illustrated that, on an absolute scale, within-subject effects of time pressure are small compared to between-subject differences. This phenomenon implies that changes in driver state can only be detected at the individual level (see also Brookhuis, De Waard, & Fairclough, 2003; Matthews, Reinerman-Jones, Barber, & Abich, 2014; Mulder, Dijksterhuis, Stuiver, & De Waard, 2009). That is, physiological measures have to be corrected for individual differences if they are to be used in real-time driver assessment applications.

7.4.5 Limitations

Our experiment is affected by several limitations. First, the order of the NTP and TP sessions was not counterbalanced because the time constraint was determined on an individual basis. Thus, our protocol did not control for learning effects and other types of carryover effects. However, this limitation can be countered, because the majority of the dependent measures showed a decreasing trend from the training to the NTP session (which, indeed, can likely be attributed to learning and acclimation) but an increasing trend from the NTP to the TP session. For example, the mean pupil diameter was 5.38 mm, 5.19 mm, and 5.37 mm in the T, NTP, and TP sessions, respectively. Such a U-shaped pattern across the three sessions is apparent for all seven physiological measures, as illustrated in Fig. 10. This pattern of results suggests that the physiological response is not a methodological artifact caused by time-on-task.

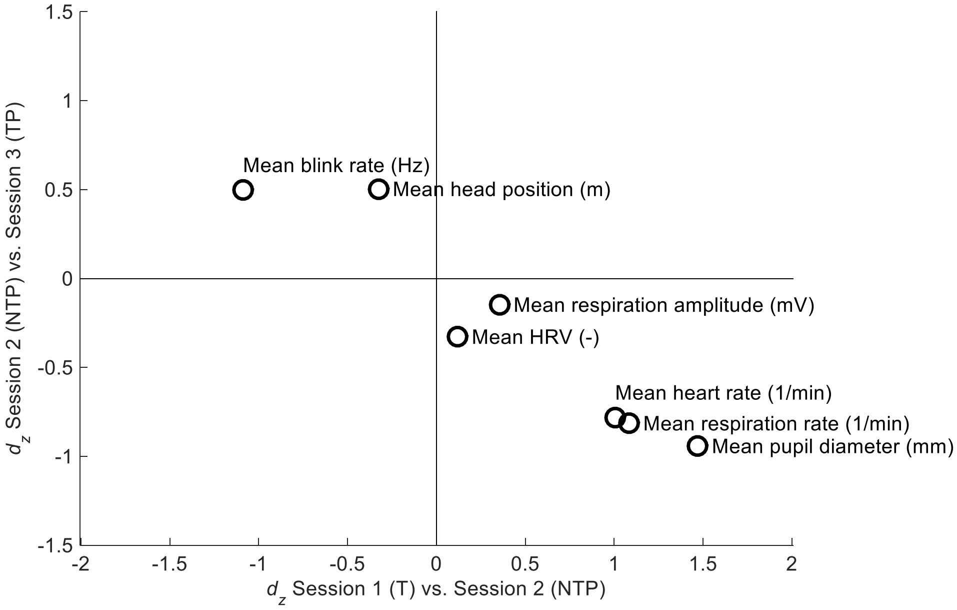

Fig. 10. Scatter plot of the Cohen's d_z effect size of Session 1 (Training session, T) versus Session 2 (No time pressure session, NTP) and the Cohen's d_z effect size of Session 2 (NTP) versus Session 3 (Time pressure, TP). These results indicate that the measures of sympathetic arousal decreased from Session 1 to 2, but increased from Session 2 ($r = -0.95$, $p = 0.001$).

A second limitation is that 28.6% of eye-tracker data had to be removed from our analysis. Missing eye-tracker data of around 30% are consistent with the literature (e.g., Ahlstrom, Victor, Wege, & Steinmetz, 2012). Because much of the data loss occurred at random events (e.g., due to eye blinks), no systematic error is expected in our results.

A third limitation is that it is unknown which mental or physical mechanisms have caused the observed physiological signals. It is likely that the effects in Table 3 are attributable at least partly to physical exertion. Indeed, the acceleration data of the limbs (Table 3) unequivocally indicate that participants were more physically active in the TP session than in the NTP session. This probably had an influence on the physiological outcomes, such as heart rate and respiratory rate, which are well known to be a function of physical activity. Moreover, Table 3 showed that the physiological measures exhibit a U-shaped pattern across the three sessions, while the self-reported time pressure exhibits a different pattern, with only a small effect between the training session and the NTP session and a very large effect between the NTP and TP session. This differential pattern suggests that the physiological measures do not capture time pressure per se. Indeed, different mental mechanisms might be at play, such as mechanisms associated with mental workload, frustration, 'time stress', anxiety, and arousal. We argue that it is impossible to uniquely identify these mechanisms and states based on the present physiological data (see also Cacioppo & Tassinary, 1990; Cacioppo, Tassinary, & Berntson, 2000). Taking pupil diameter for example, and setting aside issues of experimental control such as the fact that the pupil diameter is sensitive to environmental light conditions moderated by biological age (Näätänen, 1992; Watson & Yellott, 2012), it has been established that ''any sensory occurrence– whether tactile, auditory, gustatory, olfactory, or noxious–evokes a pupillary reflex dilation", and that ''one should not assume that pupillary reflex dilations occur only to external sensory events, because emotions, mental processes, increases in intentional efforts, and motor output also produce systematic changes in pupillary diameter." (Beatty & Lucero-Wagoner, 2000, pp. 145–146). In summary, our research showed that the time pressure manipulation (i.e., a time constraint and a virtual passenger urging to hurry up) had clear physiological effects, but it is not possible to reverse this causality and identify 'time pressure' as a unique cognitive construct from the physiological recordings. It is likely that other types of stressors, such as traffic complexity and secondary tasks, yield physiological effects that are indistinguishable from the effects that were observed in this study.

A fourth limitation is related to driving simulator validity. Driving simulators have been shown to provide measures that are strongly predictive of real-world driving (Lee, Cameron, & Lee, 2003). Reimer (2009) demonstrated the relative validity of physiological measures recorded both in a fixed base driving simulator and during a field study. However, driving simulator validity remains an important limitation in our study, and more research is recommended to validate our findings on the road.

A fifth limitation is that our participants were recruited from a technical university campus, and may be assumed to have above average intelligence, spatial ability (Wai, Lubinski, & Benbow, 2009), and a specific interest in (driving simulator) technology. It has been argued that people in high-income societies, participants from university communities in particular, are not representative of the general population (Henrich, Heine, & Norenzayan, 2010).

A sixth limitation is that our research focused exclusively on manual driving. In the foreseeable future, automated driving technologies will be introduced on the roads, a development that entails new types of psychological questions (De Winter et al., 2014; Fisher, Reed, & Savirimuthu, 2015; Young & Stanton, 2007). Specifically, the driving task is gradually changing from manual control into supervisory control, placing pressures on drivers to monitor both the environment and in-vehicle systems (Banks, Stanton, & Harvey, 2014; see also Warm, Parasuraman, & Matthews, 2008).

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Implications towards a real-world application of driver state measurement

The results in this chapter illustrate that measures of eye movements, steering control, and driver physiology strongly depend on specific driving tasks, driving context, and driving instructions. Measuring driver´s eye movements concurrently with measures of vehicle control may allow for task-specific and manoeuvre-specific driver state estimation.

Appendix A: Supplementary material

S1.1 Correlation matrices

Table S.1. Spearman correlation matrix (N = 54) for driving performance, physiological, and self-reported workload measures. Correlations per measure were determined by taking the difference between the time pressure (TP) and no time pressure (NTP) sessions

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Mean speed (m/s)															
2. Max speed (m/s)	**.39**														
3. SDLP (m)	**.47**	.18													
4. Mean steering speed	**.62**	**.37**	**.44**												
5. Throttle variance (0–1)	**.55**	**.57**	**.27**	**.42**											
6. Mean acc. right hand	**.37**	**.37**	.07	**.40**	**.38**										
7. Mean acc. right foot	**.57**	**.35**	**.36**	**.46**	**.44**	**.36**									
8. Mean pupil diameter	**.33**	**.28**	.19	.22	.25	.14	.14								
9. Mean blink rate (1/s)	-.20	-.11	.08	.00	-.18	.11	-.03	-.19							
10. Percentage clock (%)	-.10	.04	.01	.04	-.08	.02	.05	.10	-.17						
11. Percentage dials (%)	-.20	**-.43**	**-.31**	**-.27**	**-.31**	-.15	-.09	-.02	**-.32**	.20					
12. Hor. gaze variance (deg^2)	.06	-.05	.16	.20	-.04	.01	-.07	**-.29**	**.31**	.19	-.12				
13. Mean heart rate (1/min)	.15	**.29**	.03	.15	.20	.25	.13	**.45**	-.02	.04	-.02	.01			
14. Mean respiration rate	.19	**.27**	-.12	-.01	**.27**	.21	.18	**.39**	-.12	.08	.09	-.20	.24		
15. TLX mental demand (0–	.22	.21	.13	**.34**	.25	-.14	.09	**.52**	-.13	-.04	-.08	-.10	.15	.14	

Note: Correlations of magnitude greater than .27 correspond to $p < 0.05$ and are in boldface.

