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Changes of driving performance and gaze behavior of novice drivers duringa 30-min simulator-based training

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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 closeas possible tothe 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 datashowed 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, SDLPdecreases, gaze variance increases, and self-reported workload decreases. These results indicate that short-term changesin driver skill and visual behavior of novice drivers can be detected using driving simulators.

Keywords: Driving simulator; Eye movements; Driving performance

1. Introduction

Novice drivers are overrepresented in road traffic crashes[1]. Accident rates are particularly high in the first few months after obtaining a driver's license and decline as drivers gain experience [2, 3]. 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.

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Prior research has shownthat novice and experienced drivers differ in various ways. Novice drivers generally have underdevelopedvehicle control skills and less spare attentional capacity than experienced drivers[1,4].Furthermore, novice drivers have a relatively poor ability to identify and anticipate traffic hazards [5, 6]compared totheir experienced counterparts.Also, novice drivers adjust their visual search less effectively to the environmental situation [7],tend to direct their gazemore often to the immediate vicinity [8], rely less on peripheral vision for vehicle control [9], and show less variability in fixation patterns [10]. Additionally, novice drivers differ from experienced drivers when it comes to the use of in-vehicle technology [1]. For example, Wikman et al. [11] 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 beobservedat 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 [15]. 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 [12, 13]. Charlton and Starkey, 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 simulatorfora 12-week period [14].

Several longitudinal studies have found that self-reported violations increase with driving experience[16,17]. These findings are corroborated by driver-training data documentedby De Winter et al. [18]. These authors found that although errors decreasedduring driving lessons in adriving simulator, the speed of task execution and violations increased. Similarly, Underwood [19] found that during the first six months of driving, novices increased their mean road speed and tendency to cut cornerswhen 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 isattenuatedor even negative [20].

Although ample studies have investigated differences between novice and experienced drivers, and have reported learning curves of driver behavior data, only few studies have measured the changesof gaze behavior over the course of practice.We combined the datasets of three previously publishedstudies [21-23], in each of which novice drivers were practicinga 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 afairly 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.

2. Methods

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 [21]) or in possession of a driver’s license for less than 3 years (Experiments2 [22] and 3 [23]). 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

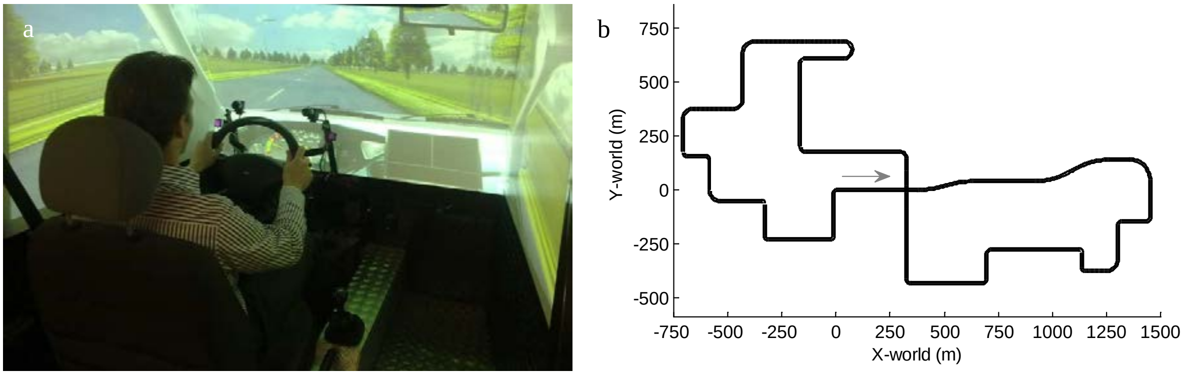

Fig. 1. (a) Photo of driving simulator (Experiment 1); (b) Top view of the course; the arrow indicates the starting location and direction.

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 [24]. 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 [23, 25]. 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.

