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

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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° 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.

Practitioner Summary: In a driving simulator study, three levels of visual fidelity were evaluated. The results indicate that the highest fidelity level, characterised by a textured environment, resulted in higher steering activity, higher driving speeds and higher variance of horizontal gaze than the two lower fidelity levels without textures.

Keywords: driving simulation; simulator fidelity; curve negotiation; eye-movements; simulator discomfort

1. Introduction

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).

1.2. 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

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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).

1.3. 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).

1.4. *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.

1.5. *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.

1.6. *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.

2. Method

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 €5 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.

2.2. Apparatus

The experiment was conducted with a fixed-base driving simulator (Green Dino; classic model) with a 180° horizontal and 45° 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 × 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 × 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.

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)

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

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.

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 €5 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.

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 90° 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 90° corners, two smooth chicanes and one 180° 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 centee of the right lane with zero speed, and the simulation did not include other traffic.

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.

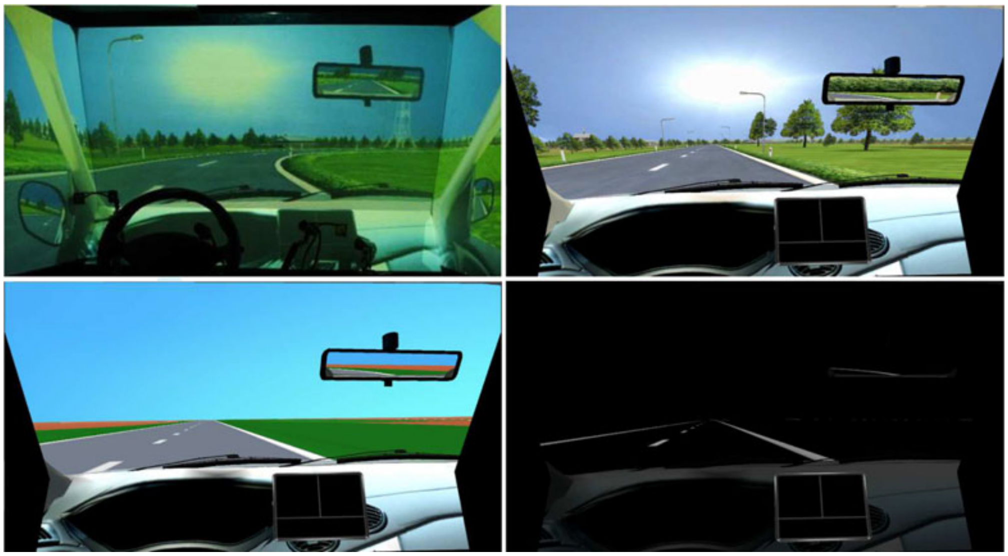

Figure 1. Top left: photo of driving simulator used in the experiment with HF visuals. Top right: screenshot of centre screen for the HF level; lower left: screenshot of centre screen for the MF level; lower right: screenshot of centre screen for the LF level.

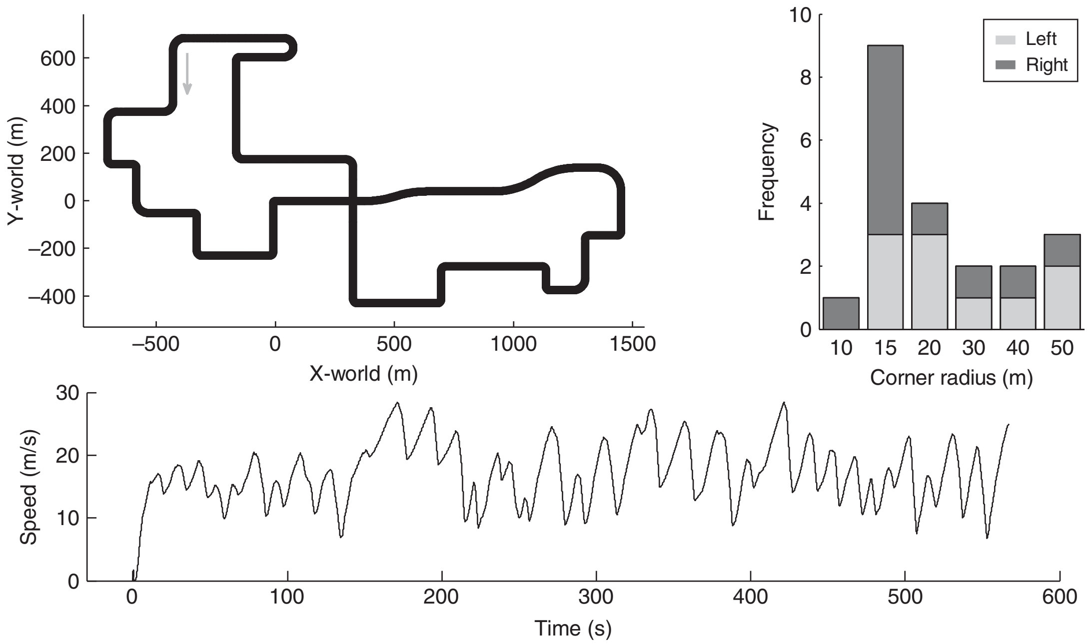

Figure 2. Top left: top view of the road geometry, the starting position and direction are indicated by the grey arrow. Top right: the distribution of the road centre line corner radius for the 90° corners. The lane centre line corner radii are 2.5 m larger or 2.5 m smaller for left- and right-hand corners,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

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 center of the right lane'.

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 10 Hz 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 430 m (mean = 379 m; 2 corners), medium radius corners, from 30 to 50 m (mean = 41 m; 7 corners) and small radius corners, from 10 to 20 m (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 (Authié 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:

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 1°/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.

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 band pass filtered gaze yaw angle signal. The variance was calculated from the band pass filtered signal instead of the original 10 Hz low pass filtered signal to remove the low frequent 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 90° 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.

