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Understanding and improving driving performance by removing and adding visual information

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Understanding and improving driving performance by removing and adding visual information

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Contents

Summary

Worldwide, over a million fatal road accidents occur each year. The majority of these crashes are caused by inadequate longitudinal control performance such as late braking and close following. Despite the fact that car driving is primarily a visual task, there is yet no clear understanding of how drivers control their vehicle in safety-critical conditions as a function of visual information. Understanding the visual information needs of drivers in different safety-critical conditions is a prerequisite for designing and validating interventions (e.g., support systems and training programs) that reduce the number and severity of collisions.

Longitudinal and lateral control tasks of driving an automobile have been extensively studied as tracking control problems. However, studies of drivers' behaviour in collisions have been scarce in general and particularly in terms of drivers' control performance. Most of the driving behaviour research considers the brake reaction time as the main factor in assessing drivers' behaviour in safety-critical conditions. Comparatively little is known about the performance of drivers after the brake onset, including the dosing and duration of the brake pedal input. In addition, previous studies did not clearly investigate the effect of visual/physical conditions such as the gap and the relative velocity between drivers and other road objects, and the visibility condition of the road on the performance and risk assessment of drivers.

In current traffic systems, drivers are responsible for navigating the vehicle safely. A variety of technological interventions have been developed to assist drivers in collision prone conditions. These technological systems often use absolute visual information (e.g., distance, time headway) to control the vehicle without taking into account driver perception. Therefore, there may be a mismatch between what such systems do and what drivers expect from such systems to do. Little human factors knowledge is available about how to design driver support systems that improve longitudinal control performance of drivers.

The first objective of this thesis is to understand how the availability and quality of visual information in safety-critical driving conditions shapes drivers' longitudinal control performance. Following this, the second objective of this thesis is to design and investigate the effectiveness of a technological solution for improving longitudinal control performance. A total

of four driving simulator experiments were conducted that assessed the effects of degraded-vision and augmented-vision conditions in safety-critical stopping and car following tasks.

The first experiment (Chapter 2) examined the effect of visual information on braking performance of drivers faced with a decelerating lead car. Four lead-car braking conditions were created by varying the deceleration of the lead car (1.7 vs. 6.5 m/s^2) and the distance between the participant's car and the lead car (13.4 vs. 33.4 m). Three visual conditions were tested: lead-car brake lights, no lead-car brake lights, and visual occlusion at the onset of lead-car deceleration. The braking behaviour of drivers has been analysed by relating the braking input of the driver to the visual information of the driving condition. The results showed that an occlusion as short as 0.4 s (about the duration of a glance on the speedometer) can dramatically increase crash risk. This implies that if following at a 0.5 s time headway (a short but not unrealistic headway), any off-road glance should be avoided. Brake lights were found to reduce brake reaction times when the lead-car deceleration was small (1.7 m/s^2) but had little added value when the lead car engaged in an emergency stop (6.5 m/s^2). In summary, the results of the first experiment indicate that an off-road glance when the most critical driving condition (short headway, high deceleration of the lead vehicle) occurs significantly increases the number of crashes. Even alert drivers require continuous visual information to be able to avoid collisions in very critical conditions.

The second experiment (Chapter 3) investigated the braking performance of drivers when stopping at a stationary target as a function of the temporal demand of the braking event and the presence versus absence of visual information during braking. The access to visual information was manipulated by occluding the screen at the start of half of the braking trials, and the temporal demand was manipulated by changing the time-to-arrival (TTA) at the onset of braking. Contrary to expectations, it was found that the lack of visual information after the brake onset reduced the maximum brake force applied by drivers, especially in braking events with short TTAs ($\leq$ 4 s). For the larger TTA values ($\geq$ 6 s), participants in the occlusion condition stopped too early and at variable positions on the road as compared to the non-occluded condition. In the occlusion condition, participants were likely to apply an intermediate brake pedal depression, whereas in the non-occluded condition participants applied low or high pedal depressions.

Overall, the findings indicate that without vision, drivers underestimate the required brake input for optimum performance in safety-critical conditions. The availability of visual information during a stopping task improves performance, even when the stopping task is urgent. This is in line with the findings in Chapter 2 which showed that drivers need (continuous) visual information even when an ‘open loop’ braking action would in theory suffice.

The third experiment (Chapter 4) investigated the underlying causes of the paradoxical phenomenon that drivers adopt short distance headways in fog compared to clear visibility conditions. The effects of visual information (fog vs. clear weather) and automation (adaptive cruise control vs. manual driving) on the subjective feeling of risk (measured during driving using a touch screen) and steering activity at different distance headways were examined. The results show that participants’ feeling of risk was lower in clear weather than in fog, especially when the headway was large. It is concluded that participants in fog try to keep the lead car *just* in sight, and that the lead car provides a guide resulting in reduced lateral control activity.

In line with the findings of Chapters 2 and 3, a lack of visual information of the lead car was found to be detrimental for the performance of drivers. It is concluded that, having access to continuous visual information is so critical that drivers reduce their headway to improve the availability and quality of visual information. The results suggest that except for extremely short headways, keeping the vehicle at the edge of the visibility threshold reduces the perceived risk. The results also showed that extremely short headways induce elevated feelings of risk, even when the driving task is automated. It is argued that adaptive cruise control systems should either avoid extremely short headways or include a driver information system to reduce the level of risk that drivers perceive in very close following distances.

In the final experiment (Chapter 5), a head-up display (dubbed Rear Window Notification Display, or RWND) was developed to improve the driver’s manual car-following performance by continuously visualizing the lead car’s acceleration and time headway on the rear window of the lead car. The effect of the system (RWND off vs. on) on the car following performance was determined when following a lead car driving with variable speed. The results showed that the RWND reduced both the mean and standard deviation of time headway, but did not increase the occurrence of potentially unsafe headways of less than 1 s. Using a linear car-following model, it was shown that when assisted by the display, participants improved their performance by adopting higher control gains with respect to inter-vehicle distance, relative speed, and acceleration compared to when they were not assisted.

In Chapter 6 a short literature review is provided on human factors issues of automated driving. It is shown that automation is no panacea and may actually lead to new types of risk compared to manual driving, such as overreliance, loss of skills, and behavioural adaptation. Several design solutions are proposed that inform and involve the human driver about the situation ahead and the automation status. Moreover, several design requirements are proposed for a cooperative adaptive cruise control (CACC) system that allows for platooning with short headways. The results of this chapter reinforce statements made in the earlier chapters that drivers need to be properly informed about the environment and automation status.

In Chapter 7, the results are summarized and the findings of Chapters 2 to 5 are interpreted by means of perceptual control models. A comparison between the experimental results and the reviewed theoretical models suggests that the perceptual sensitivity of drivers improves when the distance headway decreases, which in turn improves the accuracy of drivers' longitudinal control performance. The control models also support the performance results of the RWND system, where direct operational information about the acceleration and deceleration of the lead car provided bypasses the perceptual sensitivity threshold of drivers. Driving simulators have been considered as suitable tools with relative validity to test the effects of the availability and quality of visual information on longitudinal control of the vehicle in collision-prone conditions. Driving simulator provides an environment free of physical risk even when a driver fails to avoid a collision. The visual and kinematics conditions of simulated driving scenes are also controllable to a great extent. This chapter also further justifies the ecological validity of the tasks, and the kinematics and the frequency of the events tested in the previous experiments, and suggests several future research directions on related road safety issues.

When a collision is imminent and there is a need for a rapid manoeuvre within a very small time frame (less than a few seconds), drivers who are not fully occupied by the driving task do not have their full attention resource available to intervene. Having an understanding of the limitations of drivers in these safety-critical conditions is a prerequisite for designing

technologies that aim to enhance the performance of drivers in such situations. This thesis generated knowledge on how drivers visually control their vehicle in safety-critical conditions by showing the critical role of visual feedback in such situations and how disturbances in visual information during these conditions affect longitudinal control performance. The thesis also showed how drivers reduce their following distance as an adaptation mechanism to cope with the performance decline when the quality of visual information is degraded. Such knowledge led to the development of a RWND that keep drivers ‘in the loop’ while benefiting from technological advances. The findings of this work highlight the deficiencies that exist in drivers’ control of the vehicle in safety-critical situations and demonstrated the viability of cooperation between the human driver technologies, such as the RWND, to support drivers’ intervention in situations prone to longitudinal crashes. The results suggest that the RWND can be used along with CACC to increase network capacity without degrading safety. Mental workload and distraction effects should be evaluated in further experiments, including on-road testing in a naturalistic environment and with a more diverse population.

CHAPTER 1

Introduction

CHAPTER 1: Introduction

1. The dangers of driving

Since their appearance on the roads, automobiles have been perceived as a technology that provides individual freedom and mobility (Blanke, 2007). However, societies are now facing serious challenges, such as air pollution, congestion, and traffic injuries (e.g., Wald, 1999). About 1.25 million people are killed on roads every year and traffic collisions remain one of the main public health issues across the world (World Health Organization, 2015). When the first fatal car accident in the UK occurred in 1896, the coroner at that time was quoted as saying: “such a thing would never happen again” (McFarlane, 2010). More than 100 years later, the reality of road safety is far different from the ideal world of the coroner and many others.

Road safety is the outcome of interactions between the vehicle, the roadway, and the driver. Among this triad, the driver has been identified as the causal factor in 90% and the sole cause in about 60% of collisions (Evans, 1996; Storie, 1977, Treat et al., 1979). The driver is responsible for remaining attentive and detecting adverse events, and for providing appropriate control inputs to mitigate collision. Improper lookout and distraction are among the most frequent causes of collisions (Klauer, Sudweeks, Hickman, & Neale, 2006; Treat et al., 1979). Additionally, high speed (Aljanahi, Rhodes, & Metcalfe, 1999; Finch & Kompfner, 1994; Svenson, Eriksson, & Gonzalez, 2012; Winter, 2008) and tailgating (Adell, Várhelyi, & Fontana, 2011; Chen, Shen, & Wang, 2013; Colbourn, Brown, & Copeman, 1978) are among the main causal factors in a substantial number of road collisions in general and rear-end collisions in particular.

2. Longitudinal control: Critical to road safety

Drivers can avoid a collision through appropriate lateral control (i.e., to change the direction of motion via the steering wheel) and/or longitudinal control (i.e., to change the speed via the brake pedal and accelerator). Drivers control the speed and direction based on the information that they receive. A control adjustment follows the driver’s perception of changes in the driving scene and whether these changes require drivers to intervene and compensate. Lateral and to a lesser extent longitudinal control tasks of driving an automobile have been extensively studied as tracking control problems (e.g., McRuer, Allen, Weir, & Klein, 1977; Nash, Cole, & Bigler, 2016; Steen, Damveld, Happee, Van Paassen, & Mulder, 2011). However, collision avoidance is not a classic tracking problem, in particular if braking is the mechanism that the driver uses to avoid a collision. Most of the car following models consist of lumped parameters that produce the best fit between the model performance output and an existing driving performance dataset over a long driving period where braking is a small portion of the overall driving time (Gipps 1981; Markkula, Benderius, Wolff, & Wahde, 2012).

The lack of integration of human behaviour insight has been mentioned as one of the limits of many car following models in general and braking models in particular. For example in the majority of the models, the lack of visual information (eye-off-road) is accounted for by a pure delay. The earlier version of these models did not consider any control during the response onset and assume an immediate reaction to the obstacle even at long distances (Bevrani, Chung, & Miska, 2012). Although some of these models assume pre-defined drivers' behaviours, the empirical or theoretical validation basis of such assumptions are not well known. For example, one class of models assumed that drivers start their deceleration with a delay with respect to the stimulus and apply a constant deceleration (Brown, Lee, & McGehee, 2001; Fitch et al., 2008). The integration of the effects of viewing distance (near vs. far), the nature of the task (leader-follower vs. stopping at an on-the-road position task), and the nature of the motion (slow vs. fast deceleration) into a space perception model of drivers is a necessary step to accurately predict the limits and capabilities of drivers and to develop systems that complement drivers perception and performance as the driving space changes.

This thesis focuses on longitudinal control of the vehicle in collision-prone situations. Naturalistic driving studies have found that when trying to avoid an accident, about 85% of drivers only braked, 10% both braked and steered, and 5% only steered (Lee, Llaneras, Klauer, & Sudweeks, 2007, see also Cheng et al., 2011). Rear-end collisions account for 25% to 30% of motor vehicle injury accidents (Kiefer, LeBlanc, Palmer, Salinger, Deering, & Shulman, 1999; National Safety Council, 2011). Timely and proper braking can make a significant impact on driving safety by avoiding rear-end collisions. A kinematic analysis of driving also shows that between steering and braking, the latter is *the only* possible safe intervention in low speed (< 50 km/h) emergency events, if the time to collision is less than 1 second (Allen, Rosenthal, & Aponso, 2005).

The longitudinal control task has been extensively studied using computer simulations and offline car following models (e.g., Touran, Brackstone, & McDonald, 1999). However, empirical studies on drivers' performance in collision scenarios have been scarce. Most of the available empirical research considers the brake reaction time as the main variable for assessing drivers' performance in safety-critical conditions (e.g., Green, 2000). Little is known about the performance of drivers *after* the brake onset, including the duration and dosing of the brake pedal input in critical events (Markkula et al., 2012). The knowledge about the sensory, perceptual, cognitive, and motor mechanisms during collision avoidance has been described as fragmented and having limited validity (Markkula et al., 2012). A paradoxical observation in fog, for example, is that drivers reduce their headways compared to clear weather conditions (Hawkins, 1988; White & Jeffery, 1980). Little is known about why and how drivers change their behavior as a function of visibility, and or whether this relates to collision risk.

There are few potential reasons for the scarcity of collision studies. First, collisions and near-collisions are rare events by definition. Second, it is a technical and operational challenge to record and access data of such events in the real world. Third, to experimentally study the performance of drivers in safety-critical conditions is ethically challenging, and violates the code of conduct of the scientific community. Accordingly, all research in this thesis has been conducted in driving simulators rather than in real vehicles. Simulators allow researchers to expose participants to safety-critical events in a controlled manner, without physical risk.

3. How to support drivers with technology?

Drivers slow down the vehicle by putting pressure against the brake discs, a concept originating from horse carriages, and first used in car driving by Benz Velo in 1893 (Akamatsu, Green, & Bengler, 2013). The interaction mechanism between the driver and the brake system, whereby the driver activates and modulates the amount of the brake force using a pedal, has been the same for about a century or more. However, a recent trend is to make cars capable of avoiding accidents. It is possible to assist or complement the driver's role in risky situations, either through warnings or by intervening when the risk level exceeds a threshold (e.g., Automated Emergency Braking). Another solution is to take the driver out of the control loop entirely by means of automated driving systems. The idea of using technology to mitigate accidents sounds reasonable in theory. The irony, however, is that the car is still designed by fallible humans and that a fallible driver is still present in the vehicle. In fact, the main challenge in implementing active safety systems is said to be the human factor: "the hardest problems associated with … many related transportation technologies are 'soft;' that is, they are human factors issues of safety, usability, and acceptance .... These are problems that are many times more difficult to overcome and must be overcome, largely, in parallel with the traditionally 'hard' technological issues" (Levitan, Golembiewski, & Bloomfield, 1998, p. 111).

4. Objectives and outline of this thesis

As stated above, it is important to understand drivers' limitations and abilities in mitigating a potential collision. The first objective of this thesis is to quantify how visual information shapes longitudinal control performance. For this purpose, the so-called visual occlusion technique is used, which is a common method for determining the visual demands of car driving (Van der Horst, 2004; Senders, Kristofferson, Levison, Dietrich, & Ward, 1967). The second objective of this thesis is to investigate the effectiveness of technological solutions for improving longitudinal control performance. This thesis proposes a head-up display that supports drivers in maintaining a safe and constant headway with respect to a car in front. This solution is seen as a useful alternative to automated driving systems that keep the driver out of the control loop.

Chapters 2 and 3 examine to what extent driver's visual perception can be relied on to avoid collisions in longitudinal maneuvers. The effects of the availability of visual information and the urgency of the situation were investigated in two simulated longitudinal control tasks: stopping at a target and driving behind a decelerating vehicle. Specifically, Chapter 2 presents the results of a driving simulator experiment in which participants drove behind a vehicle that suddenly slowed down. At the moment of lead car brake onset, the screen was occluded, with the aim to investigate how a brief period of visual distraction affects braking performance and collision risk. Chapter 3 examines the extent to which the braking task is an open loop control process. To do so, the study investigated how well participants can perform a stop at a target task as a function of the presence or absence of the visual information and the available braking time.

Chapter 4 studies why drivers adapt shorter headway when they follow a vehicle in fog where the visibility condition is restricted. The changes in participants' perceived risk and performance were measured, and the utility of the results for designing systems that help drivers in longitudinal control in low visibility conditions are discussed.

Chapter 5 presents the design and investigates the effectiveness of a head-up display that assists drivers in longitudinal control to maintain their headway from a lead car that follows a non-steady speed profile. The aim of this display was to assist drivers by displaying combined information of lead-car acceleration and time headway advice on the rear window of the lead car. The design was based on the premise that a display giving visual feedback on lead-car acceleration and time headway will act as a sensory aid for human drivers and thus enhances their performance in maintaining a constant headway with respect to the lead car.

Through reviewing the challenges of having automated driving systems from a human-factors perspective, Chapter 6 highlights human-machine interaction needs for automated vehicles and proposes design requirements for Cooperative Adaptive Cruise Control. Chapter 7 provides a general discussion of the conducted studies and suggests opportunities for future research.

Each of the chapters is readable in isolation. That is, Chapters 2–6 each have their own introduction and literature review, methods, results, and discussion section.

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CHAPTER 2

The effect of a short occlusion period on subsequent braking behavior: A driving simulator study

Abstract

Most rear-end collisions occur because of visual distraction, but little is known about drivers' braking behavior after a period of distraction during which relevant visual information is unavailable. The aim of this paper was to investigate the effects of (1) visual occlusion and (2) the absence of brake lights, on drivers' braking behavior. In three driving simulator tests (1 = brake lights, 2 = no brake lights, 3 = occlusion), participants followed a car at 13.4 or 33.4 m distance with a speed of 96 km/h. At certain moments, the lead car decelerated moderately (1.7 m/s^2) or strongly (6.5 m/s^2). In the occlusion condition, the screens of the simulator blanked for 0.4 or 2.0 s when the lead car started to decelerate. Participants were instructed to brake after the occlusion ended. Results showed that occlusion (i.e., endured delay) had a detrimental effect on inter-vehicle distance, especially in the urgent braking condition (6.5 m/s^2, 13.4 m), with collision prevalences of 18%, 29%, and 67%, for the brake lights, no brake lights, and occlusion conditions, respectively. Brake lights reduced the brake reaction times when the lead-car deceleration was small (1.7 m/s^2) and not as much when the lead-car deceleration was large (6.5 m/s^2). In conclusion, if the conditions are unfavorable (short headway combined with a large lead-vehicle deceleration), then visually distracted drivers are often unable to adapt their braking to mitigate an impending collision. These findings complement existing research on driver distraction by showing that a visual distraction as short as a glance at the speedometer can dramatically increase crash risk, even when drivers are biomechanically and cognitively prepared to brake.

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CHAPTER 2: The effect of a short occlusion

1. Introduction

Each year, road traffic crashes kill over 1.2 million people, with an additional 20 to 50 million people suffering non-fatal injuries (Lozano et al., 2013; World Health Organization, 2013). Rear-end collisions account for about 20 to 30% of the road traffic crashes (Knipling et al., 1993; NHTSA, 2014; Sullivan & Flannagan, 2003). Driving simulator studies and naturalistic driving studies have found that when avoiding a collision, the majority of drivers braked without steering, despite the fact that the optimal maneuver is often steering alone or steering in combination with braking (Adams, 1994; see also Lee, Llaneras, Klauer, & Sudweeks, 2007).

Over the history of traffic safety research, several efforts have been made to predict and improve drivers' brake reaction time (e.g., Greenshields, 1936; Johansson & Rumar, 1971; Young & Stanton, 2007), with brake reaction time defined as the time between the start of the lead vehicle deceleration (often communicated with a brake light) and the start of pressing the brake pedal. Green (2000) argued that the level of expectation and the degree of urgency to brake, as well as age, gender, and cognitive load (i.e., cognitive distraction) are primary factors influencing brake reaction time. He further argued that the level of expectation is the most important factor, with average brake reaction times being about 0.7 s for situations that are entirely expected and 1.5 s or more for situations where an object/stimulus suddenly appears on the road (see also Lerner, 1993; Summala, 1981, Taoka, 1989). In a more recent literature survey, Summala (2000) argued that visual distraction is another factor that determines the brake reaction time. Summala concluded that if drivers are attentive, they are usually able to brake in about 1.0 s. However, if drivers are visually distracted (e.g., looking at the mid console), they may detect a braking lead car with a delay of up to 5 s, depending on the timing and duration of the off-road glance.

Visual distraction is the cause of a large portion of rear-end collisions (Ghazizadeh & Boyle, 2009; Young & Regan, 2007). Results of a naturalistic driving study showed that 78% of crashes "involved the driver looking away from the forward roadway just prior to the onset of the conflict" (Dingus et al., 2006, p. 162). Similarly, an in-depth analysis of 74 rear-end collisions concluded that driver inattention to the driving task and following too closely were the two most common causal factors (Knipling et al., 1993). The authors concluded that "together or separately, these two factors were associated with 93 percent (weighted) of the clinical sample"

(p. ES-2). A recent analysis of a naturalistic driving dataset comprising 905 crash events confirmed these observations and concluded that distraction was a factor in 68.3% of the crashes (Dingus et al., in press).

Although it is now an epidemiologically well-established fact that distraction is an important cause of crashes, relatively little is known about *how* a distracted driver brakes in a critical situation in order to mitigate collision. Most information on near-collision driver behavior has been based on computer simulations that are yet to be validated (Markkula, Benderius, Wolff, & Wahde, 2012). It is obvious from classical mechanics that the delayed brake reaction time associated with distraction increases the stopping distance compared to not being distracted (e.g., Lee, 1976). However, what is predicted by mechanistic equations may not hold in practice because drivers are likely to compensate for increased risk. For example, if a distracted driver is confronted with a decelerating lead vehicle, he or she may abruptly and deeply press the brakes in order to prevent collision, and therefore not be more likely to end up in a collision than a non-distracted driver who presses the brake earlier. Other than crude outcome measures such as brake reaction time and whether or not a driver brakes or crashes, there is little empirical evidence of how a distracted driver actually brakes when a collision is imminent. Our observation concurs with Hancock and De Ridder (2003) who argued that “quantitative aspects of behavioral response in the vital milliseconds before collision has rarely been reported” (p. 1115).

The aim of the present driving simulator study was to investigate how occlusion (i.e., not being able to look at the front scene) affects the braking response time of drivers who are tasked and prepared to brake right after the visual view is restored. Visual occlusion is a technique that has previously been used to study how drivers respond to a lack of visual information, and to determine the minimum visual information required to drive a car. The occlusion method has its origins in the 1960s (Senders, Kristofferson, Levison, Dietrich, & Ward, 1967), and has been applied in various driving tasks, such as lane keeping, cornering, braking, and hazard anticipation (e.g., Akamatsu, Green, & Bengler, 2013; Andersen, Cisneros, Atchley, & Saidpour, 1999; Borowsky et al., 2015; DeLucia & Tharanathan, 2009; Kujala et al., in press; Saffarian, De Winter, & Senders, 2015; Van Der Horst, 2004; Van Leeuwen, Happee, & De Winter, 2014). By means of occlusion, the effect of just visual distraction (‘eyes-off-road’) was assessed. In other words, our research is not concerned with cognitive distraction (‘mind-off-road’), biomechanical distraction (e.g., manually adjusting the radio), or auditory distraction (e.g., responding to a ringing cell phone; see Ranney, Garrott, & Goodman, 2001, for a taxonomy of distraction types).

In our driving simulator experiment, four lead-car braking conditions were created by manipulating the deceleration magnitude of the lead car and the distance between the following and lead car. The selected deceleration magnitudes of 1.7 and 6.5 m/s^2 are within the ranges reported in previous studies (e.g., Touran, Brackstone, & McDonald, 1999). The selected headways were 13.4 and 33.4 m from bumper to bumper, which at our instructed speed of 96 km/h correspond to time headways (THWs) of 0.5 and 1.25 s, respectively. A THW of 0.5 s can be regarded as a 'minimum safe distance' adopted by a sizeable portion of drivers on highways, whereas a THW of 1.25 s is regarded as comfortable and common in busy highway traffic (Hoogendoorn & Botma, 1997; Neubert, Santen, Schadschneider, & Schreckenberg, 1999; Song & Wang, 2010; Taieb-Maimon & Shinar, 2001; Treiber, Kesting, & Helbing, 2006). Such short headways are common even in traffic that is not dense. For example, a field operational test showed that the mode of the THW distribution resides at 0.8 s, with a large portion of driving time spent at headways of 0.6 s and shorter (Fancher et al., 1998). Similarly, measurements with an instrumented vehicle by Brackstone and McDonald (2007) showed that the headway was less than 0.8 s for 29% of the time.

In our study, two occlusion durations were implemented: 0.4 s (very short) and 2.0 (very long). Research shows that mean off-road glance durations range between 0.5 s (for quick glances at in-vehicle information systems such as the speedometer) and 1.5 s (for complex tasks, such as when reading street names or interacting with route navigation devices; Dingus, Antin, Hulse, & Wierwille, 1989; see also Birrell & Fowkes, 2014, for a summary of the literature). Tijerina, Barickman, and Mazzae (2004) showed that drivers are relatively likely to look away from the road when the relative speed with respect to the lead vehicle is close to zero, and a recent analysis of naturalistic driving data by Victor et al. (2015) concluded that "the majority of … crashes happen because of a rapid change in situation kinematics, often occurring just after the driver has taken his or her eyes off the road." (p. 84). These are also the conditions simulated in our research: the car following task was stationary prior to the occlusion, and drivers had to brake right after the occlusion. The participants completed multiple braking trials and were instructed what to do, which allowed us to assess the effects of occlusion delay per se, without surprising the participants.

In addition to the effect of occlusion, this study aimed to investigate the effect of the brake lights on the brake response compared to the same situation without brake lights. This experimental condition was included in order to examine whether the brake lights improve brake reaction times when responding to both large and small deceleration magnitudes compared to both with and without occlusion conditions where there is no brake light.

2. Method

2.1. Driving simulator

The experiment was carried out in the NADS Minisim fixed-base driving simulator (Figure 1). The simulator presented the driving scene on three 42-inch plasma TVs, each with 1024 x 768 pixels resolution. An additional 19-inch screen acted as an instrument panel. The simulator recorded the data of the vehicle and the control inputs at a rate of 60 Hz. Two speakers in the front provided stereo sound. Participants controlled the car using the steering wheel, brake pedal, and gas pedal, while gear changing was automated.

Figure 1. NADS Minisim driving simulator.

2.2. Participants

Twelve participants (10 males and 2 females) with a valid Ontario class G driving license (or equivalent) were recruited from the University of Toronto community. Participants were compensated with 30 Canadian Dollars. On average, the participants were 27.0 years old (*SD* = 6.8, min = 21, max = 43) and had obtained their first driving license 7.4 years ago (*SD* = 4.5, min = 2, max = 16). Seven participants had previous experience driving a simulator (3 one time, 3 two times, and 1 three times). Four participants drove between 100 and 1,000 km/year, 6 participants drove between 1,000 and 10,000 km/year, and 2 participants drove between 10,000 and 100,000 km/year (see the information questionnaire in Appendix A.2).

2.3. Experimental schedule

The experimental schedule is shown in Figure 2. After arrival, participants read and signed an information/consent form. The form described the simulator controls, the experimental steps, and the driving tasks. Next, participants filled out an intake questionnaire that collected their demographic and driving history data.

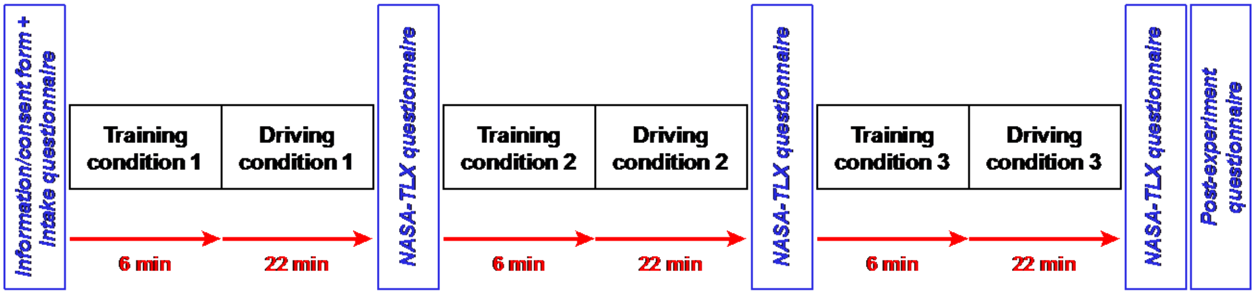

Figure 2. Timeline of the experiment; the dashed boxes indicate the stages at which questionnaires were answered; the timeline is approximate.

2.4. Simulator training

Each driving test was preceded by a 6 min training session. During the training sessions, participants gained experience with the braking tasks of the main driving tests. The driving environment was a straight two-lane road with a lane width of 3.66 m. The participants had to follow a lead car that maintained a 13.4 or 33.4 m distance (bumper-to-bumper) from the participants' car through a distance-control algorithm, and then braked with a deceleration of 1.7

or 6.5 m/s^2. The training session consisted of one braking trial for each of the four combinations of deceleration and distance. The time between the braking trials was about 80 s.

2.5. Driving tests

The experiment consisted of three driving tests, in which the visual information was different. In the first test condition, *brake lights*, the lead car's brake lights were on when the lead car braked (see Figure 3, for a screenshot). In the second test condition, *no brake lights,* the brake lights of the lead car did not turn on. In the third test condition, *occlusion*, the simulator screens automatically blanked out for a short period as the lead car started to brake, and the brake lights of the lead car did not turn on. When the lead car deceleration was large (6.5 m/s^2), the occlusion duration was 0.4 s. For the small deceleration of the lead car (1.7 m/s^2), the occlusion duration was 2.0 s. The simulator applied the deceleration of the lead car with a 0.08 s delay to the event trigger. The sequence of the three driving test conditions was counterbalanced between the participants.

Figure 3. The participant's view of the lead car with brake lights activated. In this view, the bumper-to-bumper distance was approximately 13.4 m.

2.6. Braking conditions within each driving test

Figure 4 shows the speed profiles of the lead car for the two deceleration magnitudes. In each braking trial, participants first followed the lead car at an instructed speed of 60 mph (~ 96 km/h). During this phase, the lead car automatically maintained a set gap with respect to the participant's car. For half of the trials the bumper-to-bumper distance was maintained at 13.4 m and for the other half it was maintained at 33.4 m.

Figure 5 shows the driver's view at these two distances. After the car-following phase, the lead car slowed down to 30 mph (~ 48 km/h). For half the trials, the deceleration was 6.5 m/s^2 and for the other half it was 1.7 m/s^2. The duration of the slow down for each of the two deceleration magnitudes was about 2 and 8 seconds, respectively. The combination of the two deceleration magnitudes and the two following distances generated four different types of braking conditions.

Each of the three driving tests included four trials for each of the four braking conditions. Hence, in total there were 16 braking trials within each driving test. The sequence of the braking conditions within each driving test were presented in no discernible order and differed between the three driving tests.

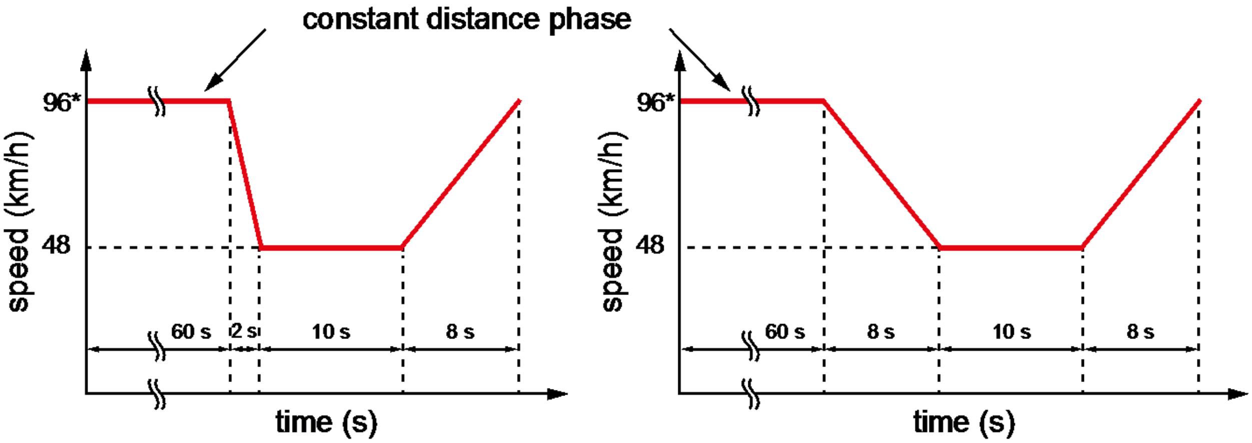

Figure 4. The lead car speed scheme for large (left) and small (right) deceleration. *Speed during the 60 s constant speed phase varied between trials, because the lead car adapted its speed to the participant in order to achieve a constant headway. The times are approximate.

2.7. Instructions to participants

Participants were informed, in writing, that the goal of this study was to investigate how drivers use visual information to control their brakes. The form stated that the task was to drive at a speed of 60 mph while following the lead car, that the lead car was controlled so that it maintained a set distance from the participant’s car, and that the lead car suddenly braked at certain moments. In addition, it informed the participants that when the lead car braked, their task was to slow down to avoid collision. The form also stated that the participants should (1) try to control the brake force and avoid slamming the brakes, (2) drive swiftly but safely as in normal driving, (3) try to keep the car centered in the right lane and not change lanes, and (4) keep the right foot on the gas pedal before starting to use the brake. Note that the participants were asked to not slam the brakes, to prevent an unrealistic 100% pedal depression throughout the trial (see Appendix A.1). Participants were further informed that they would drive three test conditions in random order as follows:

(1) Brake lights: the brake lights of the lead vehicle are on; you can start braking at any time after the lead vehicle starts braking.

(2) No brake lights: the brake lights of the lead vehicle are off; you can start braking at any time after the lead vehicle starts braking, and

(3) Occlusion: when the lead vehicle starts to brake, the screen turns off for a short period; you should start braking at any time after the occlusion clears (i.e., when the screen turns back on); the brake lights of the lead vehicle are off. It was decided to keep the brake lights off during braking in the occlusion condition, because the onset of the occlusion already signals that the lead car had started braking.

Figure 5. The participant's view of the lead car when the bumper-to-bumper distance was approximately 13.4 m (left) and 33.4 m (right).

2.8. NASA Task Load Index (TLX), confidence questionnaire, and post-experiment questionnaire

After each of the three driving tests, participants stepped out of the simulator and completed the NASA Task Load Index (TLX) questionnaire (Hart, 2006). The questionnaire included four additional items that asked about feelings of risk and confidence (see Appendix A.3). We used this four-item questionnaire in previous driving simulator research, and found that it could discriminate between occlusion/low visibility and control conditions (Saffarian et al., 2015; Saffarian, Happee, & De Winter, 2012). The items had a 21-tick scale and ranged from *Very low* to *Very high* for the mental demand, physical demand, temporal demand, effort, and frustration items, and from *Perfect* to *Failure* for the performance item. The risk and confidence items ranged from *Strongly disagree* to *Strongly agree*. At the end of the experiment, participants filled out a questionnaire that asked about the use of any specific strategy in performing the tasks during each of the three visual conditions (see Appendix A.4).

2.9. Dependent variables

The following dependent variables were used to measure the latency and amplitude of the braking response:

- *Brake reaction time (s)*. The time between the brake onset of the lead car and the brake onset of the participant's car.

- *Maximum brake pedal displacement (%)*. The maximum depression of the brake pedal that occurred during the braking trial, expressed as percentage of the full depression.