Table S.2. Pearson correlation matrix (N = 54) of driving behavior, mini driver behavior questionnaire (Mini-DBQ), and multidimensional driving style questionnaire (MDSI) measures. Correlations were determined from the average of the no time pressure (NTP) and time pressure (TP) sessions

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1. Max speed (m/s)																	
2. Mean speed (m/s)	**.65**																
3. SDLP (m)	**.46**	**.52**															
4. Throttle variance (0–1)	**.58**	**.75**	.40														
5. Brake variance (0–1)	**.28**	.19	**.38**	**.32**													
6. Steer speed (deg/s)	.27	**.43**	.20	.25	.13												
7. DBQ – violations (0–100)	**.36**	.27	.20	.08	.03	-.05											
8. DBQ – errors (0–100)	.04	-.13	.08	-.11	.22	-.13	.15										
9. DBQ – lapses (0–100)	.05	.10	.17	.06	.19	.01	.12	**.57**									
10. DSI – dissociative (0–100)	.12	-.07	.23	-.05	**.36**	-.10	.03	**.67**	**.53**								
11. DSI – anxious (0–100)	**-.33**	**-.46**	-.13	**-.38**	.07	-.04	-.26	.01	.16	**.30**							
12. DSI – risky (0–100)	.26	.21	.05	.09	-.04	-.02	**.62**	.20	.16	.18	-.06						
13. DSI – angry (0–100)	.25	.25	.19	.15	.13	.01	**.35**	.07	**.37**	.22	.11	**.29**					
14. DSI – velocity (0–100)	.11	.16	.22	.08	.22	-.02	**.57**	.21	**.31**	**.29**	.04	**.40**	**.72**				
15. DSI – distress (0–100)	.24	.22	.09	.18	-.11	.04	.10	.14	**.28**	.11	-.09	.02	.11	.10			
16. DSI - patience (0–100)	-.12	-.27	-.22	-.19	-.07	-.17	**-.29**	**-.32**	-.10	-.07	.25	-.18	**-.39**	**-.42**	.15		
17. DSI - careful (0–100)	-.05	**-.29**	-.11	**-.31**	-.10	-.07	-.03	-.03	.14	.18	**.31**	.00	.25	.01	.00	.12	

Note: Correlations of magnitude greater than .27 correspond to $p < 0.05$ and are in boldface.

Table S.3. Spearman correlation matrix (N = 54) of driving behavior, mini driver behavior questionnaire (Mini-DBQ), and multidimensional driving style questionnaire (MDSI) measures. Correlations were determined from the average of the no time pressure (NTP) and time pressure (TP) sessions

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1. Max speed (m/s)																	
2. Mean speed (m/s)	**.65**																
3. SDLP (m)	**.39**	**.34**															
4. Throttle variance (0–1)	**.53**	**.78**	**.32**														
5. Brake variance (0–1)	.27	.22	**.42**	**.38**													
6. Steer speed (deg/s)	.25	**.40**	.22	**.31**	.13												
7. DBQ – violations (0–100)	**.44**	**.31**	.16	.14	.04	.02											
8. DBQ – errors (0–100)	.00	-.14	-.02	-.14	.13	-.17	.14										
9. DBQ – lapses (0–100)	-.01	.07	.02	.03	.07	.04	.07	**.52**									
10. DSI – dissociative (0–100)	.11	-.07	.12	-.10	**.29**	-.13	-.03	**.61**	**.46**								
11. DSI – anxious (0–100)	**-.30**	**-.38**	-.04	**-.31**	.07	-.06	**-.30**	-.07	.08	.25							
12. DSI – risky (0–100)	.27	**.30**	.01	.10	-.06	.04	**.63**	.18	.04	.05	-.05						
13. DSI – angry (0–100)	**.31**	**.32**	.14	.21	.11	.05	**.36**	-.04	**.29**	.07	.05	**.39**					
14. DSI – velocity (0–100)	.10	.14	.10	.10	.21	.00	**.51**	.11	**.31**	.16	.06	**.40**	**.70**				
15. DSI – distress (0–100)	.25	.17	.08	.14	-.09	.07	.12	.09	.18	.16	-.10	.10	.08	.06			
16. DSI - patience (0–100)	-.16	**-.28**	-.21	-.21	-.10	-.18	**-.32**	**-.29**	-.17	.02	.27	**-.31**	**-.42**	**-.39**	.10		
17. DSI - careful (0–100)	.03	-.12	.05	-.20	-.18	.00	-.04	-.11	.08	.16	.25	.05	**.28**	-.04	-.01	.13	

Note: Correlations of magnitude greater than .27 correspond to $p < 0.05$ and are in boldface.

S1.2 Pupillary light reflex model

To correct the pupillary response for the pupillary light reflex, the light intensity experienced by participants was measured with a light intensity meter (Extech HD450, range = 400 cd/m^2, resolution = 0.1 cd/m^2) for seven sessions (with different participants and independent of the main experiment). Luminance data were recorded with the sensor mounted at the participant's eye position, sampled and stored at 1 Hz, and manually synchronized with the driving simulator data.

Figure S.1 (left) shows the distribution of the light intensity for the seven sessions combined. Light intensities ranged from 1.36 Log10 cd/m^2 to 1.54 Log10 cd/m^2 and averaged across the distance at 1.48 Log10 cd/m^2 (*SD* = 0.04). The small variation in light intensities justifies the linear fit to model the pupillary light reflex (Watson & Yellott, 2012). For each participant and for each session, we modelled the pupillary response as a linear function of the light intensity, and this pupillary light reflex was subtracted from the measured (uncorrected) pupil diameter. The corrected pupil diameter values were interpolated from a distance-based vector to a time-based vector before further analysis.

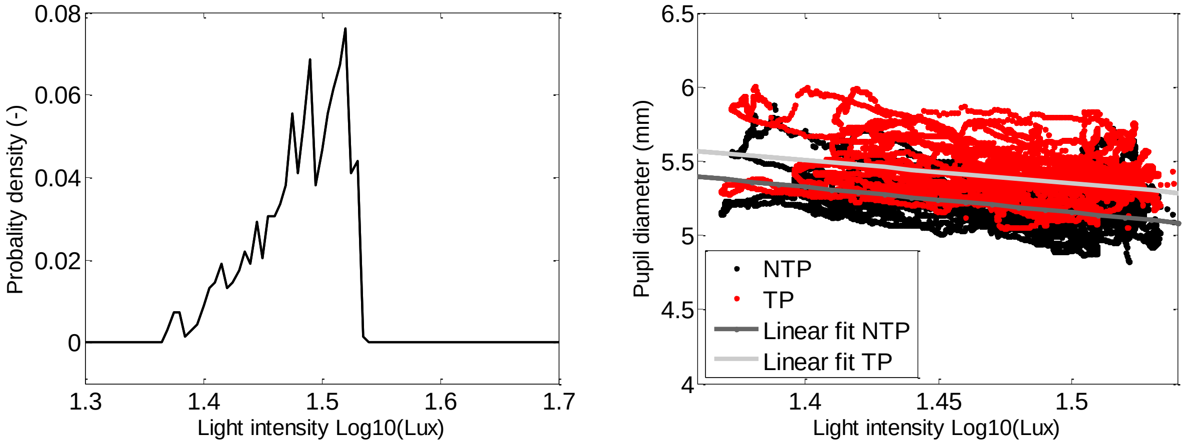

Fig. S.1. Left: Probability density distribution of light intensity for all seven sessions combined. The distribution was determined by grouping light intensity data in 1 Lux bins. Right: Relationship between light intensity and participants' averaged mean pupil diameter for both the NTP and TP sessions. The lines represent the uncorrected pupil diameter grouped per 0.5 m traveled distance. Linear fits are shown as black and gray lines.

The mean slope for all participants of the pupillary light reflex model was *M* = -1.63 mm per log10 cd/m^2 (*SD* = 0.99) for the NTP session and *M* = -1.55 mm per log10 cd/m^2 (*SD* = 1.13) for TP session. The slopes of the pupillary light reflex model did not significantly differ between the NTP and TP session ($t(49) = 0.46$, $p = 0.647$). In Figure S.1 (right) the linear model for the pupillary light reflex is demonstrated for the session-averaged pupil diameter results. The mean *uncorrected* pupil diameter was *M* = 5.19 mm (*SD* = 0.68) and *M* = 5.37 (*SD* = 0.66) for the NTP and TP sessions and the mean *corrected* pupil diameter was *M* = 5.19 mm (*SD* = 0.67) and *M* = 5.35 (*SD* = 0.65) for the NTP and TP sessions, respectively.

Figure S.2 shows the mean vehicle speed, the mean corrected and uncorrected pupil diameter, and the light intensity as a function of the travelled distance. Figure S.2 demonstrates the effect of the pupillary light reflex correction on the pupil diameter.

