The Influence of Traffic Density and Repeated Exposure to Roundabouts on Driver Behavior

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25-09-2023

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Abstract

Several studies have shown different findings on how driving behavior and performance change as drivers are exposed to various types of road complexity. This study examined how driver behavior and performance changed when exposed to two under-investigated types of road complexity; repeatedly having to negotiate roundabouts and being exposed to varying levels of traffic density. A within-subjects repeated measures design with 25 participants was employed in this study. Participants drove in a control (no roundabouts or traffic density) and an experimental condition (with repeated roundabouts and varying levels of traffic density). The results indicated that deviation from the instructed speed, braking instances and crashes all increased with more traffic density. Moreover, when repeatedly having to negotiate roundabouts, only velocity and steering variance showed an increase. These findings were unable to fully support the hypothesis that with prolonged or repeated exposure to traffic complexity/obstacles, driver performance would deteriorate. The results suggest that the different types of traffic complexity might cognitively impact drivers in different ways, herewith divergently influencing their performance while driving. Follow-up research based on this study's design, limitations, and recommendations should be conducted to investigate the intricate relationship between prolonged/repeated exposure to specific traffic complexities and driver behavior and cognition further.

Keywords: Traffic safety · Repeated exposure · Roundabouts · Traffic density · Performance · Cognition

Introduction

Accidents and injuries resulting from road traffic are increasingly being considered a large health concern nowadays (Ahmed et al., 2022). According to the World Health Organization [WHO] (2023), road traffic accidents are a significant cause of death globally, with an estimated 1.35 million deaths annually. Furthermore, in Europe alone, approximately 25.000 fatalities are reported every year following road traffic accidents according to the European Commission (2023). These numbers do not only impact the health of traffic participants, it also impacts the economy. In Europe alone, the total cost due to road crashes is approximated to be around €280 billion (Wijnen et al., 2017). So, following the aforementioned statistical trends, it is evident that driver safety on the road is an essential aspect of preventing such accidents/fatalities as well as the economic impact it brings with it.

To counteract the high number of accidents and injuries resulting from road traffic, and herewith enhance traffic safety, much research has already been conducted into understanding and predicting the behavior of drivers. Such research has contributed to the development of conceptual and computational models of driving behavior (Bi et al., 2012; Gadepally et al., 2014; Sagberg et al., 2015; Salvucci, 2006). These models help understand, predict, and test driver behavior in various driving contexts, herewith contributing to both a theoretical understanding as well as practical applications in intelligent driving systems (e.g., Advanced Driver Assistance Systems (ADAS)) (Guo et al., 2023). Within these models, many elements have been incorporated as contributing factors to driver error and fatalities, e.g., cognitive overload, (visual) fatigue, and monotony (Bier et al., 2019; De Vos et al., 2023; Hasan et al., 2022; Lu et al., 2022; Yadav & Velaga, 2022). Conversely, factors have been detected to reduce driver error and fatalities, e.g., experience and practice (Engströme et al., 2003; Rasmussen, 1984). Using the knowledge that is summarized in such established models as well as their predictive power, better practices for safe driving can be developed in terms of policy development, road design, driver training and education, and intelligent driver assistance systems (Ng & Sayed, 2004; Sheng et al., 2018). Moreover, the aforementioned safety factors that are indicated by conceptual and computational models all occur due to prolonged or repetitive exposure to driving and its complexities (Li et al., 2017; Paxion et al., 2014; Wang & Pei, 2014). This forms the scope of this research article.

The exposure to various driving obstacles/complexities and how it influences driver behavior has thus far been researched, and the findings are incorporated into conceptual and computational driver models (Hinton et al., 2022; Pekkanen et al., 2018). However, what is still less well covered by these models, is how driver behavior alters when drivers are exposed to two specific types of traffic complexity. Namely, there has been conducted little, if any, research on how driver behavior alters when drivers repeatedly have to negotiate roundabouts and are exposed to different levels of traffic density for prolonged periods (AlKheder et al., 2020; Alshannaq & Imam, 2020; Liu et al., 2018). Consequently, the present research aims to investigate how driver behavior and performance are influenced by the repeated exposure to roundabouts and the (prolonged) exposure to varying levels of traffic density.

Background

A distinction should be made between repeated exposure and prolonged exposure. Namely, whereas repeated exposure entails the interrupted facing of a certain traffic event in quick succession, prolonged exposure entails the uninterrupted engagement with a certain aspect of traffic complexity (Elvik, 2015). In this study, the impact of repeated exposure to roundabouts and the impact of prolonged exposure to traffic density is investigated.

Regarding the potential impact of prolonged exposure to traffic density on driving behavior, some previous research has been conducted (e.g. Liu et al., 2018; Olmez et al., 2021). This research will be elaborated on in the next section, serving as a basis for further investigation in our study. Furthermore, in light of how repeated exposure to roundabouts might impact the driving behavior, contrasting findings have been proposed. Namely, there are findings that advocate a positive influence of repeated exposure to road complexity on driving behavior and findings that advocate a negative influence (Patten et al., 2006; Yanko & Spalek, 2013). These will also be contrasted in later sections.

Exposure to Traffic Density and Driving Behavior

With regard to how traffic density influences drivers, some previous research has been conducted regarding its impact on drivers' cognitive load. In this light, Teh et al. (2014) have found that under high traffic density conditions, drivers' cognitive workload increased. This finding was in line with an earlier study by Schießl (2008b), who also reported a significant effect of traffic density on mental strain or workload. The increase in mental or cognitive load, in turn, might result in lowered driving performance. This was shown in various studies. For example, Kountouriotis et al. (2016b) have found that steering activity increased as cognitive load enhanced. Also, studies have found that the response times to critical driving events, such as a lead vehicle braking, significantly increased as drivers were cognitively loaded (Alm & Nilsson, 1995; Engström et al., 2010; Sonnleitner et al., 2014). Furthermore, when directly investigating the impact of traffic density on speed as a driver performance measure, Olmez et al. (2021) have found that drivers reduce their speed under high-density conditions. Moreover, they found that drivers show reduced speed maintenance, resulting in a worsened approximation to the instructed speed limit.

Previous research into the impact of traffic density has focused relatively much on drivers' changes in cognitive workload as opposed to objective performance changes (Engström et al., 2017). Moreover, the studies that did investigate the direct impact of traffic density on driving behavior and performance mostly scrutinized specific and individual aspects of driving performance, e.g., lane-keeping, speed, or crashes (Engström et al., 2017; Lord et al., 2005). To more accurately investigate how driving behavior and performance are influenced by the exposure to traffic density, a more integral and full-scale set of driver performance parameters was examined at once in this study. Namely, the speed, steering, braking and crash behavior were examined simultaneously to obtain a more comprehensive view on driving performance.