- *Maximum brake pedal displacement time (s)*. The time between the brake onset of the lead car and the moment that the maximum brake displacement occurred.

In addition, the following distance-related measures were defined:

- *Minimum following distance (m)*. The minimum distance between the participant's car and the lead car (bumper-to-bumper) that occurred during the braking trial.

- *Number of collisions (%)*. The percentage of trials in which participant's vehicle and the lead car collided. Collisions did not actually materialize during the experiment; the cars could drive through each other unimpeded.

Note that the simulator recorded the brake pedal position using a potentiometer that was calibrated such that 0% corresponded to a fully released pedal, and 100% corresponded to a fully depressed pedal as used by the simulator's vehicle dynamics model. It was determined with a ruler and load cell that 100% pedal depression corresponded to a pedal travel of 5 cm and a pedal force of about 150 N. Moreover, it was determined that the brake pedal force was approximately linear in the 0–100% working range. Note that 100% was not the physical maximum depression that could be achieved; it was in principle possible to press the brake pedal about 1 cm more deeply into the rubbers that the fully depressed brake pedal rests on.

2.10. Statistical analyses

1 of 576 trials was excluded because the participant was already braking at the moment the lead vehicle started to decelerate. An additional 22 trials were excluded because the headway deviated more than 0.5 m from the target headway (13.4/33.4 m), due to the participant not speeding up enough.

After this initial filtering of trials, temporal patterns of the throttle position, brake position, lead and participant's car speed, and bumper-to-bumper headway were examined. Specifically, for each of the three visual conditions and four braking conditions, figures were created on which the horizontal axis is the time, and the vertical axis is the average value across the 48 trials (i.e., 12 participants × 4 trials per visual condition). Note that these temporal patterns reflect the average response of all participants, and cannot be used by themselves to make unequivocal inferences about the responses of individual participants. For example, a mean brake pedal position of 50% could mean that half of the participants were braking with 100% brake position and the other 50 half were not braking, or it could mean that all participants were braking with 50% brake position.

As a complement to the temporal patterns, the means and standard deviations of the dependent measures were calculated for each of the three visual conditions and four braking conditions. That is, for each participant, the mean of each measure was calculated over four trials, and then the mean and *SD* of these means were calculated across the 12 participants.

Comparisons were performed using paired *t*-tests between (1) brake lights versus no brake lights, and (2) brake lights versus occlusion. A Bonferroni correction was applied. Accordingly, because eight statistical comparisons were done per dependent measure (i.e., four braking conditions × 2 comparisons), the significance level was reduced to 0.05/8 = 0.00625. For the self-report questionnaire items, the significance level was reduced to 0.05/2 = 0.025.

3. Results

3.1. Driving performance and behavior

Figure 6 shows the temporal patterns of the throttle position. Most participants released the throttle immediately, with the fastest reaction times being about 0.35 s. In occlusion condition trials, some participants released the throttle after the occlusion ended, an effect that can be clearly seen in the small-deceleration small-headway condition (Figure 6 left top, 2 s occlusion). Figure 6 also shows that participants without brake lights released the throttle relatively late when the lead car deceleration was small.

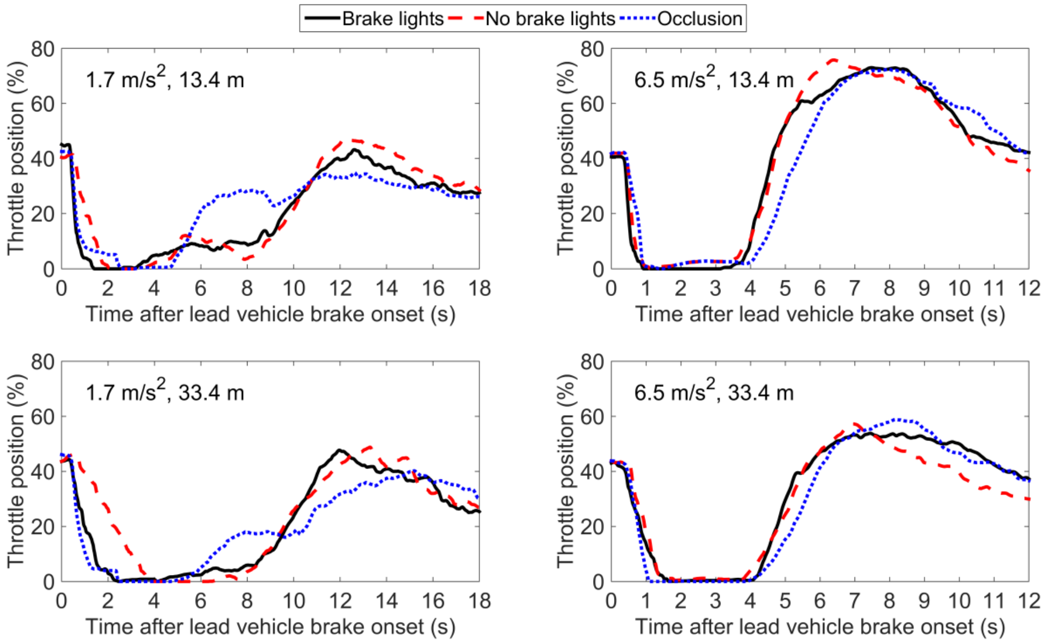

Figure 6. The mean throttle pedal position during the different braking conditions.

Figure 7 shows the temporal patterns of the brake pedal displacement. The means, standard deviations, and results of the statistical tests of the brake reaction time, maximum brake position, and time of maximum brake position are shown in Table 1 to Table 3. Figure 7 and Table 2 show that the maximum brake pedal displacement was largest for the most urgent condition (i.e., large deceleration 6.5 m/s^2, small following distance of 13.4 m), and overall lowest for the least urgent condition (i.e., 1.7 m/s^2, 33.4 m).

Figure 7 and Table 1 show that when the lead car deceleration was small (i.e., 1.7 m/s^2), the brake lights resulted in faster reaction times than the no-brake-lights situation. Table 1 also shows that the brake reaction time significantly increased for occlusion compared to the brake light condition (except for the large-deceleration small-headway condition). This increase of brake reaction time is expected, as drivers were instructed to brake after the occlusion period ended (2.0 s when the lead deceleration was small, and 0.4 s when the lead deceleration was large). These effects can also be seen in Figure 8, which shows the temporal patterns of the speed of both cars.

Table 2 shows that when the deceleration was small, drivers in the no-brake-lights and occlusion conditions pressed the brake pedal further than drivers in the brake lights condition. Furthermore, in the small-deceleration small-headway condition, drivers without brake lights reached the maximum brake pedal displacement significantly later than they did with brake lights (Table 3).

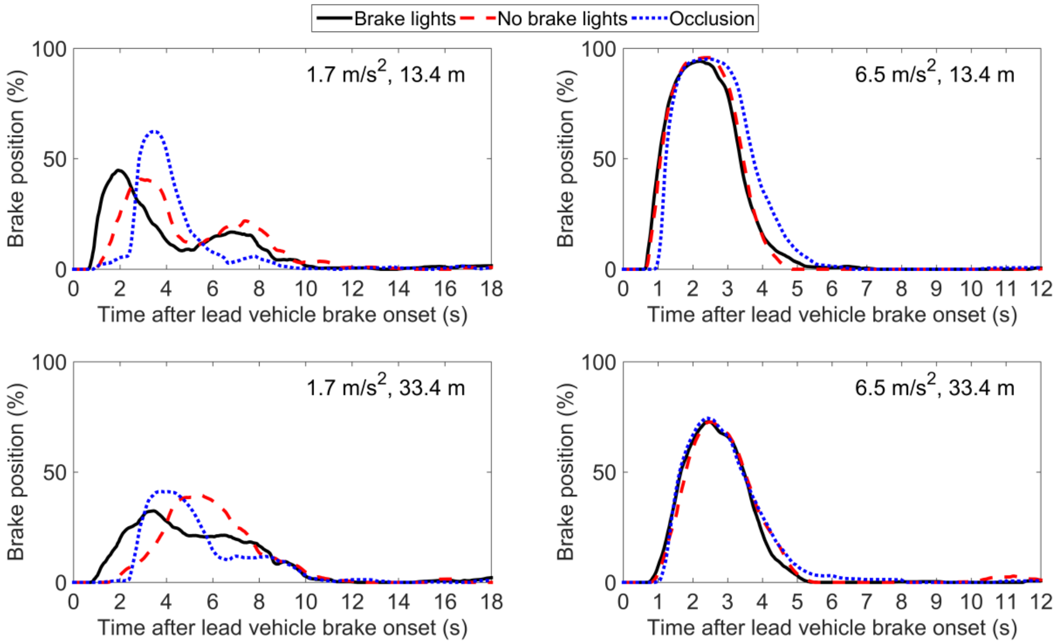

Figure 7. The mean brake pedal position during the different braking conditions.

Table 1. Descriptive statistics of participants' brake reaction time (s).

Condition	**Brake lights (B)**	**No brake lights (N)**	**Occlusion (O)**	**B vs. N**	**B vs. O**
	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**	**Paired *t* test results (*df* = 11)**	
1.7 m/s^2, 13.4 m	0.970 (0.220)	1.639 (0.433)	2.169 (0.471)	$\mathbf{p < 0.001}$ $t = -5.387$	$\mathbf{p < 0.001}$ $t = -6.848$
1.7 m/s^2, 33.4 m	1.747 (0.474)	3.077 (0.660)	2.507 (0.349)	$\mathbf{p < 0.001}$ $t = -5.029$	$\mathbf{p < 0.001}$ $t = -6.033$
6.5 m/s^2, 13.4 m	0.812 (0.090)	0.866 (0.111)	1.082 (0.064)	$p = 0.079$ $t = -1.933$	$\mathbf{p < 0.001}$ $t = -9.688$
6.5 m/s^2, 33.4 m	1.173 (0.016)	1.330 (0.211)	1.246 (0.104)	$p = 0.045$ $t = -2.260$	$p = 0.167$ $t = -1.480$

Note. Participants sometimes braked before the occlusion period ended (i.e., before 2.0 s when the deceleration was small). This occurred in 14 of 46 trials, 7 of 47 trials, 0 of 48 trials, and 0 of 47 trials, for the four respective braking conditions.

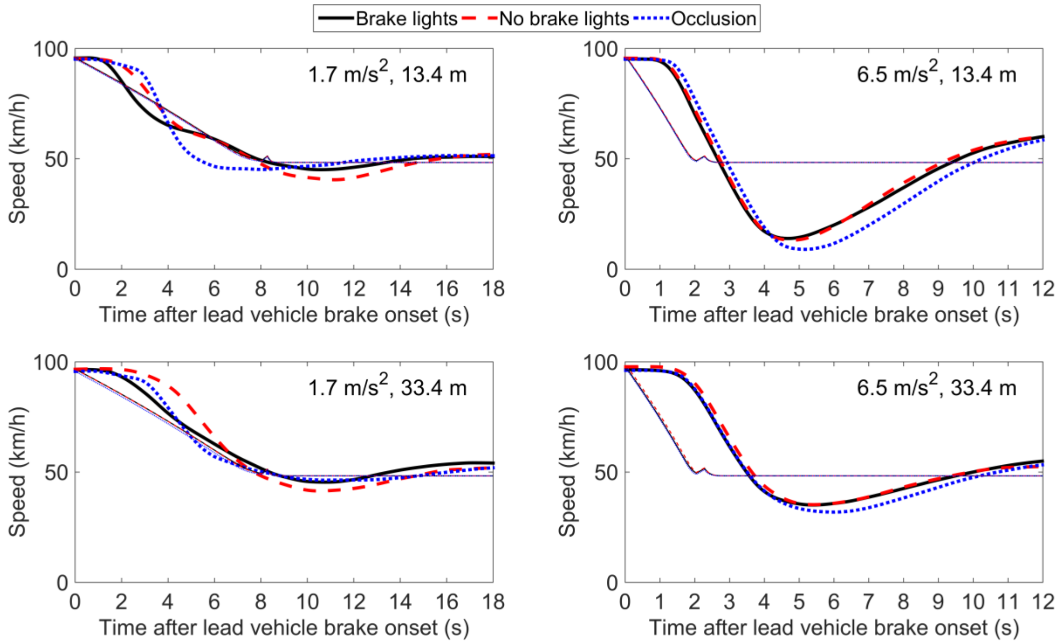

Figure 8. The mean participant's car speed (thicker lines) and the mean lead car speed (thinner lines) during the different braking conditions. Note that the small bump in lead car speed (at 8.3 s for the 1.7 m/s^2 conditions, and at 2.3 s for the 6.5 m/s^2 conditions) is an artifact of the lead car's controller, and is inconsequential.

Table 2. Descriptive statistics of participants’ maximum brake pedal displacement (%).

Condition	**Brake lights (B)**	**No brake lights (N)**	**Occlusion (O)**	**B vs. N**	**B vs. O**
	M (SD)	**M (SD)**	**M (SD)**	**Paired t test results (df = 11)**	
1.7 m/s^2, 13.4 m	49.678 (8.686)	52.711 (11.451)	64.816 (12.571)	$p = 0.243$ $t = -1.234$	**$p = 0.002$** $t = -4.098$
1.7 m/s^2, 33.4 m	40.441 (7.825)	50.030 (11.451)	47.969 (11.215)	**$p = 0.002$** $t = -3.947$	$p = 0.009$ $t = -3.191$
6.5 m/s^2, 13.4 m	91.967 (11.255)	96.664 (6.157)	95.459 (8.128)	$p = 0.023$ $t = -2.652$	$p = 0.028$ $t = -2.530$
6.5 m/s^2, 33.4 m	74.732 (12.878)	76.950 (9.676)	77.237 (14.827)	$p = 0.443$ $t = -0.796$	$p = 0.307$ $t = -1.070$

Figure 9 shows the temporal patterns of the following distance. The means (and standard deviations) per condition of the minimum distance and the number of collisions are reported in Table 4 and Table 5, respectively. The smallest distances and the largest numbers of collisions were found for the most urgent condition (i.e., 6.5 m/s^2, 13.4 m). In this condition, the mean distance gap was negative at 3 s after the lead vehicle brake onset (Fig. 9, right top). With the brake lights, drivers had a larger following distance than they had when there were no brake lights. The following distance was also shorter in the occlusion condition than it was in with the brake lights condition. The effect of occlusion was most pronounced in the urgent condition (i.e., 6.5 m/s^2, 13.4 m, 0.4 s occlusion). In this urgent condition with occlusion, the number of collisions was as high as 67%, compared to 18% in the condition with brake lights (t (11) = −5.478, $p < 0.001$).

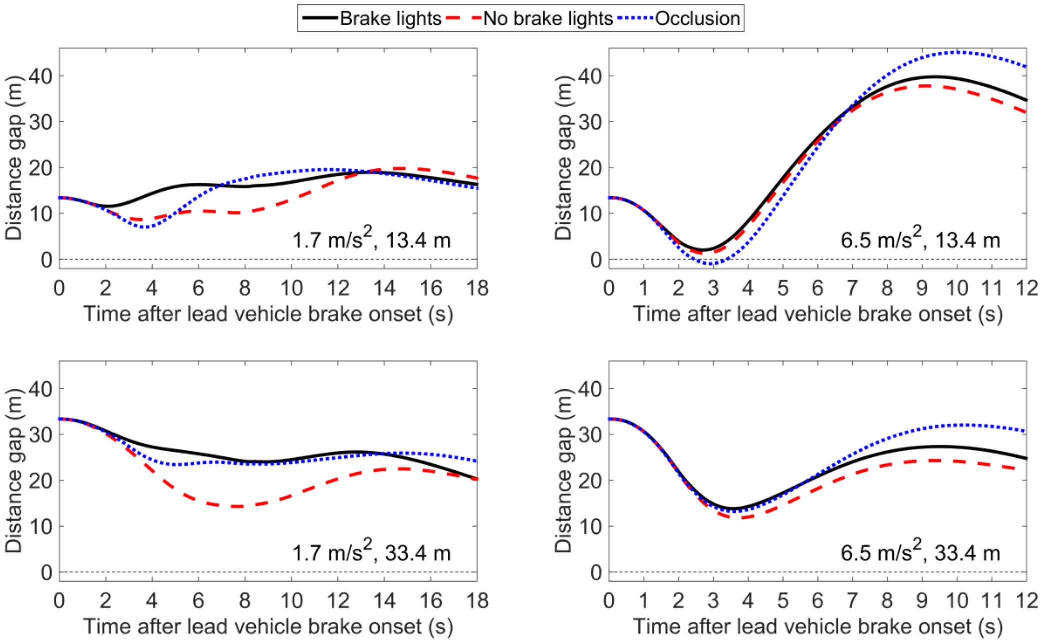

Figure 9. The mean bumper-to-bumper distance during the different braking conditions.

Table 3. Descriptive statistics of participants' maximum brake pedal displacement time (s).

Condition	**Brake lights (B)**	**No brake lights (N)**	**Occlusion (O)**	**B vs. N**	**B vs. O**
	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**	**Paired *t* test results (*df* = 11)**	
1.7 m/s^2, 13.4 m	2.825 (1.365)	4.446 (1.129)	3.784 (1.027)	$\boldsymbol{p = 0.004}$ $t = -3.649$	$p = 0.085$ $t = -1.889$
1.7 m/s^2, 33.4 m	5.245 (2.508)	5.116 (0.774)	5.126 (1.196)	$p = 0.849$ $t = 0.195$	$p = 0.859$ $t = 0.182$
6.5 m/s^2, 13.4 m	2.009 (0.284)	1.915 (0.395)	1.992 (0.455)	$p = 0.232$ $t = 1.266$	$p = 0.807$ $t = 0.250$
6.5 m/s^2, 33.4 m	2.601 (0.412)	2.765 (0.524)	2.632 (0.599)	$p = 0.218$ $t = -1.308$	$p = 0.806$ $t = 0.252$

Table 4. Descriptive statistics of participants’ minimum distance gap (m).

Condition	**Brake lights (B)**	**No brake lights (N)**	**Occlusion (O)**	**B vs. N**	**B vs. O**
	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**	**Paired *t* test results (*df* = 11)**	
1.7 m/s^2, 13.4 m	8.797 (1.747)	7.140 (1.304)	6.400 (1.944)	**$p = 0.004$** $t = 3.668$	**$p = 0.003$** $t = 3.851$
1.7 m/s^2, 33.4 m	17.178 (5.474)	11.548 (3.679)	14.716 (5.843)	$p = 0.009$ $t = 3.188$	$p = 0.164$ $t = 1.492$
6.5 m/s^2, 13.4 m	2.262 (0.985)	1.159 (2.251)	−1.060 (1.618)	$p = 0.075$ $t = 1.968$	**$p < 0.001$** $t = 8.500$
6.5 m/s^2, 33.4 m	12.556 (3.118)	10.522 (2.875)	12.061 (3.731)	**$p = 0.001$** $t = 4.281$	$p = 0.533$ $t = 0.644$

Table 5. Descriptive statistics of participants’ number of collisions (%).

Condition	**Brake lights (B)**	**No brake lights (N)**	**Occlusion (O)**	**B vs. N**	**B vs. O**
	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**	**Paired *t* test results (*df* = 11)**	
1.7 m/s^2, 13.4 m	0 (0)	0 (0)	0 (0)	-	-
1.7 m/s^2, 33.4 m	0 (0)	0 (0)	0 (0)	-	-
6.5 m/s^2, 13.4 m	18.1 (25.8)	29.2 (36.7)	66.7 (30.8)	$p = 0.104$ $t = -1.773$	**$p < 0.001$** $t = -5.478$
6.5 m/s^2, 33.4 m	0 (0)	0 (0)	0 (0)	-	-

3.2. Self-reports

Table 6 shows the results of the TLX and confidence questionnaires. It can be seen that there were no major differences between the three conditions. However, participants in the occlusion condition reported somewhat higher temporal demands than in the brake lights condition. This finding is unsurprising as drivers indeed had less time to complete the brake in the occlusion condition (2.0 s and 0.4 s for the small and large deceleration of the lead car, respectively).

A number of participants indicated that when brake lights were unavailable, they tried to look for other visual features that could help time their braking, such as the rear tire or the angular pitch of the car that occurs when slowing down. For the occlusion condition, two participants reported that they released the accelerator during the occlusion period (cf. Figure 6 showing that the majority of participants released the throttle before the occlusion ended). A number of participants indicated that in the brake lights condition, their strategy was to focus on the brake lights (only).

Table 6. NASA TLX and four additional questions about feelings of risk and self-confidence.

	Brake lights (B)	**No brake lights (N)**	**Occlusion (O)**
	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**
TLX Mental demand	48 (27)	50 (33)	60 (22)
TLX Physical demand	41 (28)	40 (34)	48 (26)
TLX Temporal demand	36 (25)	33 (25)	45 (18)
TLX Performance	37 (25)	31 (24)	51 (32)
TLX Effort	50 (26)	56 (31)	57 (17)
TLX Frustration	36 (29)	21 (28)	35 (21)
I had a feeling of risk	35 (24)	37 (34)	37 (25)
I think I drove more safely than the average participant	64 (18)	65 (21)	57 (18)
I found the driving task easy	71 (19)	63 (25)	61 (17)
I felt confident in my own capability to act appropriately	80 (17)	76 (21)	70 (18)

Note. The results are shown in percentages from 0% (lowest on the scale) to 100% (highest on the scale).

4. Discussion

This research examined how drivers' braking behavior is influenced by (1) a brief lack of visual information at the lead-vehicle brake onset combined with the instruction to brake after this occlusion ended, and (2) the absence of the brake lights. We investigated drivers' braking response in a car-following scenario for two levels of deceleration and two levels of inter-vehicle distance. In our study, participants knew what to expect. That is, the participants knew there would be a number of lead car braking trials and knew what stimulus signaled the lead car braking (i.e., the activation of the brake lights or the start of the occlusion).

When there were brake lights, the reaction time was faster than when there were no brake lights. This result can be interpreted in light of the fact that in the brake lights condition there were *two* cues which the participants could use (the brake lights & the looming of the lead car) whereas in the no-brake-lights condition there was *one* cue (the looming of the lead car). However, the beneficial effect of brake lights on brake reaction time was statistically significant only in the low deceleration conditions (i.e., a lead car deceleration of 1.7 m/s^2). These findings are in line with previous research which has shown that it is difficult for drivers to detect the low deceleration level of a lead car by means of vision (e.g., Braunstein & Laughery, 1964; Park, Lee, & Koh, 2001; Tharanathan & DeLucia, 2007).

Our research provides a confirmation of the importance of brake lights, a feature which manufacturers introduced in 1916. Brake lamps were mandated by the 1960s, and have undergone refinement in the past decades (Moore & Rumar, 1999). Various brake light patterns and locations have been proposed (e.g., Berg, Berglund, Strang, & Baum, 2007; Hope et al., 2011; Li & Milgram, 2008; McIntyre, 2008; Sivak, Conn, & Olson, 1986). The central high mounted stop lamp, arguably a “human factors success story” (Malone, 1987), is one design now available in many consumer vehicles (see also Theeuwes & Alferdinck, 1995; McKnight & Shinar, 1992; Stanton & Baber, 2003). Conventional brake lights only indicate the onset and not the intensity of the lead vehicle brake. Thus, researchers have tested alternative types of brake lights, including systems that provide continuous, rather than binary, information about the lead vehicle’s deceleration (e.g., Li & Milgram, 2008; Saffarian, De Winter, & Happee, 2013; Voevodsky, 1974). More recently, forward collision warning systems have been introduced, which offer the brake signal inside the driver’s vehicle (Abe & Richardson, 2006; Ho, Reed, & Spence, 2007; Lee & Peng, 2005; Meng, Ho, Gray, & Spence, 2015; Parasuraman, Hancock, & Olofinboba, 1997).

With occlusion, participants seemed to be eager to press the brakes as quickly as possible in order to avoid collision. For example, when the headway was 13.4 s and the lead car braked hard (i.e., 0.4 s occlusion), the mean brake reaction time was 1.082 s for the occlusion condition, and

0.812 s for the brake lights condition. The difference is only 0.27 s (=1.082 s − 0.812 s), which is less than the occlusion interval of 0.4 s. When the occlusion duration was long (2.0 s), participants pressed the brakes before the occlusion ended in 19% of the trials with large distance headway and 30% of the trials with small distance headway, respectively (Table 1). Thus, although the brake reaction time of drivers in the occlusion condition was longer than in the brake lights condition, the additional time taken was less than the occlusion interval (0.4 or 2.0 s), indicating that, in the absence of visual information, participants were cognitively and biomechanically primed to press the brakes.

Occlusion had a negative effect on the distance headway compared to the condition without occlusion, an effect that was most pronounced in the urgent braking condition (6.5 m/s^2, 13.4 m, see Tables 4 and 5). The adverse effects of visual distraction and corresponding time delay can be partially explained using classical mechanics. Suppose that two cars follow each other in the same lane, and assume that both cars are able decelerate at a constant deceleration of 6.5 m/s^2 ($a = –6.5$ m/s^2). Also, assume that the brake reaction time of the following car is 1 s ($t_b = 1$ s), the initial speed of both cars is 96 km/h ($V_0 = 26.67$ m/s), and the initial headway is 0.5 s ($D_0 = 13.4$ m). It can be calculated that the vehicles will collide 2.58 s ($t_c = 2.58$ s) after the lead vehicle starts braking (i.e., $t_c = –(a \cdot t_b^2 + V_0 \cdot t_b + D_0)/(2 \cdot a \cdot t_b)$). However, what is predicted by Newtonian equations may not hold in a practical human-machine assemblage, because drivers may tactically and strategically adapt their braking timing and dosing in high-urgent conditions in order to moderate their collision risk.

A few tenths of a second of occlusion (0.4 s) already proved to be detrimental regarding the probability of collision, being as high as 67% for occlusion condition compared to 18% for the brake lights condition. The pedal displacement patterns were almost saturated in the emergency braking condition (cf. Fig. 7, right top), and therefore the 0.4 s occlusion period is ‘lost time’ that directly translates into ‘lost headway’ without much ability to compensate by pressing the brake further. Contrastingly, when the lead vehicle deceleration was small (2.0 s occlusion), then participants in the occlusion condition adapted their behavior to the time lost by braking harder (Fig. 7, left). In summary, our results demonstrate how a brief moment of distraction, as small as 0.4 s (comparable to the duration of a brief glance at the speedometer), can seriously increase the crash risk when the headway is short and the lead vehicle performs an emergency brake. These strong effects were observed despite the fact that the occlusion onset provided a salient cue that the lead vehicle started decelerating, allowing the participants to cognitively and biomechanically prepare themselves for the subsequent braking. Previous research has illustrated that performing non-visual tasks by drivers impairs their reaction time between 0.5 to 1 s (Lamble, Kauranen, Laakso, & Summala, 1999). Consequently, the presented results of this study may well be a conservative assessment of the detrimental effect of a short visual distraction.

An analysis of the 100-car naturalistic driving study by Victor and Dozza (2011) showed that longer than 1 s glances away from the forward scene are dangerous. Based on a cross-sectional analysis of naturalistic driving data, they recommended that glances should always be short (< 1 s). Our study suggests that a visual distraction as short as 0.4 s is hazardous in a specific emergency brake scenario where the lead-vehicle deceleration and initial headway are unfavorable.

The present findings may be of use in the design of in-vehicle warning/feedback systems that alert/inform the driver when following too closely. Various systems are on the market and under development, such as forward collision systems, brake assist systems, and brake warning systems (e.g., Hildebrandt et al., 2015). The present results suggest that such systems may be ineffective in preventing crashes, if they do not brake automatically yet allow the driver to follow at very close headways. In order to support drivers, a design may be used that provides real-time feedback to the driver about the degree of hazard in front of the driver (e.g., Mulder, Mulder, Van Paassen, & Abbink, 2008; Charissis & Papanastasiou, 2010) or as a function of momentary visual distraction (Donmez, Boyle, & Lee, 2007, 2008; Itoh, Abe, & Yamamura, 2014). Here it should be noted that there is an obvious balance between productivity/mobility and safety: Headway feedback/advisory systems should not enforce a driver to drive at overly long headways, because this may hamper traffic flow efficiency or stimulate other vehicles to cut in to that gap (e.g., this is an issue with ACC systems, Larsson, 2012). An alternative solution is to coach or train drivers so that they improve their driving attitudes. This may be a difficult endeavor as violations are found to be resistant to change and may even increase with experience/practice (De Winter et al., 2009; De Winter, Wieringa, Kuipers, Mulder, & Mulder, 2007; Foss, 2011; Stanton, Walker, Young, Kazi, & Salmon, 2007). Our findings are also relevant for the design of automated driving systems, for which brake reaction time in takeover scenarios is a crucial performance measure (De Winter, Happee, Martens, & Stanton, 2014). An example is a platooning system, which automates the car following task by adopting a very short headway. Our results suggest that such technology needs to be extremely reliable so the manual takeover is not required (see also De Waard, Van der Hulst, Hoedemaeker, & Brookhuis, 1999).

In interpreting the real world implications of our results, several limitations need to be considered. First, it is known that people underestimate the ‘true’ distance to a lead car in the NADS Minisim with as much as 70% (see Saffarian et al., 2015, for an evaluation), which may imply that participants brake differently in response to a lead car than they would do in a real car. This distance underestimation may be caused by the limited resolution of the screens, lack of stereopsis, or other visual limitations of the driving simulator (Andersen, 2011). On the other hand, it has been suggested that driving simulators provide valid results regarding the measurement of brake reaction time (McGehee, Mazzae, & Baldwin, 2000). Our brake reaction times to the brake lights (0.8–1.7 s, see Table 1) are in line with brake reaction times observed on the roads (Green, 2000; Johansson & Rumar, 1971; McIntyre, 2008; Summala, 2000; Young & Stanton, 2007).

Second, one may argue that the number of participants was small ($N = 12$). On the other hand, our findings are theoretically plausible and yielded p values that were substantially smaller than the nominal alpha value, indicating that the findings have high evidential value (despite the fact that statistical power might seem small beforehand).

Third, our setup lacked the vestibular and kinesthetic feedback that drivers normally experience during braking maneuvers. Because of lack of motion, drivers in a driving simulator usually brake harder and more abruptly than they do in a real vehicle (Boer, Girshik, Yamamura, & Kuge, 2000; De Groot, De Winter, Mulder, & Wieringa, 2011). The lack of motion is likely to have influenced the brake modulation compared to real driving, but it is unlikely that it would have much of an effect on the brake reaction time (i.e., when not yet decelerating). Note that driving simulators typically lack *absolute* validity (i.e., numeric similarity between the simulator and a real vehicle), but exhibit acceptable *relative* validity (i.e., a similarity of effect sizes, or signs of effects, between the simulator and a real vehicle; Kaptein, Theeuwes, & Van der Horst, 1996). Even driving simulators with six degrees-of-freedom motion platforms cannot generate realistic sustained motion (e.g., Bürki-Cohen, Soja, & Longridge, 1998). Hence, it remains to be seen whether more valid results would have been obtained with a classic motion platform. A simulator with linear drive motion may be recommended for future research (Nordmark, Jansson, Palmkvist, & Sehammar, 2004).

Fourth, in our experiment, the driving scene was occluded completely (except for the speedometer). In real car driving, distracted drivers may still extract valuable cues from the environment using peripheral vision (Lamble et al., 1999; Summala, Lamble, & Laakso, 1998; Terry, Charlton, & Perrone, 2008). Although peripheral vision is not good at determining fine detail, it may still be useful for detecting brake lights or rapidly closing objects.

Finally, because this research aimed to assess visual distraction rather than cognitive distraction, drivers in the present study were instructed in such a way as to experience no ‘surprise’ effects. Participants each completed 48 trials in a within-subjects design, which means that the effects were statistically reliable compared to experiments in which participants’ one-off surprise reaction is tested (e.g., Hault-Dubrulle, Robache, Pacaux, & Morvan, 2011). As a result of the large number of trials, it is likely that participants became accustomed to the procedure. Furthermore, the braking trials were homogeneous, with the duration of the occlusion period always corresponding to the same lead car deceleration (i.e., 2.0 s occlusion always corresponded to 1.7 m/s^2 deceleration, and 0.4 s occlusion always corresponding to 6.5 m/s^2 deceleration). That is, participants knew (or could infer) that a change in lead vehicle speed is a signal that it will be slowing down, and this knowledge presumably led the participants to focus acutely on the lead vehicle. The self-reported strategies confirm that drivers behaved intelligently. Participants reported that, to compensate for the lack of visual information, they paid closer attention to visual features of the car when the brake lights were not present. Thus, our study measured the effect of visual distraction (or: ‘endured delay’ in brake initiation), are applicable to alert and practiced drivers, and are informative regarding what *could happen* in a near-accident scenario. It is expected that the detrimental effect of a period of distraction would be even stronger for drivers in unexpected and surprise conditions.

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CHAPTER 3

Measuring drivers’ visual information needs during braking: A simulator study using a screen-occlusion method

Abstract

It is commonly accepted that vision plays an important role in car braking, but it is unknown how people brake in the absence of visual information. This simulator study measured drivers ’ braking behavior while they had to stop their car at designated positions on the road. The access to visual information was manipulated by occluding the screen at the start of half of the braking trials, while the temporal demand was manipulated by varying the time-to-arrival (TTA). Results showed that for the longer TTA values (⩾ 6 s), participants in the occlusion condition stopped too early and at variable positions on the road as compared to the control condition. The lack of visual information after the brake onset reduces the maximum brake input applied by drivers in braking events with short TTAs. The results also show that the lack of visual information slows down drivers in building their brake response profile when the TTA is short. Overall, the findings imply that the availability of visual information during a stopping task where drivers need to stop at a precise location (e.g., a stop sign or a cross section) improves performance for both urgent and non-urgent stopping tasks, despite the fact participants underestimated the distance to objects by 70% (as determined with a distance estimation test).

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CHAPTER 3: Measuring drivers’ visual information needs during braking

1. Introduction

1.1. The role of braking in driving safety

Automobile driving presents a myriad of opportunities for accidents. Braking is probably the most common reaction of drivers to an impending collision (e.g., Gkikas, Richardson, & Hill, 2009; Malaterre, Ferrandez, Fleury, & Lechner, 1988). A kinematic analysis of driving shows that between steering and braking, the latter is the only possible safe intervention in low speed (< 50 km/h) emergency events, whereas at higher speeds evasive steering is possible as well (Allen, Rosenthal, & Aponso, 2005). It has been reported that rear-end collisions account for about 30% of all motor vehicle injury accidents (National Safety Council, 2011). While proper braking can save lives and limbs, improper braking can escalate the risk of collision. For example, if a driver brakes when not needed, he or she increases the risk of a rear-end collision (Inagaki & Sheridan, 2012).

1.2. Locomotion theories of braking behavior

Despite its fundamental role in driving safety, drivers’ braking behavior is not well understood. Several attempts to explain braking behavior have used locomotion theories. According to these theories, the control of locomotion is ‘prospective’, which means that the perceptual system provides information about the future, and the actor adjusts the course of action to satisfy the requirements of the task (e.g., Warren, 1998; Zago, McIntyre, Senot, & Lacquaniti, 2009). Most of the existing braking theories assume that drivers perceive possible collisions and accordingly adjust the vehicle speed to avoid colliding (Andersen & Sauer, 2004; Lee, 1976; Yilmaz & Warren, 1995). The driver’s role is to close the control loop and return to a collision-free trajectory.

Time to collision (TTC; also called time to arrival, TTA, in case the target on the road is a stop sign/line rather than another road user, see Hancock & Manser, 1998) is among the proposed parameters that drivers use to perceive the possibility of collision. The well-known tau hypothesis explains how humans perceive TTC (Lee, 1976). Specifically, the tau hypothesis suggests that humans observe TTC using the ratio between the image size of objects they might collide with and the rate the size of this image changes. The tau hypothesis states that TTC is an optical parameter that is perceived directly in the eye's frame of reference. Lee (1976) proposed that drivers can use the temporal derivative of tau (known as tau-dot or $\dot{\tau}$) to determine the sufficiency of the braking deceleration when approaching an object in the path of motion: if $\dot{\tau} > -0.5$, the deceleration is sufficient and the driver stops before colliding with the front object. If $\dot{\tau} < -0.5$, the deceleration is not sufficient and the driver will collide with the front object if the deceleration is kept constant. Maintaining $\dot{\tau} = -0.5$ results in a constant deceleration that brings the vehicle to stop just before touching the object (Bardy & Warren Jr, 1997; Lee, 1976).