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 SmartEyesystem, 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

2.3. Procedures

The three experiments were conducted independently. Each experiment evaluated a particular training method using a between-subject design with a control group and a treatment group. The analyses in this paper are based on the control group data of 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[26]. Afterwards, 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 [27]. After completing the three training sessions in Experiment 1 and 3, participants drove an immediate retention session with the same instructions as provided for thesetraining sessions. The participants from Experiment 2 drove four training sessions (Table 2). The total experiment duration was40–50 min for all participants.

2.4. Driving task

Allsessions 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[25] 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 on the same location in the virtual environment and with the vehicle stationary on the center of the right lane. Figure 1 (a)shows a photo of the simulator and virtual environment, and Figure 1 (b) 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, theinstructions were repeated on the front projection of the simulator.

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) [23,25]. If more than 60% of eye tracker data were removed from a session, the entire session was excludedfrom the analysis.

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

1) *Mean speed (m/s).*
2) *Mean lateralposition (MLP) (m)* was used as a measure of lane keeping bias.
3) *Standard deviation lateralposition (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)* (deg^2) was calculated on the straight road segments[22].
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 [22,28].
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.

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 measurementswas30.9%. 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 shownfor each of the dependent measures. Itcan 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 rear view mirror. Self-reported overall workload decreased from 39.5% in Session 4 to 33.1% in Session 1. The largest decrease was observed for the Mental demand, Temporal demand, and Frustration items of the TLX.

Table 3.Means with standard deviations in parentheses of the dependent measures for the four driving sessions. The *p* values and effect sizesare 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.

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.

Figure 2 illustrates the correlation between sessionsfor three selected variables. It shows a reduction of GRC(a) and SDLP (c), and the increase in HGV (b) from Session 1 to 4. The figure also shows the large

Table 4. Correlation matrix ofthe 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 ($N = 20$) couldnot be included from the correlation matrix. Correlations that are statistically significant ($p<.05$) are in boldface.

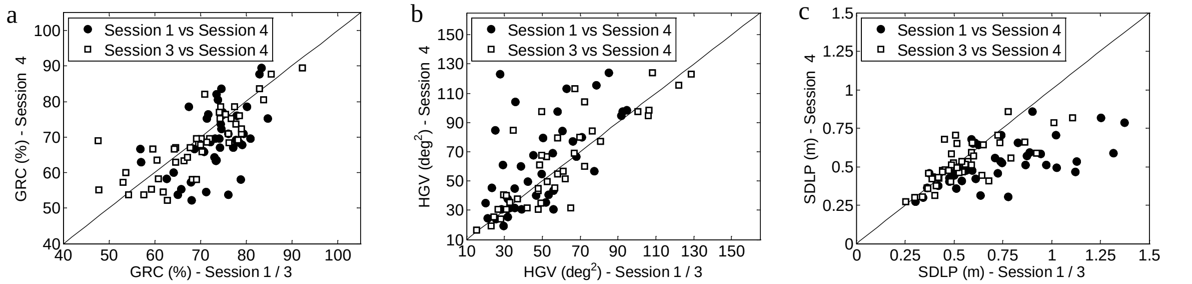

Fig. 2.Associations between selected dependent measures (Session 4 vs. Session 1 / 3). From left to right are shown the Gaze Road Center (GRC; N = 46), Horizontal Gaze Variance (HGV; N = 46), and the Standard Deviation Lane Position (SDLP; N = 50). The corresponding correlation coefficients are shown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

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.

Figure 3 (a) illustrates the reduction in steering activity from Session 1 to 4. Figure 3 (b) 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.

The gaze pitch (downward) angle below the horizon and the HGV as a function of driving speed are shown in Figure 4 (a) and (b). 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 (b) illustrates the significant increase in HGV from Session 1 to Session 4.