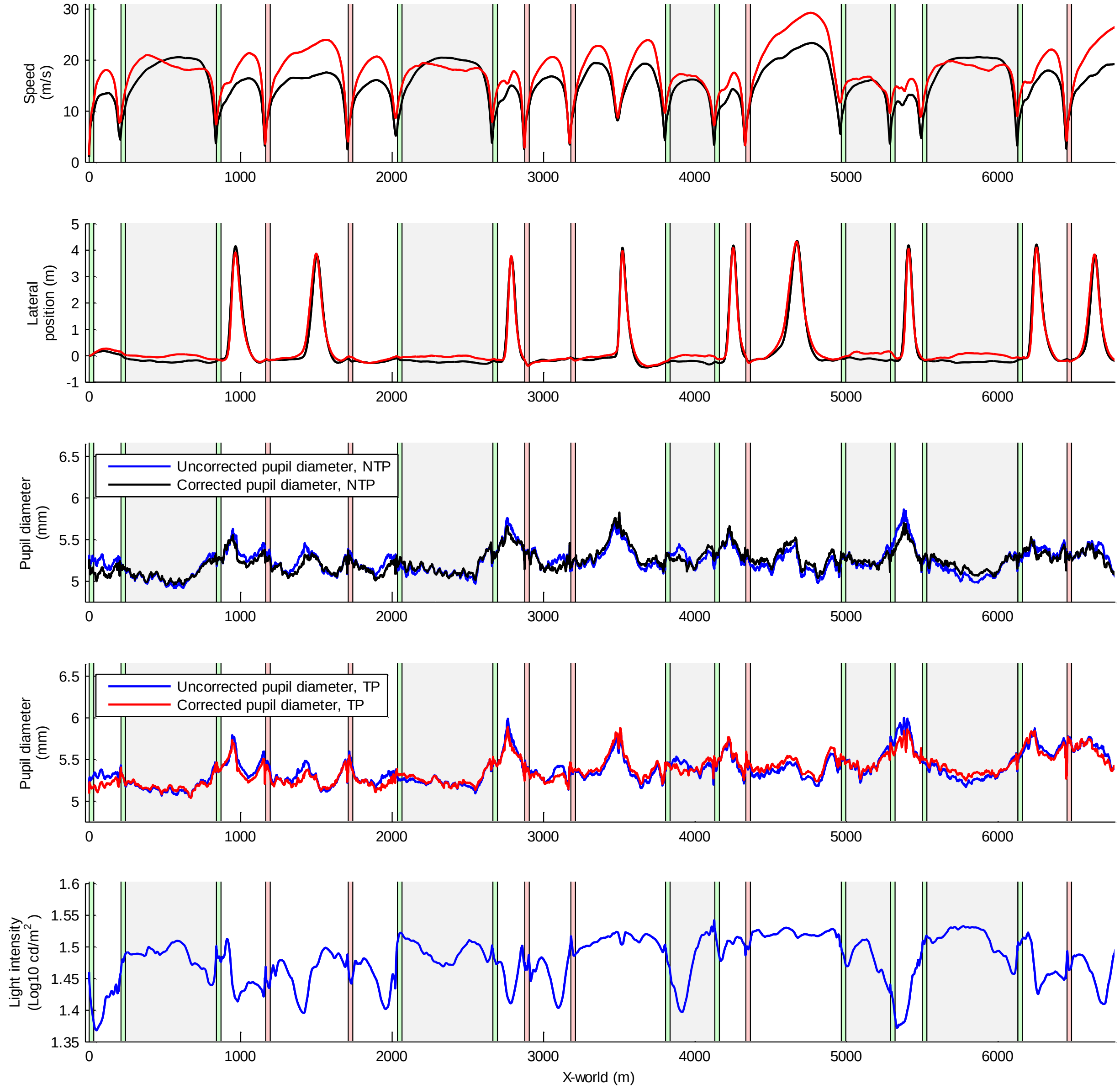

Fig. S.2. Speed, lane position, pupil diameter, and light intensity as a function of travelled distance. The speed, lane position, and pupil diameters for the NTP and TP sessions are shown in black and red, respectively. The uncorrected pupil diameter and light intensity are shown in blue. Speed, lane position, and light intensity were determined using a spatial sliding window of 4 m. The corrected and uncorrected pupil diameters were determined using a temporal sliding window of 3 s. The intersections with and without traffic are indicated by green and red shading, respectively. Car following situations are indicated by gray shading and the overtaking maneuvers can be identified by lateral positions exceeding 2 m.

Chapter 8

Towards a real-time driver workload estimator: an on-the-road evaluation

Abstract

Driver distraction is a leading cause of crashes. The introduction of in-vehicle technology in the last decades has added support to the driving task. However, in-vehicle technologies and handheld electronic devices may also be a threat to driver safety due to information overload and distraction. Adaptive in-vehicle information systems may be a solution to this problem. Adaptive systems could aid the driver in obtaining information from the device (by reducing information density) or prevent distraction by not presenting or delaying information when the driver's workload is high. In this paper, we describe an on-the-road evaluation of a real-time driver workload estimator that makes use of geo-specific information. The results demonstrate the relative validity of our experimental methods and show the potential for using location-based adaptive in-vehicle systems.

Van Leeuwen, P. M., Landman, R., Buning, L., Heffelaar, T., Hogema, J., van Hemert, J. M., ... & Happee, R. (2016). Towards a real-time driver workload estimator: an on-the-road study. In N. A. Stanton, S. Landry, G. Di Bucchianico, & A. Vallicelli (Eds.), *Advances in Human Aspects of Transportation: Proceedings of the AHFE 2016 International Conference on Human Factors in Transportation* (pp. 1151–1164). Orlando, Florida. Springer International Publishing (adapted with minor changes).

8.1 Introduction

Driver distraction is a leading contributor to road traffic crashes (Dingus et al., 2016). A recent naturalistic driving study showed that as much as 78% of crashes were related to distraction (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006). Because of the increasing prevalence of technological aids, road safety has improved considerably in the last decades. However, certain in-vehicle technologies such as infotainment systems and handheld electronic devices are themselves a source of distraction and crash risk (Dingus et al., 2006; Dingus et al., 2016; Lee, 2007; Kountouriotis & Merat, 2016; Verwey, 2000). Distracted driving not only reduces lane-keeping accuracy (Engström, Johansson, & Östlund, 2005; Santos, Merat, Mouta, Brookhuis, & De Waard, 2005) but also increases the brake reaction time to critical environmental events (Hibberd, Jamsom, & Carsten, 2013). Furthermore, a complex in-vehicle display may result in an 'information overload' (Green, 2000).

A potential remedy to these problems may be the use of adaptive information systems (Hancock & Verwey, 1997). Adaptive information systems aid the driver by warning for upcoming high-workload situations or by adapting the information presentation. For example, when driver workload is high, an adaptive system may (1) switch to auditory presentation instead of visual presentation, (2) reduce the amount of information, or (3) present no information.

A workload-adaptive in-vehicle information system not only requires knowledge of the current driver workload. An estimate of the future workload is required as well. The use of the momentary workload only as input to the adaptive in-vehicle system would result in the adaptation being too late for the driver, and therefore drivers would not benefit from such a system (Piersma, 1991). Prediction of driver workload may seem a difficult task (Zhang, Owechko, & Zhang, 2004) due to the dynamics of traffic, interactions between road users, and moment-to-moment driver variability. Verwey (1993; 2000) found that the traffic situation is a vital determinant of workload that could be used for real-time workload estimation.

Similar to the approach by Verwey (2000), we propose to estimate driver workload based on the location of the vehicle in the world. Specifically, using GPS coordinates and an online route map database, the driver's workload was estimated in real time based on road type, distance to junctions, and vehicle speed and acceleration. In our project, we explored the feasibility of using the workload estimate for real-time adaptation of visual information presentation on a navigation device (see also Piechulla, Mayser, Gehrke, & König (2003)).

Previous research has demonstrated the measurement of driver workload using physiological measures (Brookhuis & De Waard, 2010; May, Kennedy, Williams, Dunlap, & Brannan, 1990; Recarte, Perez, Conchillo, & Nunes, 2008), measures of driver performance (He & McCarley, 2011), and self-report evaluations (Pauzie, 2008). In the present paper, we evaluated our experimental vehicle and our driver workload estimator in an urban, rural, and highway environment. Specifically, we evaluated vehicle speed, driver inputs, heart rate, respiratory rate, eye gaze, pupil diameter, and self-reported effort as a function of travelled distance along the route, a secondary mental arithmetic task, and the estimated workload level.

8.2 Methods

8.2.1 Participants

Six participants from the HAN employee community volunteered to participate in this research. Participants filled out an intake questionnaire with general items (age, gender, wearing glasses, driving history, use of navigation systems).

The participants were four males (mean age: 28.5, *SD* = 7.8) and two females (mean age: 29.0, *SD* = 1.4). Participants were in possession of a driver's license for an average of 8.7 years (*SD* = 5.1) with a minimum of 3 years and reported a mean annual mileage of 12,217 km (*SD* = 11,398). Four participants mentioned the use of glasses, one participant wore glasses during the experiment, and one participant reported the use of contacts. All participants indicated the use of navigation devices in their normal driving.

8.2.2 Apparatus

The experiment was conducted using a manual drive E91 320d BMW test vehicle. The vehicle was equipped with data acquisition connected to the CAN bus, allowing the collection of vehicle state variables (e.g., speed) and driver input variables (e.g., steering angle). Participants' physiological responses were measured using ECG electrodes and a respiration belt from TMSi (PolyBench, software version 1.30.0.3521) placed around the chest. Eye and head movements were recorded using a remote-mounted eye tracker from SmartEye (SmartEye Pro, software version 6.1.4). All data were synchronized and stored using The Observer XT (Noldus, software version 12.0.825 NBD) at sampling rates varying from 5 to 60 Hz. The navigation device was an Android tablet with prototype TomTom navigation software (Samsung Galaxy Tab 2, P3110 with Android 4.0).