Research findings do not draw a conclusive picture regarding the use of tau in the timing of arrival tasks and drivers' control of braking. Although Yilmaz and Warren (1995) showed that participants relied on the $\dot{\tau} = -0.5$ threshold and that their brake adjustments were proportional to the deviation from this threshold, several theoretical and experimental findings do not readily support the validity of the tau hypothesis (e.g., Bardy & Warren Jr, 1997; Rock, Harris, & Yates, 2006). For example, several non-driving studies have found that the tau hypothesis does not accurately predict the timing of interception/avoidance of approaching objects (Caljouw, Van der Kamp, & Savelsbergh, 2004; Tresilian, 1999; Wann, 1996). In general, humans substantially underestimate TTC. The amount of TTC underestimation increases as the actual TTC increases, which raises questions about the usability of TTC in shaping human performance (Caird & Hancock, 1994; Schiff & Detwiler, 1979). The accuracy of TTC estimation depends on several factors, including the closing speed (Kiefer, Flannagan, & Jerome, 2006; McLeod & Ross, 1983; Sidaway, Fairweather, Sekiya, & McNitt-Gray, 1996) and the front object size (Caird & Hancock, 1994; DeLucia, 1991; DeLucia & Warren, 1994). Smeets, Brenner, Trebuchet and Mestre (1996) suggested that humans do not perceive TTC directly, but infer TTC using the perceived relative speed and distance with respect to the front object.

Based on the constant deceleration strategy, Boer, Kuge and Yamamura (2001) proposed that drivers' braking behaviour when stopping behind a stationary target can be described as follows:

$$\Delta u(t) = k_p \left(a^*(t) - a(t) \right) \tag{1}$$

where $\Delta u\ (t)$ is the change in the brake input at the current time (t), k_p is a proportional gain, $a\ (t)$ is the deceleration at the current time, and $a^*\ (t)$ is the desired deceleration at the current time. The desired deceleration is a function of the current speed ($v\ (t)$) and current distance ($d\ (t)$) to the target:

$$a^*(t) = \frac{v^2(t)}{2\,d(t)} \tag{2}$$

1.3. What drivers can do versus what drivers do: a gap in the current knowledge

The tau hypothesis describes how drivers can use the perceived information, but is unclear on how drivers actually behave (Green, 2008). The recent consensus is that the reaction to an impending collision is based on a variety of visual cues that correlate with the tau variable (Hecht & Savelsbergh, 2004). Tresilian (1999) suggested that interceptive or collision-avoidance actions are situation-dependent: through rehearsing the task, humans learn to identify the information that is useful for performing the task, and they filter the information that interferes with satisfactory task performance. In braking, experimental studies have shown that drivers make their braking decisions based on several factors, including the criticality of the event, the size and intensity of the event stimuli, and the global optical flow rate (Andersen, Cisneros, Atchley, & Saidpour, 1999; DeLucia & Tharanathan, 2009; Fajen, 2005a; Liebermann, Ben-David, Schweitzer, Apter, & Parush, 1995; Van der Hulst, Meijman, & Rothengatter, 1999).

In line with this view, the affordance control theory states that the perception of 'action feasibility' and not 'nullifying an error' from a preferred state (such as a constant deceleration) is the dominant mechanism that shapes the drivers' braking response (Fajen, 2005a, 2005b). Thus, instead of a deterministic response, the affordance theory predicts a range of responses that fulfil safety tasks such as collision avoidance. For example, one can imagine a scenario where a car driving at 40 m/s approaches a vehicle that is 100 m away and moving at 20 m/s. The constant deceleration of the following car that avoids collision is 2 m/s^2. However, it is very well possible to brake harder (e.g., 6 m/s^2) and thereby avoid the collision, or to wait until the lead vehicle is 50 meters ahead and subsequently brake with a constant 4 m/s^2 deceleration. All these braking strategies seem reasonable and possible within the affordance space.

1.4. The effect of time to collision/arrival in braking

Braking can occur at different driving speeds and at different amounts of time or distance available to respond. Obviously, a larger deceleration is required when the speed is higher, or when the distance to the target is shorter. The Fitts' speed-accuracy trade-off predicts that the accuracy of a response is inversely proportional to the speed of that response (Fitts, 1954). Fitts' law has been applied to various locomotion tasks including steering on a curved road: the time to successfully complete a course increases with the length of the course and decreases with the road width (Zhai, Accot, & Woltjer, 2004). The results of a previous simulation and empirical study by De Groot, De Winter, Wieringa, and Mulder (2013) confirm that when stopping at an intersection, the braking response is largely determined by the speed and distance at the onset of braking.

1.5. Distance underestimation

Humans are able to visually estimate position and velocity, and to a lesser degree acceleration (Dubrowski & Carnahan, 2002; Gottsdanker, Frick, & Lockard, 1961). However, research in human perception suggests that the perceptual world of humans is different from the physical world (Gilinsky, 1951; Loomis & Philbeck, 2008). Gilinsky's law of visual space perception describes the relation between the physical and the perceived world. Specifically, Gilinsky's empirical model relates the perceived distance (*d*) to the real distance (*D*) via an idiosyncratic parameter (*A*) that captures the maximum limit of the perceived distance, as follows:

$$\frac{d}{D} = \frac{A}{A+D} \tag{3}$$

The model predicts that the limiting values of the perceived distance for a given observer is equal to the visual distance from the observer to the horizon. Thus, parameter *A* represents the maximum limit of the perceived distance.

This relation may have an important implication for driving safety and for our understanding of how drivers use visual information to control distance with brake systems, as it suggests that drivers perceive the world with compressed distances relative to the physical reality. It also states that the greater the distance, the greater the relative underestimation. Gilinsky's model suggests that a drivers' visual system is equipped with a 'safety' mechanism. That is, if drivers underestimate distance headway, they may adopt a more conservative braking behavior.

1.6. The potential of occlusion methods for understanding driver information needs

While driving, visual information is sometimes unavailable, because drivers may be visually distracted or because the visual scene is blocked by conditions such as rain or fog. Former experiments have used the so-called occlusion method to gain insight into how humans perform driving tasks in the absence of continuous visual information (Andersen et al., 1999; Godthelp, 1986; Senders, Kristofferson, Levison, Dietrich, & Ward, 1967; Van der Horst, 2004; Van Leeuwen, Happee, & De Winter, 2014). For example, using a shutter by means of which participants could request looking periods when they wished to, Senders et al. (1967) showed that as the speed of the car and the density of the surrounding traffic increase, the attentional demand of driving increases as well. Van der Horst (1990) used stroboscopic occlusion to suppress optic flow information and showed that with the occlusion, the minimum TTC of the participants during braking-to-full-stop manoeuvers was larger and more variable than in the control condition without occlusion.

Godthelp (1984) studied the extent to which the steering control task can be performed without visual information. The results showed that drivers are able to keep their car on the road even when they intermittently sample the road. Godthelp, Milgram and Blaauw (1984) also introduced the concept of time to line crossing (TLC), which represents the available time that drivers can neglect the steering task until the vehicle passes the boundaries of the road. The shorter the TLC, the more urgent is the need for applying a steering correction. Recently, Van Leeuwen et al. (2014) investigated the effect of restricting the visual information of different parts of the driving scene (near view vs. far view) on drivers' steering behavior. They found that lack of preview resulted in abrupt and coarse steering corrections, reduced steering precision, and an increased number of road departures.

While former attempts to quantify the visual demand of driving tasks such as steering (Godthelp, 1986) and cruising at a constant speed on highways (Senders et al., 1967) have been made, the visual demand of braking has not yet been determined. This study aimed to investigate to which extent the absence of visual information during the course of braking affects drivers' braking behavior. Is braking a tacit pre-programmed strategy that drivers learn and execute with minimum dependency on visual information during its execution, or do drivers depend on the visual information to brake properly?

1.7. The present study

The current driving simulator study investigated how well drivers can stop at a stationary target as a function of the presence versus absence of visual information during the course of their braking. Participants were asked to execute a series of braking maneuvers requiring a stop at a predefined spot on the road. In the occlusion condition, the screens blanked when a certain TTA was reached, while in the control condition, the simulator provided an auditory signal when the TTA was reached.

Our hypothesis was that the lack of visual information affects the braking pattern of drivers, and that the size of the effect depends on the time available to brake. Specifically, it was expected that participants brake sooner and harder when the brake scene is occluded than when it is not occluded, as participants have to rely on an underestimated perceived distance at the start of the braking trial. Moreover, these effects were expected to be stronger for larger TTA values, because according to Gilinsky (1951) the distance underestimation is greater when the distance to the target is larger.

We also examined the effects of a variable versus fixed brake onset on participants' braking behavior. Specifically, one group of participants was allowed to start to brake at any moment after the TTA was reached, while a second group of participants was instructed to brake immediately after the TTA was reached. Hence, the results of the former group provide a relatively naturalistic investigation of how drivers behave, while the second group provides a more controlled setting, in which the effect of TTA on braking behavior itself is determined.

2. Method

2.1. Driving simulator

The experiment was carried out in a fixed-based NADS Minisim driving simulator. The simulator provided a 130-degree horizontal by a 24-degree vertical field of view at 48-inch viewing distance The simulator mimicked the sound of the passenger car using two speakers at the front. The roadway vibration was simulated using a bass speaker located below the driver's seat. The brake and gas pedals, the steering wheel, the automatic gearshift, and the seat resembled those of an actual vehicle. The simulator measured both driver inputs and telematics data at a rate of 60 Hz (see Chapter 2 for a more detailed description and a photo of the simulator).

2.2. Participants

For this experiment, 24 participants (19 men and 5 women) with a valid Ontario Class G driving license were recruited from the University of Toronto community. All the participants provided written informed consent (Appendix B.1) and were compensated with a payment of 20 Canadian Dollars. Participants' demographics and frequency of driving, cycling, and playing video games were collected using an intake questionnaire (Appendix A.2). On average, the participants were 27.0 year old (*SD* = 6.0 years) and had obtained their driving license in 2005 (*SD* = 5.1 years; the experiment was conducted in February 2014). Four participants had used a driving simulator in the past. The majority of the participants (20 out of 24) drove more than 10 km per week, and 21 participants drove more than 1000 km per year (Table 1). One participant drove less than 100 km on an annual basis. During the experiment, the participants drove in cruise control mode before executing the braking tasks. Thirteen participants reported they used cruise control at least once or twice a year (Table 2).

Table 1. Distribution of the participants based on per-week (D1, in km) and per-year (D2, in 1000s of km) driven distance.

$D1 < 10$	$10 \leq D1 < 100$	$100 \leq D1 < 1000$	$D1 \geq 1000$	
4	13	7	0	
$D2 < 0.1$	$0.1 \leq D2 < 1$	$1 \leq D2 < 10$	$10 \leq D2 < 100$	$D2 \geq 100$
1	2	13	5	3

Table 2. Frequency of driving, using cruise control, playing video games, and cycling among the participants.

	Drives a car	Uses cruise control	Plays video games	Rides a bicycle
Less than 1-2 times per year	0	11	5	8
At least 1-2 times per year but less than once per month	4	7	5	8
At least once per month but less than once per week	3	4	6	4
At least once per week but less than once per day	12	2	7	3
At least once per day	5	0	1	1
Total	**24**	**24**	**24**	**24**

2.3. Experimental setup and test conditions

2.3.1. Participant instructions and driving task information

The experiment consisted of questionnaires, reaction time tests, and driving tests using the simulator (see Figure 1 for an overview of the stages of the experiment).

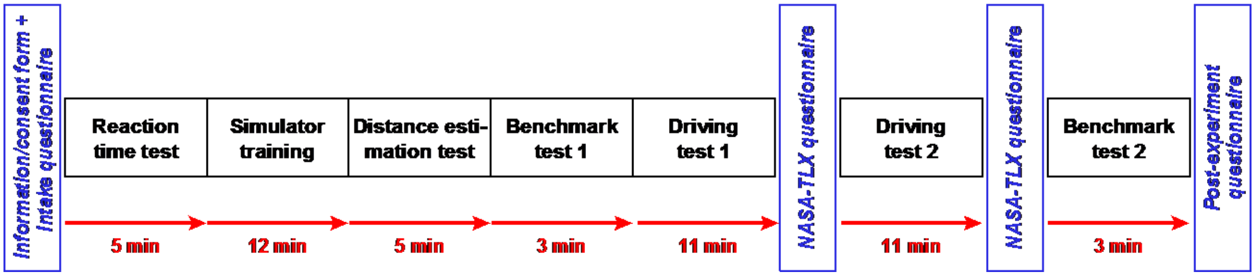

Figure 1. Timeline of the stages of the experiment. The dashed boxes indicate the stages at which the questionnaires were completed. The time below each horizontal arrow indicates the duration of each task, excluding breaks.

Upon arrival, participants read and signed the consent form, which informed them about the simulator controls and provided an overview of the experimental stages and tasks. After signing the consent form and confirming their interest to continue, participants filled out a questionnaire that gathered information about their demographics and driving history. Participants were free to take a break between the individual stages of the experiment.

2.3.2. Reaction time test

The reaction times of the participants were measured using two separate visual and auditory tests (Cognitive Fun!, 2014). The tests were performed using a NX 50 Logitech mouse and a 1286 CTO Lenovo laptop computer stationed at a separate desk outside the driving simulator laboratory. The volume level of the laptop was set at 40 (arbitrary units of the laptop computer). The resolution of the screen was 1366 × 768 pixels. Each test consisted of 10 trials, of which the first 5 were considered as warm-up and discarded from the analyses. In the visual reaction time test, the participants had to click a mouse button as soon as a green balloon appeared. The balloon was always the same size and appeared at the same location. In the auditory reaction time test, the participants had to click a mouse button as soon as they heard a beep.

2.3.3. Simulator training

A training session was used to familiarize the participants with the simulator controls. An analysis of steering-wheel reversal and lane-position data showed that the time required to adapt the steering response is less than 5 minutes (McGehee, Lee, Rizzo, Dawson, & Bateman, 2004). Based on measuring squared correlation coefficient of the speed versus distance, Jamson and Smith (2003) suggested that after five to six attempts, drivers in a simulator can perform a full stop braking task in a manner similar to that observed in real vehicles. Their recommendation was based on fitting a polynomial model to speed versus distance profiles, and determining the similarities between those profiles in reality and in a driving simulator. With these findings in mind, the training session was designed to provide sufficient exposure to the main control of the simulator. The road of the training session consisted of a left bend, followed by a right bend and a straight road. The length and average radius of the first bend were about 2500 m and 3600 m, respectively. The length and average radius of the second bend were about 1500 m and 2700 m, respectively. The length of the straight road was about 5300 m. On the straight road, participants completed eight braking trials that were identical to the trials of the main driving tests. There was one trial for each of the four TTA values, and for both the control and occlusion conditions (see Section 2.3.5 for further details on the test conditions). As pressing the brake pedal switched off the cruise control system, the participants were instructed how to reactivate this system after braking.

2.3.4. Distance estimation test

The distance estimation test was conducted to measure the distance perception of the participants in the simulator environment. As the participant was seated in a stand-still vehicle, a stationary car appeared at a fixed distance in front of the participant's vehicle (Figure 2) and remained visible for 7 seconds. The participants had to verbally report the estimated distance between their seat and the rear bumper of the lead car after the stationary car disappeared. The car reappeared at another pre-set distance 8 seconds after it disappeared. Each distance estimation test consisted of two series of distance estimation trials with an identical set of 10 pre-set distances presented in different orders. The ten presented distances were 5, 10, 15, 20, 30, 40, 60, 80, 120, and 160 meters in no discernible order (see Appendix B.3 for the screenshots of these distances). The range of the presented distances is about three times larger than the range of the distances reported in Gilinsky's (1951) seminal experiment, considering the large inter-object distances that can occur in driving. Participants were free to estimate the distances in either feet or meters, depending on their level of comfort with metric or imperial system. Only one participant opted to estimate the distances in feet.

Figure 2. Screenshot of the distance estimation test, the distance represented in this picture is 20 m.

2.3.5. Driving tests and participant groups

Two driving tests were used to measure the participant's braking response in the presence or absence of the visual information. The first test condition, named 'occlusion', consisted of a series of braking trials where participants had to start braking after the driving scene was occluded. During an occlusion, the entire front screen was automatically blacked out for 10 seconds. The second test condition, named 'control', involved braking with normal vision. In the braking trials of this test, participants started braking after they heard a beep. The beep had a frequency of 587 Hz and was 0.42 s long.

Participants were divided into two groups, either responding 'at' or 'sometime after' the braking signal. The first 12 participants were instructed to start braking immediately after the beep or occlusion was triggered. The second 12 participants were instructed to start braking at any time after the trigger of the occlusion or beep sound. Both groups were instructed in writing. Furthermore, before the start of each test, participants were orally informed whether the test they would be confronted with was the occlusion or the control condition.

In all braking trials, the participants' task was to (1) stop the vehicle by braking at a certain position on the road indicated by a white circular patch with a drum at either side of the road (Figure 3), and (2) maintain the vehicle in the center of the road. Participants could drive on top of the white circle unimpeded. There were no other vehicles on the road and there were no collisions during any of the experimental sessions. In both driving tests, participants completed a straight road stretch of 9000 m. The width of the lane in all the experiments was 3.66 m.

Figure 3. View of the stopping target of the braking trials in the main driving tests.

The sequence of the control and occlusion conditions were counterbalanced among the participants. Half of the participants were randomly selected to drive the control condition as their first driving test. For the other half, the first driving test was the occlusion condition. Cruise control set at 27 m/s (60 mph) was active during all driving tests, except between the moment a participant started braking and the moment that s/he finished braking. The cruise control system automatically disengaged when the participants pressed the brake pedal. Participants had to engage the cruise control to automatically drive away from the completed stop.

The dashboard was visible throughout the experiment, even in the occlusion condition. However, speed maintenance before the start of the brake was not part of the task, and participants were instructed to not look at the speedometer. Participants were also instructed to avoid pumping their brakes. That is, the participants were told to brake in one controlled stop, instead of braking suddenly and subsequently coasting towards the target. The thesis author instructed and observed the participants' compliance in following the instructions.

In both the occlusion and control tests, the time available for braking was manipulated. Specifically, the braking trials were triggered (i.e., by a beep or occlusion onset) at four different TTA intervals of 2, 4, 6, and 8 s before the stopping target. At a constant cruising speed of 27 m/s, these TTA values corresponded to distances to the target of 54, 107, 161, and 215 m, respectively. The TTA was calculated from the center of the vehicle (i.e., the center of the rectangle that bounds the vehicle) to the center of the circular patch that indicated the stopping target. The two driving tests included four trials per each TTA value. Hence, each of the occlusion and control tests included 16 brake trials where the participants brought their vehicle to a full stop. The range of travelled distance between two subsequent stopping targets on the road was between 415 and 659 m. The sequence of the trials within each test had a fixed random order. Thus, the sequences of the trials were not recognizable for the participants. The sequence was also different under the control and occlusion conditions.

2.3.6. Benchmark tests

A benchmarking test was conducted before and after the main driving tests (Figure 1). The participants had to stop their vehicle four times at a target position on the road while approaching the target at 27 m/s speed. In contrast to the driving tests, the participants received no stimulus for timing their braking response. That is, there was no occlusion or beep sound in the benchmark trials and the participants were free to start braking at any moment to stop their vehicle at the target. The benchmark tests were conducted to measure the extent to which the participants' braking responses changed due to a learning effect in the simulator. The benchmark tests took place on a straight road and involved 2000 m of driving.

2.3.7. Self-report questionnaires

After the occlusion and control tests, participants were asked to step out of the simulator for a short break and to complete a six-item NASA Task Load Index (TLX) questionnaire (Hart, 2006). The questionnaire included four items that asked about feelings of risk and self-confidence. The extra items were: (1) 'I had a feeling of risk during driving', 'I think I drove more safely than the average participant in this experimental condition', 'This car-following task was easy', 'I felt confident in my own capability to act appropriately'. The questionnaire used a 21-tick scale, and ranged from *very low to very high*, except for the performance item of the TLX, which ranged from *perfect to failure*. Participants had to put a cross on a tick for each of the questionnaire items.

At the end of the experiment, participants filled out a questionnaire about their use of any specific strategy while performing the braking task during the benchmark tests and the control and occlusion conditions.

2.4. Dependent variables

For the driving tests, the following variables were used to quantify the braking response pattern of the participants in different conditions. First, for each participant, the mean of each variable was calculated over four trials under each experimental condition (i.e., the different TTA values, and the control and occlusion conditions). Trials in which a participant pressed the brakes before the beep/occlusion moment were excluded from all analyses. Next, the mean of these means was calculated across the participants.

2.4.1. Braking performance and behaviour

Brake response time (T_{rt}; *s*): The time between the start of an occlusion or beep sound and the initial brake of the participant. T_{rt} is a measure of reaction time to the brake trigger events of this experiment (Green, 2013; Young & Stanton, 2007).

Maximum brake pedal displacement (p_{max}; %): The maximum degree of the brake pedal depression expressed as a percentage. The simulator measured the brake pedal position using a potentiometer. 0% corresponded to a fully released pedal, and 100% corresponded to a fully depressed pedal. It was determined with a ruler and a load cell that 100% pedal depression corresponded to a pedal travel of 5 cm and a pedal force of about 150 N. The brake pedal force was approximately linear in the 0–100% working range. It should be noted that 100% pedal depression was not the physical maximum pedal depression; it was possible to press the brake pedal somewhat more deeply (about 1 cm) into the rubbers that the fully depressed brake pedal rests on, by applying high forces on the brake pedal.

Maximum brake pedal displacement time (t_{max}; s): The time between the start of the occlusion or beep sound and the moment that the maximum brake displacement occurs. t_{max} is an indicator of the participant's performance in timing the magnitude of the brake pedal input. Small values indicate that the participant depressed the brake pedal to its maximum level immediately after the stimulus onset.

Maximum deceleration (d_{max}; m/s^2): The maximum deceleration of the vehicle.

Distance gap (D; m): The distance gap is the difference between the stopping position of the vehicle and the position of the circular target on the road. The distance gap is an indicator of the participant's performance in stopping at the pre-determined position (cf. De Groot et al., 2013; Jamson & Smith, 2003). A negative value means that the participant stopped before the target (i.e., stopped too early), while a positive value means that the participant passed the target (i.e., stopped too late).

2.4.2. Non-driving perception and reaction time performance

Distance estimation error (E; %): The distance estimation error, calculated from the measures of the distance estimation test, is the ratio of the difference between the reported (d) and the true distance (D) over the true distance between the driver's seat and the rear bumper of the lead vehicle. Negative errors represent an underestimation of distance and positive errors represent an overestimation of distance.

$$E = 100\% \frac{d - D}{D} \tag{4}$$

Auditory and visual reaction time (RTa, RTv; s): *RTa* and *RTv* represent the mean reaction time of the participants to the standard auditory and visual stimuli, respectively. These variables were used to find whether there were any *a priori* differences between the reaction times of the participant groups.

2.5. Statistical analyses

To evaluate the effect of time to arrival, a paired *t* test was conducted between the means for the maximum TTA of 8 s versus the means for the minimum TTA of 2 s (*df* = 23). To evaluate the effect of visual information, a paired *t* test was conducted using the means for the control versus occlusion condition (*df* = 23). Interaction effects between TTA and occlusion were determined by conducting paired *t* tests between the control and occlusion conditions for each TTA separately. The between-subjects factor was the participant's group: participants in the first Group (G_{any}, $n = 12$) were told to start braking any time after the braking event triggered, and participants in the second Group (G_{at}, $n = 12$) were asked to start braking immediately at the event trigger. G_{any} and G_{at} were compared using an independent-samples *t* test (*df* = 22). Considering this to be a large number of statistical tests, a conservative false positive rate (alpha) of 0.01 was adopted, instead of the more traditional 0.05.

3. Results

Observations during the experiments and initial probing of the collected data revealed that in a few trials, participants started braking before the occlusion or presentation of the beep. Specifically, for the control condition, 19 of 384 trials were excluded (10 trials for TTA = 2 s, 8 trials for TTA = 4 s, and 1 trial for TTA = 6 s) and for the occlusion condition, 12 of 384 trials were excluded (9 trials for TTA = 2 s, 2 trials for TTA = 4 s, and 1 trial for TTA = 6 s). These early brake trials were excluded from the remaining analyses.

3.1. Reaction time and distance estimation

Descriptive statistics of reaction time and distance error estimates are reported in Table 3. Results of independent *t* tests revealed no statistically significant differences between the G_{any} and G_{at} participants.

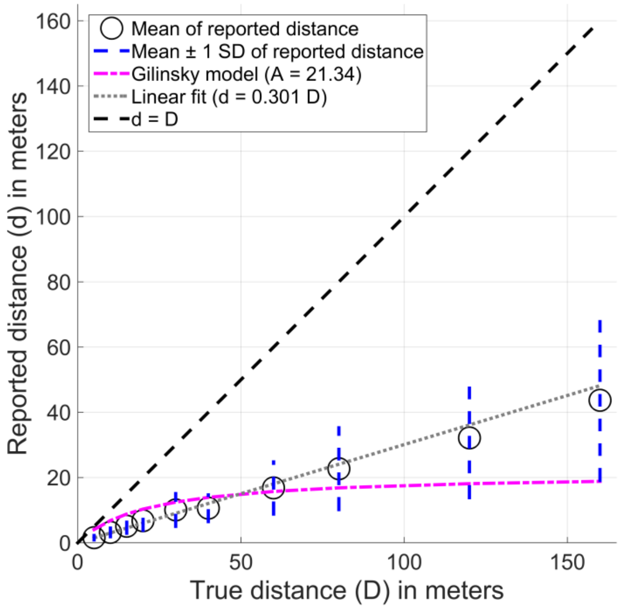

Figure 4. Means and means ± 1 standard deviation (SD) of the reported distance to the rear bumper of the front vehicle, as a function of the true distance to the rear bumper of the front vehicle. Also shown are a linear fit and Gilinsky's model using the calculated A-value (averaged across the 10 true distances). It can be seen that the participants underestimated the true distance by about 70%.

Table 3. Mean (standard deviation) of auditory reaction time (*RTa*), visual reaction time (*RTv*), and distance perception error (*E*) of participants (*N* = 12 per group).

	***RTa* (ms)**	***RTv* (ms)**	***E* (%)**
Mean G_{any} (*SD*)	214 (39)	308 (46)	-68 (12)
Mean G_{at} (*SD*)	212 (24)	301 (28)	-72 (12)
$t(df = 22)$ G_{any} vs. G_{at}	0.154	0.471	0.961
p-value G_{any}vs. G_{at}	0.879	0.643	0.347

Participants, on average, reported a distance that was consistently about 30% of the true distance (Figure 4). Accordingly, a linear fit provided a better fit than the curvilinear Gilinsky's model (Figure 4).

3.2. Braking performance and behavior

Figure 5 shows that the response time of the participants became longer as the TTA of the braking event increased ($p < 0.001$, $t = 6.509$ for TTA = 8 s vs. TTA = 2 s). In other words, participants delayed their initial response when there was more time available to bring the car to a standstill. The brake reaction time was not significantly different between the occlusion condition and the control condition ($p = 0.018$, $t = 2.535$). Figure 6 shows the standard deviations of the brake reaction time among participants. Overall, G_{at} participants had a more consistent reaction time than G_{any} participants did, which can be explained by the task instructions for G_{at} stating that participants should brake directly after the event trigger.

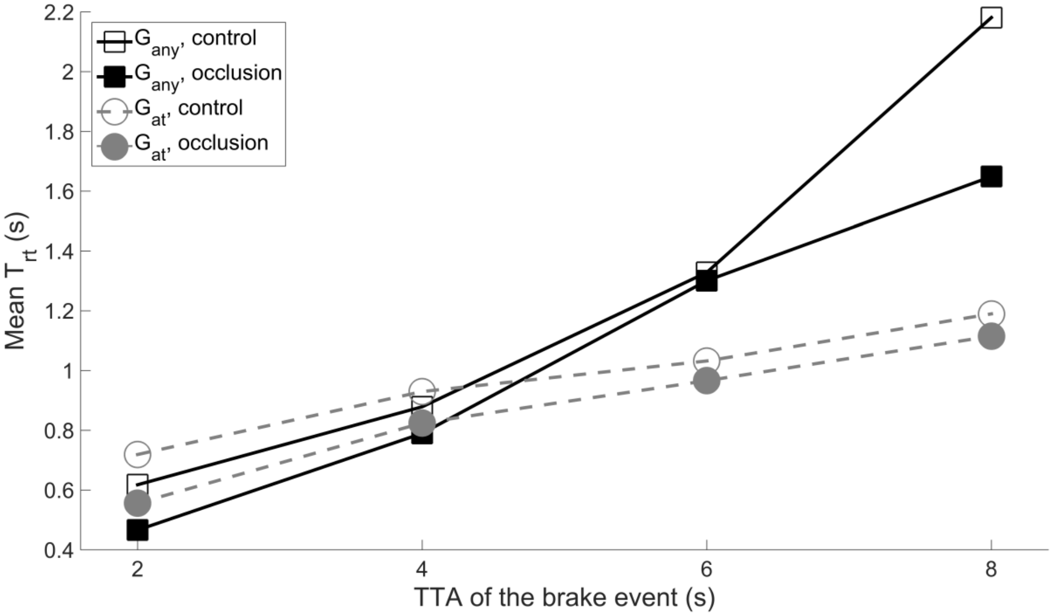

Figure 5. Mean brake response time as a function of the time to arrival (TTA), occlusion, and experimental group (Gany = braking at any time after the occlusion/beep; Gat = braking immediately at the occlusion/beep).

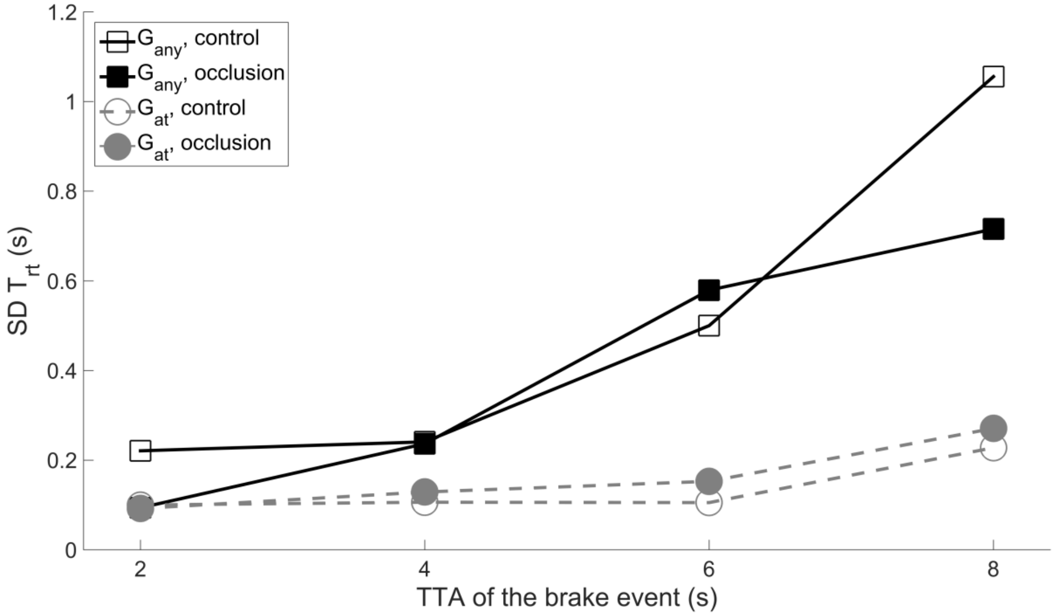

Figure 6. Standard deviation (*SD*) among participants (*N* = 12 per condition) of the mean brake response time, as a function of the time to arrival (TTA), occlusion, and experimental group (G_{any} = braking at any time after the occlusion/beep; G_{at} = braking immediately after the occlusion/beep). The standard deviation is a measure of inter-individual differences.

The results in Figure 5 further show that there is a group-TTA interaction effect regarding the brake response time (TTA = 2 s: $t = -1.943$, $p = 0.065$; TTA = 4 s: $t = -0.625$, $p = 0.539$; TTA = 6 s: $t = 2.413$, $p = 0.025$; TTA = 8 s: $t = 3.306$, $p = 0.003$), indicating that the G_{any} group delayed their initial braking response in those cases where there was more time available (i.e., a higher TTA).

The results of the maximum brake pedal displacement (Figure 7) show that participants pressed the brake less deeply when TTA was higher ($p < 0.001$, $t = -12.811$). The maximum brake displacement was larger in the control condition as compared to the occlusion condition ($p = 0.001$, $t = 3.756$). Furthermore, there was an interaction effect (TTA = 2 s: $t = 4.813$, $p < 0.001$; TTA = 4 s: $t = 2.918$, $p = 0.008$; TTA = 6 s: $t = 1.804$, $p = 0.084$; TTA = 8 s: $t = 0.818$, $p = 0.422$), indicating that for braking trials with a short TTA, participants pressed the pedal further during the control condition than they did in the occlusion condition. As could be expected, the maximum deceleration of the vehicle reveals an almost identical pattern as the maximum pedal displacement (Figure 8).

Figure 9 shows that as the TTA of the brake event increased, the maximum brake displacement occurred later during the braking trial ($p < 0.001$, $t = 13.651$). There were no statistically significant effects for the control versus occlusion conditions ($p = 0.923$, $t = -0.098$) and for G_{any} versus G_{at} ($p = 0.641$, $t = -0.473$). However, there was an interaction effect (TTA = 2 s: $t = -4.791$, $p < 0.001$; TTA = 4 s: $t = -2.633$, $p = 0.015$; TTA = 6 s: $t = 0.598$, $p = 0.555$; TTA = 8 s: $t = 3.274$, $p = 0.003$). That is, for the control condition, the time of the maximum brake pedal displacement was earlier for the shortest TTA and later for the longest TTA in comparison to the occlusion condition (see also Figure 9).

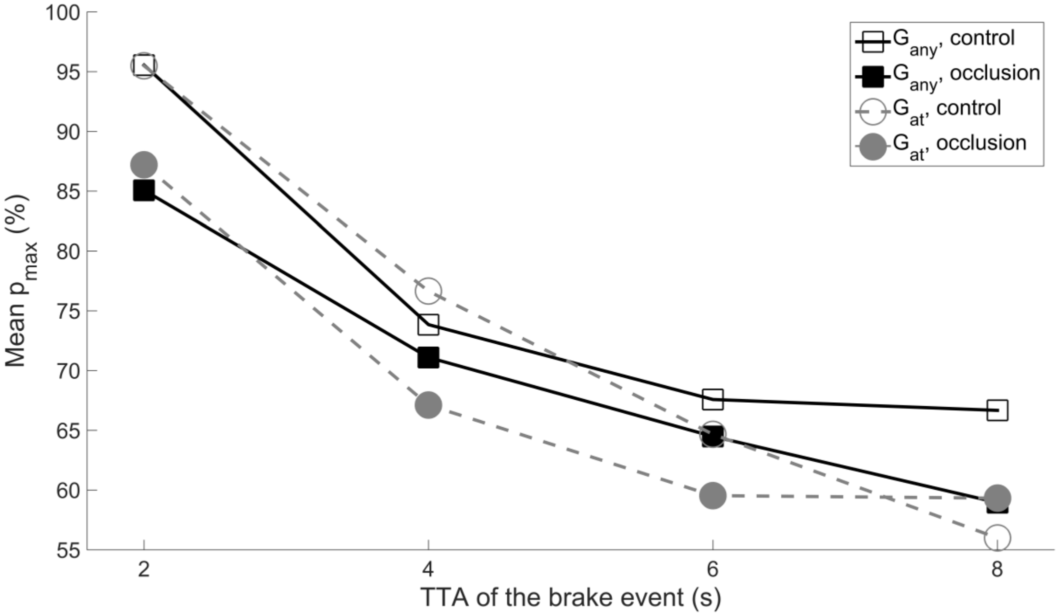

Figure 7. Mean maximum brake pedal displacement as a function of the time to arrival (TTA), occlusion, and experimental group (Gany = braking at any time after the occlusion/beep; Gat = braking immediately after the occlusion/beep).