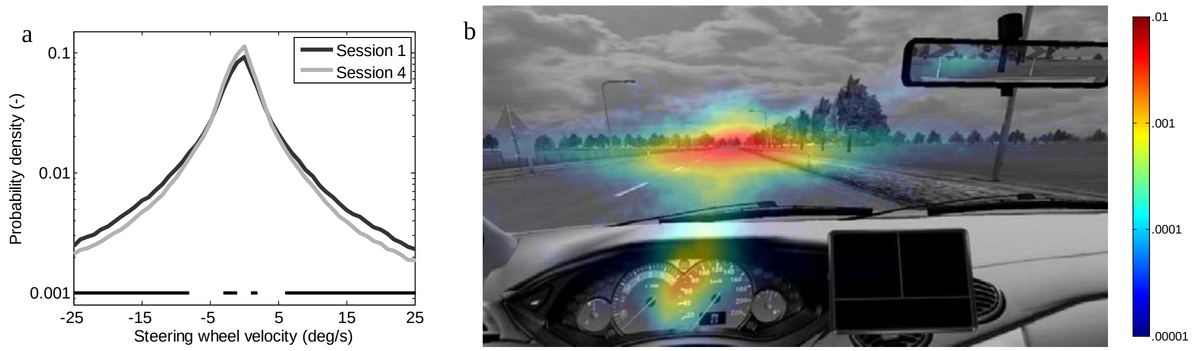

Fig. 3. (a) Distribution of the participant averaged steering wheel velocity for Session 1 and 4. The distributionswere calculated for 1 deg bins. Significant differences (*p*< .001) are indicated by horizontal black lines. (b)Heatmap showing the gaze distribution on straight road segments. The distribution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

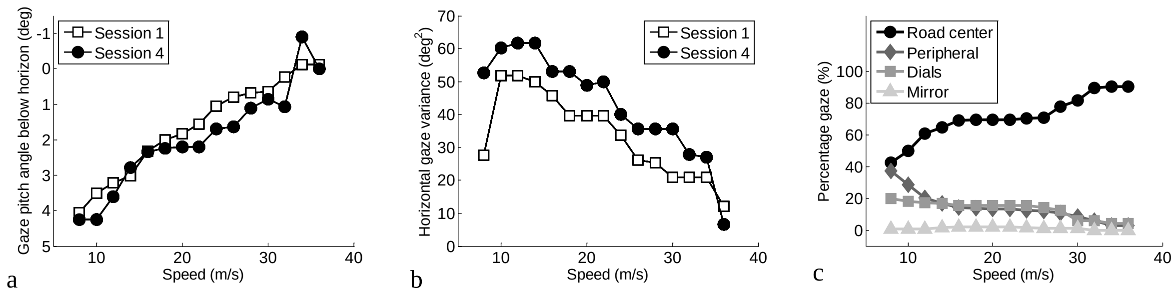

Fig. 4. Gaze pitch angle below the horizon (a) and Horizontal Gaze Variance (HGV)(b) as a function of driving speed for Session 1 and 4. (c) Gaze distribution between Road center, Peripheral area, Dials, and Mirror, as a function of driving speed, averaged across all sessions. Distributions were calculated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

The decrease in visual search as a function of driving speed is further illustrated in Figure 4 (c). 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.

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 on 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 alsofound by Shinar et al. [13], among others, and is consistent with general learning effects in perceptual and motor tasks[30]. Interestingly, we found no statistically significant differences in driving speeds betweenthe first and last session. This lack of effect may be becauseparticipants could not gain time (i.e.,the session durationswerefixedat 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 [31]. 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-basedand video-based driving studies[32, 33]. Reimer [34], for example, found a reduction in gaze distributions and a reduced peripheral vision when drivers performed a secondary cognitive task in an instrumented vehicle.

Ourresults 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[35], it was found that as driving speeds increased (hence, the task became more demanding), the gaze distribution progressivelynarrowed. Our results also showed that as drivers drove faster, they directed their gaze further ahead of the vehicle andspent less time gazing 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 may be determined to some extent by the spare amount of mental capacity [36].

In conclusion, our results demonstrate a cleareffect of practice on the driving precision and gaze tunneling of novice driversin a driving simulator.Theseresults indicate thatshort-term changes of driving performance and gaze behavior of novice drivers can be detected using state-of-the-art eye tracking equipment.A 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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