8.2.3 Driver workload estimator

TNO, in collaboration with TomTom, developed the real-time workload estimator prototype. The estimator made use of vehicle and driver input data as well as road type estimated from the geographical location, based on GPS coordinates and a route map database.

On a high level, the estimation process had several components: road type, time/distance to junctions ahead, acceleration of the car, driving speed (with respect to the speed limit), and time-on-task (how long the driver has been driving without a break). For each component, decision rules were specified that indicated the relationship between the component and workload. The components were merged into a final output of the driver workload estimator, representing a 6-point workload estimate ranging from very low to very high.

8.2.4 Procedures

Before the start of the experimental sessions, participants received oral instructions explaining the experiment and procedures. Furthermore, participants filled out the intake questionnaire, a consent form, and a traveling cost form. Next, participants performed a Landolt C test (ISO 8596, 2009) to determine their visual acuity. If the visual acuity was at least corrected-to-normal, the participants were allowed to participate.

After the visual acuity test, participants received oral instructions about the driving task. Furthermore, the self-report procedures and the secondary task were explained and practiced by the participants. After taking place in the vehicle, participants adjusted their seat to their own preference. The ECG and respiration hardware was connected to the participants, and the eye tracker was calibrated by means of a series of eye and head movements.

Participants drove three sessions: a baseline session and two times the same route of approximately 40 min. Participants drove the baseline session starting from the university campus to the starting point of the first session, a drive that took approximately 5 min. After the first 40 min session, participants had a 10 min break after which they drove back to the starting point. After completing the second 40 min session, participants drove back to the campus. When arrived at the campus, participants filled out a questionnaire regarding their driving behavior and received a gift card.

While driving, participants performed a secondary arithmetic task and rated their effort using the Rating Scale Mental Effort (RSME) (Zijlstra & Van Doorn, 1985). An experimenter sat on the passenger seat, and initiated the secondary task and marked the RSME scores. Furthermore, the experimenter marked sudden events (e.g., pedestrians crossing, unpredictable behavior of other road users).

8.2.5 Driving task and environment

Prior to the baseline session, participants received oral instructions to drive as they would drive their own car, to adhere to Dutch traffic rules including speed limits, and to be aware of other road users. In addition, drivers were asked to perform a secondary task to temporarily add workload to the driving task. Specifically, at several moments during the drive, the experimenter instructed the participants to countback in steps of three from a random number between 60 and 100.

The route was identical for all participants and both sessions, and started and ended at the same locations. Each participant drove the same route twice. A tablet with TomTom navigation concept software provided the participants with driving directions by means of a Dutch voice. After completing the first session, participants drove from the endpoint of Session 1 to the starting point of Session 2.

The route was chosen so that different traffic situations were likely to occur. The route was near the city of Arnhem (NL) and had a length of 21.5 km. The route consisted of intersections (with and without traffic lights), roundabouts, urban areas with a 30 kph speed limit, a small segment of rural area, and a highway.

The countback task and RSME rating were performed at several locations along the route. On average, participants were requested to score their RSME 6 times per session and perform the countback task 5 times per session.

8.2.6 Dependent measures

The following dependent measures were computed per session. The measures can be categorized as (1) vehicle performance, (2) driver input, (3) driver physiology, (4) subjective reports, and (5) the driver workload estimate.

1) Mean speed (kph) and absolute vehicle acceleration (m/s^2) were calculated as a measure of task efficiency, driving style, and driving safety.
2) The mean absolute steering speed (deg/s) and steer steadiness (%, defined as the percentage of time the absolute steering speed was lower than 1 deg/s) were used to represent steering activity (Rendon-Velez, Van Leeuwen, Happee, Horváth, Van der Vegte, & De Winter, 2016; Van Leeuwen, Gómez i Subils, Jimenez, Happee, & De Winter, 2015). The mean absolute throttle speed (%/s) was used to indicate throttle activity.
3) The mean heart rate (1/min) and the mean respiration rate (1/min) were recorded from the ECG and the respiration belt hardware, respectively. The mean pupil diameter (mm) measured by the eye tracker data was used as a measure of workload (Beatty, 1982). Eye gaze data were classified into four regions of interest: (1) the road center (defined as a cone with 8 degree radius around the road center), (2) the peripheral area (defined as the region outside the road center, but within the windscreen perimeter), (3) the dials and navigation, (4) and other. For a definition of the dials and navigation, see Figure 2. The mean percentage gaze at the road center (GRC, %) represents the amount of attention directed to the road ahead (Van Leeuwen, Happee, & De Winter, 2016). Eye movement data were low-pass filtered at 5 Hz because the eye tracker data were sensitive to external noise, such as vibrations. Missing data (e.g., eye blinks and camera obstructions) were automatically removed.
4) The mean RSME (0–15) was determined from the rating scale (Zijlstra & Van Doorn, 1985) that was administered during driving. To keep interference with the driving task to a minimum, the participants indicated their effort orally on a scale from 0 to 15 (equivalent to the RSME vertical line of 15 cm) where 3 is ‘normal driving’ or ‘a comfortable task load’ and 12 is more than ‘extreme effort’.
5) The driver workload estimate (1–6) was obtained from the online estimator. As mentioned above, workload was estimated based on vehicle location and vehicle state.

8.3 Results

Due to low quality eye tracker data (defined as less than 20% reliable data), the gaze data of two participants were removed. Of the remaining four participants, on average 30% (*SD* = 14%) of eye tracker data were removed, due to the tracker's inability to record eye movements. One participant made a navigation mistake and drove an additional segment (approximately 1.06 km) during the first session. The data of this additional segment were removed.

8.3.1 Descriptive results

Figure 1 provides an overview of several of the variables during the experimental route. The figure illustrates the diversity in road types (e.g., the first 4.5 km of the route consisted of a highway) and the differences in driving speed and steering activity along the route. The figure also shows the percentage of gaze at the road center, illustrating the gaze activity near corners and intersections. The RSME values seem to reveal an elevated self-reported workload at travelled distances of 5 km and 19 km. Furthermore, the driver workload estimator shows that levels 3 and 4 occurred most frequently, whereas level 5 occurred intermittently.