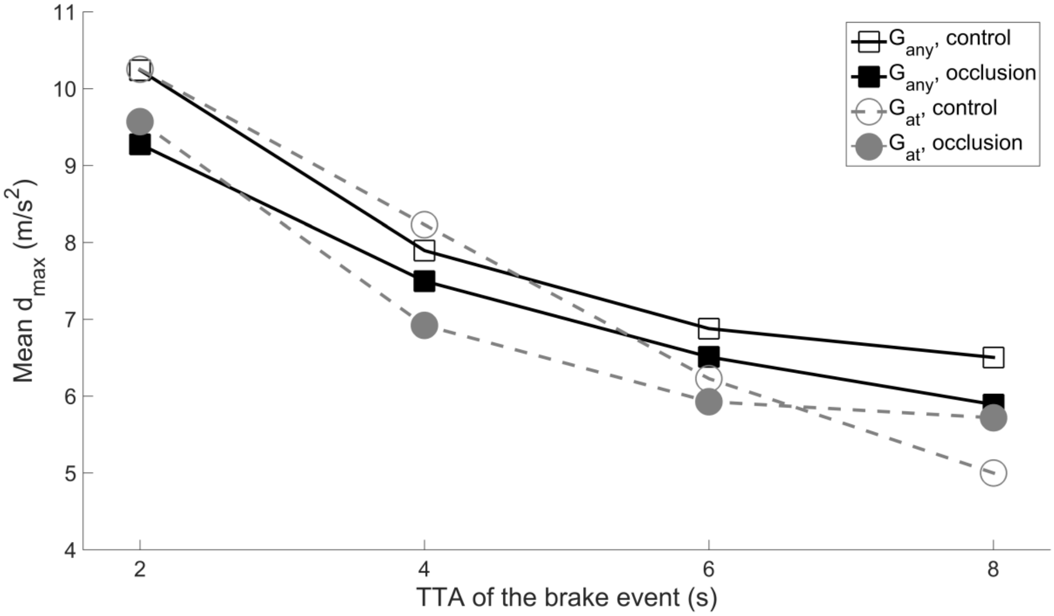

Figure 8. Mean maximum deceleration as a function of the time to arrival (TTA), occlusion, and experimental group (G_{any} = braking at any time after the occlusion/beep; G_{at} = braking immediately after the occlusion/beep).

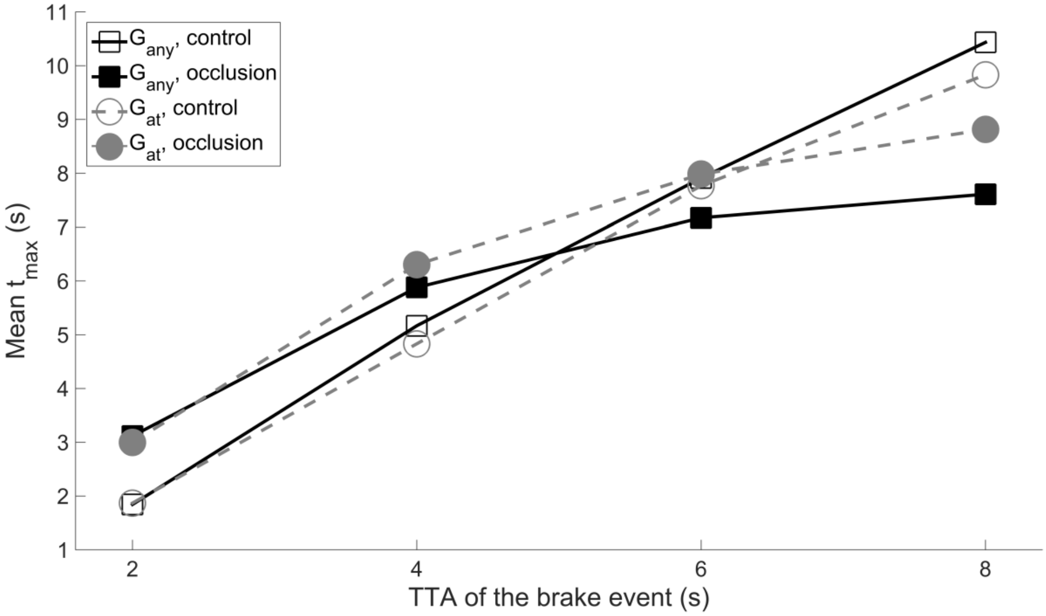

Figure 9. Mean maximum brake force time as a function of the time to arrival (TTA), occlusion, and experimental group (G_{any} = braking at any time after the occlusion/beep; G_{at} = braking immediately after the occlusion/beep).

As a supplementary analysis, the brake pedal displacement was divided into five equal ranges and subsequently the relative durations of the brake pedal depression were calculated within each of the ranges (Figure 10). As expected, it was found that the shorter the TTA, the greater the proportion of large brake pedal depression (> 80%). Furthermore, the control versus occlusion condition showed statistically significant effects for all depression ranges, except for the largest range (see Table 4). Table 4 also shows that there was a clear interaction effect. At the shortest TTA (TTA = 2 s), participants were more likely to use a large brake pedal depression (> 80%) in the control condition as compared to the occlusion condition. For the brake trials with the longest TTA (TTA = 8 s), the relative duration of < 40% braking was longer during the control condition than during the occlusion condition. This trend was reversed for the 40–60% range. In summary, in the occlusion condition participants were likely to apply intermediate brake pedal displacements, whereas in the control condition participants were more likely to operate the brakes in the extreme ranges.

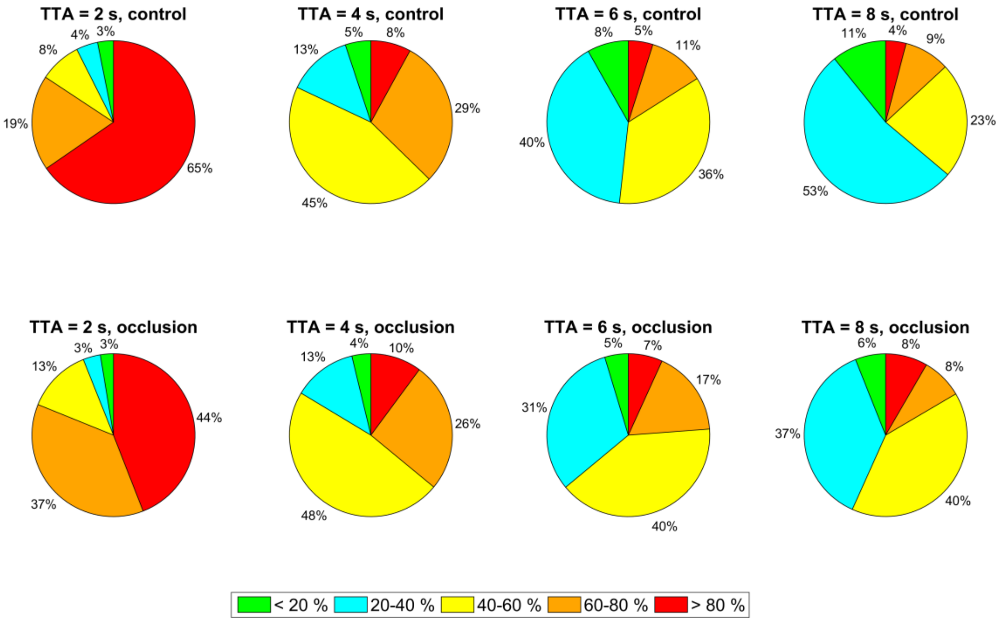

Figure 10. Time percentages of brake pedal displacement ranges as a function of the time to arrival (TTA) and occlusion. As the results for the two experimental groups were similar, the results were averaged across G_{any} (braking at any time after the occlusion/beep) and G_{at} (braking immediately after the occlusion/beep).

Table 4. *p*-values and *t*-statistics of main and interaction effects for the time percentages per brake pedal displacement range.

	TTA 8 s vs. 2 s	**Control vs. Occlusion**	**G_{any} vs. G_{at}**	**Control vs. Occlusion per TTA**			
pedal depression range				**TTA = 2 s**	**TTA = 4 s**	**TTA = 6 s**	**TTA = 8 s**
$T_{<20}$ (%)	**$p < 0.001$** $t = 5.245$	**$p = 0.001$** $t = 3.809$	$p = 0.079$ $t = 1.840$	$p = 0.057$ $t = 2.006$	$p = 0.183$ $t = 1.372$	$p = 0.011$ $t = 2.785$	**$p = 0.001$** $t = 3.736$
$T_{20\text{-}40}$ (%)	**$p < 0.001$** $t = 9.166$	**$p = 0.002$** $t = 3.544$	**$p = 0.004$** $t = -3.242$	$p = 0.210$ $t = 1.290$	$p = 0.884$ $t = 0.147$	$p = 0.018$ $t = 2.544$	**$p = 0.002$** $t = 3.489$
$T_{40\text{-}60}$ (%)	**$p < 0.001$** $t = 5.626$	**$p = 0.005$** $t = -3.111$	$p = 0.084$ $t = 1.810$	$p = 0.123$ $t = -1.599$	$p = 0.664$ $t = -0.440$	$p = 0.216$ $t = -1.271$	**$p = 0.001$** $t = -4.039$
$T_{60\text{-}80}$ (%)	**$p < 0.001$** $t = -4.296$	**$p = 0.008$** $t = -2.895$	$p = 0.195$ $t = 1.336$	$p = 0.011$ $t = -2.753$	$p = 0.693$ $t = 0.400$	$p = 0.053$ $t = -2.043$	$p = 0.730$ $t = 0.349$
$T_{>80}$ (%)	**$p < 0.001$** $t = -10.111$	$p = 0.287$ $t = 1.090$	$p = 0.571$ $t = -0.575$	**$p = 0.002$** $t = 3.252$	$p = 0.714$ $t = -0.371$	$p = 0.371$ $t = -0.912$	$p = 0.306$ $t = -1.047$

Note. The table shows the time to arrival (TTA) effect (TTA = 8 s vs. TTA = 2 s), visual effect (control vs. occlusion condition), and group effect (G_{any} who were braking at any time after the occlusion/beep vs. G_{at} who were braking immediately at the occlusion/beep). The table also shows the control versus occlusion effect for each TTA value separately. $p < 0.01$ is indicated in bold.

Figure 11 shows the results of the distance gap between the stopping position and the circular target. Both TTA 8 s vs. 2 s ($p < 0.001$, $t = -10.620$) and control versus occlusion ($p < 0.001$, $t = 4.925$) showed statistically significant results. The results in Figure 13 indicate that at the end of braking, all groups on average missed the target for the shortest TTA. There was an interaction effect as well (TTA = 2 s: $t = 0.673$, $p = 0.508$; TTA = 4 s: $t = -0.509$, $p = 0.616$; TTA = 6 s: $t = 3.054$, $p = 0.006$; TTA = 8 s: $t = 6.952$, $p < 0.001$). That is, for the occlusion condition, the distance gap shifts from stopping too late to stopping too early, as TTA increases. For the non-occluded condition, participants were able to accurately stop at the target.

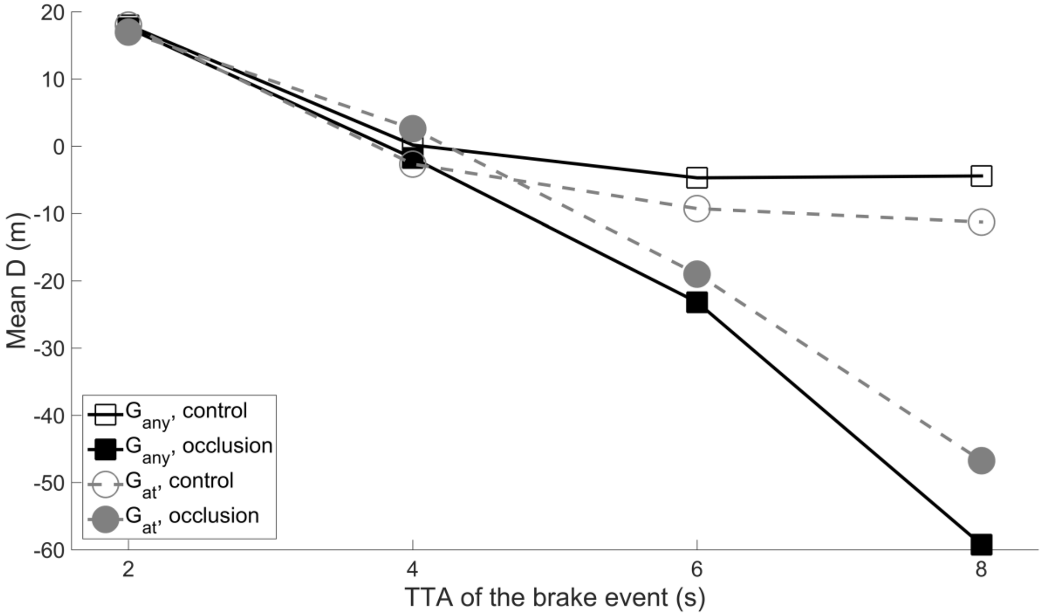

Figure 11. Mean distance gap as a function of the time to arrival (TTA), occlusion, and experimental group (G_{any} = braking at any time after the occlusion/beep; G_{at} = braking immediately after the occlusion/beep). A negative value means that the participant stopped too early, while a positive value means that the participant passed the target and stopped too late.

Figure 12 shows that intra-individual differences in the distance gap are larger for the occlusion condition than for the control condition. The standard deviation is calculated for each participant and so represents a measure of consistency of the person with respect to him/herself. For TTA = 8 s, the mean number of trials in which participants stopped on-target (i.e., defined herein as stopping within 12 m from the center of the white circle) was 45% in the control condition, compared to 3% in the occlusion condition.

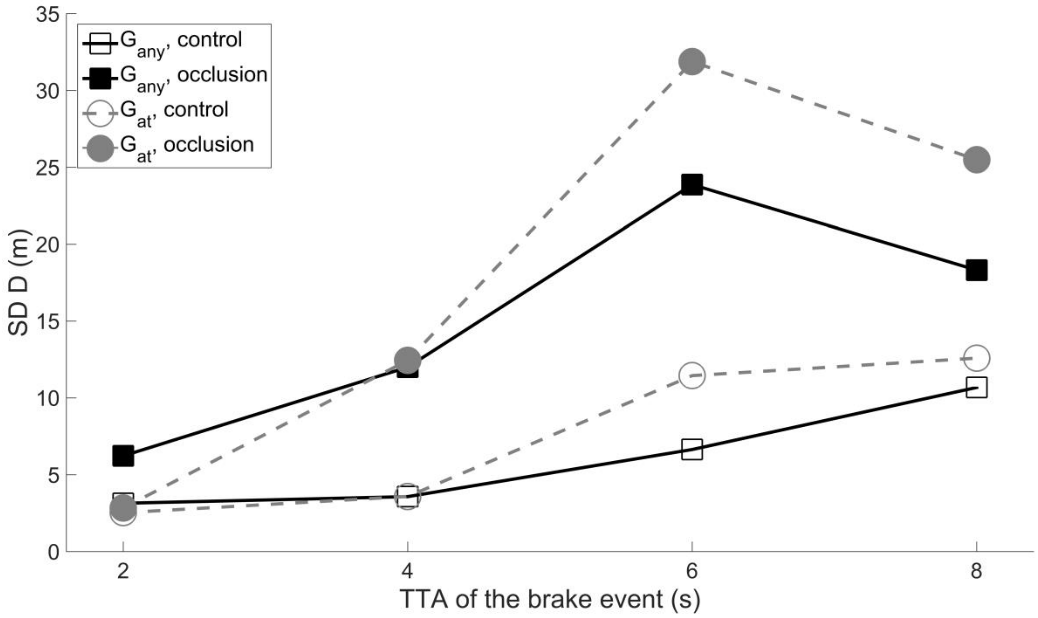

Figure 12. Standard deviation (*SD*) of the distance gap as a function of the time to arrival (TTA), occlusion, and experimental group (G_{any} = braking at any time after the occlusion/beep; G_{at} = braking immediately after the occlusion/beep). The *SD* was calculated across the four trials per experimental condition and per participant, and subsequently averaged across the 12 participants in the experimental condition. Hence, the *SD* is a measure of within-subject consistency across the four trials.

3.3. Time series analysis of braking performance

As an illustration of the above findings, this section reports the temporal pattern of the braking maneuver (i.e., pedal position, vehicle acceleration, and distance gap to the on-road target). The time-locked average of the response across the 12 participants per group was calculated (i.e., across 48 trials per each combination of TTA and occlusion/control condition). Because participants finished braking at different points in time, there were fewer data points to be averaged near the end of each time series. To minimize the effect of this noise in the pattern, the average was calculated up to the moment that all of the participants pressed the brake pedal in at least one of their four trials.

The average braking response when faced with a stopping task with short TTA of 2 s is pulse-shaped with high amplitude. As TTA of the braking event increases, participants responded with a longer and less hard brake depression, resulting in a longer deceleration profile and lower levels of average deceleration (Figures 13 and 14). For TTA = 2 s, participants on average braked less hard in the occlusion condition as compared to the control condition (Figure 13).

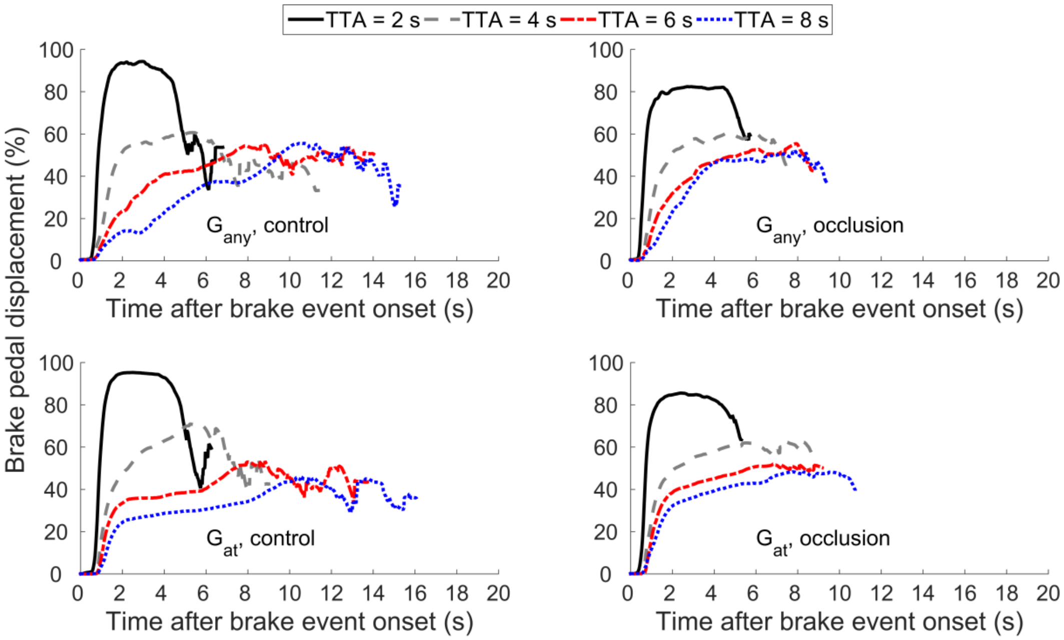

Figure 13. The average brake pedal displacement of participants during braking trials, as a function of time to arrival (TTA), participant group (G_{any} vs. G_{at}), and control and occlusion conditions. G_{any} = braking at any time after the occlusion/beep; G_{at} = braking immediately after the occlusion/beep.

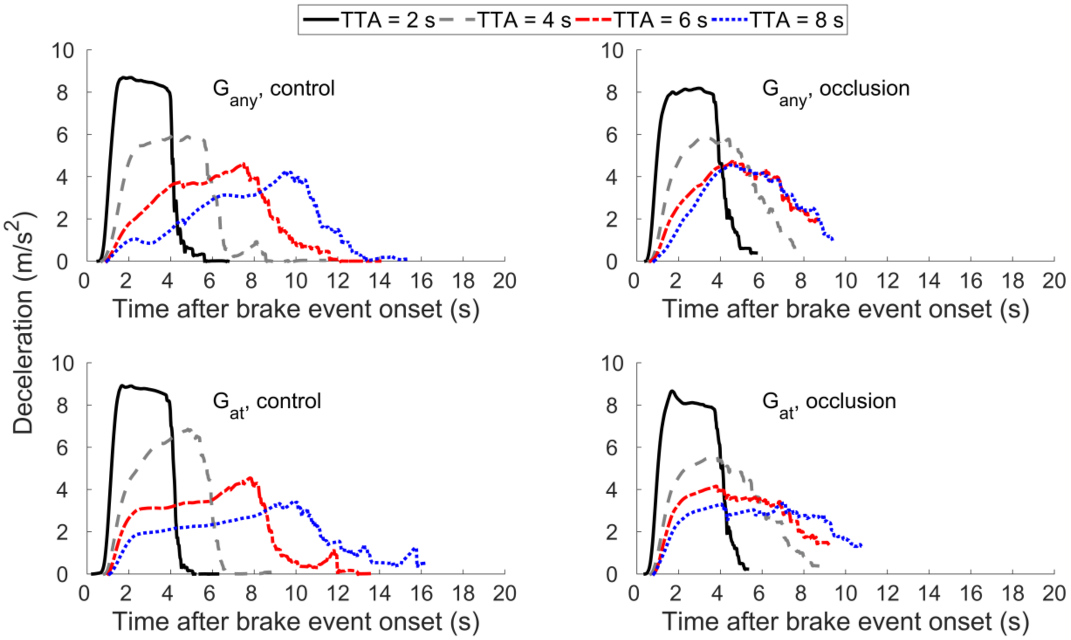

Figure 14. The average deceleration of participants during braking trials, as a function of time to arrival (TTA), participant group (G_{any} vs. G_{at}), and control and occlusion conditions. G_{any} = braking at any time after the occlusion/beep; G_{at} = braking immediately after the occlusion/beep.

Figure 15 shows the average distance gap of the participants during their brake response. When there was occlusion and the TTA was 2 s, participants, on average, stopped slightly after the target. However, when the scene was occluded, the average distance gap showed an offset proportional to the distance gap at the start of the event onset. The time series were highly similar between the two groups of participants (G_{any} vs. G_{at}).

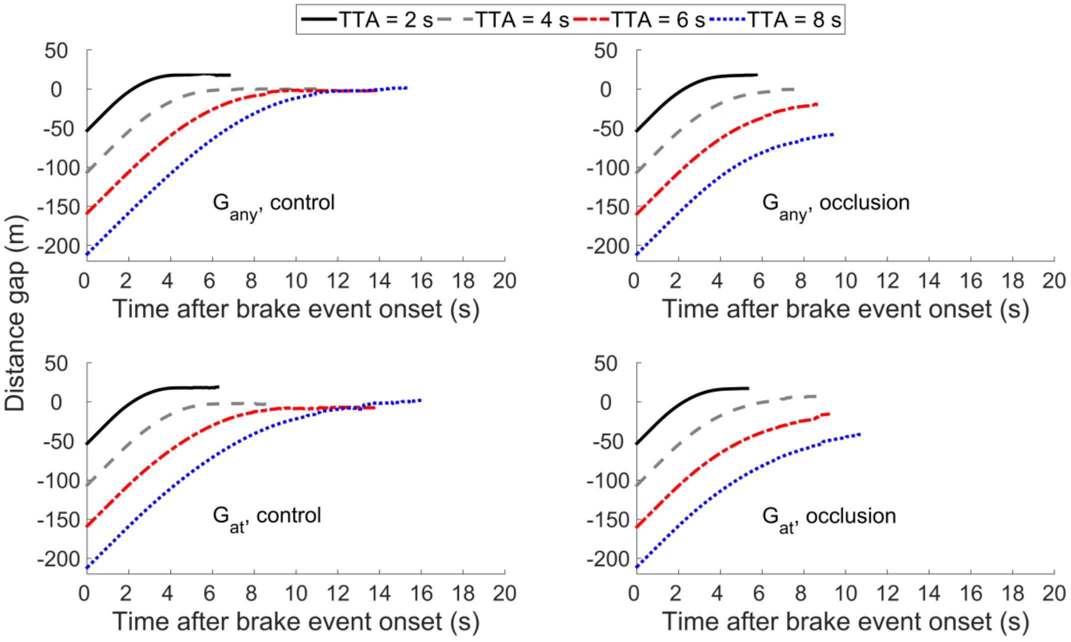

Figure 15. The average distance gap of participants during braking trials, as a function of time to arrival (TTA), participant group (G_{any} vs. G_{at}), and control and occlusion conditions. G_{any} = braking at any time after the occlusion/beep; G_{at} = braking immediately after the occlusion/beep.

3.4. Self-report questionnaires

Table 5 shows the results of the NASA TLX and the four additional questions about feelings of risk and self-confidence. Participants found the occlusion condition more demanding than the control condition. The greatest differences were observed for the mental demand item. Furthermore, participants expressed lower self-confidence when driving with occlusion and found driving with occlusion more risky and more difficult, as compared to driving in the control condition.

Finally, participants reported the strategies that they used in performing the braking task of the experiment. A few participants indicated that they used 'estimation' (2 times) or 'imagination' to brake when the scene was occluded. One participant mentioned 'mentally preparing myself with the brake force that is required' as a strategy used in the occlusion condition. Other responses implied similar strategies in using distance estimation for operation of the brake in the occlusion condition: 'tried to brake faster for short distances and very light at long distances', 'I tried to guess how many numbers I would have count in order to stop on spot (e.g. I would guess I should brake after counting to 7)', 'estimating the distance from the blackout point to the circle and transfer it to the time, so I would push the brake at the time I think I am close enough to the white circle', 'if don't feel there is a lot of distance after occlusion, I smash on the brake', and 'differentiate the pressure on the brake with distance'.

Table 5. Descriptive statistics of participants' responses to the NASA TLX questionnaire, and four additional questions about feeling of risk and self-confidence.

.	**Occlusion**		**Control**			
	G_{any}	**G_{at}**	**G_{any}**	**G_{at}**	***p*-value G_{any} vs. G_{at}**	***p*-value control vs. occlusion**
TLX Mental demand	54 (25)	55 (23)	39 (21)	35 (23)	0.871	**< 0.001**
TLX Physical demand	29 (18)	38 (27)	26 (16)	25 (19)	0.601	0.013
TLX Temporal demand	32 (22)	43 (23)	33 (19)	30 (17)	0.582	0.177
TLX Performance	50 (23)	55 (23)	34 (20)	46 (24)	0.264	0.023
TLX Effort	58 (23)	57 (23)	39 (21)	50 (23)	0.562	**0.005**
TLX Frustration	52 (28)	42 (25)	26 (24)	26 (23)	0.534	**0.002**
I had a feeling of risk during driving (Risk)	33 (29)	45 (35)	19 (21)	22 (24)	0.465	**< 0.001**
I think I drove more safely than the average participant (Safety)	65 (20)	43 (19)	65 (18)	47 (14)	**0.006**	0.506
This driving task was easy (Difficulty)	44 (23)	40 (23)	70 (20)	56 (22)	0.238	**< 0.001**
I felt confident in my own capability to act appropriately (Confidence)	66 (19)	50 (26)	84 (14)	64 (22)	0.022	**< 0.001**

Note. The table shows means across participants (standard deviations in parentheses), and the p-values for comparisons between the two participant groups (G_{any} vs. G_{at}) and between the control and occlusion conditions. The results are expressed in percentages from 0% (lowest on the scale) to 100% (highest on the scale). $p < 0.01$ is indicated in bold.

3.5. Learning effects

There were several statistically significant differences between the braking behavior of the two benchmark tests (Table 6). The maximum brake displacement and its occurrence moment did not significantly change between these two benchmark tests. However, during the second benchmark test, participants were less likely to have large brake pedal depressions (> 80%) and more likely to almost or completely release the brake (< 20%) in comparison to the first benchmark test.

These results suggest that participants learned to operate the brake pedal smoothly through the course of the experimental sessions.

Table 6. Comparison of the maximum brake pedal displacement (p_{max}), maximum brake pedal displacement time (t_{max}), and time percentages per brake pedal displacement range ($T_{<20}$, $T_{20\text{-}40}$, $T_{40\text{-}60}$, $T_{60\text{-}80}$, $T_{>80}$) during the two benchmark tests. The comparison was made between the average data of the four trials per test.

Variable	**Benchmark test 1** ***M* (*SD*)**	**Benchmark test 2** ***M* (*SD*)**	***p*-value** **Test 1 vs. Test 2**
p_{max} (%)	71.4 (13.5)	67.0 (12.8)	0.105
t_{max}	7.7 (2.9)	7.0 (2.3)	0.308
$T_{<20}$ (%)	8.3 (9.6)	16.5 (8.1)	**0.002**
$T_{20\text{-}40}$ (%)	21.5 (19.7)	32.4 (14.4)	0.040
$T_{40\text{-}60}$ (%)	35.3 (14.5)	29.0 (17.1)	0.121
$T_{60\text{-}80}$ (%)	16.1 (10.6)	16.1 (10.0)	0.991
$T_{>80}$ (%)	18.9 (13.8)	6.0 (10.0)	**< 0.001**

Note. $p < 0.01$ is indicated in bold.

4. Discussion

This experiment investigated to what extent drivers rely on open loop (i.e., use of the scene memory) versus closed loop (i.e., continuous compensation of distance and speed with respect to a target) strategies in executing a braking task was investigated. The effect of the presence versus absence of visual information on the characteristics of participants' brake responses when they were asked to stop at a target was examined. In half of the trials, the screen was blanked at a particular time-to-arrival value (TTA). Our hypothesis was that participants would brake longer and harder when the brake scene was occluded, because they had to rely on the perceived compressed distance at the start of braking as predicted by Gilinsky's model of distance perception). Contrary to expectations, it was found that when the time available to brake is short, drivers brake harder in the control condition than in the occlusion condition. The current experiment also shows that the underestimation of distance does not follow the pattern proposed by Gilinsky (1951). Potential explanations for these findings are discussed below.

4.1. Distance underestimation

The results of the current experiment indicate that in standstill conditions people underestimate the true distance to the lead vehicle in the virtual environment by as much as 70%. This 70% factor seems to be independent of the true distance, which means that a linear fit is an appropriate model of the perceived distance (based on visual inspection of Figure 4). Hence, the curvilinear model of Gilinsky for the simulator was rejected for the range of distances examined in this experiment. Baumberger, Flückiger, Paquette, Bergeron, and Delorme (2005) showed that drivers placed their car 5 m too far from the car in front (meaning they underestimated the distance to this car) when asked to position their car at mid-distance between two other cars that were moving in the adjacent right lane of the driver. Distance underestimation has been found in other virtual environments as well, for a variety of measurement methods such as verbal reporting of absolute distance, triangulation by pointing/walking, perceptually-directed action, and perceived size judgment (Knapp & Loomis, 2004; Loomis & Philbeck, 2008).

A recent study by Li, Phillips, and Durgin (2011) sheds light on why the Gilinsky model did not yield a good fit for our data. These authors showed that if distance judgement is egocentric (meaning that the distances are estimated from the observer to a point in the environment, as was done in this study), then the estimated distance is linearly compressed. On the other hand, if distance judgment is exocentric (meaning that distance is measured between two points in the environment, as was the case in Gilinksy’s research), then distance underestimation becomes progressively larger as a function of distance. Previous research into egocentric distance judgements in real and virtual environments shows that observers typically underestimate the distance to an object by 20 to 30% (Li et al., 2011; Loomis & Philbeck, 2008; Messing & Durgin, 2005), although distance underestimates of around 55% have also been reported in virtual environments (e.g., Thompson et al., 2004; Witmer & Kline, 1998).

Although the current experiment shows that the underestimation of the distance in driving simulators does not follow the pattern proposed by Gilinsky, it does confirm that drivers severely underestimate the true distance to the lead car in the virtual environment. Failure to consider this effect in designing driver support systems (by means of driving simulators) could adversely impact the effectiveness of such systems. For example, driving simulator studies on headway settings for adaptive cruise control may be invalid if drivers systematically underestimate their actual distance.

It should be noted that driving simulators have particular features that can complicate the estimation of distance. The simulator screen represents a two-dimensional picture of the environment, which prevents the use of stereopsis (i.e., depth perception through binocular vision). Furthermore, the two-dimensional simulator scene lacks the monocular parallax created by the movement of the head with respect to the world scene. Research has shown that humans are able to estimate distance more accurately in virtual environments when cues such as binocular disparity and motion parallax are available (Ellis & Menges, 1995). Other factors like the textures in the environment, perspective information and virtual eye height, shadows, screen resolution, convergence and accommodation cues, and the visibility of the frames of the screens may have also contributed to the underestimation of distance (cf. Andersen, 2011; Wu, He, & Ooi, 2007). Another factor in our distance estimation test was that the lead vehicle remained visible for only 7 s. In such a short time window, participants have little time to calculate the distance from relative size cues or other traffic scene features. Future research could clarify whether the fast-paced nature of the distance estimation task can cause enhanced distance underestimation, by comparing this result to the result of a similar task where the estimation time-window is larger. Nevertheless, the time window of the distance estimation tasks in this study is close to the time available in safety critical driving tasks (Allen et al., 2005).

4.2. The effects of occlusion

The results of the braking trials support our hypothesis that lack of visual information effects the duration, timing, and magnitude of the brake pedal depression. For TTA = 2 s, participants in the occlusion condition brought the car to a standstill at, on average, the same location as participants in the control condition did (Figure 11). However, drivers needed longer time and reduced their maximum brake input as compared to the control condition.

In the events with short TTA (i.e., TTA ≤ 4 s) participants’ maximum brake pedal depressions were smaller during the occlusion condition than they were during the control condition (Figure 7). These results are inconsistent with our hypothesis stating that people driving with occlusion brake hard because they have to rely on the compressed visual distance. One potential explanation is that the participants' brake reaction time was somewhat slower in the control condition than in the occlusion condition (Figure 5). For example, for TTA = 2 s, participants in the occlusion condition braked 0.19 s earlier than participants in the control condition, possibly because some participants braked *after* the 0.4 s beep had ended. Participants in the control condition should have compensated this delay by using a higher amount of pedal displacement. Another possibility is that participants have learned to use the simulator during the training session and the first benchmark test, and therefore were able to brake efficiently despite the severe underestimation of distance. Our comparison between the first and second benchmark tests confirms that people had adapted to the driving simulator by reducing their brake pedal depression (Table 6). A third possibility is that with the urgent conditions (TTA ≤ 4 s), participants cannot detect that they are likely to miss the target and therefore do not feel the urge to press the brake as far as possible.

When there was ample time available at the start of the braking maneuver (TTA ≥ 6 s), participants in the occlusion condition brought their vehicle to a stop well before the target. The results further indicate that participants pressed the brake at an intermediate position when the driving scene was occluded. Arguably in the TTA ≥ 6 s conditions, participants cannot know when to release and regulate the brake pedal input, and they therefore apply a constant brake input (known as 'hold' strategy). The interaction effect between the visual condition and TTA (Table 4 and Figure 11) illustrates that people driving in the occlusion condition were more likely to press the brake at an intermediate position (60–80% for TTA = 2 s, and 40–60% for TTA = 8 s) than people driving in the control condition. However the people driving in the control condition were more likely to 'slam' the brakes (i.e., to press their brakes as deeply and as quickly as possible) at TTA = 2 s or release the brakes (at TTA = 8 s). These results are consistent with a study by Andersen et al. (1999) in which participants non-interactively observed a scene in which the motion decelerated at a constant rate followed by a blackout of the display. Their results showed that the longer the blackout period, the less accurate participants were in determining whether they were on collision course with a stop sign.

In summary, for large TTA values (TTA ≥ 6 s), participants in the occlusion condition, on average, stopped well before the target and did so in an inconsistent manner (i.e., high within-subject standard deviations of the stopping distance). In the occlusion condition with TTA = 2 s, participants stopped on the target almost as accurately as in the control condition. Still, for these braking trials, participants in the occlusion condition pressed the pedal less hard (Figure 7) and reached lower peak decelerations (Figure 8) than in the control condition.