Positive Influence of Repeated Exposure

With regards to repeated exposure to roundabouts, the arguments as to why it could positively influence driving performance mostly pertain to experience and practice. Namely, according to Paxion et al. (2014), the level of driving experience, both long-term and short-term (i.e., repeated exposure), influences how drivers process the information related to the driving tasks at hand. Specifically, it was shown by Patten et al. (2006) that with increased experience (i.e., repeated exposure), drivers engage in a more automatic manner of processing the information required for the driving task. This means that, compared to not having been exposed to a certain driving task, the mental workload would become much lower when having been repeatedly exposed to that same driving task (Patten et al., 2006; Rasmussen, 1980, 1987). Because of this reduction in cognitive workload with repeated exposure, and hence the increase in spare cognitive capacity, it is argued in this line of thought that the spare cognitive capacity is devoted to other aspects of the driving task at hand (Posner et al., 2004). So, in line with this theory and findings, it might be the case that with repeated exposure to roundabouts, driving behavior might improve.

Several studies have found support for this argument. Namely, Fors et al. (2010) found that after being repeatedly exposed to a lead vehicle decelerating, drivers self-reported a higher attentiveness and preparedness while driving as well as that drivers tend to keep a bigger distance from the lead vehicle. Furthermore, speed as a driver performance measure was shown by Colonna et al. (2016) to change when drivers were repeatedly exposed to the same route and its corresponding complexity. Namely, they found that as drivers became more familiar with the same road and its complexities, their speed increased and deviated less from the instructed speed limit while also showing less variation in their speed.

Regarding braking as a performance measure, an early study by Muto and Wierwille (1982) reported that response times to a critical event – the sudden deceleration of a lead vehicle in a simulated car-following scenario – were longer for early exposures compared to later, more repeated exposures. In line with this early finding, a study conducted by Engström et al. (2010) found that with repeated exposure to a lead vehicle braking event, accelerator pedal release times were shortened. This finding was replicated by Aust et al. (2013) and Markkula et al. (2013), who obtained similar results. Moreover, beyond the brake reaction times, Lee et al. (2002) previously showed that with repeated exposure to lead vehicle braking events, drivers also show reduced deceleration forces compared to the first exposure to a lead vehicle braking event. These findings illustrate that repeated exposure to driving complexity improved the braking performance of drivers.

Negative Influence of Repeated Exposure

Findings that advocate a negative effect of repeated exposure on driving performance go against the claim that the resulting spare cognitive capacity, following drivers' more automated processing with repeated exposure, is devoted to the driving task at hand. They argue that under more automated processing situations, and thus mental underload, one's own thoughts might be a source of distraction (Giambra, 1995; Smallwood & Schooler, 2006). This distraction by one's own thoughts is called mind-wandering, and it can be defined as a cognitive state in which the thought processes that occupy the mind are focused on topics that are unrelated to the task at hand (Smallwood & Schooler, 2006). The incidence of mind-wandering has been shown to increase as a task becomes more repetitive (i.e., when drivers are repeatedly exposed) (Cunningham et al., 2000; Mason et al., 2007; Teasdale et al., 1995). Furthermore, mind-wandering has been shown to negatively affect the driving behavior, as Yanko and Spalek (2013) found that mind-wandering drivers took longer to respond to an induced peripheral event (e.g., pedestrians crossing) and kept less of a safe distance from lead vehicles, both leading to higher crash risk. So, in line with this theory and findings, it might be the case that with repeated exposure to roundabouts, driving behavior might deteriorate.

Other studies have also found support for this argument. Namely, Martens and Fox (2007) showed that with becoming familiar with a road through repeatedly engaging in its complex situations/obstacles, drivers become inattentive to sudden alterations from the expected course of events compared to drivers unfamiliar with the road. Furthermore, Yanko and Spalek (2013) found that drivers who were repeatedly exposed to a driving scenario took significantly longer to respond to an induced peripheral event (e.g., pedestrians crossing) and that repeatedly exposed drivers kept less of a safe distance from lead vehicles, both leading to higher crash risk.

Current Study

The aim of the present study is to investigate how driver behavior and performance alter when drivers are faced with two specific types of traffic complexity; repeatedly having to negotiate roundabouts and having to negotiate different levels of traffic density. Using the outcomes of this study, the knowledge gap in current conceptual and computational models of driving along with the conflicting research findings can be addressed. More specifically, better practices for safe driving can be informed in terms of policy development, road design, driver training and education, and intelligent driver assistance systems (Ng & Sayed, 2004; Sheng et al., 2018). Hence, the research questions addressed in this study are (1) how would driving behavior change due to the two distinct complexity types (roundabouts and traffic density) and, if there is any significant effect (2) do they indicate improvement or deterioration in performance?

In this experiment, drivers' behavior and performance were compared while driving in a low-density as well as a high-density traffic condition. Furthermore, within both the low-density and high-density traffic condition, drivers were repeatedly exposed to roundabouts, which they had to negotiate. Next to the low-density and high-density traffic condition, there was a control condition with no exposure to traffic density or roundabouts (so no complexity), in which we expected the best driving performance (Stinchcombe et al., 2011; Tran et al., 2017). Driving performance was measured as the number of crashes, braking instances, steering variance and velocity. More crashes, more braking actions, and higher steering variance were considered indicative of a deterioration in performance (Charly & Mathew, 2020; McLaughlin et al., 2009; Owens et al., 2011), whereas a smaller deviation from the instructed speed was indicative of an improvement in performance (McLaughlin et al., 2009; Yadav & Valega, 2021). Corresponding to theories and findings advocating a negative influence of (repeated) exposure to road complexity, we hypothesized that increased traffic density and repeated exposure to roundabouts negatively influence performance. More specifically, we expected that higher traffic density and repeated exposure to roundabouts would yield more crashes and braking instances, a higher steering variance and a bigger deviation from the instructed speed limit.