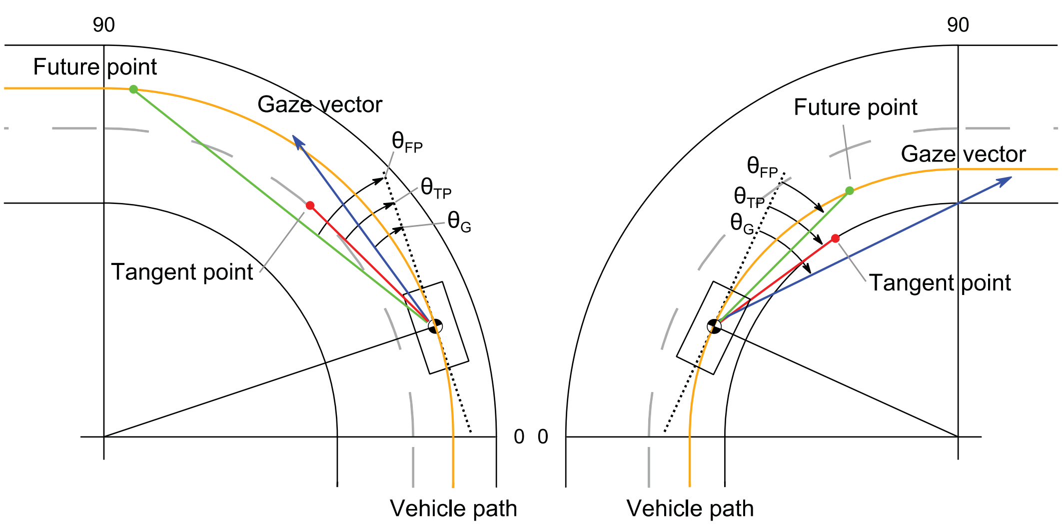

Figure 3. Definitions of the TP- and FP-positions, and of TP angle (θ_{TP}), FP angle (θ_{FP}) and gaze angle (θ_G) with respect to the vehicle heading angle. Definitions are given for left- and right-hand 90° corners. Both figures indicate a positive TP and FP angular error of approximately 10° and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

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).

2.7. Statistical analyses

Remote-mounted eye trackers can be sensitive to the loss of gaze tracking as a result of the systems 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.

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 parentheses) 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)

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° angular position and returned to the centre of the lane after the 90° angular position.

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°/s to 10°/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 nosignificant 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° angular corner position.

Table 3. Means, standard deviations (between parentheses) and F and p values for the repeated measures ANOVA.

	Visual fidelity level			Significance		
Dependent variable	Low	Medium	High	F	p	Between levels
Driving performance						
Number of departures (#)	2.5 (2.0)	2.8 (3.0)	1.6 (1.5)	3.52	0.037	
Mean abs. deviation lateral position (m)	0.71 (0.22)	0.72 (0.25)	0.63 (0.17)	9.08	**0.000**	LF–HF & MF–HF
Standard deviation lateral position (m)	0.95 (0.31)	0.94 (0.33)	0.80 (0.23)	6.36	**0.004**	LF–HF & MF–HF
Mean speed (m/s)	17.9 (1.8)	18.2 (1.8)	18.8 (1.3)	9.50	**0.000**	LF–HF & MF–HF
Max speed (m/s)	29.3 (3.5)	29.6 (3.0)	31.9 (3.6)	4.57	0.016	
Steering wheel steadiness (% of time)	26 (6.0)	25 (5.4)	17 (2.8)	85.0	**0.000**	LF–HF & MF–HF
Gaze behaviour						
Horizontal gaze variance straights (deg^2)	43.2 (26)	51.7 (35)	75.0 (58)	9.96	**0.000**	LF–HF & MF–HF
Horizontal gaze variance corners (deg^2)	12.5 (13)	12.0 (13)	14.3 (15)	1.00	0.375	
Mean TP error (left) (deg)	−2.13 (7.0)	−1.77 (7.2)	−2.03 (6.2)	0.20	0.824	
Mean TP error (right) (deg)	−3.57 (4.0)	−3.37 (2.1)	−3.10 (3.2)	0.03	0.970	
Mean FP error (left) (deg)	−5.91 (4.7)	−6.12 (4.2)	−5.23 (4.6)	0.38	0.691	
Mean FP error (right) (deg)	6.51 (4.6)	7.39 (4.0)	6.10 (3.5)	1.76	0.190	
Workload measured with NASA TLX						
Mental demand (%)	50 (23)	45 (24)	45 (25)	1.01	0.372	
Physical demand (%)	31 (23)	24 (17)	25 (19)	2.92	0.064	
Temporal demand (%)	31 (16)	29 (13)	31 (21)	0.11	0.898	
Performance (%)	40 (19)	45 (24)	42 (20)	0.51	0.605	
Effort (%)	54 (20)	54 (20)	48 (21)	1.37	0.264	
Frustration (%)	37 (22)	36 (27)	29 (19)	2.09	0.135	
Self-reported presence						
Reality awareness (%)	39 (24)	43 (24)	51 (19)	2.26	0.116	
Interaction (%)	56 (24)	65 (17)	66 (17)	3.06	0.056	
Motivation (%)	53 (23)	58 (19)	61 (17)	1.96	0.152	
Visual involvement (%)	34 (25)	51 (24)	68 (19)	22.3	**0.000**	LF–HF & MF–HF
Auditory involvement (%)	55 (23)	52 (21)	55 (17)	0.63	0.538	
Moving sense (%)	44 (23)	50 (17)	61 (18)	6.86	**0.002**	LF–HF
Self-reported discomfort						
Discomfort (%)	23 (28)	15 (20)	23 (24)	2.10	0.134	
Oculomotor (%)	15 (23)	21 (26)	23 (30)	1.15	0.326	
Disorientation (%)	11 (22)	14 (21)	16 (23)	0.92	0.404	
Nausea (%)	8 (17)	8 (17)	8 (17)	0.02	0.980	

Note: Significance between LF and HF and MF and HF is indicated with LF–HF and MF–HF, respectively.