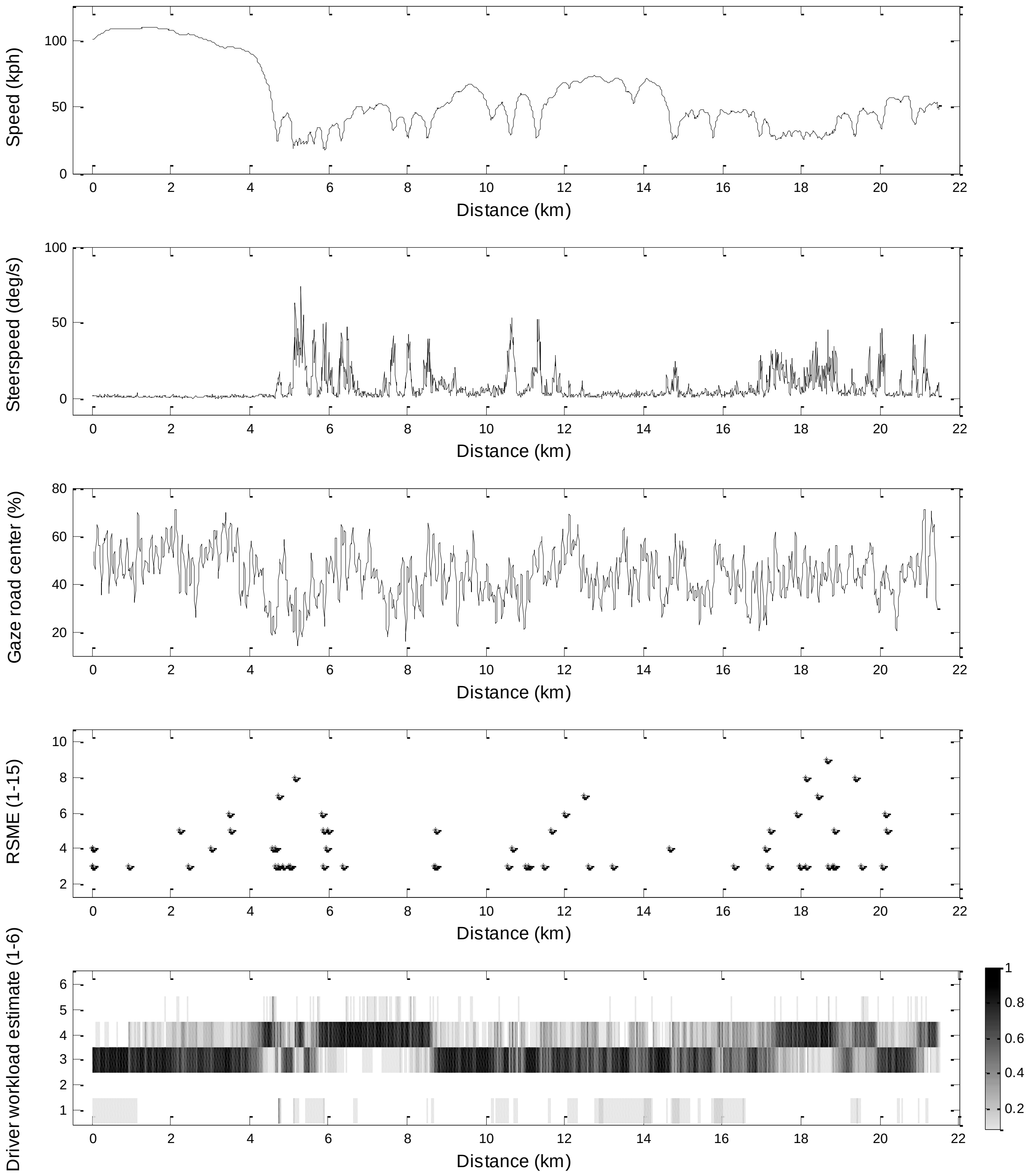

Fig. 1. Driving speed, absolute steering speed, gaze road center, Rating Scale Mental Effort (RSME), and workload estimate distribution as a function of travelled distance along the experimental route. The speed, absolute steering speed, and gaze road center were averaged across participants and sessions. All RSME reports for all participants and both sessions are shown. The workload estimate distribution was determined by averaging across the six participants and two sessions, and ranges from 0 out of 12 (white) to 12 out of 12 (black).

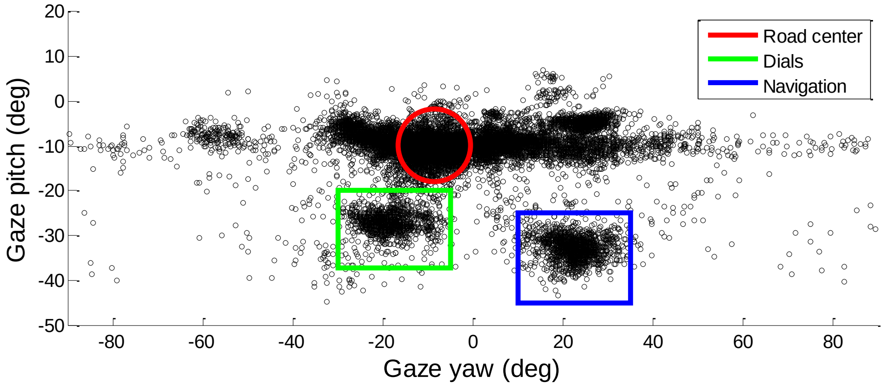

Fig. 2. Raw gaze data of one selected participant, together with regions of interest.

Figure 2 shows the gaze distribution of one selected participant, illustrating the regions of interest and the main areas of visual attention. The gaze samples are centered on the 8-degree circle that represents the road center (averaged across the two sessions, participants directed their gaze 60% of the time at the road center). The dials and the navigation device were glanced at for 5% of the time (for all participants during both sessions). The gaze swirls to the left and right of the road center indicate lateral eye movements, for example while driving in a curve.

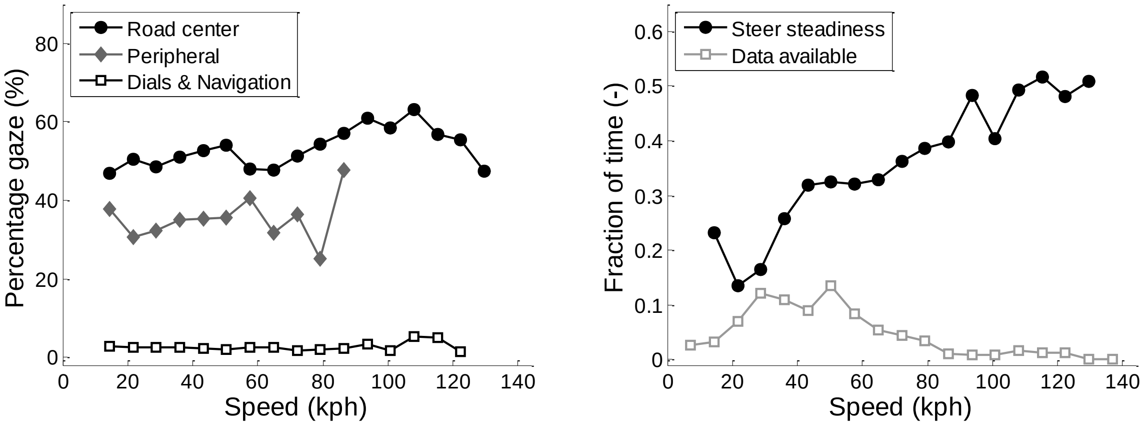

Fig. 3. Gaze distribution (left) and steering activity (right) as a function of driving speed. Data were extracted per 7.2 kph wide bin, and averaged across participants and both driving sessions. The data from 0 to 10.4 kph were removed from the figure. Note that participants drove faster than 90 kph for less than 5% of the time, which explains the oscillatory behavior of the distributions for speeds greater than 90 kph. The gray line with square markers in the right figure indicates how much data were available at a given driving speed.

Figure 3 illustrates the association between driving speed and gaze distribution (left) and between driving speed and steer steadiness (right). It suggests that participants were more likely to allocate attention to the road center with increasing driving speed (left). Moreover, steering steadiness increases with increased driving speed (right).

8.3.2 Countback task

Table 1 shows the results of selected measures averaged across the 10 s period before and the 10 s after the start of the countback task. Figure 4 illustrates the effect of the countback task on participants' heart rate and respiration rate. No statistically significant differences and small effect sizes between the two periods were observed for the driving performance measures (mean speed, steering speed, and throttle speed). The heart rate increased slowly from the start of the countback task and peaked at about 10 seconds after the start of the countback task. Furthermore, the respiration rate decreased after the start of the countback task. No clear differences were observed for the pupil diameter before versus after the start of the countback task.

Table 1. Means (standard deviations in parentheses) for the 10 s period before and the 10 s period after the start of the countback (CB) task. *p* values from the dependent *t* test (effect size in parentheses) and correlations (Spearman ρ, *N* = 6, *N* = 4 for the gaze measures) between the before and after segments are shown. Effect sizes were determined as Cohen's $d_z = t/N^{0.5}$

Dependent measure	10 s before CB	10 s after CB	*p* value ($\lvert d_z \rvert$)	Correlation (ρ)
Mean speed (kph)	10.95 (3.1)	10.54 (2.2)	0.380 (0.43)	0.943
Acceleration (m/s^2)	0.48 (0.14)	0.40 (0.15)	0.449 (0.56)	-0.543
Steer speed (deg/s)	15.93 (8.7)	15.88 (6.1)	0.992 (0.01)	0.143
Throttle speed (%/s)	6.25 (1.1)	5.75 (2.5)	0.620 (0.24)	0.086
Heart rate (1/min)	77.37 (8.2)	78.22 (8.1)	0.053 (1.13)	1.000
Respiration rate (1/min)	18.20 (1.6)	15.25 (3.2)	0.076 (1.00)	0.314
Pupil diameter (mm)	1.99 (0.37)	1.99 (0.50)	0.994 (0.00)	0.900
Gaze navigation (%)	2.91 (1.16)	2.99 (1.40)	0.791 (0.17)	1.000
Gaze road center (%)	53.0 (15.5)	52.5 (17. 3)	0.920 (0.06)	0.800

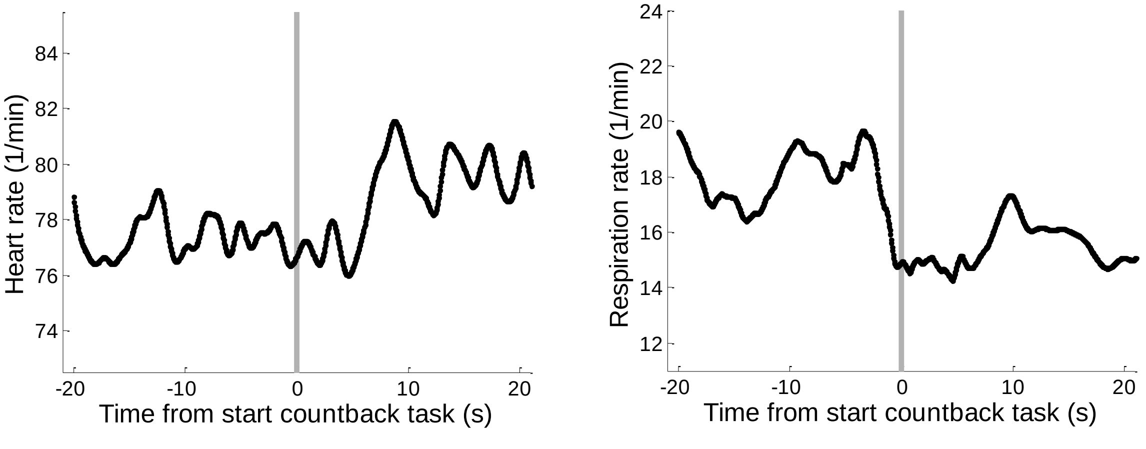

Fig. 4. Mean heart rate (left) and respiration rate (right) before and after the start of the countback task. Means were computed by averaging across all trials. The start of the countback task is indicated by the vertical line at 0 s. The countback task lasted approximately 10 s. Note that due to the manual annotation, the starting time slightly varied across trials.