Methods

Participants

Twenty-five participants (16 male and 9 female) took part in the study in exchange for course credits (mean age 25.5 years old, s.d. 8.3 years). 23 subjects were in possession of a driver's license, and they indicated that, on average, they drove every day (n = 11), 2-5 times per week (n = 6), once per week (n = 2), two to three times per month (n = 2), and never (n = 2). The remaining two participants who were not in possession of a driver's license indicated not to be partaking in any driver training program at that point in time. Participants were only eligible for study participation if they were at least 18 years of age, had normal or corrected to normal vision, and were not susceptible to motion sickness to the extent that it might harm them. A post-hoc power analysis conducted using G*Power version 3.1.9.7 (Faul et al., 2007) indicated that with a total sample size of 25 and an effect size of 0.5, the achieved power was 60% at a significance criterion of $\alpha = .05$.

Ethical approval was granted by the ethical committee of the Behavioural, Management and Social Sciences (BMS) faculty of the University of Twente with request number 230301. The participants read an information sheet and signed an informed consent form before the study (see Appendix A & B).

Apparatus

Driving Simulator & Driving Scenes

A two-dimensional fixed-base simulator was used for this experiment (see Figure 3 below). The visual simulation was projected onto a 2x3 meter screen (resolution of 1280 x 1024 pixels) which was attached to the wall, distanced at approximately 2 meters in front of the driver seat on the fixed base of the simulator. Moreover, the fixed-base driving simulator was set up with Logitech gear, including a PlayStation Evolution driver seat, G29 steering wheel, pedals, and a shift stick. The (visual) simulation was developed with the Unity Platform (editor version 2021.3.24f1).

Participants operated a regular automatic transmission passenger car, of which the participant view can be seen in Figure 4 below. Furthermore, two driving scenes/tracks were developed. Namely, one driving track for the control condition and one driving track for the experimental condition (i.e., both the low and high traffic density conditions) (see Figure 5 below). Both driving tracks were set in a mountainous area and featured straight sections as well as curves. The driving track in the experimental condition also consisted of roundabouts and other traffic. Both the low-density and high-density traffic condition were part of the experimental condition, and thus consisted of the same driving track. The low-density condition and high-density condition only differed on the number of other cars in traffic on the road (i.e., the level of traffic density). The control condition consisted of a different driving track with no complexity, meaning no roundabouts or other traffic at all.

The performance variables velocity, steering angle and braking actions were collected with a sampling rate of 1000 Hz. Manual data tracking was employed to collect the number of crashes for each participant in each condition, as the simulation was not programmed in such a way as to collect this data automatically. Unnecessary programs that were running on the computer were turned off to enhance the quality of the simulation.

Figure 3

The Fixed-Base Driving Simulator

Figure 4

Participant View in the Control Condition (Left) and Experimental Condition (Right)

Figure 5

Driving Tracks for the Control Condition (Left) and the Experimental Condition (Right)

Note. Each intersection in the experimental condition (right) corresponds to a roundabout. Both the low-density and high-density traffic condition consisted of the experimental condition track.

Pre-experimental Questionnaire

Participants filled out a pre-experimental questionnaire (see Appendix C), in which they specified their age, gender, nationality, visual acuity, driving license possession and, if in possession of a driving license, subsequent years of driving experience and actual frequency of driving on the road. If not in possession of a driver's license, participants were also asked if they took part in a driver training program at that point in time. The pre-experimental questionnaire was conducted via Qualtrics, an online survey tool.

Stimuli & Tasks

In the control condition, participants drove around a two-lane driving track (7.5m wide) with no other cars, pedestrians or any other road obstacles/complexity. In the experimental condition (i.e., both the low and high traffic density conditions), participants drove on a different two-lane driving track (7.5m wide), as there was other traffic and as there were roundabouts, which participants were exposed to in a repeated manner at every intersection (see Figure 5 above). All roundabouts were regular single-lane roundabouts, and all other cars in traffic were regular passenger cars. Both the drive in the control and experimental conditions took approximately 16 minutes.

Moreover, participants' drive in the experimental condition was divided into four equal time blocks of driving (4 x 4 minutes). These blocks differed in their induced complexity in turn. Namely, the first block was equally complex as the third block while the second block was equally complex as the fourth block. Herein, Blocks 1 and 3 had a lower complexity that was induced compared to Blocks 2 and 4. Complexity was manipulated between these blocks by increasing the amount of traffic, with two other cars in traffic in Blocks 1 and 3 compared to fifteen other cars in traffic in Blocks 2 and 4. In other words, the control condition had no traffic density at all, whereas experimental Blocks 1 and 3 were low-density blocks, and Blocks 2 and 4 were high-density blocks. The specific sequence of the different blocks (Block 1 - Block 2 – Block 3 – Block 4) ensures balancing of the effect of experience for each condition.

The task for all participants was to drive around both the driving track of the control condition as well as the driving track of the experimental condition how they would normally do so. Herein, participants were instructed to adhere to a speed limit of 50km/h in all conditions (and blocks), just like on normal city roads in the Netherlands. More specifically, while driving in the experimental condition (and blocks), they negotiated different levels of traffic density (low vs. high) and repeatedly negotiated roundabouts.

Procedure

Participants were welcomed by the experimenter and invited to the lab room in which the driving simulator was located. In the lab, after reading the information sheet and providing their informed consent and demographic details, participants first received all necessary instructions and subsequently started with the experiment. These instructions entailed an explanation of the experiment, what participants could expect, their task, and the speed limit of 50 km/h to which they should adhere in all conditions and blocks. After the instructions, participants sat down in the driving simulator.

The experiment took place in a dark room, with participants first getting acquainted with the mechanisms of the driving simulator in a five-minute practice drive. In this practice drive, participants enhanced their feel of the steering, braking and accelerating sensitivity of the driving simulator. Moreover, they also practiced steadily driving 50km/h, braking and switching lanes, as overtaking other traffic was a possibility and occasionally a necessity in the experimental condition.

After the practice session, the experiment commenced, starting with the control condition for every participant. In this condition, they drove for approximately 16 minutes before commencing the experimental condition. Similarly, in the experimental condition, participants drove approximately 16 minutes, divided into phases of four blocks of the total driving time. After each 4-minute block of the experimental condition, the amount of traffic was altered for the next block, leading to a 20s break in between blocks.

After completing both conditions, participants were thanked for their participation and escorted out of the lab room. In total, a single-participant experimental session took approximately 40 minutes.

Design

A within-subjects design with one main categorical variable (traffic density: low vs. high) and one continuous variable (number of roundabouts passed) was employed in this study. The dependent variables consisted of driver behavior/performance measures; namely velocity (vehicle speed (km/h)), vehicle steering angle variance (percentages), braking instances (count) and number of crashes (count). The main independent variables were traffic density and the number of roundabouts passed by the driver. Herein, the control condition represented no traffic density and no roundabouts, whereas Blocks 1 & 3 of the experimental condition represented low-density and repeated roundabouts and Blocks 2 & 4 represented high-density and repeated roundabouts.