4.3. The effects of task instructions

The results of this experiment showed that imposing the brake onset instructions had little effect on the brake response characteristics. The largest difference between G_{any} (the group braking at any time after the occlusion/beep) and G_{at} (the group braking immediately at the occlusion/beep) was obtained in the brake response time itself. The uniform timing (i.e., low *SD*s, see Figure 6) among the G_{at} trials indicates that G_{at} participants responded as instructed: right after the brake stimulus. In the case of low urgency (TTA = 8 s), G_{any}'s average brake onset showed a delay of about 1 s compared to G_{at} (Figure 5). Summarizing, the brake response pattern did not noticeably differ between the G_{any} and G_{at} groups. The effects of the temporal urgency of the situation (TTA value) were stronger than the effects of task instruction.

4.4. Limitations of this research

One limitation of this study is that participants were vigilant and well instructed. In reality, emergency events can occur as surprise conditions where drivers have poor situation awareness. In addition, our simulator lacks tactile/vestibular-motion feedback. It has been found before that people brake more smoothly and with lower peak decelerations in a real vehicle than in a simulator, especially when the simulator does not provide physical motion feedback (Boer, Girshik, Yamamura, & Kuge, 2000; De Groot, De Winter, Mulder, & Wieringa, 2011; Siegler, Reymond, Kemeny, & Berthoz, 2001). A third limitation is that the participants in this study were relatively young, with a mean age of 27 years; two-thirds being younger than 30 years. There is some evidence that older participants make more conservative, but less accurate, decisions in braking tasks (e.g., Andersen et al. 1999; Bian & Andersen, 2014). Future research should investigate whether our results can be generalized to different age and experience levels. A fourth limitation of this study is that the results may be specific to the simulator's brake system design, including such factors as the physical brake pedal stiffness, brake pedal amplitude, and the virtual brake dynamics model of the simulator. Many participants in the TTA = 2 s condition pressed the brakes at the full 100% depression, giving rise to a ceiling effect. It is possible that differences between the control and occlusion condition would have been larger if the brake pedal had been stiffer. One recommendation that stems from these observations is that the brake pedal stiffness in real cars should not be too high, as people have a tendency to under-brake when they lack visual information. This recommendation is in line with previous research showing that in situations with high urgency, drivers do not use their full braking capacity (Kassaagi, Brissart, & Popieul, 2003).

4.5. Implications of this research

The scenario investigated in this research (braking to a full stop at a target) can occur in various real life situations such as stopping behind stationary vehicles, at stop signs, or at traffic lights at signalized intersections. The results may be useful for explaining drivers’ responses in these situations and for determining the most effective remedies for accidents (e.g., training, design of warning systems). Many advanced driver assistance systems (ADAS) are designed to reduce drivers’ brake reaction time (e.g., Fancher, Bareket, & Ervin, 2001; Lee & Peng, 2005; Piao & McDonald, 2008; Wang, Zhang, Zhang, & Li, 2013). The present results may be useful for defining future research in this area.

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CHAPTER 4

Why do drivers maintain short headways in fog? A driving simulator study evaluating feeling of risk and lateral control during automated and manual car following

Abstract

Drivers in fog tend to maintain short headways, but the reasons behind this phenomenon are not well understood. This study evaluated the effect of headway on lateral control and feeling of risk in both foggy and clear conditions. Twenty-seven participants completed four sessions in a driving simulator: clear automated (CA), clear manual (CM), fog automated (FA) and fog manual (FM). In CM and FM, the drivers used the steering wheel, throttle and brake pedals. In CA and FA, a controller regulated the distance to the lead car, and the driver only had to steer. Drivers indicated how much risk they felt on a touchscreen. Consistent with our hypothesis, feeling of risk and steering activity were elevated when the lead car was not visible. These results might explain why drivers adopt short headways in fog.

Saffarian, M., Happee, R., & De Winter, & J. C. F. (2012). Why do drivers maintain short headways in fog? A driving simulator study evaluating feeling of risk and lateral control during automated and manual car following, *Ergonomics, 55*, 971–985. (adapted with minor textual changes)

CHAPTER 4: Why do drivers maintain short headways in fog?

1. Introduction

Fog is one of the most dangerous conditions a motorist can drive in. Crashes in fog tend to be more severe than crashes in clear weather and are associated with pile-ups involving multiple fatalities (Abdel-Aty, Ekram, Huang, & Choi, 2011; Al-Ghamdi, 2007; Johnson, 1973; Musk, 1991; Sumner, Baguley, & Burton, 1977; Whiffen, Delannoy, & Siok, 2003). Because fog is a rare weather condition, the numbers of fatal road traffic crashes in fog account for only about one to three percent of the total (Organization for Economic Co-operation and Development, 1994). However, on an absolute scale, fog contributes to a considerable number of fatalities. In representative Western countries such as the United States, Canada, and Germany, the annual number of fatal traffic crashes in fog has been estimated at 355, 54 and 33, respectively (Lerner, 2002 cited in Debus et al., 2005; National Highway Traffic Safety Administration Fatality Analysis Reporting System [NHTSA-FARS], 2009; Whiffen et al., 2003).

A peculiar phenomenon of driving in fog is that drivers tend to maintain a shorter headway to the lead vehicle than they do in clear weather. Motorway measurements by White and Jeffery (1980) showed that when visibility dropped below 200 m, drivers reduced their headway, expressed as both inter-vehicle distance and as temporal separation. At a visibility distance of 150 m, about 30% of vehicles maintained headways within 2 s. This percentage was some 2.5 times higher than the percentage observed in normal traffic flow in clear weather. According to White and Jeffery, these findings demonstrate that fog causes platooning and provokes unsafe behavior. Similar findings were reported by Hawkins (1988). A driving-simulator study by Ni, Kang, and Andersen (2010) found that older drivers in particular followed at short headways in fog.

When driving in fog, a driver is deprived of preview and road texture information that may be relevant to lateral control. A simulator study by Uc et al. (2009) found that drivers with Parkinson’s disease had poorer lane-keeping accuracy than controls, and that the effect size was larger in mild fog than in clear weather. Brooks et al. (2011) found that the mean percentage of the driving time that the vehicle was entirely within its lane was reduced in fog, but only when the visibility distance dropped below 30 m. A small study in a driving simulator by Malaterre, Hary, & Quéré (1991) showed that driving in fog reduced low frequency steering wheel movements (between 0.1 and 0.3 Hz), indicating reduced use of visual preview information.

They hypothesized that a lead vehicle might serve as a guide in lateral control. However, their experiment found no significant differences in steering behavior between driving in fog with versus without the presence of a lead car. As Caro, Cavallo, Marendaz, Boer, and Vienne (2009) pointed out, no experimental data is currently available that proves the influence of the lead car on lateral control in fog.

Caro et al. (2009) showed that maintaining shorter headways in fog led to shorter response times than long headways, due to better contrast and improved visibility of the leading vehicle outline. This suggests that headway reduction is an adaptive mechanism in drivers to achieve faster discrimination of relative motion. The results by Caro et al. (2009) are supported by Kang, Ni, and Andersen (2008), who found that drivers in fog have difficulty detecting rapid speed changes in the lead car.

Another mechanism that may be operating in fog is altered distance perception (Brown, 1970). A fog chamber experiment has shown that in fog people overestimate distance by as much as 60% (Cavallo, Colomb, & Doré, 2001). However, overestimation of distance can only marginally explain the short headways observed in fog, because distance overestimation occurs only in extremely dense fog when just the lead vehicle's lights remain visible and the lead car's outline cannot be perceived (Caro, 2008).

Fog decreases visual stimulation of the peripheral field, reduces global optical flow, and creates a featureless environment. All this may cause drivers to underestimate their speed (Malaterre et al., 1991; Musk, 1991), resulting in headway reduction. Underestimation of speed could be aggravated by the fact that the driver cannot easily check the speedometer while concentrating on the road ahead (Musk, 1991). Snowden, Stimpson, and Ruddle (1998) confirmed that as fog becomes denser, subjects perceived driving scenes to be moving more slowly, and drove at faster speeds in a low-fidelity driving simulator. However, these results are contradicted by a number of studies using more sophisticated driving simulators (e.g., Debus et al., 2005; Owens, Wood, & Carberry, 2010).

In addition to these studies, which use perceptual mechanisms to explain headway reduction, a number of researchers have alluded to emotional variables such as fear, worry, or sense of risk, to explain the headway reduction. There is good reason to believe that emotional variables play a crucial role in car driving. General theories of car driving behavior suggest that psychological mechanisms in car driving can be conceptualized as avoidance of threat (Fuller, 1984) or risk (Näätänen & Summala, 1974). According to Musk (1991), fog is the weather hazard that drivers fear most. Edwards (1996) pointed out that motorway drivers may be anxious about losing sight of the lead vehicle, being struck by another vehicle from behind, or becoming detached from the road environment. Driving in fog without the presence of a lead vehicle also increases the chance of sudden confrontations with slow-moving vehicles, and drivers may therefore be reluctant to lead a queue (Musk, 1991). A survey of 1,773 drivers found that a psychological push-pull mechanism with respect to other cars contributes to short headways (Schönbach, 1996). In this study, 65% of respondents indicated that it is usually reassuring for them if they see the taillights of the car ahead. A recent driving-simulator study by Broughton, Switzer, and Scott (2007) found that high lead-car speed combined with dense fog prompted two distinctive behaviors in the drivers they tested: one group ceased to follow the lead car within visible limits and dropped back to a longer following distance. The other group maintained visual contact with the lead car, possibly at the expense of safety. These results indicate that the visibility threshold might function as a psychological barrier, separating drivers into laggers (who drive at lower speeds at the expense of unguided driving) and non-laggers (who closely follow a lead car that provides guidance).

Of the reported mechanisms explaining headway reduction, the roles of lateral control and emotional variables such as feeling of risk have hardly been studied experimentally. The present study aimed to understand why drivers maintain short headways in fog by focusing on lateral control and subjective feeling of risk. This paper investigated these two mechanisms using a paradigm involving automated car following at seven preprogrammed following distances, including the condition when the lead car is not visible. Previous driving-simulator research by Lewis-Evans, De Waard, & Brookhuis (2010) showed that the participants' feeling of risk as a function of headway has a horizontal asymptote towards increasing headway: Feeling of risk was low or nil at large headways, but showed an increase around 28 m (i.e., a temporal separation of 2.0 s in that study), and increased further for shorter headways. It was expected that an asymptotic pattern would be replicated in clear weather, but would not be present in foggy conditions. Moreover, it was hypothesized that if the lead car were out of sight in foggy conditions (i.e., large headways), drivers would report higher levels of subjective risk than when the lead car was visible. Furthermore, it was expected that when the lead car is not visible, a more active lateral control behavior would occur, indicating compensatory steering due to lack of preview.

Drivers’ feeling of risk and lateral control behavior during manual and automated car-following scenarios were compared for both foggy and clear weather conditions. It was hypothesized that automatic car following would result in lower feelings of risk and reduced lateral control activity than manual car following because of the reduced physical and mental activity required.

2. Method

2.1. Participants

Twenty-seven participants (twenty-two men and five women) who held a driver’s license for at least six months were recruited from the university community. All participants provided written informed consent. The experiment was approved by the Human Research Ethics Committee of the Delft University of Technology.

Analysis of an intake questionnaire showed that the mean age of participants was 28.9 years (*SD* = 2.8 years) and they had held a driving license for on average 10.0 years (*SD* = 3.4 years). Fifteen participants reported that they had driven in a simulator before, and five reported playing video games for at least one hour a week. The response to the item “I have good steering skills (for instance in cycling or computer games)” rated 7.4 (*SD* = 1.6) on average, on a scale from one (*completely disagree*) to ten (*completely agree*). Four participants reported driving daily, nine drove weekly, and fourteen monthly or less. Twenty-one participants reported no experience with cruise control systems or indicated that they used cruise control systems less than once a year.

2.2. Apparatus

The fixed-base driving simulator (Figure 1) provided a realistic simulation of a mid-class passenger car with 180° field of view and surround sound. This simulator is used for initial driver training in the Netherlands (Green Dino, 2011). The pedals, steering wheel, ignition key, and seat resembled those of an actual car, and gear changing was automatic. The steering wheel provided force feedback with a passive spring system. The steering sensitivity (i.e., a parameter representing the ratio of lateral acceleration to steering wheel angle) was calibrated to correspond to the steering sensitivity of cars on the road (Katzourakis, De Winter, De Groot, S., & Happee, 2012). The simulation data stream was updated at 50 Hz. The virtual world was depicted by three LCD projectors (one front projector, NEC VT676, brightness 2,100 ANSI lumens, contrast ratio 400:1, resolution 1,024 × 768 pixels; two side projectors, NEC VT470, brightness 2,000 ANSI lumens, contrast ratio 400:1, resolution 800 × 600 pixels). The dashboard, interior, and mirrors were integrated in the projected image. The car model used in this study had an automatic transmission.

Figure 1. Driving simulator in the experimental setup. The lead car is driving 31 m ahead of the participant's car. The driver is indicating the level of risk he is feeling on the touchscreen mounted on the steering wheel. Note that the eye-tracking equipment was not used in this experiment.

2.3. Experimental conditions

The experiment contained four sessions, each featuring a weather/driving condition applied in a within-subject design: clear automated (CA), clear manual (CM), fog automated (FA), and fog manual (FM). The order of sessions was counterbalanced using a Latin square. In the CM and FM sessions, the drivers operated the steering wheel, throttle, and brake pedals. In the CA and FA sessions, an automatic controller regulated the throttle and brake, and the driver had only to steer the car. In all CA and FA sessions, headway as a function of time was identical throughout the session.

The fog was created by blending a light grey color with each rasterized pixel fragment's post-texturing color. The blending factor was a linear function of the distance in eye coordinates to the fragment being fogged and was 100% for 40 m. The subjective visibility threshold of the lead car corresponded to a bumper-to-bumper distance of approximately 35 m, representing dense fog (Musk, 1991).

Table 1. Summary of the behavior of the lead car and participant's car (i.e., following car) during the experiment.

	Lead car in all sessions	**Participants' car in clear automated (CA) and fog automated (FA) sessions**	**Participants' car in clear manual (CM) and fog manual (FM) sessions**
Constant-speed phase (40–300 s)	Constant speed of 80 km/h	Seven 10-s intervals with constant distance (26, 81, 16, 31, 6, 21, and 161 m). In between these intervals, the automatic controller adjusted the distance.	Manual longitudinal control using brake and throttle pedals
Variable-speed phase (330–420 s)	Multisine speed profile with mean speed = 99 km/h and *SD* of speed = 10 km/h	Multisine speed profile; follows lead car at virtually constant distance of 30 m (*SD* = 0.5 m). Mean speed = 99 km/h and *SD* of speed = 10 km/h.	Manual longitudinal control using brake and throttle pedals

Note. In all sessions, drivers had to steer themselves while gear changing was automatic.

All sessions took place on a straight motorway with three 5-m wide lanes. There was no other traffic besides the participants' car and the lead car driving along the right-hand lane. The speed profile of the lead car was the same in all sessions (see Section 3.2). Each session contained two main phases: a 260-s constant-speed phase during which the lead car kept a constant-speed (i.e., from 40 s to 300 s) and a 90-s variable-speed phase during which the lead car's speed was a multisine with different phase shifts (from 330 s to 420 s). The multisine was designed such that lead car speed was not predictable for the participant (cf. Jagacinski & Flach, 2003). The automatic controller used the start-up phase (0–40 s) and transition phase (300–330 s) to acquire the desired initial following distance and velocity. At the start of the experiment, the participant's car stood still, 35 m behind the lead car. The automatic controller resembled a real adaptive cruise control (ACC) system and used a string-stable sliding mode controller to ensure constant spacing with respect to the lead car (Rajamani et al., 2000). In the constant-speed phase, the automatic controller successively maintained the following seven bumper-to-bumper distances (with corresponding time interval of the session in parentheses): 26 m (50–60 s), 81 m (80–90 s), 16 m (120–130 s), 31 m (150–160 s), 6 m (180–190 s), 21 m (210–220 s), and 161 m (260–270 s). Thus, the lead car was not visible for two of the seven distances. The inter-vehicle distance of 31 m is shown in Figure 1. In the variable-speed phase, the automatic controller kept the following distance close to 30 m (*SD* = 0.5 m). The behavior of both lead car and participant's car is summarized in Table 1.

2.4. Information provided to participants

Participants were informed in writing that the goal of the experiment was to investigate how visibility (i.e., presence or absence of fog) and adaptive cruise control (ACC i.e., a system that automatically keeps a constant following distance to the car in front) influence driving performance and behavior. They were also informed about the four experimental conditions, the simulator controls, the questionnaire, and risk measurement (see below). The instructions stated that their task was to 1) follow the car in front, 2) drive swiftly but safely, and 3) always keep the car accurately centered in the right-hand lane and not overtake or change lanes. Finally, the documentation informed drivers about the possible occurrence of simulator sickness, and stated that they could leave the experiment any time they wished.

2.5. Procedures

On arriving at the driving-simulator laboratory, participants read the information sheet, signed the informed consent form, and completed a short intake questionnaire. They then sat in the simulator and performed two practice sessions of four minutes each, the first with clear vision, the second with the fog. In the first two minutes of each practice session, participants drove manually and in the last two minutes, they drove with the automatic controller activated.

Next, the participants completed the four 420 s experimental sessions. After each session, participants got out of the simulator for a short break (about four minutes) and to fill in a questionnaire containing the six-item NASA Task Load Index (Hart & Staveland, 1988; a widely used questionnaire in driving research, see e.g., De Groot, Centeno Ricote, & De Winter, 2012; Dey & Mann, 2010; Hart, 2006; Stinchcombe & Gagnon, 2010) as well as four items on the participant's feeling of risk and self-confidence. The extra items were: 1) "I had a feeling of risk during driving", "I think I drove more safely than the average participant in this experimental condition", "This car-following task was easy", "I felt confident in my own capability to act appropriately", all on a 21-tick scale from 0% (strongly disagree) to 100% (strongly agree).

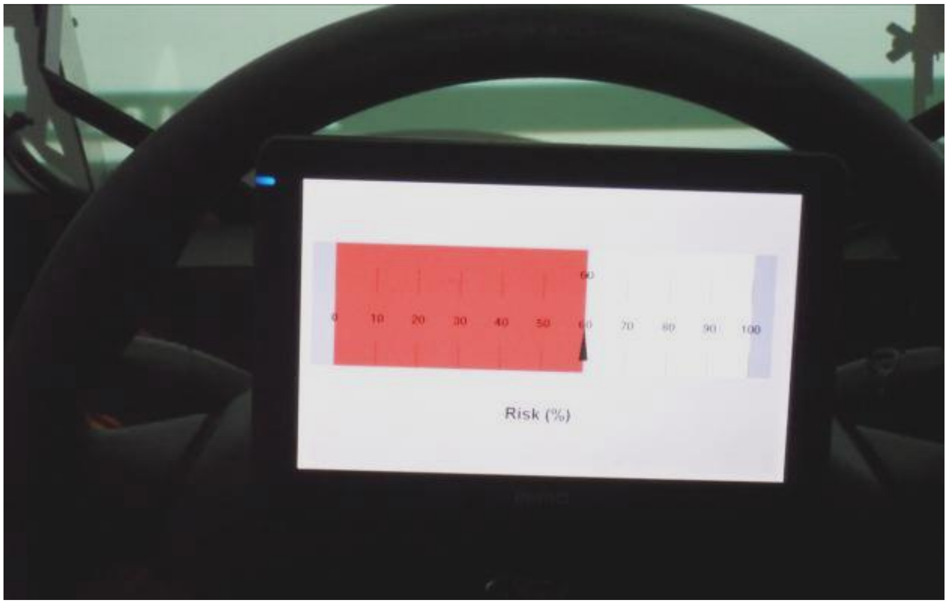


Figure 2. The touch screen interface used by the participants to indicate their feeling of risk at several prescribed moments.

During all sessions, participants had the secondary task of indicating their feeling of risk using a touchscreen mounted on the steering wheel. At the sound of a beep, the participants had to rate how much risk they felt on a scale from 0% (no risk at all) to 100% (extremely risky), on a horizontal bar with 10% increments (Figure 2). The beep was produced at the following moments of each session, t = 50, 80, 120, 150, 180, 210, 260, 310, 330, 350, 370, 390, and 410 s. The first seven beeps corresponded to the seven following distances in the constant-speed phase with the automatic controller, and the remaining six beeps were displayed every 20 s in the variable-speed phase.

2.6. Dependent variables

First, the steering angle data was filtered using a second-order Butterworth forward-reverse digital filter with a cutoff frequency at 1 Hz, using MATLAB's *filtfilt* function, in order to remove sensor noise. Next, steering activity was calculated by applying a finite impulse response (FIR) forward-reverse digital filter on the absolute steering angular speed, also using MATLAB's *filtfilt* function. The filter assigned equal weight to samples and used a 10 s interval (i.e., 10 s before and 10 s after). By applying such a low pass filter, a reliable indication about the participants' temporal fluctuations of steering activity within the session was obtained.

Descriptive statistics (means and standard deviations of participants) of the following measures were calculated for the constant-speed phase and variable-speed phase.

2.6.1. Vehicle control activity

- *Mean steering activity (deg/s)*: Steering activity is a measure of lateral control. A low steering activity indicates smooth steering, whereas a high value describes compensatory and corrective steering.

- *Standard deviation of the throttle position (%)*: This measure represents the participant's activity with the throttle pedal.

- Standard deviation of the brake position (%): This measure represents the participant's activity with the brake pedal.

2.6.2. Driving performance

- *Standard deviation of lateral position (SDLP; m)*: SDLP is a commonly used measure describing a driver's swerving on the road (e.g., Brookhuis, De Waard, & Fairclough, 2003; Dijksterhuis, Brookhuis, & De Waard, 2011; Van der Zwaag et al., 2012).

- *Mean following distance (m).*

- *Standard deviation of following distance (m)*: This measure describes how well the participant nullified distance differences with respect to the lead car (cf. Brookhuis, De Waard, & Mulder, 1994, showing that this is a valid measure that can be used in an on-the-road test battery)

2.6.3. Subjective evaluation

- *Mean feeling of risk (%)*: This measure represents the average risk level as indicated on the touchscreen.

- *Responses to the questionnaire (%).*

In order to test our hypotheses regarding feeling of risk and lateral control as a function of following distance, steering activity levels and following distances were extracted from the constant-speed phase at *t* = 55, 85, 125, 155, 185, 215, and 265 s, in the middle of each of the 10-s constant-distance intervals. The feeling-of-risk levels were extracted at the end of each 10-s interval, that is, at *t* = 60, 90, 130, 160, 190, 220, and 270 s.

2.7. Statistical analyses

Comparisons between experimental sessions and following distances were all conducted with paired *t* tests. Because of the heterogeneity of variances between groups, and the expected nonlinear relationships between feeling of risk and steering activity versus distance, simple *t* tests were preferred over complex bivariate or multivariate tests. The steering activities and feeling-of-risk levels corresponding to the seven following distances in the constant-speed phase were rank transformed (Conover & Iman, 1981) prior to submitting to the *t* test, for higher robustness and to cope with possible outliers.

3. Results

3.1. Excluded sessions

One participant driving in the FM session did not keep the lead car in sight, maintaining a speed of about 40 km/h throughout the session and gradually increasing the following distance to about 4.5 km. Later on, this participant said that he had chosen to drive at this speed because he wanted to maintain a safe stopping distance in case an obstacle appeared on the road. Due to the long following distance, this session and corresponding questionnaire were withdrawn from the analysis. The first participant in the experiment braked repeatedly in the FA session, thereby inadvertently interfering with the automatic controller. This session and corresponding questionnaire were also withdrawn from the analysis. After this session, the written task instructions was clarified by including a statement that told drivers not to press the brake pedal during the automated sessions. Analysis of the results showed that in all later CA and FA sessions, participants obeyed the instructions and did not use the brakes.

Two participants driving in the FM session lost contact with the lead car in the variable-speed phase, resulting in long following distances (> 200 m). The CM session was stopped accidently at 400 s instead of 420 s for one participant. The variable-speed phase for these three sessions was withdrawn, but their constant-speed phase and questionnaire results were kept in the analysis. In summary, all twenty-seven participants were included in the analysis, but two sessions were excluded completely, and for three other sessions, the variable-speed phase was excluded.

3.2. Descriptive statistics

Table 2 shows descriptive statistics for all four sessions. FM resulted in closer following (lower *M* Distance) and more consistent car following (lower *SD* Distance) than CM. Driving in fog evoked more active steering and higher feeling of risk than driving in clear visibility (FM > CM and FA > CA). The SDLP was lowest in the FM session compared to the other sessions, indicating that manual driving in fog resulted in superior lane-keeping performance. The questionnaire results showed that fog resulted in a higher level of risk and mental and physical demands, compared to clear visibility (FM > CM and FA > CA).

Figures 3 to 6 illustrate the following distance, speed, feeling of risk, and steering activity, respectively, as a function of time for each of the four sessions. Figure 3 shows that for FM, drivers adopted a closer headway throughout the session compared to CM. Figure 4 shows that in the FM session, participants followed the lead car by closely matching the lead-car speed profile (high control gain) in the variable-speed phase, whereas in CM, drivers were able to ‘absorb’ the speed variations of the lead car with limited speed adaptations, because of the larger following distance. The high control gain, indicating higher longitudinal control activity for FM compared to CM, is also demonstrated by *SD* Throttle and *SD* Brake in Table 2.

The feeling of risk presented in Figure 5 shows a wider range of risk feeling with automated car following (CA and FA) than with manual car following (CM and FM). Fog resulted in overall higher feelings of risk than clear conditions (FA > CA, FM > CM). Figure 6 shows that steering activity was highest with the lead car out of sight (distance > 35 m) in the fog sessions, that is *t* = 80–90 s and *t* = 260–270 s in FA, as well as around *t* = 315 s in FA and FM.

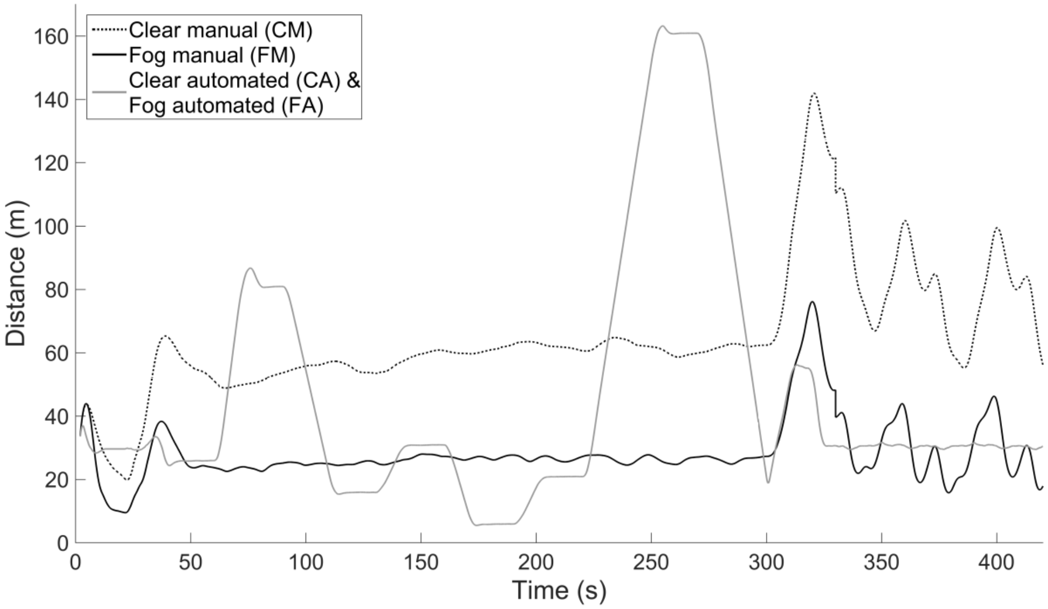


Figure 3. Following distance during the experiment for all four experimental conditions. The lines represent the participants' average per time point. Note that distance as a function of time is identical for each driver in clear automated and fog automated.

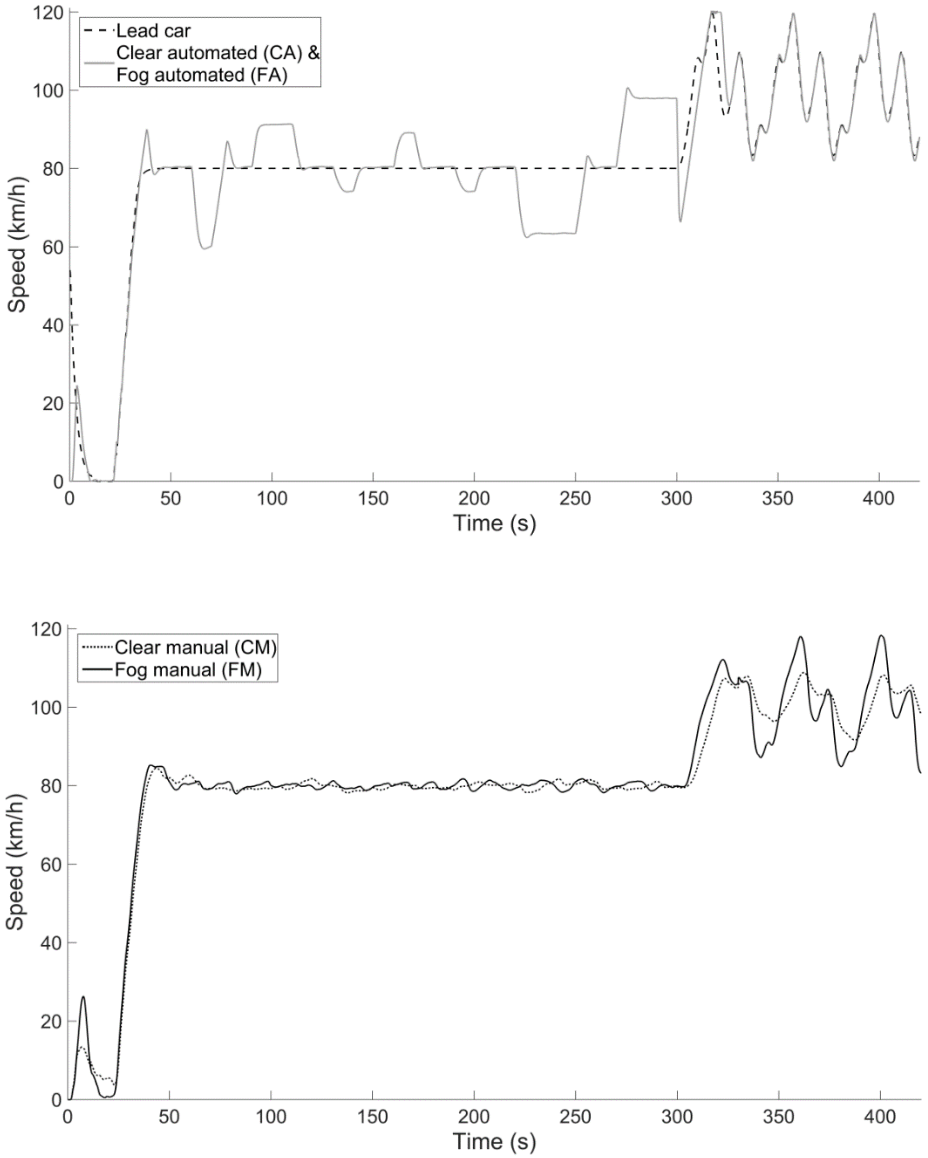
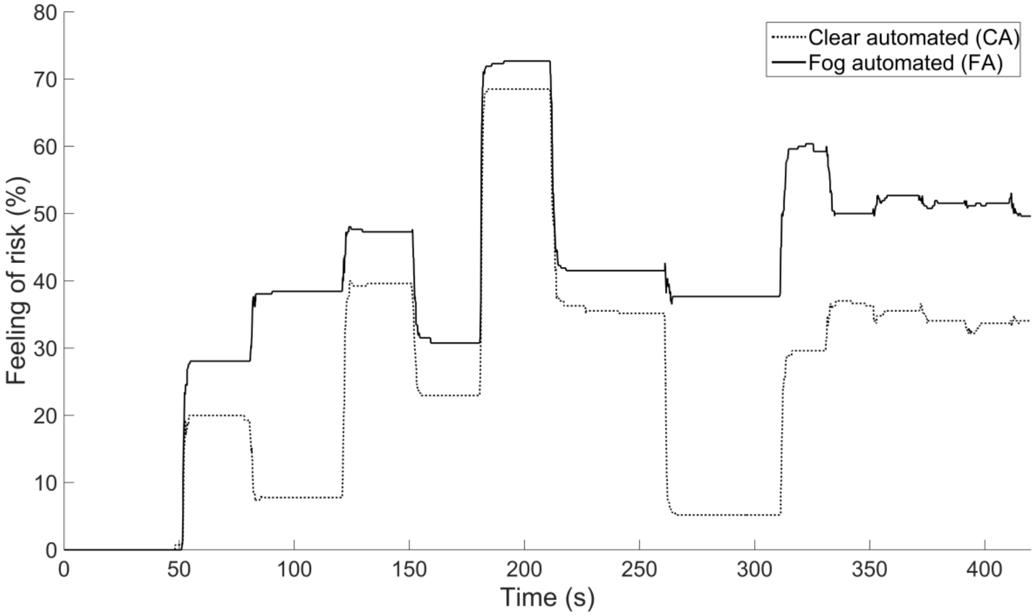


Figure 4. Speed of the driver's car and the lead car during the experiment, for all four experimental conditions (top: lead car in all conditions, clear automated, and fog automated; bottom: clear manual and fog manual). The lines represent the participants' average per time point. Note that speed is identical for each driver in clear automated and fog automated. The automatic controller required some time to catch up with the lead car in the transition between constant-speed and variable-speed phase (300–330 s).



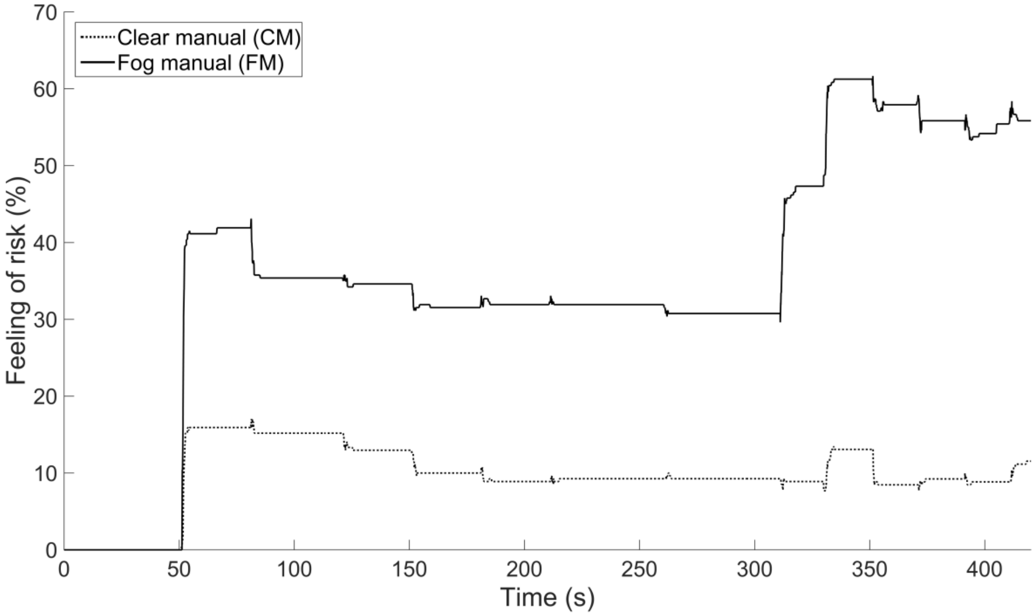


Figure 5. Feeling of risk as indicated by drivers during the experiment for all four experimental conditions (top: clear automated and fog automated; bottom: clear manual and fog manual). The lines represent the participants' average per time point. Note that risk levels changed at distinct moments, when drivers responded to the sound of the beep.