A scatter plot of the 45 trials (of all participants) of the countback task illustrates the small increase in heart rate (Fig. 5 left) and a decrease in respiration rate (Fig. 5 right). Furthermore, large differences between participants can be seen.

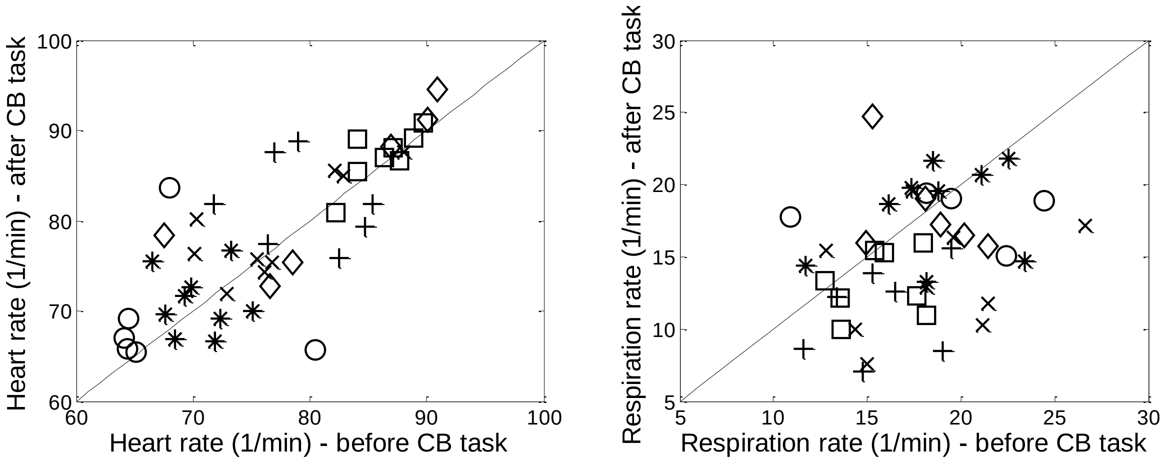

Fig. 5. Scatter plot of the mean heart rate (left) and the mean respiration rate (right) for the period 10 s before and the period 10 s after the start of the countback (CB) task. Each participant is indicated by a different marker.

8.3.3 Evaluation of the driver workload estimator

Table 2 shows the means and standard deviations of the dependent measures per estimated workload level. The driver workload was estimated to be either level 3 or level 4 for over 80% of the total time. As can be seen by the low mean speed, the first level of the workload estimator was related to low speeds or the vehicle standing still. The fifth workload level occurred less than 2% of the total time and was related to strong vehicle accelerations, indicated by the throttle speed and the acceleration. The missing values for workload levels 2 and 6 can be explained by the absence of criteria for the estimator to estimate these levels within the current experimental scenarios.

Table 2. Means (standard deviations in parentheses) of the dependent measures for the different levels of the estimated driver workload (*N* = 6, *N* = 4 for the gaze measures)

Dependent measure	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
Fraction of time (%)	6.9 (3.5)	n/a	46.6 (4.6)	44.4 (5.4)	2.1 (1.5)	n/a
Mean speed (kph)	18.8 (23.0)	n/a	49.7 (3.1)	34.3 (3.5)	35.6 (7.0)	n/a
Acceleration (m/s^2)	0.39 (0.15)	n/a	0.45 (0.04)	0.49 (0.05)	0.62 (0.14)	n/a
Steer speed (deg/s)	5.9 (2.5)	n/a	9.4 (1.8)	15.1 (2.4)	13.6 (5.5)	n/a
Throttle speed (%/s)	7.0 (3.5)	n/a	5.7 (0.9)	6.8 (0.5)	8.3 (4.0)	n/a
Heart rate (1/min)	76.8 (7.7)	n/a	77.0 (7.6)	77.8 (7.1)	79.3 (8.7)	n/a
Respiration rate (1/min)	17.9 (3.6)	n/a	17.5 (2.1)	18.2 (2.2)	18.5 (2.8)	n/a
Pupil diameter (mm)	2.22 (0.54)	n/a	2.22 (0.36)	2.27 (0.44)	2.34 (0.5)	n/a
Gaze navigation (%)	2.5 (1.5)	n/a	3.0 (1.3)	2.8 (1.4)	5.6 (4.0)	n/a
Gaze road center (%)	45.7 (17.9)	n/a	54.6 (14.5)	52.6 (11.8)	49.5 (9.4)	n/a
RSME (0–15)	3.8 (1.4)	n/a	4.3 (1.4)	4.5 (1.7)	4.4 (1.7)	n/a

Several dependent measures showed an increase from level 3 to level 4. Figure 6 shows the effects between level 3 and level 4 for the heart rate (left), respiration rate (middle), and RSME reports (right). It can be seen that individual differences were large relative to the difference between level 3 and level 4.

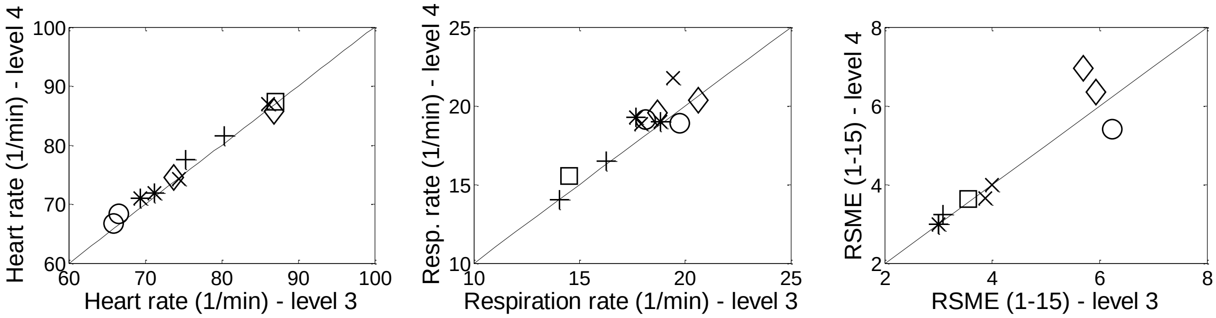

Fig. 6. Scatter plot of heart rate (*N* = 11), respiration rate (*N* = 11), and Rating Scale Mental Effort (RSME; *N* = 9) between level 3 and 4 of the driver workload estimator. Markers are session-averaged values per participant. Each participant is indicated by a different marker.

8.4 Discussion

In this paper, we described the methods and results of an on-road experiment including an online driver workload estimator. Consistent with results from Verwey (2000), the results suggest that driver workload is location-dependent. Averaged across participants, the RSME values were high at specific locations in our experimental route. This is further illustrated by the steering activity and gaze behavior along the route, ranging from low steering activity and a higher percentage of gaze directed to the road center on the highway to high steering activity and a lower percentage of gaze directed to the road center in the urban area.

The percentage of gaze directed at the road center tended to increase with increasing driving speeds, whereas the steering activity decreased (i.e., steering steadiness increased) with increasing driving speeds. These results are similar to results found in driving simulator studies (Bartmann, Spijkers, & Hess, 1991; Rendon-Velez et al., 2016; Van Leeuwen et al.,2015), and illustrates the relative validity of the measurements obtained with our experimental setup.

Consistent with the literature, the secondary arithmetic task resulted in an elevated physiological response. Specifically, the secondary task resulted in increased heart rate, a finding consistent with Reimer and Mehler (2011) who found similar results when participants performed an n-back arithmetic task (see also Mehler, Reimer, Coughlin, & Dusek (2009)). Our results also illustrate that the heart rate response was relatively slow (Fig. 4) (Rendon-Velez et al., 2016). The respiration rate responded quickly to the elevated cognitive load as the participants initiated the count-back task. However, this response may be caused by the nature of our secondary task; literature has shown a reduction of respiration rate as participants engage in speech tasks (Bernardi et al. 2000). No substantial effects of the secondary task were found on the control activity of the participants. This finding may be explained by the small cognitive impact of the secondary task as compared to the complex driving task.

Our driver workload estimator estimated the workload to be at intermediate levels (levels 3 or 4 on the 6-point scale) for more than 80% of the time. Trends were observed between the workload estimate and the RSME results, heart rate, and respiration rate. However, further research into the workload estimator is recommended. Considering the fact that individual differences are large, particular attention is needed to creating person-specific baseline values.

Conducting experiments in a complex naturalistic environment entails several limitations. Because of the exploratory nature of this research, our small sample size does not allow firm conclusions. The naturalistic environment has strong ecological validity, but also introduces side effects (e.g., weather conditions, varying traffic, and vibrations). These effects not only influence experimental control, but also influence the quality of the physiological data. For example, we found no significant effect of the arithmetic task on pupil diameter, which could be explained by the influence of variable lighting conditions (Watson & Yellott 2012).

With this study, a first step has been taken to explore the feasibility of estimating workload in a naturalistic driving environment. Our results correspond to previous findings in driving simulators and in the literature, and demonstrate the validity of the instrumented vehicle for assessing driver workload. The implementation of geo-specific data for driver workload estimation shows promise for application in future adaptive in-vehicle information systems.