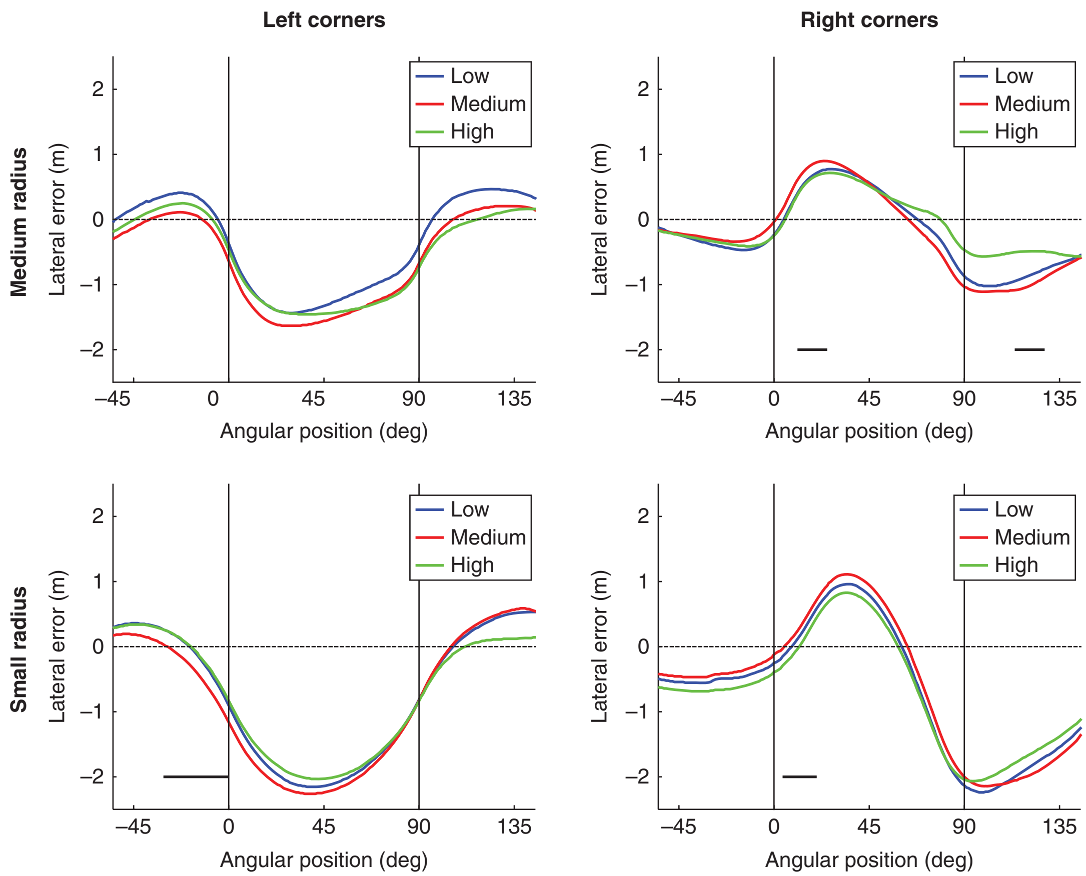

Figure 4. Mean lateral deviation from lane centre, averaged across all participants. The left figures show the lateral error of left-hand corners for the medium corner radii, (top) and small corner radii (lower). The right figures show the lateral error of right-hand corners for medium corner radii, (top) and small corner radii (lower). 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 centre 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° angular positions.

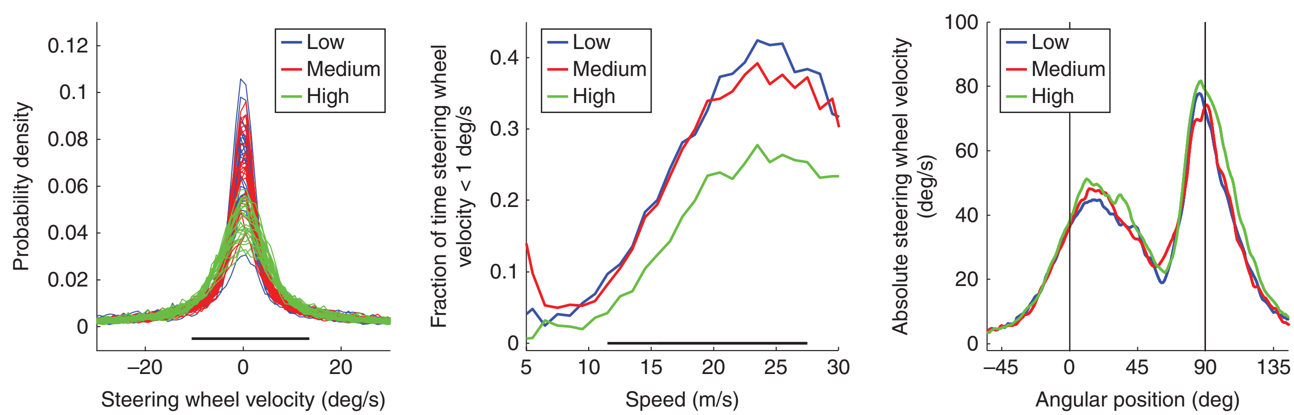

Figure 5. Left: distribution of steering wheel velocity of individual participants for the three visual fidelity levels. The distribution was derived over 1° bins. Centre: steering wheel steadiness as a function of driving speed derived over 1 m/s bins and averaged per bin. Right: mean absolute steering wheel velocity during all corners for the three visual fidelity levels. Corner start and end are indicated by vertical lines at 0° and 90°, 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° angular positions (right figure).

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.

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.

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

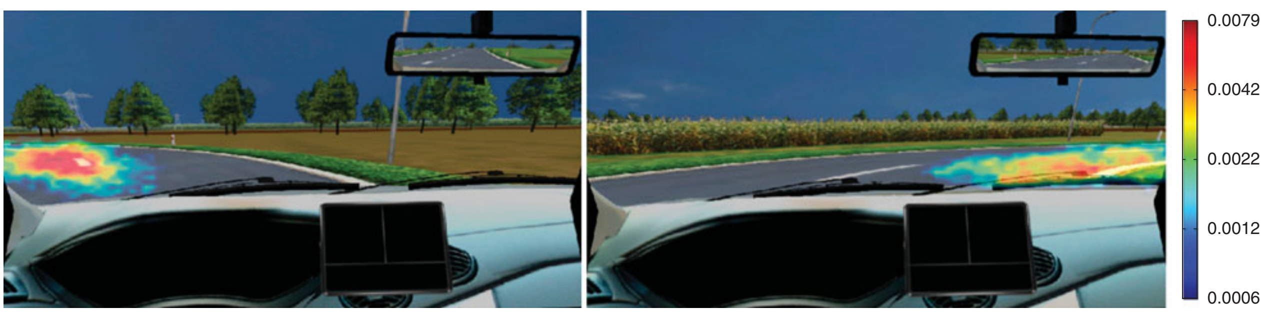

Figure 6. Heatmap of the gaze probability density function during all left- (left) and right-hand (right) medium of all medium and small radii corners for the high visual fidelity level. Gaze distributions were determined by aggregating gaze data from the corner onset until corner exit of all participants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