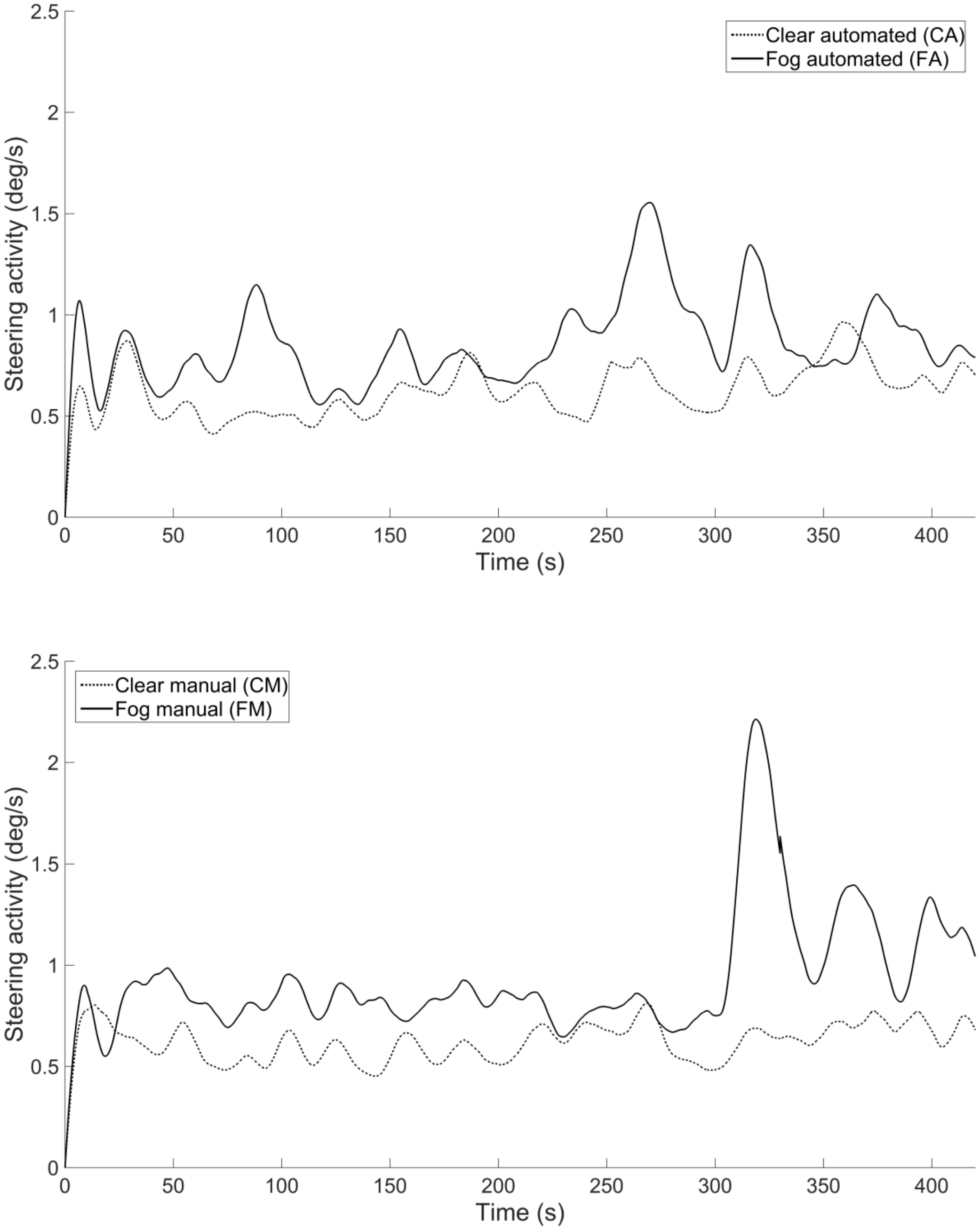


Figure 6. Steering activity during the experiment for all four experimental conditions (top: clear automated and fog automated; bottom: clear manual and fog manual). The lines represent the participants' average per time point.

Table 2. Descriptive statistics, showing the means across participants (standard deviations in parentheses), and the *p*-values for comparisons between sessions.

	CA	**CM**	**FA**	**FM**	***p*** **CA vs. FA**	***p*** **CM vs. FM**	***p*** **CA vs. CM**	***p*** **FA vs. FM**
Constant-speed phase (40–300 s)								
M Steering activity (deg/s)	0.58 (0.30)	0.59 (0.21)	0.85 (0.41)	0.81 (0.33)	**.000**	**.000**	.712	.587
SD Throttle (%)	-	9 (4)	-	12 (6)	-	**.001**	-	-
SD Brake (%)	-	0.7 (2.0)	-	1.2 (2.8)	-	**.025**	-	-
SDLP (m)	0.37 (0.14)	0.30 (0.10)	0.34 (0.09)	0.26 (0.08)	**.043**	**.009**	**.003**	**.000**
M Distance (m)	55 (0)	59 (47)	55 (0)	26 (5)	-	**.000**	.665	**.000**
SD Distance (m)	48 (0)	16 (14)	48 (0)	5 (2)	-	**.000**	**.000**	**.000**
M Feeling of risk (%)	26 (15)	11 (11)	40 (15)	32 (18)	**.000**	**.000**	**.000**	**.004**
Variable-speed phase (330–420 s)								
M Steering activity (deg/s)	0.74 (0.51)	0.69 (0.28)	0.86 (0.46)	1.15 (0.48)	.197	**.000**	.489	**.000**
SD Throttle (%)	-	18 (7)	-	30 (6)	-	**.000**	-	-
SD Brake (%)	-	2.0 (3.1)	-	9.4 (3.7)	-	**.000**	-	-
SDLP (m)	0.36 (0.12)	0.34 (0.10)	0.34 (0.12)	0.27 (0.08)	.531	**.000**	.360	**.036**
M Distance (m)	30 (0)	81 (45)	30 (0)	29 (8)	-	**.000**	**.000**	.500
SD Distance (m)	0 (0)	21 (8)	0 (0)	12 (5)	-	**.000**	**.000**	**.000**
M Feeling of risk (%)	35 (23)	10 (10)	51 (24)	57 (23)	**.000**	**.000**	**.000**	.109
Questionnaires								
TLX Mental demand (%)	25 (22)	27 (24)	42 (23)	51 (21)	**.000**	**.000**	.622	.062
TLX Physical demand (%)	17 (15)	23 (21)	25 (18)	35 (22)	**.005**	**.016**	.063	.075
I had a feeling of risk during driving (%)	44 (23)	20 (19)	63 (23)	59 (25)	**.002**	**.000**	**.000**	.323
This car-following task was easy (%)	77 (21)	75 (20)	68 (22)	51 (23)	.103	**.000**	.726	**.001**

Note 1. CA = Clear automated, CM = Clear manual, FA = Fog automated, FM = Fog manual, TLX = Task Load Index

Note 2. Table includes only four selected questionnaire items that reveal large effects. p values < .05 are in boldface.

3.3. Feeling of risk as a function of following distance

Figure 7 illustrates the feeling of risk in the constant-speed phase as a function of following distance. Corresponding means and standard deviations are provided in Table 3. The differences in feeling of risk between CA and FA were relatively small at 6, 16, 21, 26, and 31 m (t = 1.89, 2.72, 1.67, 3.46, 2.44; *p* = .070, .012, .107, .002, .022) compared to the CA-FA differences in feeling of risk at 81 and 161 m (*t* = 7.57, 11.7, both *p* < .001).

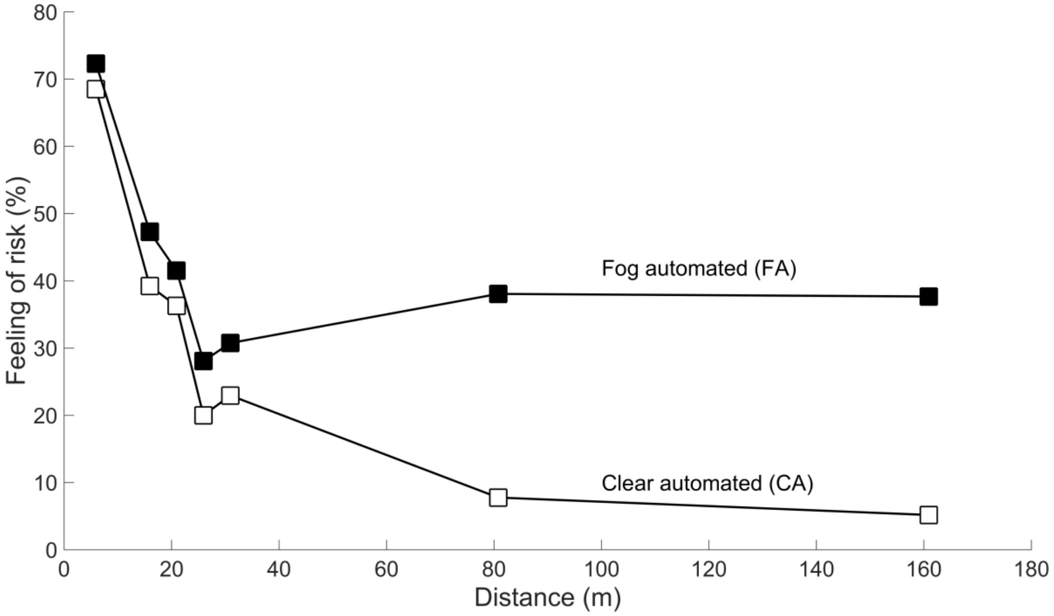


Figure 7. Mean of feeling of risk versus mean of following distance, derived from various moments in the constant-speed phase (*t* = 60, 90, 130, 160, 190, 220, and 270 s). Mean distances are sorted in ascending order with a line connecting the points.

Table 3. Means (standard deviations in parentheses) of participants' following distance, feeling of risk, and steering activity during the constant-speed phase.

	Distance (m)			Feeling of risk (%)				Steering activity (deg/s)			
***t* (s)**	**CA and FA**	**CM**	**FM**	**CA**	**CM**	**FA**	**FM**	**CA**	**CM**	**FA**	**FM**
55	26 (0)	54 (53)	24 (12)	20 (17)	16 (18)	28 (18)	41 (22)	0.57 (0.25)	0.72 (0.63)	0.76 (0.41)	0.87 (0.47)
85	81 (0)	53 (65)	24 (8)	8 (13)	15 (16)	38 (22)	35 (19)	0.52 (0.28)	0.55 (0.19)	1.09 (0.84)	0.82 (0.27)
125	16 (0)	54 (56)	26 (7)	39 (26)	13 (16)	47 (22)	35 (20)	0.58 (0.41)	0.63 (0.35)	0.63 (0.44)	0.89 (0.39)
155	31 (0)	61 (58)	28 (7)	23 (21)	10 (14)	31 (18)	32 (21)	0.67 (0.43)	0.65 (0.26)	0.93 (0.77)	0.73 (0.35)
185	6 (0)	62 (54)	27 (6)	69 (22)	9 (13)	72 (25)	32 (19)	0.80 (0.78)	0.63 (0.34)	0.82 (0.65)	0.92 (0.68)
215	21 (0)	62 (38)	26 (6)	36 (21)	9 (11)	42 (21)	32 (19)	0.66 (0.35)	0.67 (0.36)	0.73 (0.45)	0.86 (0.50)
265	161 (0)	59 (40)	26 (6)	5 (11)	9 (10)	38 (21)	31 (19)	0.79 (0.87)	0.77 (0.63)	1.49 (1.07)	0.86 (0.44)

Note 1. CA = Clear automated, CM = Clear manual, FA = Fog automated, FM = Fog manual. Distance and steering activity were extracted at the middle of each 10-s interval (time denoted as t), whereas feeling of risk were extracted at the end of each 10-s interval (t + 5 s).

Figure 7 further shows that in FA, the feeling of risk follows a distinct pattern, with risk being high for the shortest following distance (6 m), decreasing up to about the visibility threshold, and then rising with increasing distance. A paired *t* test showed that the feeling of risk in FA was significantly *higher* for a following distance of 81 m ($t = 2.08$, $p = .048$) and 161 m ($t = 2.03$, $p = .053$), as compared to a following distance of 26 m. In contrast, for CA, the feeling of risk was *lower* for 81 m ($t = -5.18$, $p < .001$) and 161 m ($t = -6.57$, $p < .001$) compared to the feeling of risk at 26 m. In other words, consistent with our hypothesis, the reported feeling of risk in FA was elevated when the lead car was not visible (i.e., distance > 35 m).

3.4. Lateral control as a function of following distance

Figure 8 shows the influence of following distance on steering activity, with corresponding means and standard deviations shown in Table 3. It can be seen that steering activity was higher for FA than CA. The differences between FA and CA were relatively small at 6, 16, and 21 m ($t = 0.12, 0.90, 0.68$; $p = .906, .375, .503$).

They were somewhat larger at 26 and 31 m ($t = 1.58, 2.40$; $p = .126, .024$), and were very large at 81 and 161 m ($t = 5.63, 4.73$, both $p < .001$). Mean steering activity when following at a distance of 161 m in FA was 1.49 deg/s, which is considerably higher than mean steering activity at 21 m (0.73 deg/s, $t = -4.71$, $p < .001$). For CA, these means were 0.79 and 0.66 deg/s, respectively, an insignificant effect ($t = -0.27$, $p = .788$). These results support our hypothesis that steering activity is high when the lead car is out of sight (distance > 35 m in fog).

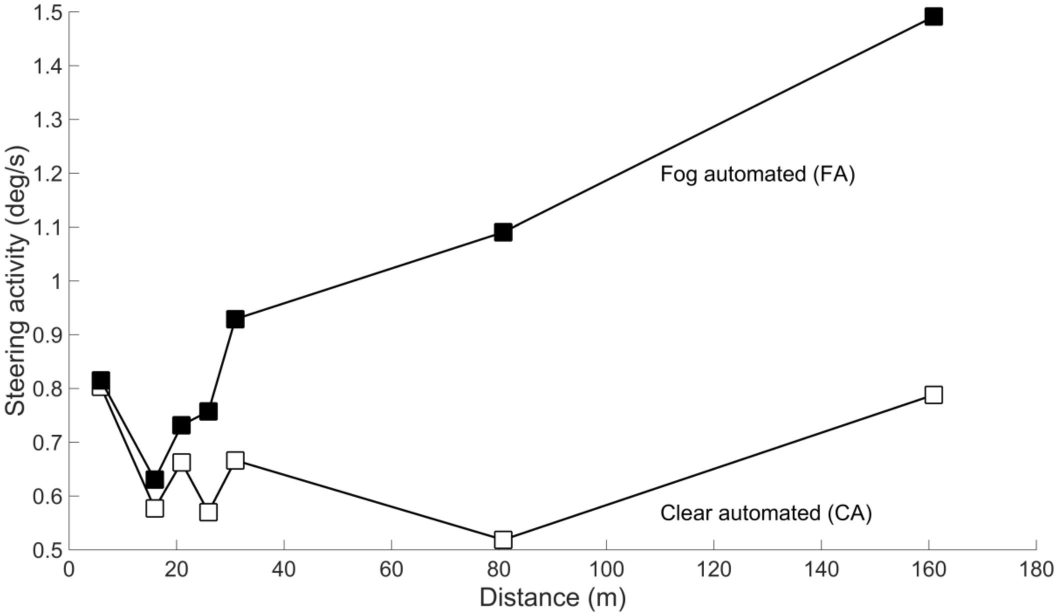


Figure 8. Mean steering activity versus mean of following distance, derived from various moments in the constant-speed phase (*t* = 55, 85, 125, 155, 185, 215, and 265 s). Mean distances are sorted in ascending order with a line connecting the points.

3.5. Differences between automated and manual car following

Additionally, it was investigated whether feeling of risk and steering activity differed between manual and automated car following. Table 2 shows that for the constant-speed phase, feeling of risk was significantly higher during automated compared to manual following (CA > CM and FA > FM). Steering activity, on the other hand, revealed no significant differences between the automatic and manual sessions. Note that the mean following distances also differed during the sessions (cf. Figure 3) and could have acted as a confound. Therefore, this study investigated whether feeling of risk and steering activity were different between automated and manual following when following distance was taken into consideration.

In FM, the mean following distance was 26 m and mean feeling of risk was 34% (averages of the seven values shown in Table 3). This feeling of risk in FM was not significantly different from the feeling of risk in FA at 26 m (28%, $t = 1.71$, $p = .100$). The mean following distance for CM was 51 m, and mean feeling of risk was 12% (averages again taken from Table 3). The feeling-of-risk value does not deviate significantly from the corresponding value in CA (15%, $t = -1.09$, *p* = .286; the average feeling of risk for the 31 m and 81 m distances in CA was used). In other words, there were no significant differences during the constant-speed phase between automated and manual car following in the indicated feeling of risk, when equivalent following distances are compared.

Mean steering activity for the seven distances in FM was 0.85 deg/s (average of the seven values shown in Table 3), significantly higher than mean steering activity in FA at 26 m (0.76 deg/s, *t* = 2.65, *p* = .014). The mean steering activity for CM was 0.66 deg/s, which was significantly higher than the steering activity in CA, averaged for the 31 m and 81 m distances (0.59 deg/s, *t* = 2.27, *p* = .032). Summarizing, when equivalent following distances are compared, steering activity was slightly higher in FM compared to FA, as well as for CM compared to CA.

4. Discussion

The aim of this study was to understand the mechanisms behind the observation that drivers maintain short headways in fog by focusing on the effects of headway and fog on lateral control (i.e., steering activity) and subjective feeling of risk during driving. During manual car following in fog, participants maintained headways that were just within the visibility threshold. Even though drivers were instructed to follow the car in front, three drivers lost contact with the lead car in fog. Broughton et al. (2007) similarly found that fog separates drivers into so-called non-lagging and lagging drivers.

For clear automated (CA), an asymptotic pattern for feeling of risk versus following distance was found, supporting a previous driving-simulator study by Lewis-Evans et al. (2010). Consistent with our hypotheses, for automated car following in fog (FA), steering activity and feeling of risk were elevated when the lead car was out of sight as compared to when the car was in sight. The lowest feeling of risk was observed when the lead car was *just* within the visibility threshold. These results suggest that the lead vehicle provides a guide, resulting in reduced lateral control activity. The standard deviation of lateral position (SDLP, a measure of lateral swerving performance) was lowest when manually driving in fog, indicating that drivers used the increased steering activity to improve their lateral performance (see also De Groot, De Winter, Garcia, Mulder & Wieringa, 2011; He & McCarley, 2011; Macdonald & Hoffmann, 1980).

When distance was taken into account, feeling of risk showed no difference between manual and automatic car following. The lack of difference between automated and manual driving is remarkable, given that the ACC relieved the driver of two important tasks: controlling the pedals and remaining vigilant with respect to the lead car's behavior. Note that the baseline levels of mental or physical demand (i.e., in the CM and FM sessions) were already low to begin with (Table 2) suggesting that floor effects may have occurred. A pilot experiment with other participants found lower subjective risk (as reported in a questionnaire) for automatic than for manual car following in fog. In this other experiment, the lead car had large fluctuations in speed, creating a more demanding driving task (Happee, Saffarian, Terken, Shahab, & Uyttendaele, 2011).

Our research provides the first experimental evidence to explain the role of feeling of risk and lateral control in headway reduction. Of course, this does not rule out that other mechanisms might play a role as well. For example, there is also support for the influence of fog on relative speed perception (Boer, Caro, Cavallo, & Arcueil, 2007; Boer, Caro, & Cavallo, 2008; Caro et al., 2009).

Despite its substantive findings, our study is not free of limitations. First, the lead car always drove perfectly down the center of the lane. A more realistic condition could have been achieved by implementing natural lane-keeping behavior for the lead car.

Second, a lane width of 5 m was used in this experiment which is relatively wide. On Dutch or North American motorways, for example, lane widths of 3.5 or 3.7 m are standard. It is known that reduction of lane width reduces SDLP, increases lane-boundary crossings, lowers speed, and increases subjective ratings of risk and mental effort (e.g., Dijksterhuis et al., 2011; Godley, Triggs, & Fildes, 2004; Lewis-Evans & Charlton, 2006; Yagar & Van Aerde, 1983). Lane width is likely to interact with lateral control behavior in fog, because drivers may use the lane markers as visual guidance. The interactive effect of lane width on lane maintenance in fog is an interesting topic for further research.

Third, this study did not involve traffic other than the car in front, which limits the external validity of the results. In real traffic, it has been observed that fog reduces the frequency of overtaking (White & Jeffery, 1980). Drivers who would normally overtake a lead car in clear visibility will be inclined to remain in their own lane in fog, potentially contributing to reduced headways. Furthermore, in real traffic, fog muffles sound, which might also contribute to the tendency to close following, and the ability to anticipate collisions (Musk, 1991).

Fourth, our fixed-base driving simulator used in this research offered medium fidelity in terms of visual cues and auditory cues and did not stimulate the vestibular organ. Drivers tend to behave differently in a simulator than they would do in a real car, demonstrating comparatively higher driving speeds, jerkier acceleration and braking behavior, altered lateral control behavior, and reduced perception of risk (e.g., Blana & Golias, 2002; Boer, Girshik, Yamamura, & Kuge, 2000; De Groot, De Winter, Mulder & Wieringa, 2011; De Groot & De Winter, 2011; Green, 2005; Hurwitz, Knodler, & Dulaski, 2005; Lew et al., 2005). Although driver behavior in the simulator is possibly biased in the absolute sense, simulators have proven value for establishing *relative* comparisons between different groups of drivers or experimental conditions, including drivers’ risk-taking behavior (e.g., Bédard, Parkkari, Weaver, Riendeau, & Dahlquist, 2010; Deery & Fildes, 1999; De Winter et al., 2009; Godley, Triggs, & Fildes, 2002; Green, 2005; Lee, Lee, Cameron, & Li-Tsang, 2003; Reimer & Mehler, 2011; Wang et al., 2010).

Fifth, in order to acquire identical headways as a function of time in the CA and FA sessions, it was chosen to present the headways in the same order (26, 81, 16, 31, 6, 21, and 161 m) for each participant. There is some concern in the traffic-psychology literature that lack of randomization can distort self-reported feeling of risk (see Lewis-Evans & Rothengatter, 2009 for a comprehensive study). However, these concerns apply particularly to research that presents the independent variable in a monotonically ascending order, which was clearly not the case in this study which applied a semi-random order, and applied the sessions (i.e., CA, CM, FA, and FM) in fully randomized order.

Sixth, the results may depend on the type of simulated fog. It seems that researchers use vastly different methods for simulating fog of various densities (e.g., Allen, Rosenthal, Aponso, & Park, 2003; Broughton et al., 2007; Hoogendoorn, Hoogendoorn, Brookhuis, & Daamen , 2010, 2011; Kolisetty, Iryo, Asakura, & Kuroda, 2006; Pretto & Chatziastros, 2006; Rimini-Doering, Manstetten, Altmueller, Ladstaetter, & Mahler, 2001; Stanton & Pinto, 2000; Takayama & Nass, 2008; Van der Hulst, Rothengatter, & Meijman, 1998). Snowden et al. (1998) used a uniform contrast reduction whereas Dumont, Paulmier, Lecocq, and Kemeny (2004) proposed rendering sophisticated fog for both daytime and nighttime conditions, including light from headlamps scattered back by minute water droplets. In our experiment a thick fog was simulated using color blending as a function of distance without simulating fog lights which may remain visible when the outline of the car is no longer in sight (cf. Caro, 2008). Subjectively the simulated fog was realistic and none of the participants reported anything unusual regarding its appearance.

How can the present results be used to improve road safety? Our results suggest that headway reduction in fog does not constitute irrational or irresponsible driver behavior as has been suggested by several authors (e.g., Hawkins, 1988). Instead, headway reduction provides advantages such as smoother lateral control behavior, reduced feeling of risk (and, arguably, reduced objective risk), as well as improved perception of speed differences (demonstrated by Caro et al., 2009). Therefore, drivers should not be advised to maintain larger headways. Instead, drivers should be encouraged to reduce speed in order to shorten stopping distance.

Several studies have found beneficial effects of fog signaling and speed advisory systems (e.g., Hogema & Van der Horst, 1997; see also Hassan & Abdel-Aty, 2011 for a questionnaire study), whereas computerized traffic detection and warning systems on motorways are commonplace internationally. Another option is to give drivers proper advice about the impending situation. For example, Charissis & Papanastasiou (2010) used a simulator to test a head-up display (HUD) system in foggy conditions. Their HUD provided minimalist visual representations of real objects, such as lead vehicle symbols, lane symbols, and traffic symbols indicating congestion in close proximity. They found that the HUD dramatically reduced the number of collisions and improved subjects’ maintenance of following distance, when compared to unaided driving. A third option is to use ACC using radar measurements of inter-vehicle spacing, or cooperative adaptive cruise control (CACC) using vehicle-to-vehicle communication (Naus, Vugts, Ploeg, Van de Molengraft, & Steinbuch, 2010). ACC and CACC automate the driving task and allow precise control of shorter headways between following vehicles. As illustrated in Figure 7, shorter headways can induce an elevated feeling of risk, even with automation. Thus also with automation a driver information system may be needed to inform drivers of the actions taken by the automated system and to provide sufficient reassurance about proper functioning of the system.

In conclusion, the present results suggest that there are two advantages to maintaining a close headway in fog: reduced feeling of risk and improved lateral control. These results are valuable for devising effective driver assistance and support systems.

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CHAPTER 5

Enhancing driver car-following performance with a distance and acceleration display

Abstract

A car-following assisting system named the Rear Window Notification Display (RWND) was developed, with the aim of improving a driver's manual car-following performance. The RWND presented lead-car acceleration and time headway (THW) (i.e., inter-vehicle distance divided by the speed of the following car) on the rear window of a lead car, which was driven automatically. A simulator-based experiment with 22 participants showed that the RWND reduced both the mean and standard deviation of THW but did not increase the occurrence of potentially unsafe headways of less than 1 s. The parameter estimation of a common linear car-following model showed that drivers accomplished the performance improvements by adopting higher control gains with respect to inter-vehicle distance, relative speed, and acceleration. A post-experiment questionnaire revealed that the display was generally not regarded as a distraction nor did participants think that it provided too much information, with means of 4.0 and 2.9, respectively, on a scale from one (completely disagree) to ten (completely agree). The results of this study suggest that the RWND can be used along with Cooperative Adaptive Cruise Control to increase traffic flow without degrading safety.

Saffarian, M., Happee, R., De Winter, J. (2013). Enhancing driver car-following performance with a distance and acceleration display. *IEEE Transactions on Human-Machine Systems, 43*, 8–16. (adapted with minor textual changes)

Furthermore, a preliminary version of this work was initially published in a conference proceedings: Saffarian, M., & Happee, R. (2011). Supporting drivers in car following: a step towards cooperative driving. In *Proceedings of the IEEE Intelligent Vehicles Symposium* (pp. 934-944), Baden-Baden, Germany.

CHAPTER 5: Enhancing driver car-following performance

1. Introduction

Because of developments in electronics, communication technology, and the processing power of computers, drivers are increasingly aided by Advanced Driver Assistance Systems (ADAS). A growing number of vehicles are now equipped with Adaptive Cruise Control (ACC), a system that has the capacity to adjust both brake and throttle, so as to maintain a constant headway with respect to the vehicle in front (Adell, Várhelyi, & Fontana, 2011; Kesting, Treiber, Schönhof, & Helbing, 2008; Van Nes, Houtenbos, & Van Schagen, 2008). Marchau, Van Nes, Walta, and Morsink (2010) reviewed intelligent speed adaptation systems, ranging from those that provide information to those that intervene in vehicle operation and noted that in all the reviewed studies, ACC reduced speeding violations and speed variability.

Several studies have evaluated traffic-flow and human-factors aspects of car-following with different ACC systems in various driving conditions (Chiang, Wu, Perng, Wu, & Lee, 2010; Gietelink, Ploeg, De Schutter, & Verhaegen, 2006; Hamdar, Treiber, Mahmassani, & Kesting, 2008; Mulder, Pauwelussen, Van Paassen, Mulder, & Abbink, 2010; Van Arem, Van Driel, & Visser, 2006). Evidence suggests that although ACC potentially enhances safety by helping drivers maintain constant speed and headway (Davis, 2004), drivers must be aware of its limitations and intervene if ACC cannot handle a situation, such as on approaches to sharp curves, when the lead car brakes sharply, or in the event of system failure (Rudin-Brown & Parker, 2004; Seppelt & Lee, 2007; Stanton & Marsden, 1997; Young & Stanton, 2007). Current experience shows that drivers are less likely to use ACC in heavy traffic (Marsden, McDonald, & Brackstone, 2001), which is precisely the situation where the greatest benefits could be achieved in traffic flow (shorter headways, avoiding coming to a full stop), safety (more homogenous traffic patterns), and fuel efficiency (following lead vehicles within their wake region and reducing the frequency and severity of braking and acceleration).

A next generation of ACC systems, known as Cooperative Adaptive Cruise Control (CACC), is addressing the stability limits of conventional ACC systems (Naus, Vugts, Ploeg, Van de Molengraft, & Steinbuch, 2010; Rajamani et al., 2000). CACC systems communicate their kinematic state using high bandwidth vehicle-to-vehicle communication. With CACC, it is possible to guarantee stability in traffic flow, meaning that inter-vehicle distance-errors decrease as they propagate along the platoon (Gietelink et al., 2006; Naus et al., 2010). Simulations have shown that traffic throughput could increase significantly if 60% (or more) of all cars were equipped with CACC technology (Milanés, Alonso, Bouraoui, & Ploeg, 2011; Van Arem et al., 2006). However, in the introductory phase of cooperative driving, penetration rates would be low, making it desirable to design a system that can influence the behavior of drivers of cars without such equipment and facilitate cooperation with those vehicles that do have it.

This paper proposes a system that assists drivers of non-equipped cars by displaying combined acceleration information and headway advice on the rear window of cars equipped with CACC. In this simulator study, participants using the Rear Window Notification Display (RWND) directly control the vehicle with the gas and brake pedals and the steering wheel. The system design was based on the hypothesis that a display giving visual feedback on lead-car acceleration and time headway (THW) will act as a sensory aid for human drivers and thus enhance their car-following performance.

The paper is organized as follows: Section 2 presents the concept and design of the RWND. Section 3 describes the test procedure and experimental setup for evaluating the display in a driving simulator. To examine the effect of the RWND, three types of measures were used: (1) traditional measures, such as mean and standard deviation of THW, to describe observable performance and behavior; (2) parameters of a linear driver model, to clarify how drivers use distance, speed, and acceleration information, and how they adapt their control behavior; and (3) a questionnaire surveying drivers' opinions. Section 4 discusses our results, while Section 5 deals with the implications of our research and suggests follow-up research.

2. Methods

2.1. The RWND

Previous research shows that while drivers can detect speed changes, they are not good at estimating the duration and intensity of such changes, especially regarding approaching objects (e.g., Cavallo & Cohen, 2001; De Winter, Spek, De Groot, & Wieringa, 2009). Brake lights provide a salient binary cue about deceleration and thus have an alerting function. However, traditional brake lights provide no information about the intensity of braking or about acceleration. This study hypothesized that augmented information on acceleration and deceleration intensity would be essential for improving car-following performance.

THW, defined as inter-vehicle distance divided by the speed of the following car, is a key indicator of the capacity of any transit system, and correlates with a driver’s perception of risk as measured with psychophysical methods (Kondoh, Yamamura, Kitazaki, Kuge, & Boer, 2008). It has also been found that drivers’ preferred THW in real car-following situations is independent of speed (Taieb-Maimon & Shinar, 2001). Thus, THW was selected as the second parameter for the display, combining the safety perception of drivers with network capacity. THW and acceleration have complementary integrator and differentiator characteristics, respectively. Through visualized information of THW and acceleration, the human operator can observe both the long and short-term effect of their control actions during car-following.

Studies have found that people do not make veridical judgments of speed and distance (e.g., Runeson, 1974, see also Chapter 3 of this thesis). The RWND here was designed to directly communicate the action that is required, rather than displaying a desired headway or speed in numerical form. The layout of the RWND is presented in Figure 1. The display employed one horizontal bar and one vertical segment to communicate lead-car acceleration and THW respectively. In order to facilitate stimulus response compatibility, the horizontal bar was aligned with the gas and brake pedal positions. Thus, lead-car acceleration was shown on the right, with the bar filling up from the middle of the bar to the left with red for deceleration, and to the right with green for acceleration, respectively. The length of the filled portion was proportional to the magnitude of acceleration or deceleration. Both sides of the bar were full at an acceleration or deceleration magnitude of 1.6 m/s^2 (and above).

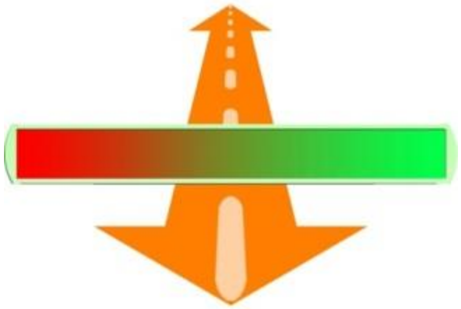
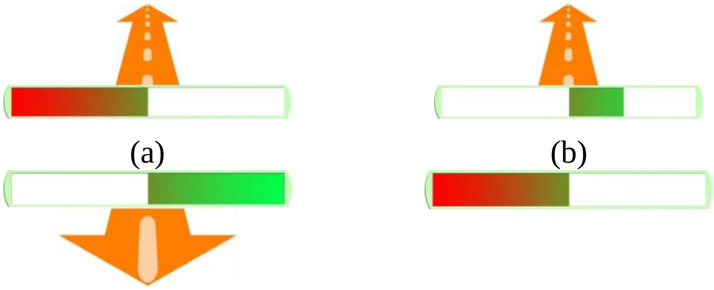


Figure 1. Rear Window Notification Display (RWND): Arrows indicate time headway (THW) deviations (up means that the driver is too far and should close the gap; down means that the driver is too close and should open the gap) and the horizontal bar indicates lead vehicle acceleration (right, color coded with green is acceleration; left, color coded with red is deceleration).

The second segment of the RWND consisted of one upward and one downward arrow positioned above and below the horizontal bar. Colored orange, the arrows indicated THW in terms of deviation from the desired margin. Only one arrow appeared at a time. An upward arrow meant the driver should follow closer. If the downward arrow appeared, the following driver was too close and needed to increase THW. When no arrow was visible, the THW was within the desired range and no action was required. The size of the arrows did not change with respect to the magnitude of the THW deviation. The THW values that triggered the appearance of the arrows were adjustable. In this study, the setting was as follows: when THW was less than 1 s, the downward arrow appeared, while a THW greater than 1.5 s made the upward arrow visible. This approach is also known as bandwidth augmented feedback; it stimulates satisficing rather than optimizing behavior and prevents the driver from becoming distracted by or dependent on the feedback (De Groot, De Winter, Garcia, Mulder, & Wieringa, 2011). Because the augmented feedback is visible only when the information is needed for potential action, this avoids problems that arise with continuous concurrent feedback, such as over-corrective control inputs (Van Leeuwen, De Groot, Happee, & De Winter, 2011). These thresholds and other aspects of the display were based on a subjective interpretation of safe and comfortable driving during pilot tests in the driving simulator. Moreover, a 1 s headway is the lowest minimum recommended value for maintaining safe headway and is associated with comfortable driving (Taieb-Maimon & Shinar, 2001). To illustrate functionality, Figure 2 shows four different states of the display.



(a) (b)

(c) (d)

Figure 2. Four possible states of the RWND: (a) Lead car brakes strongly – THW is greater than 1.5 s (decelerate but close the gap); (b) Lead car is accelerating moderately – THW is greater than 1.5 s (accelerate and close the gap); (c) Lead car is accelerating hard – THW is less than 1.0 s (accelerate but widen the gap); (d) Lead car brakes strongly – THW is between 1.0 s and 1.5 s (decelerate and maintain current gap).

In the simulator environment, the RWND was projected onto the rear window of the lead car. The size and position of the display was adjusted based on the relative distance and position of the lead car, so that for the driver it seemed as if the display was attached to the lead car. Figure 3 shows the simulator environment with RWND. In this snapshot, the lead car was decelerating and the follower was instructed to increase the gap with respect to the lead car.