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Conclusions, discussion,

and

recommendations

Conclusions

The aim of this thesis was to derive relationships between concurrently recorded eye-movement and driver behavior variables in closed-loop driving tasks. Drivers of varying experience and skill level performed self-paced driving tasks in experiments using a driving simulator. During the experiments, the simulator display was either deteriorated or augmented. A synthesis of these measurements may lead to improved understanding of how to assess (real-time) driver state, which may ultimately benefit road safety.

In Part I the use of driving simulators for the assessment of drivers was evaluated. The effect of manipulating the visual information presented to novice drivers while learning to drive was investigated in Part II, whereas in Part III measures of eye movements and human physiology were implemented aiming towards real-time application of driver state assessment. In these three parts, the following main conclusions were made:

1) Eye movements and head movements exhibit a strong dependency on task instructions and maneuver type (Chapters 6 & 7).
2) Synchronous measurements of eye movements and steering behavior are of substantial added value for understanding driver gaze behavior (Chapter 1 & 7).
3) It is feasible to alter drivers’ visual behavior (e.g., looking far ahead, visual search) by means of simulator-based training, but the effectiveness of a short training is limited (Chapters 3–5).
4) Driver eye- and head movements are subject to large individual differences. Large individual differences occur even if drivers are instructed to perform the same driving task in the same environment. Some of these differences can be explained by driving experience (Chapters 2 & 6).

Discussion

This section interprets the results from the individual chapters in relation to the lateral vehicle control model as discussed in this thesis' preface and the overall thesis conclusions (see Figure 1 for a repetition of the model). In each chapter, either the task, or the drivers' experience level, or the driving simulator visuals was changed, and the ensuing effects on the drivers' input, the vehicle state, and the drivers' eye movements and physiology were analyzed. The structure of this section follows the main conclusions of this thesis and references the chapters from which the conclusions are drawn. Each conclusion is illustrated with results from the corresponding chapter. Note that the order of these discussions/conclusions does not follow the order of the chapters.

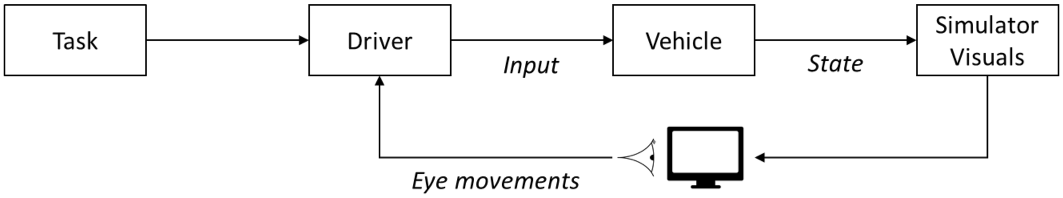

Fig 1. Simplified driver model (adapted from Flach, 1990). In this case a simulator-based driving task is assumed. In real driving, the visual stimuli are provided through the windows of the car.

The first main finding of this thesis is the strong dependency of eye movements on the driving task and manoeuvre type, which is further illustrated by discussing Chapter 6 and 7. In Table 1, the results from Chapters 6 and 7 are summarized; this table shows the driving task and the resulting steering input, the lane keeping performance and the eye movements. In Chapter 6 the participants were tasked to keep the vehicle close to the center of the lane while completing four driving sessions, and in Chapter 7 participants were tasked to minimize the task completion time (drive a fixed distance in minimum time). These different task instructions resulted in opposing results in terms of steering activity, lane keeping performance, and eye movements. The participants in Chapter 6 *reduced* their steering activity and improved their lane keeping performance as they drove multiple sessions with the same instructions, whereas the participants in Chapter 7 *increased* their steering activity and showed poorer lane keeping performance when they were instructed to reduce the task completion time as compared to a normal-driving baseline condition.

Furthermore, the participants in Chapter 6 *increased* their horizontal gaze variance as they drove more practice sessions, while the participants in Chapter 7 *reduced* their horizontal gaze variance as they drove on straight road segments during their time pressured driving task. These findings are consistent with the effect of visual tunnelling (Engström, Johansson, & Östlund, 2005; Reimer, 2009), when narrowing of the visual attention occurs due to elevated mental demands.

Table 1. Summary of steering, lane keeping, and eye movement results of Chapters 6 and 7

Chapter	Driving task	Steering control	Lane keeping performance	Eye movements
6	Drive close to the lane center	Lower steering activity with increasing driving experience	Improved accuracy and precision with increasing driving experience	Increased gaze variance with increasing driving experience
7	Complete the task in the minimum possible time	Higher steering speeds during time pressure compared to no time pressure	Increased SDLP during time pressure compared to no time pressure	Horizontal gaze variance reduces on straight roads and increased before intersections during time pressure compared to no time pressure

Task dependency of eye movements in general tasks has been demonstrated by Yarbus (1967), who observed: “Depending on the task in which a person is engaged, i.e., depending on the character of the information which he must obtain, the distribution of the points of fixation on an object will vary correspondingly, because different items of information are usually localized in different parts of an object” (p. 192). This effect is clearly illustrated in Chapter 7, where the eye movements of participants changed during the driving sessions as they performed different sub-tasks (e.g., when approaching intersections or when overtaking stationary vehicles).

The second main finding is that synchronous measurements of eye movements and steering behavior are essential in understanding driving behavior. This is illustrated in Chapter 1, where the degradation of the simulator visuals concurrently influenced the driver’s steering input, the vehicle performance, and the driver’s eye movements. By degrading the quality of visual information, drivers made fewer steering actions and showed poorer lane keeping performance. Consistent with the closed loop driver model (Figure 1), the simulator visuals influence the driver behavior and the resulting vehicle performance, emphasizing the necessity of concurrent measures of the driver steering behavior, vehicle performance, and eye movements. Contrary to traditional methods, which often report session-averaged findings, the methods used in this thesis were able to discriminate changes in a driver’s eye movements and physiology during various driving manoeuvres at a high temporal resolution.

Use of driving simulators for driver training

In part II of this thesis the training of the visual behavior of novice drivers has been investigated by deterioration or augmentation of the simulator visuals. In Table 2 the main results and the manipulation of the simulator visuals are reported. In each chapter, the drivers were instructed to drive as close to the centre of the lane as possible while performing a self-paced lane keeping task. The results from the three chapters can be explained by the simplified driver model: removing or adding specific visual information required for accurate lane keeping influenced the drivers’ eye movements, resulted in altered steering behavior, and influenced the lane keeping performance (see Table 2).

In Chapter 3 essential visual information near or far ahead of the vehicle was removed from the simulator visuals during three training sessions. The drivers' lane keeping performance and steering behavior were affected by removing visual information close to the vehicle as well as far ahead of the vehicle consistent with models on the two-level models of steering control (Donges, 1978; Salvucci & Gray, 2004).

Table 2. Summary of steering, lane keeping, and eye movement results of Part II

Chapter	Simulator visuals	Steering control	Lane keeping performance	Eye movements
3	Near view (NV) and far view (FV) occlusion	Lower steering reversal rate and higher rapid steering wheel turns during FV*	Higher standard deviation of lateral position (SDLP) during both FV and NV and lower lane keeping accuracy during NV*	Gaze restricted by FV and NV occlusion*
4	Lateral lane position feedback	Increased steering wheel steadiness*	Increased time spent driving within a lane center error band*	Extensive fixation on feedback area*
5	Visual search task	Equivalent steering activity to control group*	Equivalent SDLP to control group*	Increased gaze variance*

**As compared to control condition*

When a visual search task was added to the driving task (Chapter 5) the novice drivers' lane keeping performance and steering control was unaffected, indicating that similar steering task performance was achieved while drivers were tasked to concurrently sample task-irrelevant information. In Chapter 4, novice drivers were found to benefit from concurrent additional visual information, suggesting that intrinsic visual information can be augmented, so that novice drivers' show improved lane keeping performance. Providing novice drivers with augmented visual feedback may prove beneficial in the short-term (Chapter 5). However, more research is warranted to prevent the potentially negative effects of augmented feedback (Salmoni, Schmidt, & Walter, 1984), such as the risk that novices may develop maladaptive short-term steering corrections due to the augmented feedback (e.g., Lee & Carnahan, 1990).

The results from Part II illustrate that the eye movement behavior of novice drivers can be trained and altered during a relatively short training period. Novice drivers benefitted from augmented feedback during training (Chapter 5) and improved their visual search while concurrently performing a lane keeping task (Chapter 4). Similar results regarding the training of eye movements have been found in studies involving novice driver's hazard perception skills (Crundall, Andrews, Van Loon, & Chapman, 2010; Pradhan, Pollatsek, Knodler, & Fisher, 2009), and the results in this thesis illustrate that novice's eye movements can also be effectively trained during general driving tasks (curve negotiation). However, it must be stated that training of novice drivers' eye movements should be done with caution, as the training of visual attention of drivers (who may lack the attentional resources) may reduce traffic safety. More specifically, redirecting visual attention during a training program may reduce visual attention to other relevant sources of visual information (Crundall et al., 2012).