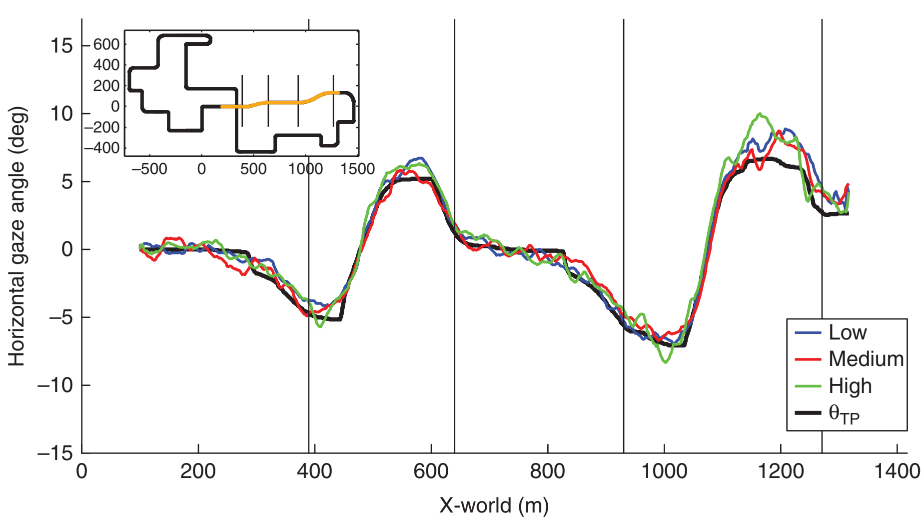

Figure 7. Horizontal gaze angle (θ_G) for large corner radii for the three visual fidelity levels averaged across all participants. The black line shows the angle to the TP (θ_{TP}) averaged over all levels and participants. The vertical straight lines indicate the corner onset and corner end, which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

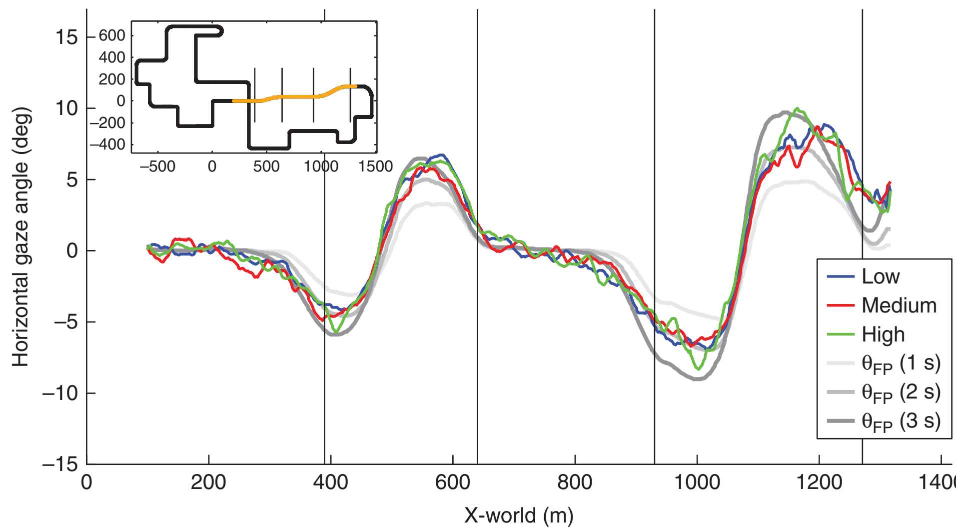

Figure 8. Horizontal gaze angle (θ_G) for large corner radii for the three visual fidelity levels averaged across all participants. The grey lines show the angle to the future point (θ_{FP}) for preview times of 1, 2 and 3 s averaged across all levels and participants. The vertical straight lines indicate 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.