Altogether, the control condition served as a reference condition in which there was no complexity at all (no traffic density and no roundabouts), and was utilized to be compared to the low-density and high-density conditions of the experimental condition. More specifically, the control condition was employed to compare driving performance when drivers face complexity (experimental condition) as compared to no complexity (control condition). The purpose of the experimental condition was to investigate driving performance as drivers repeatedly negotiate roundabouts as well as to compare driving performance during low-density and high-density traffic.

Data Analysis

To analyze the effect of traffic density on velocity, steering, braking and crash behavior, paired samples Wilcoxon signed-rank test were employed between the low traffic-density condition (the combination of experimental Blocks 1 and 3) and high traffic-density condition (the combination of experimental Blocks 2 and 4). Effect sizes for the influence of traffic density on driver performance measures were calculated by dividing the Wilcoxon's test statistic (Z-value) by the square root of the total number of data observations (n-value), leading to an effect size (r-value) (Fritz et al., 2012). Furthermore, to analyze the relationship between repeated exposure to roundabouts and the driving performance measures, Spearman's rank-order correlation analyses between the number of passed roundabouts and the performance variables were employed for each block of the experimental condition. These non-parametric tests were employed as normality of the data could not be assumed for any of these dependent variables/performance parameters. This was indicated by an Anderson-Darling test of normality, which was significant (all $p < .01$).

Moreover, the aforementioned relationships between repeated exposure to roundabouts and the driving performance measures were further visualized in graphs while applying a locally weighted scatterplot smoothing (LOESS) method. Herein, LOESS is a nonparametric, graphical tool for depicting relationships between variables. Due to the non-parametric nature of our obtained data, the LOESS smoothing method is most applicable for visualization instead of other methods like the ordinary least squares (OLS) regression method (Jacoby, 2000).

Results

When analyzing the effect of traffic density on the driver performance measures, averaged across the entire conditions (low vs. high density) per participant, a paired samples Wilcoxon signed-rank test indicated a significant difference between the low-density and high-density condition for velocity, the number of braking instances, and the number of crashes. Namely, velocity was significantly higher in the low-density condition (*Mdn* = 44.16, *n* = 25) compared to the high-density condition *(Mdn* = 41.19, *n* = 25*), Z* = -4.27, *p* < .01, with a large effect size *r* = -.60 (see Figure 6 below). The number of braking instances was found to be significantly lower in the low-density condition (*Mdn* = 8.00, *n* = 25) compared to the high-density condition *(Mdn* = 16.00, *n = 25), Z* = -4.29, *p* < .01, with a large effect size *r* = -.61 (see Figure 7 below).

Figure 6

The Difference in Velocity Between Low-Density and High-Density Traffic

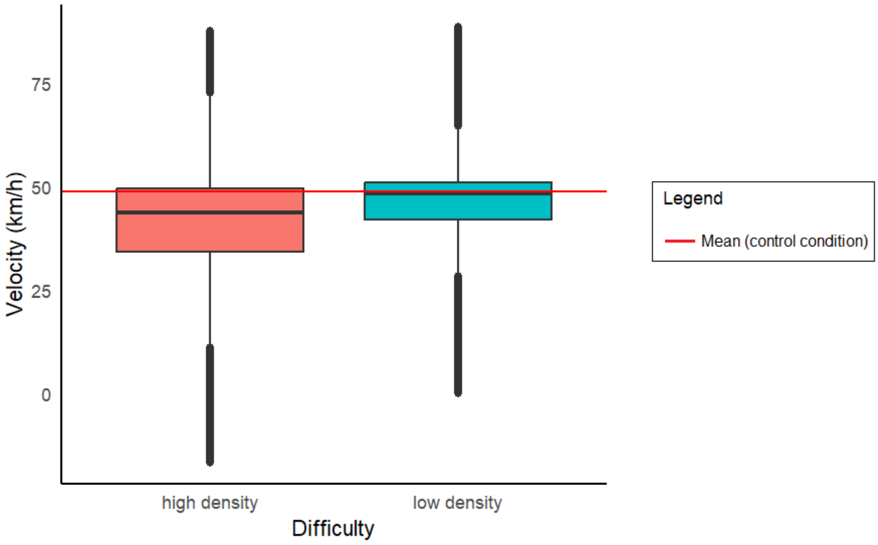
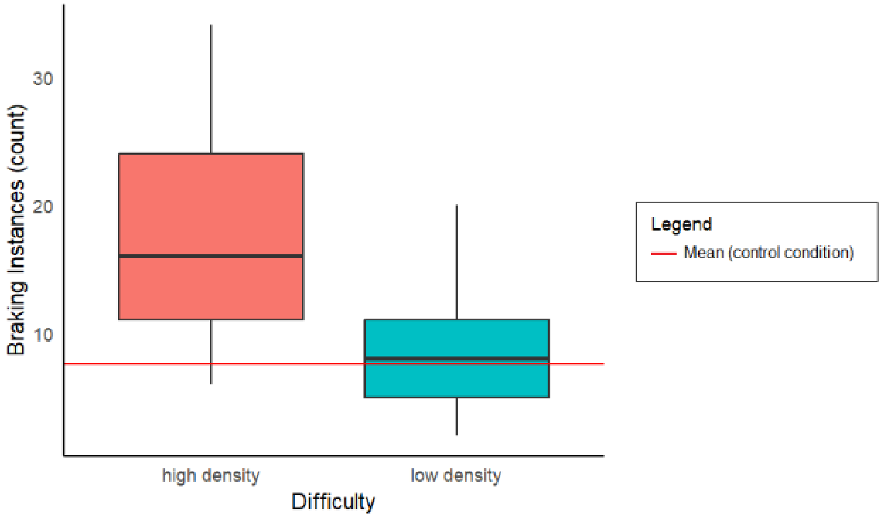