Figure 3. The RWND in the fixed-base driving simulator.

2.2. Driving simulator

The experiment was conducted using a fixed-base simulator manufactured by Green Dino, with customized data collection. The simulator consisted of a cabin, an Intel Pentium IV 3.0G computer that ran both the graphics and driving scenario of the simulator software, and a projector screen which provided a 180 degree horizontal field of view for the driver seated in the cabin. The virtual world was projected by three LCD projectors (front projector NEC VT676, brightness 2,100 ANSI lumens, contrast ratio 400:1, resolution 1,024 × 768 pixels; side projectors NEC VT470, brightness 2,000 ANSI lumens, contrast ratio 400:1, resolution 800 × 600 pixels). Integrated visuals of the road and other traffic, along with the car's features such as dashboard and mirrors, were shown on the projector screen. The cabin of the simulator resembled the front portion of a regular passenger car and was equipped with gas, brake, and clutch pedals, steering wheel, and indicators. The simulator software recorded driver actions to control the vehicle and the state of the vehicles in the virtual environment. The car model used in this study had an automatic transmission.

2.3. Participants

In total 22 drivers (17 men and 5 women) with an average age of 21.9 (*SD* = 1.8 years) and an average driving experience of 3.1 years (*SD* = 1.6 years) participated in the experiment. All were students at TUDelft, aged from 19 to 26, and were required to have held a driving license for a minimum period of one year. All participants gave informed consent. Participants were not paid for taking part in the experiment.

2.4. Experiment design and procedures

On arrival at the test location, the participants filled in an intake questionnaire, which recorded their personal information (name, age, and contact details), driving experience, and self-rated driving skills (Appendix D.3). They were also asked if they spent more than one hour playing video games on a weekly basis. Drivers were randomly allocated into two groups. The experimental group (*n* = 12; 4 women; mean age = 21.5; mean driving experience = 2.8 years) was tested with the RWND and the control group (*n* = 10; 1 woman, mean age = 22.3; mean driving experience = 3.4 years) was tested without the RWND.

Prior to the experiment, the participants were given written instructions. These explained how to use the simulator, including how to adjust the seat position and control the car with the steering wheel, gas, and brake pedals. The instructions also included details about the duration of the test and indicated that the task was to drive behind a lead car with a constant THW throughout the whole session, without overtaking. Both groups were informed verbally that the recommended THW was between 1 and 1.5 s. For the participants tested with the RWND, the operation of the display was also explained in writing. They were informed that they drove properly if the THW was kept within the acceptable range with respect to the front car. Before the start of the experiment, they were also given verbal instructions on how to interpret the display. They were free to ask questions or seek further explanation about the system prior to starting the test.

Each participant completed one training session and two test sessions. The training session was a short introduction of 300 s in an urban environment that allowed drivers to become acquainted with driving in the simulator. The training session exposed drivers to common maneuvers, including negotiating busy or slow traffic, slowing down, speeding up, changing lanes, and steering without the RWND. After training, drivers from both groups completed two 700 s driving sessions. The control group completed these sessions without the RWND. Participants from the experimental group drove the first session without the RWND and the second session with this display. During the experimental group’s second session (driving with the RWND), the vertical arrows switched off after 550 s without prior notice. This was done to quantify whether arrows were effective to help drivers comply with keeping the headway between 1 and 1.5 s, even after the feedback was absent. The acceleration information from the horizontal bar remained unchanged. After each session, the participants stepped out of the simulator for a break of approximately 3 minutes. The design of the experiment is summarized in Figure 4. The lead car in both 700 s sessions had a predefined, but subjectively unpredictable, speed profile with speeds ranging from 15 km/h to 110 km/h representing a highway with busy traffic (see Figure 5). The speed profile of the lead car was set to be identical for every test. However, small random variations existed between individual sessions, induced by the modeled dynamics of other traffic.

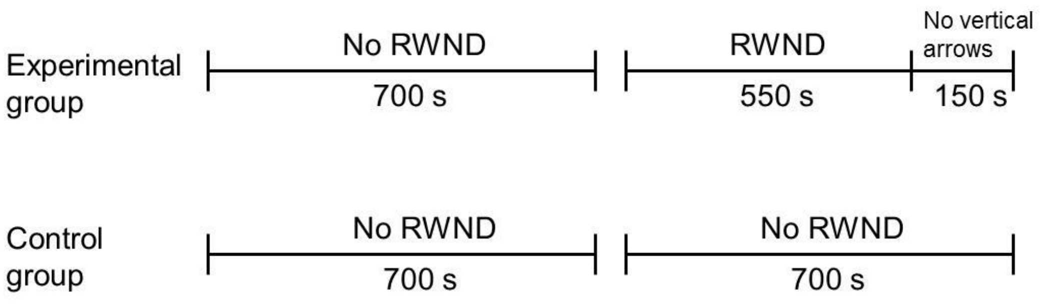


Figure 4. The experimental design.

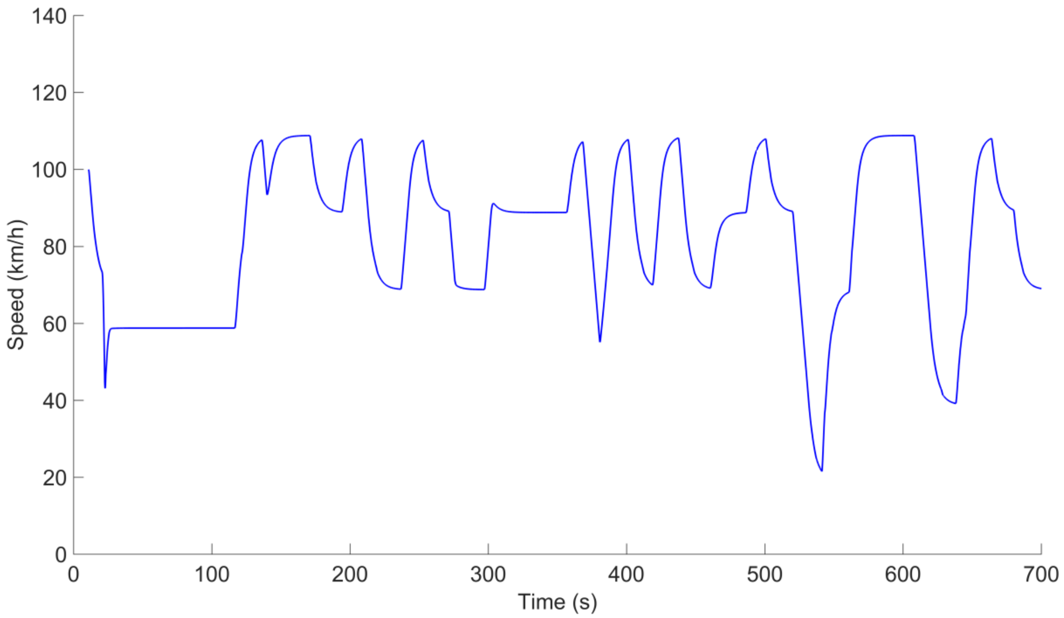


Figure 5. Speed profile of the lead car.

2.5. Dependent measures

2.5.1. Traditional performance measures

The traditional car-following performance measures calculated for each session and each participant were as follows:

- *Minimum distance (m)*: The minimum distance between the front bumper of the participant's car and the rear bumper of the lead car.

- *Maximum distance (m)*: The maximum distance between the front bumper of the participant's car and the rear bumper of the lead car.

- *Mean distance (m)*: The average distance between the front bumper of the participant's car and the rear bumper of the lead car.

- *Mean relative speed (*Δv*) (m/s)*: The average of the absolute difference between the speed of the participant's car and the speed of the lead car.

- *Mean acceleration (*m/s^2*)*: The average of the absolute acceleration of the participant's car.

- *Mean jerk (*m/s^3*)*: The average of the absolute jerk of the participant's car. Jerk is used to evaluate the speed of the brake and throttle operations.

- *THW < 1 s (% of time)*: The percentage of time that the THW was less than 1 s, indicating that the following vehicle was too close.

- *1 s ≤ THW < 1.5 s (% of time)*: The percentage of time that the THW was between 1 and 1.5 s.

- *THW ≥ 1.5 s (% of time)*: The percentage of time that the THW was greater than 1.5 s.

2.5.2. Driver-model parameters

Parameters of a generic driver model were estimated for each session and each participant, aiming to quantify the effect of the RWND on the driving behavior in terms of feedback delays and gains. This study used a common linear car-following model (Abbink, 2006; Brackstone & McDonald, 1999; Helly, 1959). The acceleration a_i of the participant's car (i) was expressed as:

$$a_i(t) = K_v \Delta v_i(t-\tau) + K_d \left\{ \Delta x_i(t-\tau) - h_i(t) \right\} + K_a a_{i-1}(t-\tau) \tag{1}$$

$$h_i(t) = h_0 + h_v v_i(t) \tag{2}$$

With τ being the driver's visuomotor delay, Δv_i the speed difference between the lead and the participant's car, Δx_i the following distance and a_{i-1} the acceleration of the lead car. Variable $h_i(t)$ describes the desired following distance with h_0 representing the desired distance at standstill and

h_v an additional THW describing the dependence of the desired distance on the speed v_i of the participant's car. K_v, K_d, and K_a represent speed, distance, and acceleration gains. K_v and K_d are corrective feedback gains controlling relative speed and distance. The acceleration gain K_a represents feedforward control; when $K_a = 1$ the participant's car would follow the lead car perfectly. Such an acceleration gain is not commonly included in car-following driver models, but has been added here to describe the expected use of the acceleration display of the RWND.

A nonlinear Levenberg-Marquardt optimization algorithm was used to estimate the individual-driver parameters for each session. The model parameters were estimated by minimizing the squared deviation of predicted and measured vehicle motion. Realistic feedback delays were estimated when using an acceleration-based error criterion, while delays where often estimated to be zero when using a distance-based criterion. The parameter h_0 could only be estimated when distance was included in the criterion. In order to select the most appropriate error criterion, and to quantify the estimation accuracy, a sensitivity analysis was performed using a model simulation with known parameters and re-estimating the parameters for 10 sets of randomly selected initial parameters with 10 added noise realizations. Optimal accuracy was obtained with a criterion using the weighted sum of the errors in following distance and acceleration such that both constitute about 50% of the criterion. It was not possible to accurately estimate both parameters h_0 and h_v for this scenario due to their interacting role and, hence, a fixed value $h_v = 1$ as in Helly (1959) was adopted for all tests. With these choices all parameters except for the position feedback gain K_d showed estimation errors below 10%.

2.5.3. Subjective evaluation

After the second session, the participants were asked to step out of the simulator and complete a questionnaire. The responses were scaled from 1 (completely disagree) to 10 (completely agree), and focused on the drivers' subjective analysis of the simulated car-following task. Participants from the experimental group were also asked to rate the RWND's usefulness, readability, visibility, clarity, and distracting effect, as well as the amount of information it provided. A set of relevant questions was selected for describing the subjective rating on specific aspects of the tests and the display (Table 1).

2.6. Statistical analyses

The effect of the RWND was evaluated by (1) comparing the two sessions of the experimental group, and (2) by comparing the experimental group’s second session with the control group’s second session. Two comparisons served as negative control: (1) the two sessions of the control group were compared to determine whether performance in the simulator was stable and not distorted by learning effects, and (2) the experimental group’s first session and the control group’s first session were compared to verify whether group behavior was comparable, indicating adequate randomization.

The two groups were compared with an independent-samples *t* test, whereas the two sessions of the same group were compared using a paired *t* test. The Type I error rate (alpha) was set at .05. The analyses were all based on the data recorded between 60 s and 550 s per session. The first 60 s were excluded, because the car started from standstill, resulting in initially large THWs, and the driver variability occurring in the speedup phase of the car was not of interest.

Two analyses assessed the effect of two phases in the second session: (1) for the experimental group, the data between 60 s and 550 s was compared with the final 150 s (i.e., between 550 s and 700 s), and (2) the final 150 s of the experimental group were compared with the final 150 s of the control group.

With regard to the post-test questionnaire, descriptive statistics (means and standard deviations) were reported, and comparisons between experimental and control group were carried out using an independent-samples *t* test.

3. Results

3.1. Subjective evaluation

As shown in Table 1, drivers rated the simulator as moderately realistic and gave a low score to their ability to judge speed accurately (Q11). The RWND was rated positively on readability (Q12), amount of information (Q14), perceived effectiveness (Q16), and understandability (Q17) (6.3 to 8.3 on the scale from 1 = completely disagree to 10 = completely agree). Questions Q13 and Q15 resulted in low scores, indicating that the display was generally regarded as not being distracting, nor did it provide too much information. The relatively high standard deviation on Q13 was associated with two participants who reported that they found the RWND to be distracting (8 and 9 on the scale from 1 to 10). The preferences for driving a car with RWND (Q18), following RWND advice (Q19) and the potential to solve traffic jams (Q20) were rated as moderate to positive (4.7 to 6.7 on the scale from 1 to 10) with a high standard deviation, partly because one participant gave a rating of 1 in response to Q18, Q19, and Q20.

Table 1. Participants' subjective rating (means with standard deviations in parentheses) on a scale from 1 (completely disagree) to 10 (completely agree).

#	**Question item**	**Experimental group *M* (*SD*)**	**Control group *M* (*SD*)**	***p***
5	I had problems concentrating on the driving task.	4.0 (2.1)	4.0 (1.9)	1.000
7	The simulator is realistic.	5.6 (2.1)	4.3 (1.3)	.107
8	The simulator visual scene is realistic.	6.2 (2.1)	5.5 (2.1)	.443
9	The simulator controls are realistic.	4.8 (1.7)	4.7 (1.9)	.949
10	I was able to judge distances accurately.	5.3 (1.9)	5.8 (2.3)	.579
11	I was able to judge speed accurately.	4.3 (2.1)	5.2 (2.2)	.358
12	I was able to read the information given by the RWND at the advised distance.	7.2 (1.5)	-	-
13	The RWND was distracting me.	4.0 (2.4)	-	-
14	The RWND was giving me enough information.	6.8 (1.5)	-	-
15	The RWND was giving me too much information.	2.9 (1.9)	-	-
16	The RWND helped me to improve keeping the right distance to the preceding car.	6.3 (2.5)	-	-
17	I could understand the information given on the RWND.	8.3 (1.1)	-	-
18	I prefer driving with RWND over a car which is not equipped with a RWND.	4.7 (2.6)	-	-
19	In real traffic I would follow the advice of the RWND to help increase road capacity.	6.2 (2.4)	-	-
20	The RWND had great potential to help solve traffic jam problems.	6.7 (2.7)	-	-

Note. Q1 to Q11 were common for both groups. Q12 to Q20 were specific to the experimental group tested with RWND (n = 12 for the experimental group; n = 10 for the control group).

3.2. Traditional performance measures and driver-model parameters

For the experimental group using the RWND in session 2, several significant effects in both traditional measures (Table 2) and estimated model parameters (Table 3) were found, as compared to the control group in session 2 and the experimental group in session 1. With RWND, reductions were evident in the mean and maximum following distance, average speed difference (Δv), and time that THW exceeded 1.5 s. However the percentage of time that THW was below 1 s remained at the same level, suggesting that safety was not compromised. Figure 6 shows that the time percentage in which the time headway was between 1 and 1.5 s was greater in the RWND sessions than in the sessions in which the RWND was unavailable. This indicates that the RWND improved drivers' adherence to the instructed time headway range. At the same time, acceleration and jerk increased significantly, indicating more and/or stronger control actions.

Table 2 and Table 3 reveal no significant differences between the experimental and control groups in session 1, confirming their similarity. For the control group, which drove both sessions without RWND, THW exceeded a value of 1.5 less and was more frequently in the desired range of 1–1.5 s, in session 2 than in session 1, whereas no significant effects were found for the other measures, suggesting very limited learning effects between sessions.

Figure 7 shows a typical model result for one driver in one session. The distance is well predicted up to 160 s, but the driver allows a large gap at 175 s where the model maintains a shorter following distance. The distance, speed, and acceleration gains of the drivers' model are roughly doubled with the RWND, which indicates that drivers control activity increases with the use of the RWND.

These effects are highly significant for the speed gain K_v but not significant for the distance gain K_d and the acceleration gain K_a. The acceleration gain K_a is estimated to be negligible (< .02) in 6 out of 10 cases without RWND and in 3 out of 11 cases with RWND (in the optimization K_a was constrained to a minimum of zero). If drivers adopted an acceleration gain $K_a = 1$, they would follow the lead car perfectly and the feedback terms K_v and K_d would only be needed for additional correction of imprecise feedforward control. The estimated K_a values around 0.12 suggest that such behavior was not achieved, even with RWND. When using RWND, the estimated desired following distance at zero speed h_0 is reduced in agreement with the reduced mean and maximum distance, as shown in Table 2.

Table 2. Descriptive statistics of traditional performance measures.

Group and session – mean (*SD*)	Min distance (m)	Max distance (m)	Mean distance (m)	Mean Δv (m/s)	Mean acc (m/s^2)	Mean jerk (m/s^3)	THW <1s % of time	1≤ THW <1.5s % of time	THW ≥1.5s % of time
Session 1. Experimental group (RWND OFF)	13.9 (6.1)	134.3 (67.3)	57.2 (29.7)	2.11 (0.80)	0.57 (0.13)	0.45 (0.17)	17 (26)	20 (18)	61 (35)
Session 1. Control group (RWND OFF)	10.9 (5.4)	139.3 (64.6)	55.4 (25.4)	2.17 (0.59)	0.54 (0.10)	0.40 (0.11)	9 (10)	23 (18)	66 (24)
Session 2. Experimental group (RWND ON)	14.1 (4.4)	65.8 (18.9)	33.6 (6.8)	1.27 (0.31)	0.64 (0.09)	0.55 (0.17)	10 (10)	69 (12)	21 (12)
Session 2. Control group (RWND OFF)	11.9 (6.5)	99.0 (17.0)	45.7 (11.5)	2.04 (0.52)	0.59 (0.05)	0.43 (0.09)	12 (11)	34 (15)	54 (21)
Comparison - *p* values									
Experimental vs. Control (session 1)	.248	.861	.879	.846	.568	.400	.376	.711	.712
Experimental vs. Control (session 2)	.358	**<.001**	**.006**	**<.001**	.113	.065	.579	**<.001**	**<.001**
Session 1 vs. Session 2 (experimental group)	.945	**.004**	**.022**	**.003**	**.026**	**.019**	.240	**<.001**	**<.001**
Session 1 vs. Session 2 (control group)	.681	.079	.315	.589	.196	.435	.274	**.050**	**.048**

Note. Means of participants with standard deviations in parentheses, and *p*-values for group comparisons, *n* = 12 for the experimental group, *n* = 10 for the control group; All results based on the data recorded between 60 and 550 s of the sessions.

Table 3. Descriptive statistics of driver-model parameters.

Group and session – mean (*SD*)	VAF Δx	VAF acceleration	K_v (1/s)	K_d (1/s^2)	K_a (-)	τ (s)	h_0 (m)
Session 1. Experimental group (RWND OFF)	0.57 (0.16)	0.43 (0.15)	0.27 (0.12)	0.016 (.013)	0.076 (0.078)	0.72 (0.45)	30.4 (28.7)
Session 1. Control group (RWND OFF)	0.65 (0.10)	0.45 (0.09)	0.24 (0.06)	0.018 (.020)	0.079 (0.115)	0.80 (0.37)	25.9 (13.7)
Session 2. Experimental group (RWND ON)	0.59 (0.14)	0.45 (0.13)	0.58 (0.33)	0.097 (.171)	0.124 (0.115)	0.69 (0.19)	8.4 (4.3)
Session 2. Control group (RWND OFF)	0.63 (0.11)	0.44 (0.10)	0.24 (0.06)	0.026 (.020)	0.084 (0.124)	0.67 (0.35)	18.7 (8.7)
Comparison - *p* values							
Experimental group vs. control group (session 1)	.214	.735	.422	.789	.954	.643	.651
Experimental group vs. control group (session 2)	.465	.843	**.005**	.210	.444	.855	**.002**
Session 1 vs. session 2 (experimental group)	.768	.628	**.010**	.139	.257	.873	**.019**
Session 1 vs. session 2 (control group)	.469	.543	.558	.376	.921	.497	.137

Note. Means of participants with standard deviations in parentheses, and *p*-values for group comparisons, *n* = 12 for the experimental group, *n* = 10 for the control group; All results based on the data recorded between 60 and 550 s of the sessions. VAF = variance accounted for.

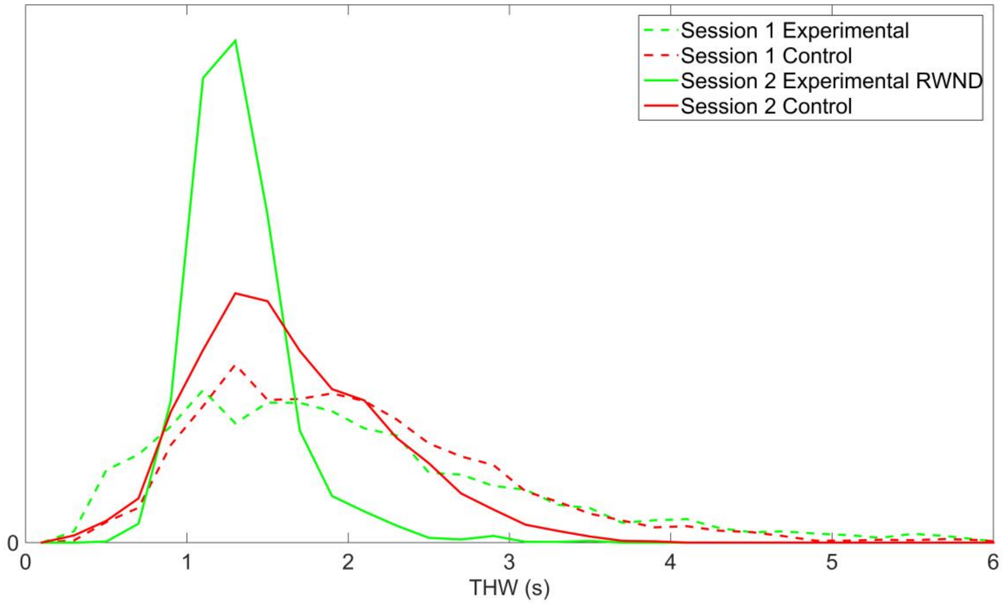


Figure 6. THW distribution for all four conditions.

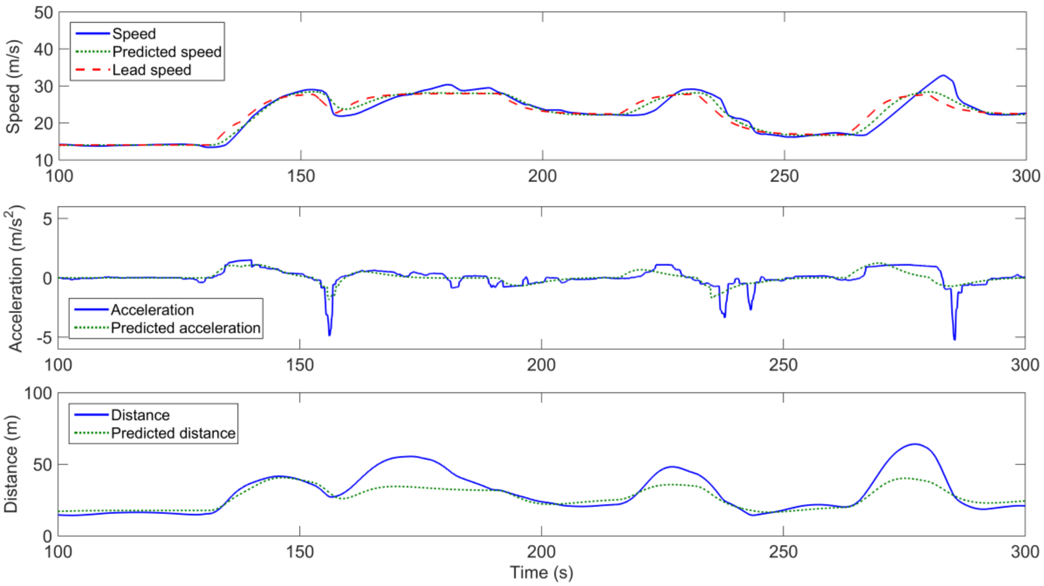


Figure 7. Test data and model fit for one of the participants (session 2, control group).

Of the 32 relationships probed in Table 2 and Table 3 (experimental group session 2 vs. control group session 2 & experimental group session 1 vs. experimental group session 2), 16 were significant at the .05 level, and 6 were significant at the .001 level. The *p* value for session 1 versus session 2 comparison of the experimental group regarding $1 < \text{THW} < 1.5$ equaled $4.9*10^{-8}$, with all 12 participants improving their performance. This indicates that even after applying a Bonferroni correction for multiple testing, by multiplying the *p* value by 32, the *p* value would still be extremely small and the risk of Type I errors would be negligible.

Finally, the results for the first and second phase of the RWND session were compared. The arrows indicating THW were switched off after 550 s without notifying the drivers. The acceleration display remained active during the entire session. With RWND in phase 2 the time that THW was in the recommended range of 1–1.5 s was reduced from 69% to 40% ($p < .001$) while such a trend was not observed in the control group in session 2 (from 34% to 39%, $p = .172$). This suggests that the THW arrows effectively assisted the driver. No further significant differences between phase 1 and phase 2 with RWND were found, possibly as a result of the short time frame involved (150 s with vertical indicators disengaged). In phase 2 of session 2 the mean Δv with RWND (1.21 m/s) was significantly ($p = .026$) lower than in the control group (1.72 m/s), indicating benefits of the RWND even when only the acceleration is displayed.

To illustrate the effects of the RWND on car-following behavior, the driver-model response for a simple scenario consisting of a ramped increase of lead-car speed was simulated. These simulations show the nominal driver behavior as captured by the model, and thus exclude unpredictable and/or time variant behavior as present in the original data. Figure 8 shows the predicted effect of the RWND simulating the average model parameters in session 2. Apparently, tighter nominal control is achieved with RWND. The conventional measures (see Table 2) and the model parameters (see Table 3) of the experimental group indicated substantial variations between subjects. Figure 9 illustrates these between-subject variations by plotting simulated responses using the estimated parameters of individual participants.

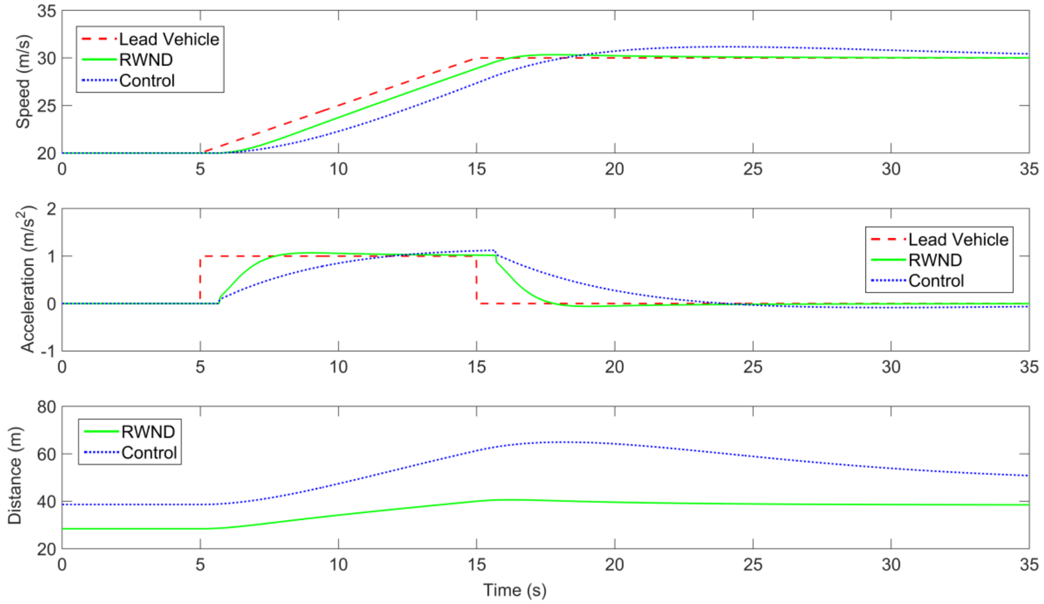


Figure 8. The simulated response of the control group and the experimental group (RWND) to a 10 s, 1 m/s^2 constant lead vehicle acceleration using the average of the identified driver model parameters.

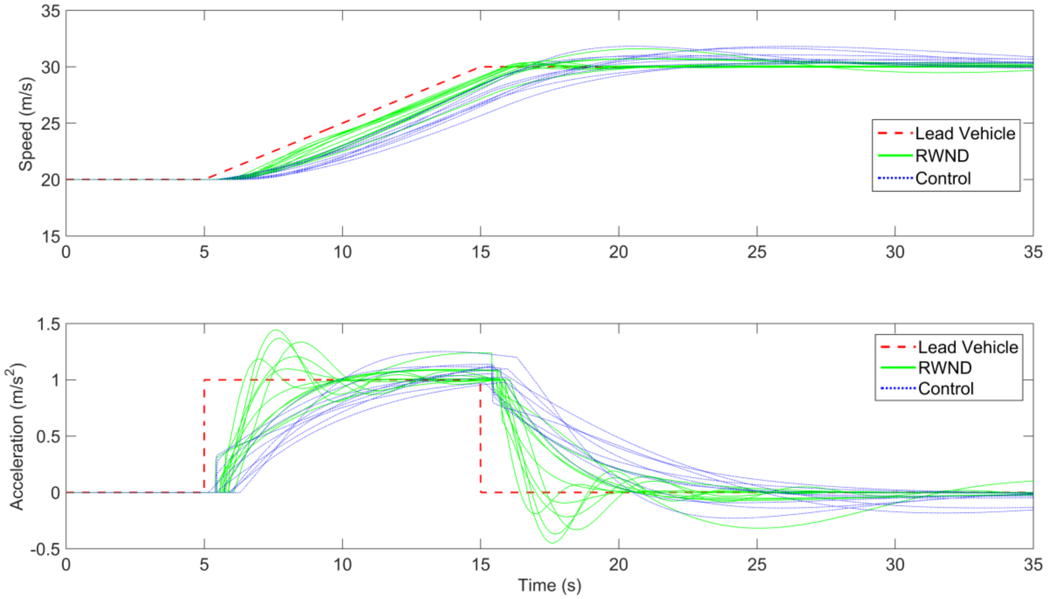


Figure 9. The simulated responses of the drivers in the control group and the experimental group (RWND) to a 10 s, 1 m/s2 constant lead vehicle acceleration using the identified driver model parameters.

4. Discussion

This study presented a novel advisory display to improve drivers' car-following performance. The display projected acceleration and THW information onto the rear window of the lead car. The most important finding is that drivers with RWND outperformed the control group by achieving a smaller headway and reduced speed differences with respect to the lead car. Drivers with RWND maintained more homogenous headways during car following, with a significantly reduced occurrence of large gaps between vehicles. The occurrence of short THW (< 1 s) did not increase because of the RWND, suggesting that safety was not compromised. This performance gain was achieved with a significantly larger acceleration and jerk in the RWND condition indicating enlarged control effort. Note that this study was performed in a fixed-base simulator, where the lack of haptic and vestibular acceleration cues may have induced abrupt gas and brake pedal actions.

The driver-model parameters provided complementary information with respect to the traditional performance measures and gave information about how drivers use distance, speed, and acceleration information with and without the RWND. The time delay identified from the model was roughly similar to the values reported by Brackstone and McDonald, (1999) and Brackstone, Waterson, & McDonald, (2009). The driver-model parameters showed that drivers with RWND achieved enhanced car-following performance by adopting higher control gains. This result confirms earlier findings that drivers are capable of using augmented information on a lead car's acceleration during car-following (Sultan, Brackstone, & McDonald, 2004). The driver-model parameters indicate that the acceleration gain K_a is relatively low and varies between participants even when an acceleration cue is displayed. It may be that the acceleration cue merely helps drivers to detect speed changes more effectively. Figure 8 and Figure 9 illustrate nominal driver behavior as captured by the driver model. While Figure 8 presents 'average' behavior, Figure 9 shows substantial between-driver variations. To investigate the advantages of using RWND in complex traffic flows, the driver model (with parameter sets representing between-driver variations) can be applied to simulate RWND benefits in microscopic traffic-flow models.

The questionnaire revealed that the display was generally regarded as not distracting, suggesting that the RWND may have potential in real vehicles. Participants rated the driving simulator as moderately realistic and indicated that they had some difficulty judging speed accurately. These results correspond to previous research using the same driving simulator (De Groot, De Winter, Mulder, & Wieringa, 2011), and may be explained by the lack of vestibular motion cues, the limited resolution provided by the LCD projectors, and the lack of binocular depth cues. However, driver-simulator validity is an on-going field of investigations, and simulators have proven to be valuable tools as far as relative comparisons between experimental conditions are concerned (Kemeny & Panerai, 2003; Reymond & Kemeny, 2000).

Van der Hulst, Meijman, & Rothengatter (1999) argued that the late detection of lead-car deceleration is the primary human error in distance keeping. A study by Brackstone et al. (2009) showed that the behavior of the car in front has the largest influence on the chosen headway, as compared to other factors such as road type and traffic-flow condition. Muhrer and Vollrath (2010) examined the role of expectation in car following (e.g. when a lead car suddenly brakes). Their findings suggest developing assisting systems that generate anticipation in drivers, especially in a car-following driving situation where the lead car is driving at a constant speed and drivers cannot foresee the need for action. Knowing that a primary source of information during the car-following task is available through the brake lights of the leading car, different brake light arrangements have been tested to improve the accuracy and speed of drivers' reaction time and their situation awareness (Alferdinck, 2004; Alferdinck & Theeuwes, 1995). A dynamic brake light concept has been studied as well in a driving simulator, showing that subjects braked sooner when brake lights were artificially expanding as a function of the hazard. This concept was most effective for poor visibility conditions (e.g. at night without headlights), making the lead vehicle brake lights most salient (Li, 2006; Li & Milgram, 2008). The RWND effect is comparable to the effect of brake lights, as they both communicate the lead vehicle action to the driver. The distinguishing factor is that, unlike traditional brake lights, the RWND communicates the magnitude of acceleration and deceleration to the driver, helping him to better implement the start, duration, and level of control action in response to lead-car behavior. Given that human understanding and interaction with ACC is one of the barriers for achieving ACC benefits in different working regimes (Marsden et al., 2001), a display similar to RWND could support drivers in their understanding of ACC and next generation technology, such as CACC. Some examples of this include visualizing the performance and limits of ACC systems, indicating proper conditions for initiating transitional maneuvers such as gap creation, joining or separation, and authority exchanges between car and driver.

The RWND could be placed on the inside of a rear window, possibly integrated with an extra brake light, such that the rear view is not compromised, or it could be placed externally, taking into account legal requirements for brake lights and regular illumination. The height and dimensions of the display should follow regulations in place for the Center High Mounted Stop Lamps (CHMSL) in passenger cars (Kahane & Hertz, 1998), whereas variables such as color and intensity would have to follow the limits drafted in relevant standards (UNECE, 2008). Finally, it should be noted that the current RWND is designed to be displayed on a rear window, in order to assist following cars that are not equipped with CACC. Similar results are expected if the information is shown on a head-up display in the following car itself.

5. Conclusion and recommendations

This paper reported on a Rear Window Notification Display (RWND) developed to help drivers follow cars precisely and accurately. Displayed on the rear window of the lead car, the RWND showed the time headway and acceleration of the lead car in an intuitive way for the human driver. The simulator-based study showed that the RWND is capable of enhancing driver car-following behavior, reducing mean time headway (THW) and speed and distance variance at the expense of more control effort. Drivers did not consider the RWND to be a distraction, possibly because the arrows did not appear when THW was within the desired range of 1–1.5 s. In conclusion, the results of this study suggest that the RWND can be used along with CACC to increase network capacity without degrading safety. Mental workload and distraction effects should be evaluated in further experiments, including on-road testing in a naturalistic environment and a more diverse population.