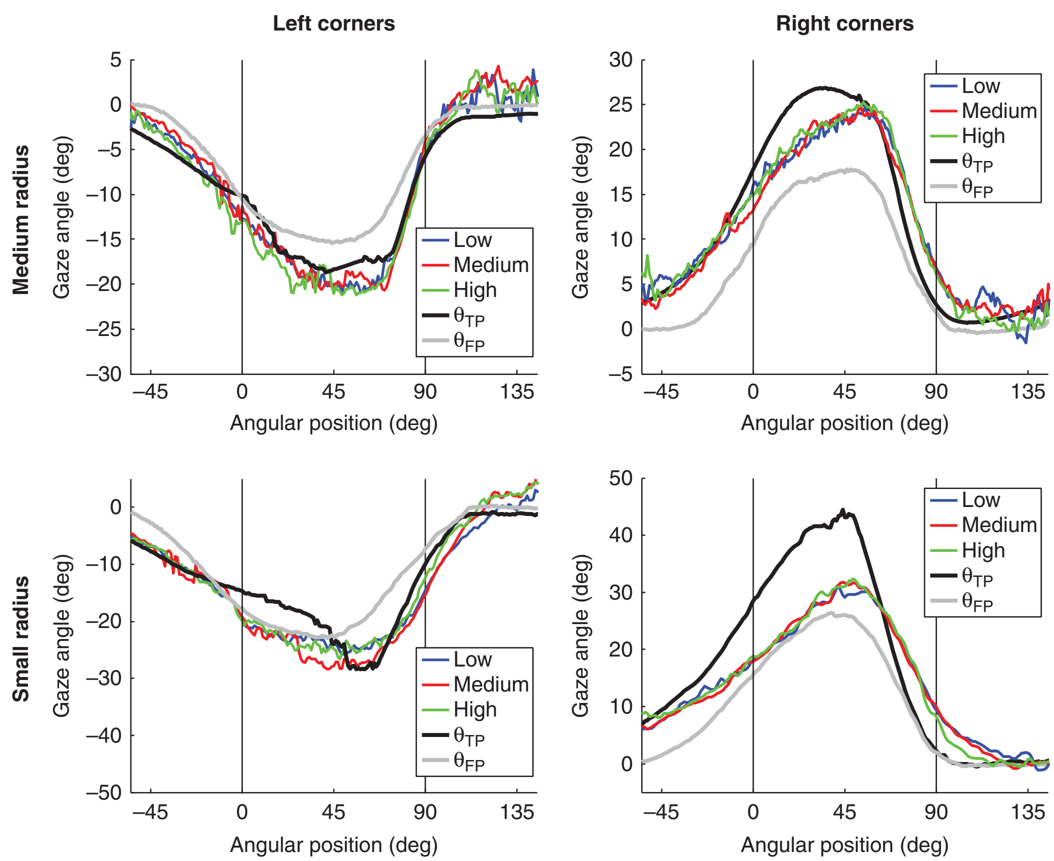

Figure 9. Horizontal gaze angle (θ_G) for medium and small corner radii averaged across all participants. The left figures show the gaze angle (θ_G) in left corners for medium (top) and small (lower) corner radii. The right figures show the gaze angle (θ_G) in right corners for medium (top) and small (lower) corner radii. The black line shows the angle to the TP (θ_{TP}) averaged over all participants, and the grey 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° angular positions.

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.

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.

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 detectible 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 HF 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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Supplementary material

Supplemental content may be viewed online at http://dx.doi.org/10.1080/00140139.2015.1005172.

References

Ahlstrom, C., T. W. Victor, C. Wege, and E. Steinmetz. 2012. “Processing of Eye/Head-Tracking Data in Large-Scale Naturalistic Driving Data Sets.” *IEEE Transactions Intelligent Transportation Systems* 13 (2): 553–564. doi:10.1109/TITS.2011.2174786.

Air Line Pilots Association. 2007. *ALPA White Paper: The Need for Motion in Flight Simulation*. Washington, DC: ALPA International.

Assum, T., T. Bjørnskau, S. Fosser, and F. Sagberg. 1999. “Risk Compensation – The Case of Road Lighting.” *Accident Analysis and Prevention* 31 (5): 545–553. doi:10.1016/S0001-4575(99)00011-1.

Authié, C. N., and D. R. Mestre. 2011. “Optokinetic nystagmus is Elicited by Curvilinear Optic Flow During High Speed Curve Driving.” *Vision Research* 51: 1791–1800.

Authié, C. N., and D. R. Mestre. 2012. “Path Curvature Discrimination: Dependence on Gaze Direction and Optical Flow Speed.” *PLOS ONE* 7 (2): e31479.

Banks, V. A., N. A. Stanton, and C. Harvey. 2014. “Sub-Systems on the Road to Vehicle Automation: Hands and Feet Free but Not ‘Mind’ Free Driving.” *Safety Science* 62: 505–514. doi:10.1016/j.ssci.2013.10.014.

Birrell, S. A., M. S. Young, and A. M. Weldon. 2013. “Vibrotactile Pedals: Provision of Haptic Feedback to Support Economical Driving.” *Ergonomics* 56 (2): 282–292. doi:10.1080/00140139.2012.760750.

Bittner, A. C., B. F. Gore, and B. L. Hooey. 1997. “Meaningful Assessments of Simulator Performance and Sickness: Can’t Have One Without the Other?” *Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting*, 1089–1093. Albuquerque, NM, September 22–26, 1997.

Blana, E. 1996. *Driving Simulator Validation Studies: A Literature Review*. Institute of Transport Studies, University of Leeds, Working Paper 480.

Boer, E. R. 1996. “Tangent Point Oriented Curve Negotiation.” In *Proceedings of the 1996 IEEE Intelligent Vehicles Symposium*, Tokyo, Japan, September 19–20, 1996 7–12.

Boyle, L. N., and J. D. Lee. 2010. “Using Driving Simulators to Assess Driving Safety.” *Accident Analysis and Prevention* 42 (3): 785–787. doi:10.1016/j.aap.2010.03.006.

Brooks, J. O., R. R. Goodenough, M. C. Crisler, N. D. Klein, R. L. Alley, B. L. Koon, W. C. Logan Jr., J. H. Ogle, R. A. Tyrrell, and R. F. Wills. 2010. “Simulator Sickness During Driving Simulation Studies.” *Accident Analysis and Prevention* 42 (3): 788–796. doi:10.1016/j.aap.2009.04.013.

Chattington, M., M. Wilson, D. Ashford, and D. E. Marple-Horvat. 2007. “Eye-Steering Coordination in Natural Driving.” *Experimental Brain Research* 180 (1): 1–14. doi:10.1007/s00221-006-0839-2.

Chatziastros, A., G. M. Wallis, and H. H. Bülthoff. 1999. “The Effect of Field of View and Surface Texture on Driver Steering Performance.” In *Vision in Vehicles VII*, edited by A. G. Gale, I. D. Brown, C. M. Haslegrave, and S. P. Taylor, 253–259. Amsterdam: Elsevier Science.

Cobb, S. V., S. Nichols, A. Ramsey, and J. R. Wilson. 1999. “Virtual Reality-Induced Symptoms and Effects (VRISE).” *Presence: Teleoperators and Virtual Environments* 8 (2): 169–186. doi:10.1162/105474699566152.

Dahlstrom, N., S. Dekker, R. Van Winsen, and J. Nyce. 2009. “Fidelity and Validity of Simulator Training.” *Theoretical Issues in Ergonomics Science* 10 (4): 305–314. doi:10.1080/14639220802368864.

De Groot, S., F. Centeno Ricote, and J. C. F. De Winter. 2012. "The Effect of Tire Grip on Learning Driving Skill and Driving Style: A Driving Simulator Study." *Transportation Research Part F: Traffic Psychology and Behavior* 15 (4): 413–426. doi:10.1016/j.trf.2012.02.005.

De Groot, S., J. C. F. De Winter, J. M. Garcia, M. Mulder, and P. A. Wieringa. 2011. "The Effect of Concurrent Bandwidth Feedback on Learning the Lane-Keeping Task in a Driving Simulator." *Human Factors* 53 (1): 50–62. doi:10.1177/0018720810393241.

De Waard, D., F. J. Steyvers, and K. A. Brookhuis. 2004. "How Much Visual Road Information Is Needed to Drive Safely and Comfortably?" *Safety Science* 42 (7): 639–655. doi:10.1016/j.ssci.2003.09.002.