Figure 7

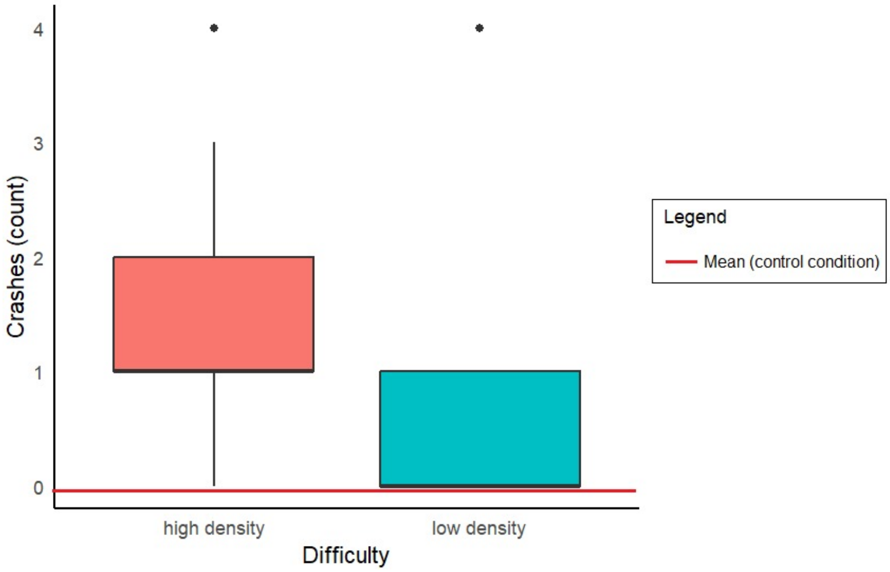
The Difference in Braking Instances Between Low-Density and High-Density Traffic



Furthermore, the number of crashes was observed to be significantly lower in the low-density condition, with a total of 11 crashes (*Mdn* = 0.00, *n* = 25) compared to the high-density condition, with a total of 35 crashes (*Mdn* = 1.00, *n = 25), Z* = -2.96, *p* = .003, with a moderate effect size *r* = -.42 (see Figure 8 below). However, the steering variance, computed per condition and per participant across five-second chunks of driving, was shown to not be significantly different between the low-density condition (*Mdn* = 20.63, *n* = 52) and the high-density condition *(Mdn* = 42.91, *n* = 49)*, Z* = -.54, *p* = .59.

Figure 8

The Difference in Crash Numbers Between Low-Density and High-Density Traffic



When separately comparing the low-density and high-density traffic conditions to the control condition, a paired samples Wilcoxon signed-rank test indicated that the steering variance, braking instances, and crash instances were significantly lower in the control condition. On the other hand, velocity was shown to be significantly higher in the control condition as compared to both the low-density and high-density traffic condition. In general, bigger effect sizes were found between the control condition and the high-density traffic condition as compared to between the control condition and the low-density traffic condition. The outcomes of the paired samples Wilcoxon signed-rank tests can be seen in Tables 1 and 2 below.

Table 1

Wilcoxon Signed-Rank Test Outcomes Between the Control and Low-Density Condition

Measure	Control		Low-density		*Z*	*r*	*p*
	Mdn	*n*	*Mdn*	*n*			
Velocity	48.89	25	44.06	25	-4.13	-.58	< .001
Steering variance	.47	192[a]	20.63	52[a]	-6.06	-.51	< .001
Braking instances	4.00	25	8.00	25	-2.82	-.40	.005
Crashes	.00	25	.00	25	-2.71	-.38	.007

[a] The steering variance was computed across every 5 seconds of driving, leading to 52 averaged data observations within the low-density condition and 192 averaged data observations within the control condition

Table 2

Wilcoxon Signed-Rank Test Outcomes Between the Control and High-Density Condition

Measure	Control		High-density		*Z*	*r*	*p*
	Mdn	*n*	*Mdn*	*n*			
Velocity	48.89	25	40.99	25	-4.37	-.62	< .001
Steering variance	.47	192[a]	42.91	49[a]	-6.01	-.51	< .001
Braking instances	4.00	25	16.00	25	-3.20	-.45	.001
Crashes	.00	25	1.00	25	-3.89	-.55	< .001

[a] The steering variance was computed across every 5 seconds of driving, leading to 49 averaged data observations within the high-density condition and 192 averaged data observations within the control condition

Next, when analyzing the relationship between the number of roundabouts passed while driving and the driving performance, small but significant Spearman's rank-order correlation values were found for velocity in all four blocks (Block 1 ($r_s = .20$, $p < .01$), Block 2 ($r_s = .17$, $p < .01$), Block 3 ($r_s = .16$, $p < .01$) & Block 4 ($r_s = .15$, $p < .01$)). This is visualized in Figure 9 below.

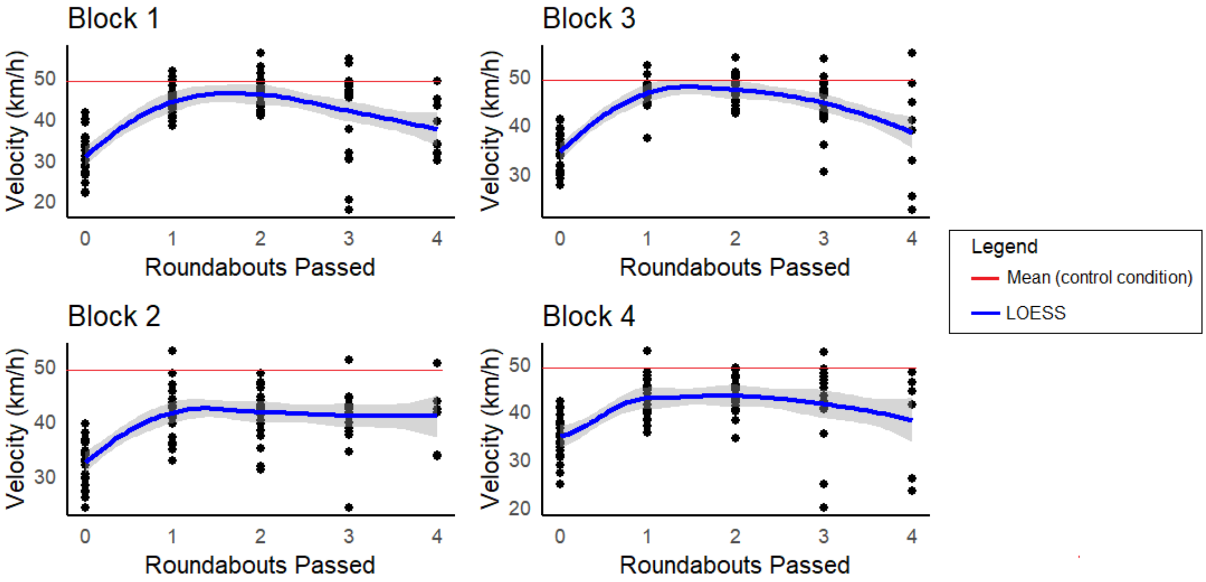
For the steering variance, an increase in steering variance was observed with more exposure to roundabouts for Block 1 ($r_s = .38$, $p < .01$), Block 2 ($r_s = .44$, $p < .01$), Block 3 ($r_s = .39$, $p < .01$) and Block 4 ($r_s = .42$, $p < .01$). This is visualized in Figure 10 below.