The effectiveness of the training studies in this thesis was limited due to the short training sessions. The training effectiveness was assessed by using the same virtual vehicle, the same lane keeping task, and the same driving environment (Chapters 3 & 4) or a different virtual scenario (Chapter 5). However, for driver training to be effective, the trained skills should demonstrate transfer to new and more demanding traffic circumstances (Groeger & Banks, 2007).

Retention was assessed by performing immediate (Chapter 3 & 5) or next day (Chapter 4) retention sessions. Driving skill is normally developed over years of driving experience (Mayhew, Simpson, & Pak, 2003; Pradhan et al., 2005) limiting the effectiveness of a short-term training. In a recent review on hazard perception skills in young drivers, one study out of 19 assessed the long-term effects of training (McDonald et al., 2015) compared to the other 18 studies, which focused on immediate or within-one-week evaluation of trained skills. The lack of published research on long-term transfer in driver training and the relation between laboratory training effects and real-world crash outcomes illustrate the challenges of simulator-based driver training.

Individual differences in eye and head movements

The results in this thesis show that the within-subject differences related to tasks and training, are often small compared to individual (between-subject) differences for measures of driving behavior, eye movements, and physiology. Various studies have explained individual differences by factors of personality, experience, gender, culture, etc. (Lajunen & Summala, 1995; Özkan, Lajunen, Chliaoutakis, Parker, & Summala, 2006, Ulleberg & Rundmo, 2003). In Chapters 2 and 6, the individual differences caused by driving expertise and experience were illustrated.

During the short training sessions, the novice drivers (Chapter 6) improved their lane keeping performance, reduced their steering activity, and increased their horizontal gaze variance. This illustrates that driver behavior changes as drivers gain short-term experience of the same route/task (see also Martens & Fox, 2007).

The presence of individual differences implies that for applications using measures of driving behavior, eye movements, or driver physiology, these measures should be treated at the individual level (see also Brookhuis, De Waard, & Fairclough, 2003; Matthews, Reinerman-Jones, Barber, & Abich, 2014). This means that the drivers' measurements should be corrected by driver-specific reference (baseline) measurements.

Limitations

Most of the experiments in this thesis were conducted in a fixed base driving simulator. Even though driving simulators are known to be able to provide metrics that are predictive of real-world driving (e.g., Lee, Cameron, & Lee, 2003), several perceptual cues were not provided in the experiments. For instance, in real-world driving, drivers are able to perceive the lateral acceleration as a measure of their cornering speed (Reymond, Kemeny, Droulez & Berthoz, 2001) and differences in the perception of speed and depth in simulated versus real driving have been shown (Panerai et al. 2001). Specifically, concerning Chapter 2, the racing driver sample may be more accustomed to using haptic and vestibular acceleration cues (which were lacking in the simulator) as compared to our non-racing driver sample. Considering that a growing amount of evidence suggests that valid results can be obtained with limited simulator fidelity (e.g. Lee, 2004), the driving simulator validity remains an important limitation in this thesis.

A second limitation is that the eye tracker equipment is prone to data loss (i.e., the system's inability to detect facial features or pupils), which can be due to infrared reflections, physical obstruction of a participant's pupils (e.g. by the frame of a participant's glasses), or large head movements which cause the participants pupils to move outside the camera's field of view. Some missing eye tracker data is inevitable, as eye blinks obscure the participants' pupils for short fractions of time. For example, in Chapter 7 an average blink rate of 0.29 Hz was found for drivers during the no time pressure session. Assuming a medium blink duration of 135 ms (Benedetto, Pedrotti, Minin, Baccino, & Montanari, 2011), this results in an approximately 4% data loss due to blinks.

In this thesis the data loss ranged from 13.0% (Chapter 2) to 30.9% (Chapter 6). The random nature of the data loss (e.g., due to blinks), results in no systematic error in the eye movement data. Literature reports data losses of approximately 30% (e.g., Ahlstrom, Victor, Wege, & Steinmetz, 2012) for eye trackers used in driving simulator settings; however, data loss reports vary in the literature due to data quality criteria (Holmqvist, Nyström, & Mulvey, 2012). This thesis specifically reported details concerning the data loss in each chapter, in an attempt to ensure openness regarding eye tracker data quality and analysis methods.

The sample sizes in this thesis were modest, which increases the risk of false positives or false negatives findings (Ioannidis, 2005). Furthermore, the participants were often recruited from a technical university. Engineering students possess an above-average intelligence (Wai, Lubinski, & Benbow, 2009), and intelligence is known to be predictive of driving safety (Whitley et al., 2010). Furthermore, engineering students tend to have a specific interest in driving simulator technology. Summarizing, the generalizability of the results in this thesis may benefit from a larger and more representative sample.

A final limitation is that the experiments in this thesis focused exclusively on manual driving. In the foreseeable future, automated driving technologies will be introduced on the roads, a development that entails new types of psychological questions (De Winter, Happee, Martens, & Stanton., 2014; Fisher, Reed, & Savirimuthu, 2015). More specifically, the driving task will gradually change from a manual control task into a supervisory control task, requiring the driver to simultaneously monitor the environment and in-vehicle systems (Banks, Stanton, & Harvey, 2014).

Recommendations

In this thesis the relationship between measures of eye movements, driver behavior, and driver physiology in closed loop driving tasks have been discussed. The results from this thesis lead to the following recommendations for future research.

A main finding of this thesis concerns the task- and maneuver-dependency of eye and head movements. This means that it is imperative to perform synchronous measurements of eye movements and driver performance variables for understanding the behavior of drivers. For a deeper understanding of the information processing of the driving task-related information, a more thorough understanding of human neurology is recommended. Future research should focus on the application of functional brain imaging techniques (EEG, fMRI) in combination with measures of eye movements and human physiology in closed loop driving tasks.

In this thesis three transfer of training studies (Chapters 3–5) were conducted, aimed at improving novice drivers' lane keeping performance and visual search. The experiments conducted consisted of training phases lasting approximately 30 minutes. Successful transfer of training occurs when learned skills transfer to new or more demanding traffic situations (Groeger & Banks, 2007). In this thesis, retention of the trained skills was assessed immediately after the training or the next day, whereas driving skills are known to develop during years of licensed driving (Mayhem, Simpson, & Pak, 2003). Therefore, future research should be aimed at studying the transfer of training to real vehicles and long-term retention.

The results from this thesis illustrate the strong validity of several physiological measures as indicators of drivers experiencing increased mental demands due to time pressure (Chapter 7). Furthermore, several measures (e.g., pupil diameter) showed a high temporal resolution as compared to other variables indicative of a driver's mental demands (e.g., cardiac measures). The relative validity and temporal resolution of the physiological measures show future potential for real-time driver state estimation. For future research it is recommended that physiological measures are combined with other measures from the driver state (e.g., control actions), data from the vehicle (e.g., vehicle speed and position), and data from outside the vehicle (information regarding the vehicle environment; e.g., surrounding traffic, traffic signs and other geo-specific information). Furthermore, due to strong individual differences found in the measures of driver's physiology, it is recommended that future applications focus on correcting physiological measures by driver-specific reference (baseline) measurements.

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List of publications

Journal publications

Rendon-Velez, E., Van Leeuwen, P. M., Happee, R., Horváth, I., Van der Vegte, W. F., & De Winter, J. C. F. (2016). The effects of time pressure on driver performance and physiological activity: a driving simulator study. *Transportation research part F: traffic psychology and behaviour, 41*, 150–169.

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Damveld, H. J., Wentink, M., Van Leeuwen, P. M., & Happee, R. (2012). Effects of motion cueing on curve driving. *Proceedings of the Driving Simulation Conference 2012*, Paris, France.

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Curriculum Vitae

Born in Gouda, The Netherlands, 11 January 1983.

Education

2001–2005

BSc Aerospace engineering, Delft University of technology.

2005–2009

MSc Aerospace engineering, Delft University of technology. Graduated at the Aerodynamics Department.

2010–2019

PhD study at the Delft University of Technology, Faculty of Mechanical,
Maritime and Materials Engineering, Department of BioMechanical Engineering.

Work experience

2007–current

Race engineer in various single seater categories.

Propositions

These propositions are regarded as lending themselves to opposition and as defendable, and have been approved as such by the promotors prof. dr. F.C.T. van der Helm, dr. ir. J.C.F. de Winter, and dr. ir. R. Happee.

1. A simulator´s visual fidelity level has pronounced effects on driver's behavior, but no effect on driver's eye movements (this thesis).
2. When driving a race car, being *off* throttle and being *full* throttle is more important than being *on* throttle (this thesis).
3. Skills at the tactical level are a more important determinant of being a good racing driver than skills at the operational level.
4. The measurement validity of eye trackers depends on how to handle the bad data, not the good data.
5. Instructing drivers to drive faster in a driving simulator yields research results that benefit road safety; instructing drivers to drive faster in a real car impairs road safety.
6. Pupil diameter is known to be a highly valid measure of workload but is a useless measure for driver workload monitoring in real vehicles.
7. Information from outside the vehicle (geographic, traffic, context) contains sufficient elements required for a reliable and valid estimate of driver workload.
8. The scientific literature on driver training is mostly invalid because of publication bias.
9. Race car driver simulator training has evolved from a novelty to a necessity.