De Winter, J. C. F., S. De Groot, M. Mulder, and P. A. Wieringa. 2007. "The Fun of Engineering: A Motion Seat in a Driving Simulator." In *Proceedings of the Driving Simulator Conference North America*, Iowa City, IA, September 12–14, 2007 77–85.

De Winter, J. C. F., P. M. Van Leeuwen, and R. Happee. 2012. "Advantages and Disadvantages of Driving Simulators: A Discussion." In *Proceedings of Measuring Behavior 2012, 8th International Conference on Methods and Techniques in Behavioral Research*, edited by A. J. Spink, F. Grieco, O. E. Krips, L. W. S. Loijens, L. P. J. J. Noldus, and P. H. Zimmerman, 47–50. Wageningen: Noldus Information Technology B.V., August 28–31, 2012.

Donges, E. 1978. "A Two-Level Model of Driver Steering Behavior." *Human Factors* 20: 691–707.

Dziuda, Ł., M. P. Biernacki, P. M. Baran, and O. E. Truszczyński. 2014. "The Effects of Simulated Fog and Motion on Simulator Sickness in a Driving Simulator and the Duration of After-Effects." *Applied Ergonomics* 45 (3): 406–412. doi:10.1016/j.apergo.2013.05.003.

Elvik, R. 2004. "To What Extent Can Theory Account for the Findings of Road Safety Evaluation Studies?" *Accident Analysis and Prevention* 36 (5): 841–849. doi:10.1016/j.aap.2003.08.003.

Fischer, M., L. Eriksson, and K. Oeltze. 2012. "Evaluation of Methods for Measuring Speed Perception in a Driving Simulator." In *Proceedings of Driving Simulation Conference Europe*, edited by S. Espié, A. Kemeny, and F. Mérienne, 214–229. Paris, September 6–7, 2012 Inrets.

Fisher, D. L., M. Rizzo, J. Caird, and J. D. Lee, eds. 2011. *Handbook of Driving Simulation for Engineering, Medicine, and Psychology*. Boca Raton, FL: CRC Press.

Flemisch, F. O., K. Bengler, H. Bubb, H. Winner, and R. Bruder. 2014. "Towards Cooperative Guidance and Control of Highly Automated Vehicles: H-Mode and Conduct-by-Wire." *Ergonomics* 57 (3): 343–360. doi:10.1080/00140139.2013.869355.

Gawron, V. J., and T. A. Ranney. 1990. "Curve Negotiation Performance in a Driving Simulator as a Function of Curve Geometry." *Applied Ergonomics* 21 (1): 33–38. doi:10.1016/0003-6870(90)90071-5.

Gibson, J. J. 1958. "Visually Controlled Locomotion and Visual Orientation in Animals." *British Journal of Psychology* 49 (3): 182–194. doi:10.1111/j.2044-8295.1958.tb00656.x.

Hancock, P. A. 2009. "The Future of Simulation." In *Human Factors in Simulation and Training*, edited by D. Vinccnzi, J. Wise, M. Mouloua, and P. A. Hancock, 169–186. Boca Raton, FL: Taylor & Francis.

Hancock, P. A., and T. B. Sheridan. 2011. "The Future of Driving Simulation." In *Handbook of Driving Simulation for Engineering, Medicine and Psychology*, edited by D. Fisher, M. Rizzo, J. Caird, and J. Lee. Boca Raton, FL: CRC Press.

Hart, S. G., and L. E. Staveland. 1988. "Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research." In *Human Mental Workload*, edited by P. A. Hancock and N. Meshkati, 139–183. Amsterdam: North-Holland B.V.

Hettinger, L. J., K. S. Berbaum, R. S. Kennedy, W. P. Dunlap, and M. D. Nolan. 1990. "Vection and Simulator Sickness." *Military Psychology* 2 (3): 171–181. doi:10.1207/s15327876mp0203_4.

Hettinger, L. J., and G. E. Riccio. 1992. "Visually Induced Motion Sickness in Virtual Environments." *Presence: Teleoperators and Virtual Environments* 1: 306–310.

Holmqvist, K., M. Nyström, and F. Mulvey. 2012. "Eye Tracker Data Quality: What It Is and How to Measure It." In *Proceedings of the 2012 Symposium on Eye Tracking Research and Applications (ETRA 2012)*, 45–52. Santa Barbera, CA.

Hurwitz, D. S., M. A. Knodler, and D. M. Dulaski. 2005. "Speed Perception Fidelity in a Driving Simulator Environment." In *Proceedings of the Driving Simulator Conference North America*, 343–352, Orlando, FL, November 30–December 2, 2005.

Johnson, D. M. 2005. *Introduction to and Review of Simulator Sickness Research* (Research Report 1832). Arlington, VA: U.S. Army Research Institute for the Behavioral and Social Sciences.

Jurgensohn, T., M. Neculau, and H. P. Willumeit. 1991. "Visual Scanning Pattern in Curve Negotiation." In *Vision in Vehicles III*, edited by A. G. Gale, I. Gale, I. Brown, C. M. Haslegrave, I. Moorhead, and S. P. Taylor, 171–178. Amsterdam: Elsevier Science.

Kallberg, V. 1993. "Reflector Posts-Signs of Danger?" *Transportation Research Record* 1403: 57–66.

Kandil, F. I., A. Rotter, and M. Lappe. 2009. "Driving is Smoother and More Stable When Using the Tangent Point." *Journal of Vision* 9 (1): 1–11. doi:10.1167/9.1.11.

Kandil, F. I., A. Rotter, and M. Lappe. 2010. "Car Drivers Attend to Different Gaze Targets When Negotiating Closed vs. Open Bends." *Journal of Vision* 10 (4): 1–11. doi:10.1167/10.4.24.

Kaptein, N. A., J. Theeuwes, and A. R. A. Van der Horst. 1996. "Driving Simulator Validity: Some Considerations." *Transportation Research Record* 1550 (1): 30–36. doi:10.3141/1550-05.

Karl, I., G. Berg, F. Rüger, and B. Färber. 2013. "Driving Behavior and Simulator Sickness While Driving the Vehicle in the Loop: Validation of Longitudinal Driving Behavior." *IEEE Intelligent Transportation Systems Magazine* 5 (1): 42–57. doi:10.1109/MITS.2012.2217995.