For the braking instances, no significant relationship between the number of braking instances and the number of roundabouts that participants had passed was observed in Block 1 ($r_s = -.09$, $p = .35$), Block 2 ($r_s = .14$, $p = .17$), Block 3 ($r_s = -.07$, $p = .49$) and Block 4 ($r_s = -.10$, $p = .33$).

Lastly, for crashes, no relationship between the number of roundabouts that a participant had passed and the number of crashes they made was observed in neither Block 1 ($r_s = .03$, $p = .73$), Block 2 ($r_s = -.01$, $p = .90$), Block 3 ($r_s = -.00$, $p = .97$), and Block 4 ($r_s = -.03$, $p = .77$).

Figure 9

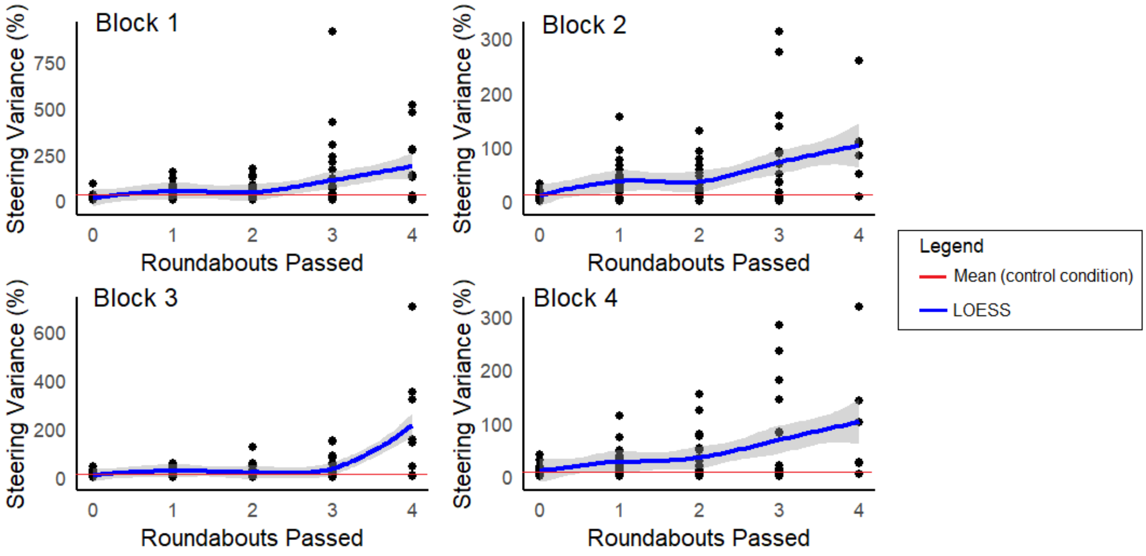
The Velocity by Roundabouts Passed per Block of the Experimental Condition



Note. Blocks 1 and 3 correspond to the low-density condition and Blocks 2 and 4 correspond to the high-density condition.

Figure 10

The Steering Variance by Roundabouts Passed per Block of the Experimental Condition



Note. Blocks 1 and 3 correspond to the low-density condition and Blocks 2 and 4 correspond to the high-density condition.

Discussion

The present study aimed to explore how prolonged exposure to varying levels of traffic density and repeated exposure to roundabouts influence driving behavior and performance. Our research questions centered around understanding the changes in driving behavior due to these types of traffic complexity and whether these changes indicated improvement or deterioration in performance. Furthermore, it was hypothesized that exposure to increased traffic density and repeated exposure to roundabouts would negatively impact driving behavior and performance. Moreover, it was hypothesized that the combination of the two types of traffic complexity (roundabouts and traffic density) would lead to a deterioration in performance compared to a control condition with no such road obstacles/complexity at all. To test the hypotheses, participants drove in both a no-density (control), low-density, and high-density traffic condition, in which participants also repeatedly had to negotiate roundabouts in the low-density and high-density traffic condition. The hypotheses were partly supported by the results of this study.

Complexity and Performance

The results of the present study found support for the claim by previous research that increased driving complexity leads to a deterioration in driving performance (De Waard et al., 1995;

Olmez et al., 2021). Namely, the within-subject data from this study showed that all driver performance measures showed a deterioration when complexity increased, as hypothesized in the Introduction. A lower speed as well as more deviation from the instructed speed limit, more variance in steering wheel position, and more braking and crash instances were observed as the complexity increased. More specifically, the largest effect sizes were found between the control condition and the high-density (and roundabouts) condition. Smaller, yet significant, effect sizes were found between the control condition and the low-density (and roundabouts) condition.

The finding that more complexity leads to a deterioration in performance might be explained by the enhanced cognitive load as a result of more complexity (Cantin et al., 2009). As drivers become more mentally loaded, various aspects of driver performance have been shown to deteriorate, as shown by Engström et al. (2017). An example of such an observed deterioration by previous research, similar to our findings, is that the standard deviation of steering wheel movements increased with more complexity (De Waard et al., 1995).

Low-Traffic Density vs. High-Traffic Density

Our findings revealed a nuanced relationship between traffic density and driving behavior, with the driving performance measures velocity, braking instances and crash instances confirming that performance deteriorated with increasing traffic density. Namely, when comparing low-density and high-density traffic conditions, we observed that velocity was higher and deviated less from the instructed driving speed of 50 km/h in the low-density condition, which indicates a better driving performance (McLaughlin et al., 2009). This suggests that drivers might have adjusted their speed to the surrounding traffic flow, demonstrating adaptability to different traffic densities. This observation aligns with studies suggesting that drivers tend to regulate their speed according to the prevailing traffic conditions (Trick et al., 2010). With prolonged exposure, this observation still holds according to the results of this study. Moreover, the finding that velocity reduced with higher traffic density is further explained by the Risk Homeostasis Theory of driving, which argues that drivers make adjustments (e.g. speed) to maintain a relatively fixed level of perceived difficulty. This might result in drivers lowering their speed when complexity increases with more traffic (Fuller, 2011). Furthermore, a difference in braking instances and crash instances was found between the low-density and high-density traffic conditions. Namely, more instances of braking and crashing occurred in the high-density condition, herewith indicating a deterioration in performance with more traffic density (Owens et al., 2011). This finding might be explained due to a higher cognitive load when having to process more stimuli (more cars), which might lead to a deteriorated anticipation process (Damm et al., 2011; Muhrer & Vollrath, 2011). The decrements in anticipation might in turn have resulted in more braking and crashing instances.