Kennedy, R. S., K. S. Berbaum, and M. G. Smith. 1993. "Methods for Correlating Visual Scene Elements with Simulator Sickness Incidence." In *Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting*, 1252–1256, Seatle, WA, October 11–15, 1993.

Kennedy, R. S., N. E. Lane, K. S. Berbaum, and M. G. Lilienthal. 1993. "Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness." *The International Journal of Aviation Psychology* 3 (3): 203–220. doi:10.1207/s15327108ijap0303_3.

Kim, N. G., and M. T. Turvey. 1999. "Eye Movements and a Rule for Perceiving Direction of Heading." *Ecological Psychology* 11 (3): 233–248. doi:10.1207/s15326969eco1103_3.

Kolasinski, E. M. 1995. *Simulator Sickness in Virtual Environments* (Technical Report 1027). Alexandria, VA: U.S. Army Research Institute for the Behavioral and Social Sciences.

Kountouriotis, G. K., K. A. Shire, C. D. Mole, P. H. Gardner, N. Merat, and R. M. Wilkie. 2013. "Optic Flow Asymmetries Bias High-Speed Steering Along Roads." *Journal of Vision* 13 (10): 1–9. doi:10.1167/13.10.23.

Land, M. F., and J. Horwood. 1995. "Which Parts of the Road Guide Steering?" *Nature* 377 (6547): 339–340. doi:10.1038/377339a0.

Land, M. F., and D. N. Lee. 1994. "Where We Look When We Steer." *Nature* 369 (6483): 742–744. doi:10.1038/369742a0.

Lappe, M., F. Bremmer, and A. V. Van den Berg. 1999. "Perception of Self-Motion from Visual Flow." *Trends in Cognitive Sciences* 3 (9): 329–336. doi:10.1016/S1364-6613(99)01364-9.

Lappe, M., A. Grigo, F. Bremmer, H. Frenz, R. J. V. Bertin, and I. Israel. 2000. "Perception of Heading and Driving Distance from Optic Flow." In *Proceedings of Driving Simulation Conference*, 25–31, Paris, September 6–8, 2000.

Lappi, O. 2014. "Future Path and Tangent Point Models in the Visual Control of Locomotion in Curve Driving." *Journal of Vision* 14 (12): 1–22. doi:10.1167/14.12.21.

Lappi, O., E. Lehtonen, J. Pekkanen, and T. Itkonen. 2013. "Beyond the Tangent Point: Gaze Targets in Naturalistic Driving." *Journal of Vision* 13 (13): 1–18. doi:10.1167/13.13.11.

Lappi, O., J. Pekkanen, and T. Itkonen. 2013. "Pursuit Eye-Movements in Curve Driving Differentiate Between Future Path and Tangent Point Models." *PLOS ONE* 8 (7): e68326.

Lee, J. D. 2004. "Simulator Fidelity: How Low Can You Go?" *Proceedings of the Human Factors and Ergonomics Society 48th Annual Meeting*, 2253, New Orleans, LA, September 20–24, 2004.

Levine, O. H., and R. R. Mourant. 1996. "Effect of Visual Display Parameters on Driving Performance in a Virtual Environments Driving Simulator." In *Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting*, 1136–1140, Philadelphia, PA, September 2–6, 1196.

Li, L., and J. Chen. 2010. "Relative Contributions of Optic Flow, Bearing, and Spay Angle Information to Lane Keeping." *Journal of Vision* 10 (11): 1–14. doi:10.1167/10.11.16.

Luke, T., A. M. Parkes, and R. Walker. 2006. "The Effect of Visual Properties of the Simulated Environment on Simulator Sickness and Driver Behavior." In *Proceedings of Driving Simulation Conference Europe*, 253–262, Paris, October 4–6, 2006.

Mars, F. 2008. "Driving Around Bends with Manipulated Eye-Steering Coordination." *Journal of Vision* 8 (11): 1–11. doi:10.1167/8.11.10.

Martens, M. H., and G. D. Jenssen. 2012. "Behavioural Adaptation and Acceptance." In *Handbook Intelligent Vehicles*, edited by A. Eskandarian, 117–138. London: Springer Verlag.

Mollenhauer, M. A. 2004. *Simulator Adaptation Syndrome Literature Review* (Technical Report). Royal OAK, MI: Realtime Technologies Inc.

Mourant, R. R., N. Ahmad, B. K. Jaeger, and Y. Lin. 2007. "Optic Flow and Geometric Field of View in a Driving Simulator Display." *Displays* 28 (3): 145–149. doi:10.1016/j.displa.2007.04.011.

Mourant, R. R., and T. H. Rockwell. 1972. "Strategies of Visual Search by Novice and Experienced Drivers." *Human Factors* 14: 325–335.

Mourant, R. R., and T. R. Thattacherry. 2000. "Simulator Sickness in a Virtual Environments Driving Simulator." In *Proceedings of the Human Factors and Ergonomics Society 44th Annual Meeting*, 534–537, San Diego, CA, July 29–August 4, 2000.

NASA TLX. n.d. "NASA TLX Paper/Pencil Version." *NASA TLX: Task Load Index*. http://humansystems.arc.nasa.gov/groups/tlx/downloads/TLXScale.pdf

Panerai, F., J. Droulez, J. M. Kelada, A. Kemeny, E. Balligand, and B. Favre. 2001. "Speed and Safety Distance Control in Truck Driving: Comparison of Simulation and Real-World Environment." In *Proceedings of Driving Simulation Conference*, 91–107, Sophia-Antipolis Nice, September 5–7, 2001.

Parkes, A. M. 2005. *Improved Realism and Improved Utility of Driving Simulators: Are They Mutually Exclusive?. HUMANIST TFG Workshop on the Application of New Technologies to Driver Training*. Brno: Czech Republic.

Pinto, M., V. Cavallo, and T. Ohlmann. 2008. "The Development of Driving Simulators: Toward a Multisensory Solution." *Le Travail Humain* 71 (1): 62–95. doi:10.3917/th.711.0062.

Pretto, P., and A. Chatziastros. 2006. "Changes in Optic Flow and Scene Contrast Affect the Driving Speed." In *Proceedings of the Driving Simulator Conference Europe*, 263–272, Paris, October 4–6, 2006.

Pritchard, S. J., and S. T. Hammett. 2012. "The Effect of Luminance on Simulated Driving Speed." *Vision Research* 52 (1): 54–60. doi:10.1016/j.visres.2011.10.014.