On the contrary, no difference in low-density and high-density traffic was found for the steering variance, herewith disconfirming that increased traffic density deteriorates performance. This finding contradicts previous research by e.g., Macdonald and Hoffmann (1980), who found that steering variance increased with increasing task demand (e.g., high traffic density). A possible explanation as to why no difference was found in this study, might be because of the time frame in which the steering variance was successively computed. The chosen five-second time frame might not have been ideal for accurately studying improvements or declines in driving performance. Rapid and uncontrolled steering movements, which best reflect steering performance (McLean and Hoffman, 1975), might not have been accurately captured. While such movements could occur within five seconds, they might not exceed the maximum variation observed when no such movements were present. To better assess steering performance, an alternative for future research would be to analyze instances where steering variation surpasses a predefined threshold within a certain timeframe, herewith showing better indication of rapid and uncontrolled steering movements (McLean and Hoffman, 1975).

Repeated Exposure to Roundabouts

It was observed that with repetitive exposure to roundabouts, the steering variance of participants increased. This indicated a deterioration in performance, as hypothesised (McLaughlin et al., 2009). This finding might be explained by the theory of mind-wandering, which was introduced before. This theory poses that with repetitive exposure to (monotonous) complexity, or roundabouts in this case, automation of the driving task increases, herewith freeing up cognitive energy. This spare cognitive energy might be devoted to thoughts not related to the driving task at hand, leading to drivers being distracted by their own stream of consciousness and showing reduced performance (Giambra, 1995; Smallwood & Schooler, 2006). An alternative explanation to this finding could be that drivers tend to steer more as opposed to braking when avoiding potential crashes, as shown in a study by Kusano and Gabler (2013).

Contrarily, the flow of performance in terms of velocity disconfirmed our hypothesis. Namely, it was observed in this study that velocity actually better approximated the instructed 50km/h with repeated exposure to roundabouts, indicating a performance improvement. This is in line with studies showing that drivers improve their speed maintenance with an enhanced familiarity with a route (Colonna et al., 2016). Opposite to steering behavior, it might be that the successive completion of roundabouts might lead to an enhanced confidence on part of the driver (De Craen et al., 2008; Rosenbloom et al., 2007). The enhancement in confidence might in turn lead to more aggressive driving behaviors (i.e., higher speed). This could be explained by the Risk Allostasis Theory, which argues that temporal fluctuations while driving, e.g. enhanced confidence, might heighten one's preferred level of perceived difficulty, leading to an increase in velocity (Fuller, 2011). Future research might incorporate measures of emotional fluctuations like confidence to assess the impact of repeated exposure on driving behavior.

Lastly, disconfirming our hypothesis, no change in braking and crash instances was found as drivers repeatedly faced roundabouts. This finding contrasts existing studies that found that with repeated exposure to critical lead-vehicle braking events, braking performance enhanced for later exposures (Aust et al., 2013; Markkula et al., 2013). This might be explained by the way the experiment was structured. Namely, it might have been the case that there was too much of a resting period in between obstacles (roundabouts) to have an effect on the braking and crash performance variables. The relatively long road sections in between roundabouts, in combination with a fixed complexity level in each experimental block, might have caused a regeneration of cognitive energy for participants after each roundabout, leading to no change in the specific braking/crash performance (De Waard, 1996). Moreover, as was argued for the change in steering behavior, it might be that braking instances did not change due to participants generally steering more as opposed to braking when avoiding potential crashes, as shown in a study by Kusano and Gabler (2013).

Implications

The findings provide a valuable contribution to the development of a comprehensive and advanced driver model that captures the cumulative function of behavior resulting from diverse events and distractions (traffic density, obstacles such as roundabouts, etc.). In practical terms, Advanced Driver Assistance Systems (ADAS) could further benefit from these models while predicting performance decay (Petraki, 2020). Our study's findings can be leveraged to enhance the effectiveness of ADAS by incorporating an understanding of how (repeated) exposure to different types of traffic complexity influences behavior. Herewith, ADAS could be optimized to predict performance decay over time. For instance, the increased steering variance we observed in response to repeated roundabout exposure could be utilized as an indicator of potential cognitive fatigue or the need for heightened alertness (Nakayama et al., 1999; Oh & Lee, 2017). ADAS algorithms could then adapt their interventions to ensure that drivers remain engaged and responsive, particularly in situations that demand increased attention (Liu et al., 2017). More specifically, through real-time and context-aware algorithms, these systems can effectively enhance driving safety and convenience. In this way, based on the findings from this study, lane-keeping assistance, adaptive cruise control, and collision avoidance systems can be specifically improved as changes in steering, speed, braking and crash behavior were observed in this study.

Furthermore, city planners and road authorities can utilize the research findings to optimize road design and traffic management strategies. Understanding the impact of (short-term) repeated exposure to complexity on drivers' behavior can aid in designing road networks that minimize potential hazards and confusion (Calvi, 2014). Incorporating driver-friendly features, clear signage, and well-organized traffic flow can reduce the cognitive load on drivers and promote safer navigation through (repeated) complex traffic situations (Babić et al., 2020). For instance, traffic engineers can use the research findings to implement efficient (and less-repeated) roundabout design, herewith ensuring a smoother and safer traffic flow.

Limitations and Future Research

A first limitation of this study pertains to the sample size. Namely, the sample consisted of 25 participants, with 60% power as indicated by a post-hoc power analysis. Therefore, future attempts in this research area should consider larger sample sizes, as this would allow for a more robust examination of the relationships under investigation. Moreover, the research sample mostly consisted of students, herewith limiting the representativeness of the sample. Future research should employ more diverse samples.

A second limitation pertains to the time of driving. Namely, the time of driving in the control and experimental condition was 16 minutes, which was even divided into four blocks of merely 4 minutes in the experimental condition. These amounts of time might not have been sufficient to thoroughly investigate the research question, as it was observed that participants oftentimes merely managed to negotiate three roundabouts. A longer driving time might result in more repeated exposure to complexity, herewith enhancing the comprehensiveness, reliability and validity of the findings.

Third, in general, even though the driving simulator was of relatively high fidelity, the simulated environment may not fully accurately imitate real-world driving, herewith limiting the ecological validity of the study. Therefore, a recommendation is to attempt to answer similar research questions by incorporating real-world driving conditions, provided its (ethical) feasibility. If real-world driving studies are considered not feasible, a subsequent recommendation for future studies is to enhance the fidelity of the driving simulator, herewith enhancing the ecological validity of the study results in turn.

Lastly, this study focused on the driver performance in terms of observable performance metrics. The intricate relationship between the performance and driver's cognitive processes, however, remains relatively unclear. Future research should incorporate data collection methods which measure cognition. A possible method could be to employ electroencephalography (EEG), which is able to compare the cognitive activity at different points in time and in different driving conditions, herewith allowing for an inference about cognitive processing during repeated or prolonged exposure to complexity while driving (Zhang et al., 2021). Next to EEG, future research could employ physiological measures like electrodermal activity to make inferences about cognitive load while driving and how it relates to performance changes when drivers are successively exposed to road obstacles/complexity (Sonnleiter et al., 2014).

Conclusion

Driver's performance in terms of velocity, braking instances and crashes deteriorated with prolonged exposure to an increase in traffic density, with velocity decreasing and braking and crash instances increasing with more traffic density. Furthermore, when repeatedly having to negotiate roundabouts, drivers' velocity and steering variance increased. These findings contribute to the development of more advanced and comprehensive driver models that capture the cumulative function of behavior resulting from diverse events and distractions (e.g., traffic density, obstacles such as roundabouts, etc.). Such driver models can be leveraged to improve traffic safety by optimizing ADAS, road design, and driver training and education. However, as this study regarded observable performance metrics, future research should further investigate the intricate relationship between driving behavior and cognition when drivers are (repeatedly) exposed to complexity. Moreover, it was observed that increased traffic density and repeated exposure to roundabouts, both elements that were shown to enhance driving complexity, impacted the driving performance in different ways. This might suggest that (repeated) exposure to different road complexities/obstacles induces different types of cognitive load, which should be further investigated.

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Appendices

Appendix A

Dear participant,

Thank you for participating in our study, which serves the purpose of a Master's thesis. The goal of the study is to investigate to what extent environmental factors affect driving performance. This is an important area of research, as many traffic incidents/accidents happen in the face of varying environmental complexity while driving. Using the outcomes of studies like this one, interventions can be made to reduce the amount of traffic accidents and make driving a safer practice altogether.

In this experiment, you will take part in a driving simulator study. This means that you will be seated in a driving simulator, while you will be asked to drive on a virtual road in which you will face several (complex) driving situations. Your driving performance, based on several measures of driving, will be recorded simultaneously.
It is important to know that research with driving simulators can cause motion sickness to participants. Therefore, we would like to emphasize the rightful possibility for you as a participant to withdraw from the experiment at any time, without having to justify your decision.

The data that will be collected (i.e., performance measures) will be saved confidentially and anonymously. This means that confidentiality, as well as anonymity, are assured during your participation in the study.

If any questions arise during or after the study, feel free to communicate your questions to the researcher. The contact information can be found here:

E-mail: m.t.d.akguel@student.utwente.nl

Do you understand the above stated information and do you agree to further participate in this study?

o Yes
o No

Appendix B

Consent Form for [*The Flow of Driving Performance in the Face of Varying Environmental Complexity: A Simulator Study*]

Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
I have read and understood the study information dated 01/05/2023, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	○	○
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	○	○
Risks associated with participating in the study		
I understand that taking part in the study involves the following risks: Motion sickness	○	○
Use of the information in the study		
I understand that information I provide will be used for the purpose of a Master's Thesis	○	○
I understand that personal information collected about me that can identify me, such as [e.g., my name or where I live], will not be shared beyond the study team.	○	○
Future use and reuse of the information by others		
I give permission for the simulator data that I provide to be archived in a repository so it can be used for future research and learning.	○	○
I give the researchers permission to keep my contact information and to contact me for future research projects.	○	○

Signatures

________________________ ________________________ _________

Name of participant Signature Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

___________________________ ____________________ _________

Researcher name Signature Date

Study contact details for further information:

Name: Maarten Akgül
E-mail: m.t.d.akguel@student.utwente.nl

Contact Information for Questions about Your Rights as a Research Participant

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee/domain Humanities & Social Sciences of the Faculty of Behavioral, Management and Social Sciences at the University of Twente by ethicscommittee-hss@utwente.nl

Appendix C

Start of Block: DEMOGRAPHICS

GENDER What is your gender?

○ Male

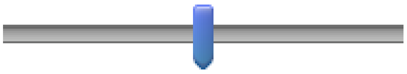
○ Female

○ Non-binary / third gender

○ Other

○ Prefer not to say

AGE What is your age?

	0 10 20 30 40 50 60 70 80 90 100
Age	

NATIONALITY What is your nationality?

○ Dutch

○ German

○ Other: ____

VISUAL ACUITY Please specify your visual acuity at the time of this experiment:

○ Normal/perfect vision

○ Corrected vision (by glasses or contact lenses)

○ Imperfect/non-corrected vision

LICENSE? Are you currently in possession of a driver's license

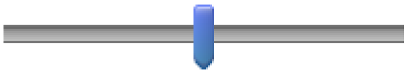
○ Yes

○ No

Display This Question:

If Are you currently in possession of a driver's license = Yes

EXPERIENCE How long are you in possession of a driver's license? (In years)

	0 10 20 30 40 50 60 70 80 90 100
Years of driver's licence possession / driving experience	

Display This Question:

If Are you currently in possession of a driver's license = No

DRIVER TRAINING Are you currently in driver training (i.e., taking driving lessons)?

○ Yes

○ No

Display This Question:

If Are you currently in possession of a driver's license = Yes

ROAD EXPERIENCE On average, how often do you drive on (European) roads?

(choose the closest possible answer)

○ Never

○ once a month

○ 2-3 times a month

○ once a week

○ 2-5 times a week

○ Every day

End of Block: DEMOGRAPHICS

Appendix D

The complete R-script(s), participant session recordings, participant data files (Text log files & Excel files), and manually tracked data (crash/road departure data) can be accessed via the following link, which redirects to a folder corresponding to this Master's thesis:

https://drive.google.com/drive/folders/1tZ7fgaWf-LQTUmcWJAa-SBmg2uIxahMW?usp=sharing