Reed, M. P., and P. A. Green. 1999. "Comparison of Driving Performance On-Road and in a Low-Cost Simulator Using a Concurrent Telephone Dialling Task." *Ergonomics* 42 (8): 1015–1037. doi:10.1080/001401399185117.

Reimer, B., B. Mehler, J. Dobres, J. F. Coughlin, S. Matteson, D. Gould, N. Chahine, and V. Levantovsky. 2014. "Assessing the Impact of Typeface Design in a Text-Rich Automotive User Interface." *Ergonomics* 57 (11): 1643–1658. doi:10.1080/00140139.2014.940000.

Rizzo, M., J. Severson, J. Cremer, and K. Price. 2003. "An Abstract Virtual Environment Tool to Assess Decision-Making in Impaired Drivers." In *Proceedings of the Second International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, 40–47, Park City, UT, July 21–24, 2003.

Robertshaw, K. D., and R. M. Wilkie. 2008. "Does Gaze Influence Steering Around a Bend?" *Journal of Vision* 8 (4): 1–13. doi:10.1167/8.4.18.

Roenker, D. L., G. M. Cissell, K. K. Ball, V. G. Wadley, and J. D. Edwards. 2003. "Speed-of-Processing and Driving Simulator Training Result in Improved Driving Performance." *Human Factors* 45 (2): 218–233. doi:10.1518/hfes.45.2.218.27241.

Salmon, P. M., M. G. Lenne, G. H. Walker, N. A. Stanton, and A. Filtness. 2014. "Using the Event Analysis of Systemic Teamwork (EAST) to Explore Conflicts Between Different Road User Groups When Making Right Hand Turns at Urban Intersections." *Ergonomics* 57 (11): 1628–1642. doi:10.1080/00140139.2014.945491.

Salvucci, D. D., and R. Gray. 2004. "A Two-Point Visual Control Model of Steering." *Perception* 33 (10): 1233–1248. doi:10.1068/p5343.

Santos, J., N. Merat, S. Mouta, K. Brookhuis, and D. De Waard. 2005. "The Interaction Between Driving and In-Vehicle Information Systems: Comparison of Results from Laboratory, Simulator and Real-World Studies." *Transportation Research Part F* 8 (2): 135–146. doi:10.1016/j.trf.2005.04.001.

Severson, J., M. Rizzo, J. Wagner, J. Cremer, A. F. Best, and M. A. Severson. 2007. "Driving Simulation: How Low Can You Go?" *Proceedings of the Driving Simulator Conference North America*, Iowa City, IA.

Sivak, M. 1996. "The Information That Drivers Use: Is It Indeed 90% Visual?" *Perception* 25 (9): 1081–1089. doi:10.1068/p251081.

Steyvers, F. J. J. M., and D. De Waard. 2000. "Road-Edge Delineation in Rural Areas: Effects on Driving Behaviour." *Ergonomics* 43 (2): 223–238. doi:10.1080/001401300184576.

Van der Horst, A. R. A. 1990. "A Time-Based Analysis of Road User Behaviour in Normal and Critical Encounters." Ph.D. thesis, Delft University of Technology, Delft.

Van Leeuwen, P. M., S. De Groot, R. Happee, and J. C. F. De Winter. 2011. "Effects of Concurrent Continuous Visual Feedback on Learning the Lane Keeping Task." In *Proceedings of the 6th International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, 482–488, Lake Tahoe, CA, June 27–30, 2011.

Van Leeuwen, P. M., R. Happee, and J. C. F. De Winter. 2013. "Investigating the Effect of a Visual Search Task for Simulator-Based Driver Training." In *Proceedings of the 7th International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, 425–431, Bolton Landing, NY, June 17–20, 2013.

Van Leeuwen, P. M., R. Happee, and J. C. F. De Winter. 2014. "Vertical Field of View Restriction in Driver Training: A Simulator-Based Evaluation." *Transportation Research Part F: Traffic Psychology and Behaviour* 24: 169–182. doi:10.1016/j.trf.2014.04.010.

Verstegen, D. M. L., and J. C. G. M. van Rooij. 2003. "Keep Systematic Training System Design Efficient!" *Proceedings of the Human Factors & Medicine Panel Symposium on Advanced Technologies for Military training*, 1–11, Genova, October 13–15, 2003.

Wann, J. P., and D. K. Swapp. 2000. "Why You Should Look Where You Are Going." *Nature Neuroscience* 3 (7): 647–648. doi:10.1038/76602.

Warren, W. H., D. R. Mestre, A. W. Blackwell, and M. W. Morris. 1991. "Perception of Circular Heading from Optical Flow." *Journal of Experimental Psychology: Human Perception and Performance* 17 (1): 28–43. doi:10.1037/0096-1523.17.1.28.

Warren, W. H., M. W. Morris, and M. Kalish. 1988. "Perception of Translational Heading from Optical Flow." *Journal of Experimental Psychology: Human Perception and Performance* 14 (4): 646–660. doi:10.1037/0096-1523.14.4.646.

Wilkie, R. M., G. K. Kountouriotis, N. Merat, and J. P. Wann. 2010. "Using Vision to Control Locomotion: Looking Where You Want to Go." *Experimental Brain Research* 204 (4): 539–547. doi:10.1007/s00221-010-2321-4.

Wilkie, R. M., and J. P. Wann. 2002. "Driving as Night Falls: The Contribution of Retinal Flow and Visual Direction to the Control of Steering." *Current Biology* 12 (23): 2014–2017. doi:10.1016/S0960-9822(02)01337-4.

Wilkie, R. M., and J. P. Wann. 2003a. "Controlling Steering and Judging Heading: Retinal Flow, Visual Direction, and Extraretinal Information." *Journal of Experimental Psychology: Human Perception and Performance* 29 (2): 677–684. doi:10.1167/3.11.3.

Wilkie, R. M., and J. P. Wann. 2003b. "Eye-Movements Aid the Control of Locomotion." *Journal of Vision* 3 (11): 677–684. doi:10.1167/3.11.3.

Witmer, B. G., and M. J. Singer. 1998. "Measuring Presence in Virtual Environments: A Presence Questionnaire." *Presence: Teleoperators and Virtual Environments* 7 (3): 225–240. doi:10.1162/105474698565686.