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CHAPTER 6

Automated driving: human-factors issues and design solutions

Abstract

The goal of this paper is to outline human-factors issues associated with automated driving, with a focus on car following. First, we review the challenges of having automated driving systems from a human-factors perspective. Next, we identify human-machine interaction needs for automated vehicles and propose some available solutions. Finally, we propose design requirements for Cooperative Adaptive Cruise Control.

Saffarian, M., De Winter, J. C. F., & Happee, R. (2012). Automated driving: Human-factors issues and design solutions. *Proceedings of the Human Factors and Ergonomics Society 56th Annual Meeting*, Boston, MA, USA, 2296–2300. (adapted with minor textual changes)

CHAPTER 6: Automated driving: human-factors issues and design solutions

1. Introduction

Automation has entered many aspects of our daily life, including the way we transport ourselves. Adaptive Cruise Control (ACC), lane keeping assistance, and blind spot assistance are being introduced into vehicles at a rapid pace. Such systems provide information and advice (e.g., warnings, suggested actions) or control the vehicle in specific longitudinal or lateral tasks. Although fully automated cars have been under investigation for about half a century (e.g., Burnham & Bekey, 1976; Geddes, 1940; Hallé & Chaib-Draa, 2005; Ioannou & Chien, 1993; Levine & Athans, 1966; Naus, Vugts, Ploeg, Molengraft, & Steinbuch, 2009), they are not yet available for public use. The challenges of vehicular automation are more than technical. Neale and Dingus (1998) stated that "the hardest problems associated with an Automated Highway System (AHS) … are 'soft'; that is, they are human factors issues of safety, usability, and acceptance, as well as institutional issues. These are problems that are many times more difficult to overcome and must be overcome, largely, in parallel with the traditionally 'hard' technological issues" (p. 111).

2. Challenges of interaction between human and automation

One might be inclined to think that automation eventually reduces the human's task to the selection of the travel destination. However, the reality is that even with highly automated systems, the contribution of the human operator is crucial (Bainbridge, 1983). Automation shifts the human's driving tasks from manual control to supervisory control of the conducted maneuvers (Geyer, Hakuli, Winner, Franz, & Kauer, 2011). Being 'out of the loop' may lead to overreliance, behavioral adaptation, erratic mental workload, skill degradation, reduced situation awareness, and an inadequate mental model of automation capabilities (cf. Endsley & Kiris, 1995; Parasuraman, Sheridan, & Wickens, 2000). In the following, we briefly revisit these issues in the driving context.

2.1. Overreliance

Overreliance (or complacency) is defined as a situation where the human does not question the performance of automation and insufficiently counterchecks the automation status. Distraction and poor judgment are two major causes of accidents (Peters & Peters, 2002). Overreliance on automation could make these problems worse. Kazi, Stanton, Walker, and Young (2007) found that drivers are not good in developing appropriate trust levels with respect to the reliability level of ACC.

2.2. Behavioral adaptation

Rajaonah, Tricot, Anceaux, and Millot (2008) showed that drivers who often use ACC had a lower perceived risk and lower workload than infrequent users of the system. An experiment by Rudin-Brown & Parker (2004) showed that drivers using ACC may be more tempted to engage in activities other than driving. Drivers using ACC tend to adopt higher speeds and shorter headways than drivers without ACC (Hoedemaeker & Brookhuis, 1998), a phenomenon which can be explained by the risk homeostasis theory (RHT) (Ward, 2000; Wilde, 1988). The RHT states that humans adapt their behavior when their perceived risk changes, to restore their target level of preferred risk.

2.3. Erratic mental workload

Automated systems have the potential to relieve the human of tasks that are complex, dangerous, or temporally demanding. Consequently, automation reduces mental workload in routine situations (e.g., Ma & Kaber, 2005; Stanton & Young, 2005). However, automation can also increase mental workload in unexpected situations (Vahidi & Eskandarian, 2003). Lee (2006) summarized several examples from the aviation and shipping industry where poorly designed automation results in an improper increase of workload.

2.4. Skill degradation

Loss of manual control skills due to automation is a serious concern in the highly automated aviation industries (Damos, John, & Lyall, 1999). Automation not only results in loss of psychomotor dexterity but also contributes to degradation of the cognitive skills required to accomplish the task successfully (e.g., Parasuraman et al., 2000).

2.5. Reduced situation awareness

High levels of automation can prevent humans from receiving feedback within a proper time window, can diminish understanding of the process under control, and result in degraded event detection and response (Norman, 1990; Sarter & Woods, 1997; Wickens, 2008; Young & Stanton, 2002). An experimental study by Spiessl & Hussmann (2011) showed that compared to manual control of the steering wheel, operators of an automated steering system adopted longer reaction times. A related issue is carrying out inappropriate actions for the mode that the automation is in, a phenomenon known as mode error (Degani, Shafto, & Kirlik, 1999). Research has shown that lack of mode awareness can significantly increase the response time of the driver (Horiguchi, Suzuki, Nakanishi, & Sawaragi, 2010). In a driving simulator experiment, Stanton, Young, & McCaulder (1997) showed that a third of the participants were unsuccessful in reclaiming control of the vehicle without collision.

2.6. Inadequate mental model of automation functioning

Automation does not control the vehicle the same way as a human does. Because of sensory limitations and regulatory requirements, automation systems have a restricted working envelope (Zheng & McDonald, 2005). For example, although ACC systems can maintain steady headway and constant speed, radars used in ACC have a limited operating range. Drivers could fail to reclaim control of the vehicle due to not clearly understanding the ACC's functional limitations (e.g., Stanton & Young, 2000).

3. Main interaction functions of human and automated car

Because of vehicular automation, humans are more engaged in supervision and intervention and less involved in manual control and continuous compensation of the vehicle (Sheridan, 1999). With ACC, humans are currently required to handle new tasks including initialization (e.g., headway setting), monitoring automation status, and takeover control (e.g., when approaching a sharp curve). Humans need to interact with the automation system for two main functions (adapted from Ran, Leight, Johnson, & Huang, 1997): (a) authority transitions, (b) human-vehicle instruction and feedback. In the following, we explain these functions.

3.1. Authority transition

An authority transition is defined as the timing and procedure of transferring responsibility from the human to automation system, and vice versa. Some situations requiring a transition are automation failure, road blockage, severe weather conditions, sudden maneuvers by another vehicle, and operator preference. A proper automation system should avoid automation surprises, and facilitate proper trust on automation (Adell, Várhelyi, & Fontana, 2011). The human should be aware of the automation system’s limits well in time and be able to take over the vehicle control when needed (Pauwelussen & Feenstra, 2010).

3.2. Human-to-vehicle instruction and vehicle-to-human feedback

Not only the presence of the feedback is important, but feedback should also be provided in a timely and useful manner. Humans may miss nonsalient warnings, whereas too salient warnings are annoying (Lee, McGehee, Brown, & Nakamoto, 2007). Feedback provided too early or inappropriately (i.e., false alarms) can result in distraction, ignoring the alarm, or shutting down the alarm system entirely (Meyer & Bitan, 2002; Parasuraman & Riley, 1997). Abe and Richardson (2005) showed that drivers trust early collision alarms more than late alarms.

Displays and automation settings may need to be configurable based on operator preference. Setting customization, however, can be a double-edged sword because of potential confusion by other users.

4. Potential solutions for interaction of human and automation

The driver-automation interaction mechanism deals with achieving the functions and purposes addressed above. In the following, we present some available frameworks.

4.1. Shared control

Several researchers have argued that interactions between human and automation should not merely consist of activations and deactivations. They have proposed developing appropriate frameworks to keep drivers involved in the control loop (Stanton & Young, 2000), allow drivers to understand the machine’s capability (Seppelt & Lee, 2007), and support the acquisition of situation awareness with a minimum of cognitive effort.

Shared control is a framework whereby the human and automation cooperate to achieve the required control action together. This approach should realize automation benefits (e.g., fast response, accurate control) while avoiding problems such as the out-of-the-loop unfamiliarity and mode errors (Flemisch et al., 2012). Abbink, Mulder, and Boer (2012) developed a haptic gas pedal and steering which has been tested as a medium for shared control for car following and curve negotiation. The gas pedal stiffness adapts according to the headway to the following car. The human can still overrule and change the distance by using more or less force on the pedals. De Winter and Dodou (2011) provided a critical reflection of the literature on the effects of shared control on road safety. They argued that force feedback should not be provided continuously, but only when deviations from acceptable tolerance limits arise.

4.2. Adaptive automation

Variation in driving conditions (e.g., infrastructure, traffic rules, traffic density, and weather) and drivers’ population (e.g., age, gender, and experience) justify designing automation systems that can adapt to these differences. Adaptive interfaces can reduce the driver’s mental workload by filtering the presentation of information according to situational requirements. Piechulla, Mayser, Gehrke, and Konig (2003) implemented such a filter as a projective real-time workload estimator based on an assessment of the current traffic situation. In a driving-simulator study, Lee et al. (2007) quantified driver sensitivity to different ranges of brake duration and magnitude. They suggested that their findings could be used to create ACC algorithms and develop brake pulse warnings. Adaptive automation can also be used to monitor and alert drivers to their impairments, such as drowsiness and inattentiveness (Victor, 2000).

4.3. Use of an information portal

Providing the relevant information at the suitable moment can assist drivers to improve their situation awareness (Seppelt & Lee, 2007; Stanton & Young, 2000). An information portal can be used to communicate required actions, provide augmented feedback (e.g., improved rear-view vision or enhanced night vision), provide recommendations for better performance (e.g., eco-driving feedback), or to highlight risky driving conditions (e.g., blind spot assistance). In automated systems, information portals can be used to avoid automation surprises and increase the acceptance rate of the system. Information portals can be implemented as visual displays, or by complementing the visual task-intrinsic information with non-visual (audio) cues (e.g., Risto & Martens, 2011; Van den Broek, Netten, Hoedemaeker, & Ploeg, 2010).

4.4. New training methods

Because the role of the human changes from manual to supervisory control, changes in driving licensing and driver training may be needed. Future drivers may have to demonstrate competency in computer skills and mode-conflict resolution, while psychomotor skills will be less relevant. Educating drivers on the capabilities and limits of automation has been proposed as a preventive strategy to minimize adverse behavioral adaptation (Rudin-Brown & Parker, 2004; Stanton & Young, 2005).

Automation can be used to develop new types of training. In theory, a consistent, accurate, and tireless automated trainer is capable of capturing every event in the vehicle, including erratic and unsatisfactory human behavior. Sensor systems can reveal transient errors or driver drowsiness, which might remain unnoticed by human trainers. The use of automated trainers can result in a quantitative evaluation of the operator, making it possible to provide feedback of human error in real-time (e.g., Panou, Bekiaris, & Touliou, 2010).

5. Requirements and potential solutions of human interaction with CACC

We propose using the Cooperative Adaptive Cruise Control (CACC) system as a main platform to integrate human-automation control. The CACC system enables a platoon of two or more vehicles driving with automated longitudinal control at a set distance parameter (e.g., time headway) through shared kinematic information (Naus et al., 2009). The scheme of such platoon is shown in Figure 1. Cooperative cars can be used in driving in reduced visibility, such as in fog, at night or on unlit motorways, and for driving long periods. In these conditions, cooperative vehicles have the potential to outperform humans in terms of safety, traffic flow, and eco-driving. In the CACC framework, one can distinguish three main maneuvers: platooning, joining, and splitting. Joining and splitting are transition maneuvers, whereas platooning involves stationary motion.

In the following, we discuss design requirements, expected human-factors issues, and design solutions for interaction between drivers and CACC. These findings are based on the human-factors issues discussed in Section 2 the CACC goals and functions briefly introduced above, and a consideration of the main interaction functions in Section 3.

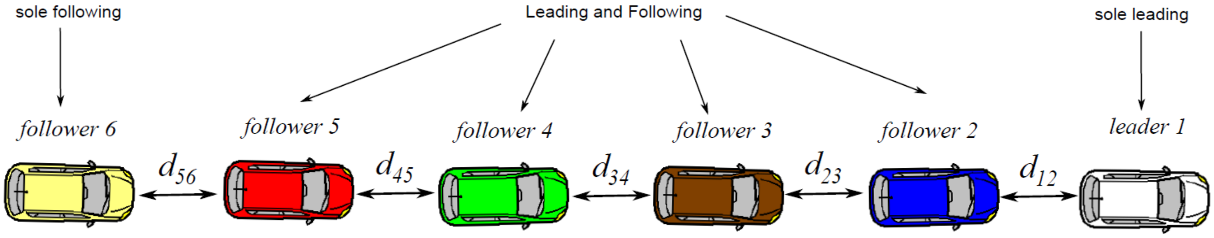

Figure 1. CACC-equipped platooning vehicles.

5.1. CACC design requirements

We assume that all vehicles are equipped with equivalent CACC systems. Thus, the issue of interaction with heterogeneous technologies is not considered.

System Initialization. The system should make drivers aware whether the CACC is enabled or disabled. Initialization should result in a clear driver understanding of what the headway and speed setting implies in terms of stopping distance and hazard. The system should enable drivers to distinguish the difference between driving in platoons and individual driving. The system should enable drivers to easily retrieve and change the headway and speed settings, and the initialization setting should not pose too much extra workload on drivers (i.e., no erratic mental workload).

Platooning. The tailgating behavior of CACC cars should gain acceptance of drivers. Drivers should not experience automation surprises, such as very rapid acceleration and deceleration, sudden closure of inter-vehicle gap, unexpected change of the topology of the platoon, and poor string stability. The system should clarify and communicate the constraints that driving in platoons pose in terms of feasible maneuvers (i.e., have a correct mental model). For example, the system should make it clear for drivers that they are not able to override the headway instantly. Drivers should have an option to come out of the platoon in a safe and smooth manner (i.e., proper trust) and should not experience very low workload levels.

Joining and Splitting can be initiated either by the platoon's control hierarchy (Hallé & Chaib-Draa, 2005) or by the human. Drivers should be able to take over vehicle control when coming out of the platoon. Drivers should not be surprised by the automation's behavior, either initiated by the controller or driver. Joining and splitting should be performed with as few as possible steps to avoid confusion (i.e., avoid mental overload). The system should make drivers aware of the start, end, and the process of the joining and splitting transitions.

5.2. CACC design solutions

Initialization. The process of selecting a headway and speed during driving is distracting and disconnects the driver from the driving task. In addition, there is a risk that the driver does not fully understand what the setting implies. The use of additional icons can be distracting, while the learning and remembering involved can impose an extra workload on drivers. An alternative option is to use a system consisting of an adaptive setting based on the driver's history of manual car following. The system can choose the average minimum headway distance and maximum speed that the driver held for more than a set period (e.g., one minute) within the most recent hour of driving. Such a mechanism will prevent the driver from having to face an unexpected following distance and bring forward an expected following distance. The CACC should be turned on by the driver who should be informed of the system status by visual/audio cues to maintain correct awareness.

Joining. When the system is on, the car should start cruising at the set speed, resort to car following when approaching a slower vehicle, and brake to a complete standstill if needed. In other words, a platoon can be joined from the rear without driver intervention. However, drivers have to be informed about large speed differences, and may be advised to change lanes to better follow their desired speed. Here, adaptive automation may be used, monitoring the driver state, and providing person-specific advice to the driver. Drivers should be aware of situations where joining is not feasible due to the maneuvers of other members of the platoon or any other constraints, such as maximum length of the platoon because of the road layout. Thus, transitions in the platoon that pose constraints on any other platooning members should be communicated to the constrained members.

Platooning. The state of the system should be clearly communicated to the driver as "Platoon Mode" through a communication portal or icon. This mode can be announced audibly and repeated at certain intervals to keep the human aware. Again, using adaptive automation, frequency, and intensity should be raised when humans are potentially less attentive (e.g., when they do not provide any input for a prolonged time).

When platooning, humans should not experience unannounced or abrupt changes. Topology changes in the platoon and the splitting off and joining of other members should be announced to avoid surprises and lowering of trust in the automation. Humans should be aware of the limits of maneuvers. For example, a human cannot close the headway beyond a certain threshold and should not steer instantly. To avoid sudden steering, haptic feedback can be used on the steering wheel.

Splitting. Drivers should be able to safely end their platooning. One potential solution is that the human increases the headway to an allowable limit. When this limit is reached the CACC system disables and the driver is informed of the shutdown via an information portal.

6. Conclusion

This chapter reviewed several human factors challenges of automated driving. We applied the issues, needs, and solutions for vehicle automation to the concept of CACC and proposed an interaction mechanism between humans and CACC. The proposed system has few modes, keeps drivers engaged in the control loop, and facilitates cooperation between drivers and their vehicles as well as among other vehicles.

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CHAPTER 7

General discussion

1. Main findings

This thesis presented the results of four driving simulator experiments investigating the effects of the availability and quality of visual information on the performance of drivers in safety-critical longitudinal control tasks. Chapters 2 to 4 examined the effects of *diminished* visual information. The tasks were avoiding collision with a decelerating preceding car (Chapter 2), stopping at a target (Chapter 3), and following a lead car in fog (Chapter 4). Chapter 5 examined to what extent *augmented* visual information can improve the performance of drivers in a car following task.

A primary finding of these experiments is that continuous availability of visual information is crucial to safe driving. The results showed that realistic yet unfavourable timing of visual distraction (a glance away from the road when the headway is short and the lead vehicle brakes hard) causes a collision with the lead car (Chapter 2). Moreover, when the screens are occluded, people cannot precisely stop their car at a designated spot on the road even though in theory a constant brake input would suffice (Chapter 3). Drivers also adopt short headways in order to see the lead car and achieve a smooth steering performance in foggy conditions (Chapter 4). Oppositely, car following performance of drivers improves when drivers have direct access to visual information about the action of the lead car and the deviation of the desired headway with respect to the lead car (Chapter 5).

In the remainder of this chapter, we interpret the results of Chapters 2 to 5, discuss lessons learned from the methods, and reflect on future research opportunities for enhancing driving performance and safety.

2. Interpretation of results using control theoretic models

The results of Chapters 2 to 5 can be interpreted in terms of the control strategies that may have been used by the participants. Mortimer et al. (1970) argued that during normal (i.e., non-emergency) braking, drivers rely on a closed loop control strategy. This means that drivers control the deceleration of their vehicle to nullify the discrepancy between the required deceleration to come to a stop at the target position/spot on the road and their observed actual deceleration. In Chapter 3, when the screen was not occluded and TTA was large, participants used closed loop control to regulate their brake pedal and stop at the designated spot on the road. However, when the screens were occluded, participants could not apply the necessary closed loop control. Put simply, if the screen is blanked, participants cannot see how far they are from the stopping position and therefore do not know how hard to brake. While this result is not necessarily surprising, it reaffirms that drivers cannot perform a standard and highly repetitive braking task without visual information feedback.

Regarding emergency situations, Mortimer et al. (1970, p. 28) indicated that “it is likely that the braking is performed in a completely open loop manner”, meaning the driver does not use visual feedback. For low TTA values (Chapter 3) or a short headway (Chapter 2) participants applied an open loop braking approach (i.e., they ‘slammed’ the brakes) regardless of the availability of visual information. Nonetheless, when visual information was available, participants *did* use some of this visual information even in the most urgent condition (TTA = 2 s, in Chapter 3). This was evident from the magnitude of the maximum depression of the brake pedal, which was larger without occlusion as compared to with occlusion. Thus, braking is not completely open loop even in the most critical braking situations. In line with Flach (1999), it is argued that braking is partly open loop and partly closed loop (Fig. 1). The less time is available to avoid a collision, the more the driver brakes in an open loop manner and the less likely he is to use visual feedback.

Chapter 4 was concerned with understanding the paradoxical phenomenon that participants adopted shorter headways in fog compared to clear weather. It was found that in fog, the feeling of risk was lowest when the lead car was just in sight. These findings can be explained with the help of a “perceptually grounded driver model for car following in fog” proposed by Boer et al. (2008) (Figure 2). The difference between the model in Figure 1 (used for explaining the results of Chapters 2 and 3) versus the model in Figure 2 (used for explaining the results of Chapter 4) is that the latter model makes use of an additional outer ‘tactical’ (cf. Michon, 1985) loop of target headway adjustment.

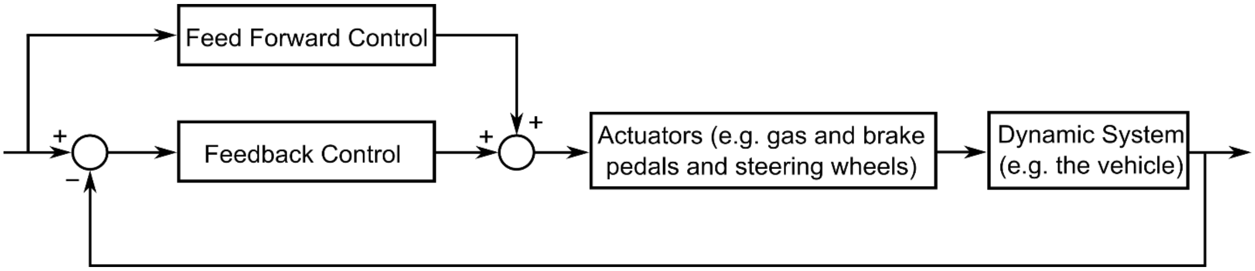

Figure 1. A combination of feed forward (open loop) and feedback (closed loop) control (figure based on *McRuer, D. T., & Jex, H. R. (1967). A review of quasi-linear pilot models. IEEE Transactions on Human Factors in Electronics, HFE-8(3), 231–249*).

Specifically, the model by Boer et al. (2008) consists of a closed loop feedback mechanism in which the visual angle error (defined as the difference between the desired and current visual angle of the lead car) and the visual angle rates are the perceptual inputs that determine the throttle and brake actions of a driver. The feedback mechanism becomes active when the change in the visual angle exceeds the driver's perceptual sensitivity. An important aspect of this model is that perceptual sensitivity improves (i.e., the Just Noticeable Difference [JND] decreases) when the distance headway (Dist variable in Figure 2) is smaller. According to the model, drivers can reduce their target headway (Dist* variable in Figure 2) to achieve a more accurate control performance. In other words, a shorter target headway has advantages in terms of improved perception of the distance to the lead car, allowing the driver to reduce the variability of headway and associated collision risk. In fog, these advantages of headway variability reduction are stronger than the advantages of increasing the target headway itself (Boer et al., 2008). Boer et al. (2008) fitted this model to empirical driving simulator data and showed that it is capable of explaining the short-headway-in-fog phenomenon. Accordingly, the model can explain why drivers' sensed feeling of risk is sometimes smaller for smaller headways. It is noted, however, that the model is a simplification of the true state of affairs; it does not account for the effects of lead car lighting nor for situations in which the lead car cannot be seen at all.

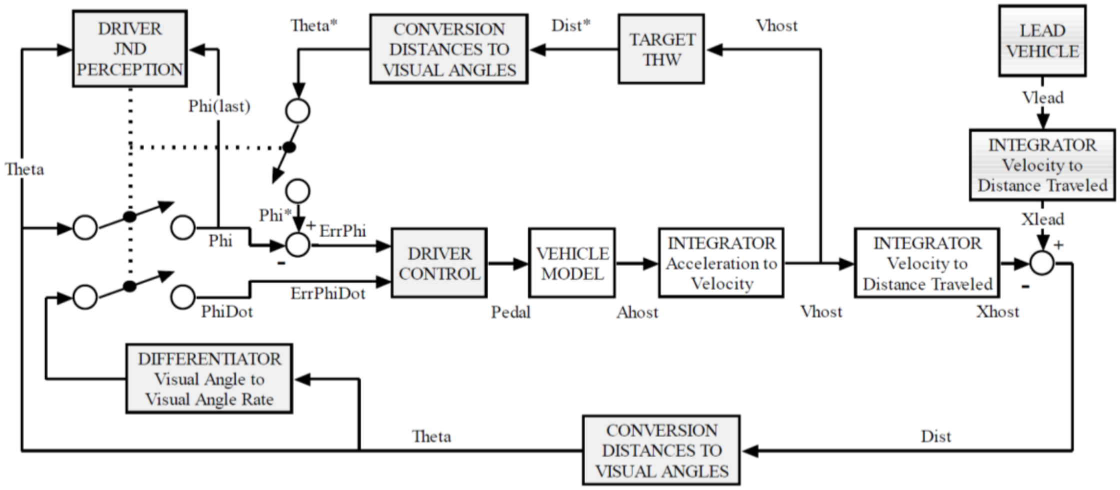

Figure 2. A perceptual model used to explain driver behaviour in fog. THW = Time headway, Ahost/Vhost/Xhost = acceleration/velocity/distance of driver’s vehicle. Xlead = distance of the lead vehicle. Dist = headway distance, Theta = visual angle of subtended by the width of the lead vehicle, Phi = the driver’s internal representation of Theta, PhiDot = the driver’s internal representation of the rate of change of Theta, JND = Just Noticeable Difference, * refers to values corresponding to driver’s target THW. Phi* and Theta* are always identical (figure from *Boer, E. R., Caro, S., & Cavallo, V. (2008). A perceptually grounded driver model for car following in fog. Proceedings of the Driving Simulation Conference Europe (pp. 247–257), Monaco*). Reprinted with kind permission of Erwin Boer.

The structure of Figure 2 can also be used to explain why the Rear Window Notification Display (RWND) system enhanced the car following performance of drivers. The RWND not only bypassed the perceptual sensitivity threshold of drivers by providing direct operational information about the acceleration and deceleration of the lead car, but it also provided tactical advice about the time headway that drivers should adopt. Both theoretical traffic models and traffic observations suggest that traffic jams are formed by large traffic flow fluctuations (Sugiyama et al., 2008). The results of Chapter 5 showed that the use of the RWND reduced both the mean and standard deviation of time headway without increasing potentially unsafe headways of less than 1 s.

Apart from relying on these ‘traditional’ measures of longitudinal control performance, Chapter 5 also included a control model and associated driver parameter identification technique. The results showed that the RWND caused participants to respond with higher gains to spacing errors with respect to the lead car. The combination of methods used in Chapter 5 (i.e., self-report questionnaires, performance measures, and control theoretic modelling) is regarded as a unique contribution of this thesis, and may be of value to assess other types of hard (technological) or soft (behavioural) safety interventions.

3. Validity of perception in driving simulators

In Chapter 3, it was found that participants substantially and proportionally underestimated the distance to a stationary lead car. Distance underestimation is not unique to virtual reality; it has also been observed in real-life driving tasks, although not as severe as the 70% underestimation as found in Chapter 3. Nonetheless, in an on-road study, Rockwell (1972) found that drivers underestimated the distance headway by as much as 30% to 60%. Several explanations for distance underestimation were proposed in Chapter 3, including the lack of several monocular and binocular depth cues in the driving simulator, and the fact that participants had little time to consciously reflect on the distance estimations, meaning they had to rely on Gibsonian direct perception (DeLucia, 2008).

Regardless of the causes of the distance underestimation, these data do pose some concerns for the validity of our results with respect to real-life applications. Distance perception bias in simulators may alter the risk perception of drivers and affect drivers’ control performance. Another issue is that the simulators used in this thesis did not feature vestibular motion feedback. Several researchers have argued that simulators without motion feedback do not possess absolute validity, but are still valid for making relative comparisons and assessments of effect sizes (De Winter, Van Leeuwen, & Happee, 2012; Sidaway, Fairweather, Sekiya, & McNitt-Gray, 1996).

Having access to perceptually valid simulator setups is particularly important for understanding drivers’ collision avoidance behaviour, considering that on-road testing of safety-critical tasks is often dangerous and thus unethical. Simulators provide experimental validity and have been used as accurate tools to assess effect sizes between conditions (relative validity). For example, simulators have been found valid for examining whether using an in-vehicle HMI improves or deteriorates driving performance compared to not using the HMI. For example, Klüver et al.

(2016) recently showed that effect sizes in rear cars generalize to low fidelity fixed-based simulator setups. Validation studies of driving simulators are becoming more and more common, partially driven by industrial needs to develop cost-effective research tools to determine the effectiveness of in-vehicle technology prior to conducting on-road studies (e.g., Klüver, Herrigel, Heinrich, Schöner, & Hecht, 2016).

4. Limitations of driving simulator research and future research directions

The experiments of this thesis consisted of simple driving tasks. There was at maximum one other road user, and the driving tasks were limited to maintaining the lane, following and responding to the vehicle ahead, or stopping on a specified position on the road. While this is different than the realm of our roads, this design was used deliberately. A relatively new and sensible view about driving simulators is that simulators should *not* be developed to be as realistic as possible, and accordingly that unnecessary distractors should be eliminated from the virtual environment (Lee, 2004; Parkes, 2012). In line with this view, in designing the tasks and the instructions of these experiments, best effort has been made to remove distraction elements by using simple driving tasks and traffic environments. Thus, the results of this thesis should be seen as a reference that may be applicable to future research into the availability and quality of visual information in more complex driving environments.

One of the questions in controlled driving experiments is how ecologically valid are the simulated scenarios in terms of the type and the frequency of the critical events. The headways (0.5 s, 1.25 s), occlusion periods (0.4 s, 2.0 s), deceleration values (1.7 vs. 6.5 m/s^2), and moments of occlusion onset (i.e., when the situation is stationary) are realistic and resemble the values observed or tested in previous research (see Chapter 2). However, the total duration of the experiments was relatively short (about 60 minutes total simulated driving time). The selected occlusion periods represent two extremes for not looking at the driving scene. While it is expected that the responses to other occlusion durations fall in between the results obtained for these two conditions, the sensitivity of drivers to the changes in the occlusion period requires further investigation.

For statistical reasons a large number of event data needed to be collected per participant. Accordingly, in the short-lasting experiments of this thesis, participants were exposed to multiple emergency stops or severe deceleration events. In real traffic, drivers are faced with a much smaller frequency of such events. In other words, despite that the selected conditions (headways, occlusion durations, lead car decelerations) are common in real traffic, the frequency with which emergency stops occurred was higher than the real traffic. Note that this limitation applies to many other traffic safety research, such as hazard perception studies, where the scenarios such as pedestrians stepping onto the road are rare in real driving per time unit, but are still *proportionally* important contributors to accidents. Still, the question remains regarding the extent to which the present results are transferable to the real world.

The risk level that is experienced by participants probably represents a conservative estimate for reality. At the same time it is likely that drivers demonstrate a startle response only at collision-prone conditions in real traffic where the perceived risk is high. It is not possible to test drivers in near-collision conditions due to ethical concerns and potential harm that is involved for participants. However, it is possible to construct collision and near-collision conditions that occur in naturalistic observations studies in simulator environments and compare drivers' responses in the controlled simulator setting with naturalistic response data. Nevertheless, the questions over the validity of the frequency and the perception of risk-prone events are applicable to any driving simulator research unless the research is duplicated in both simulators and the real world.

Because it is not possible to truly 'surprise' a person more than once in controlled experiment conditions, there was almost no surprise effect in these experiments. Drivers experienced a moderate-to-low workload and perceived risk in the experiments of Chapters 2 and 3, in which they were faced with repeated critical events (Table 1). The driving task of Chapter 4 consisted of relatively monotonous car following without emergency situations and resulted in overall low workload (Table 1). Only when the headway was extremely short did participants experience a high level of risk, but overall the task was experienced as undemanding (see Chapter 4).

Table 1. Mean self-reported workload (measured with the NASA TLX) and mean self-reported risk, for the experiments in Chapters 2, 3, and 4.

	Chapter 2			Chapter 3				Chapter 4			
	Brake lights (B)	No brake lights (N)	Occlusion (O)	Occlusion, G_{any}	Occlusion, G_{at}	Control, G_{any}	Control, G_{at}	Clear automated	Clear manual	Fog automated	Fog manual
TLX Mental demand	48	50	60	54	55	39	35	25	27	42	51
TLX Physical demand	41	40	48	29	38	26	25	17	23	25	35
TLX Temporal demand	36	33	45	32	43	33	30	18	18	29	34
TLX Performance	37	31	51	50	55	34	46	24	28	30	39
TLX Effort	50	56	57	58	57	39	50	21	27	31	43
TLX Frustration	36	21	35	52	42	26	26	24	20	37	39
I had a feeling of risk	35	37	37	33	45	19	22	44	20	63	59

Note. The width of the bars linearly corresponds to the value in the cell, ranging from 0% (no bar visible) to 100% (cell entirely filled with the bars). The questionnaire used a 21-tick scale. The TLX items ranged from *very low* to *very high*, except for the performance item of the TLX, which ranged from *perfect* to *failure*. The risk item ranged from *strongly disagree* to *strongly agree*. For the experiment of Chapter 5, the NASA TLX was not used.

One remedy to overcome the limits of studying collision-prone situations in a controlled setting like a simulator study is to gather a large amount of naturalistic driving data that contains a sufficient number of (almost) identical collision and near collision events, and verify the results of the controlled experiments with such events. Projects such as SHRP 2 (Victor et al., 2015) are on track to generate a database for this purpose using a large fleet of instrumented vehicles. A more cost-effective method is to gather a large amount of naturalistic data using smart phone technologies (Saffarian, 2015).

While the conditions tested in this thesis are among the most frequent tasks that happen on the road, their fidelity can be extended by including constraints that can exist during driving. One of these constraints is being part of a traffic stream. At present, little is known about how drivers take into account the impact of their actions on the safety of surrounding vehicles (Meskali, Barbet, Espié, & Bootsma, 2006). For example, do drivers assess the ability of the following car when hard braking is required? And if so, what cues do they use to make such assessment? It is also unknown to what extent drivers are capable of mitigating the collision risk involved in such multi-vehicle situations. Future research could employ multi-driver simulators, an approach that is gaining popularity in human factors research (Hancock & De Ridder, 2003; Houtenbos et al., 2016; Lehsing, Kracke, & Bengler, 2015; Muehlbacher, Rittger, & Maag, 2014; Oeltze & Schießl, 2015).

In this thesis occlusion was used to measure the effect of visual distraction on drivers' braking behavior (Chapter 2) and to measure the effect of visual information during braking on drivers' braking behavior (Chapter 3). Senders, Kristofferson, Levison, Dietrich, and Ward (1967) used the occlusion technique to measure the information demand (duration and frequency of looking at the driving scene) of highway driving. The same method can be used to assess whether changes in the quality of the visual information affect the information needs of drivers, how such potential changes affect their performance, and whether adaptation mechanisms (e.g. close following in fog) and technological aids (e.g. RWND) change their information demand.

5. Towards a collision-free world?

This thesis highlighted some of the limitations of humans when they rely on visual information in safety-critical driving tasks (Chapters 2 to 4). This thesis also showed that automation technology per se will not reduce drivers' feelings of risk (Chapter 4) nor actual risk (Chapter 6). Finally, this thesis showed that drivers and technology can work *cooperatively* to enhance safety (Chapter 5). The proposed Rear Window Notification Display (RWND) improved car following performance, was generally not regarded as a distraction, and has the potential to be used along with automation technology, such as Cooperative Adaptive Cruise Control. It is argued that humans and machines will increasingly cooperate and that the human-machine interface will become an increasingly crucial component of connected vehicles until wholly automated driving is technically feasible.

6. References

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Appendices

There are major concerns about lack of reproducibility of behavioral research experiments (e.g., Open Science Collaboration, 2015). These appendices are included to enhance the reproducibility of the experiments in this thesis. Without these appendices and photos a follow-up researcher will have difficulty getting the exact same results as I did because of the lack of knowledge about the protocol and the specific headway conditions.

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Appendix A: Experimental Materials of Chapter 2

Appendix A.1: Consent Form

Investigators:	Professor John W. Senders (Thesis Advisor), Mehdi Saffarian (PhD Candidate)
Duration of the experiment:	Less than 150 minutes

Dear participant,

The goal of this research is to investigate how drivers use visual information of a simulated driving scenario to control their brakes. The results of this experiment will be statistically analyzed and published in a scientific paper. All results will be treated anonymously and only used for research purposes.

Simulator controls
The experiment will be conducted in a fixed-base driving simulator. You are able to control the simulated car with the steering wheel, brake pedal and gas pedal. Gear-changing is always automatic.

Test conditions
In this experiment you will complete the following stages:

1. Reading the consent form and completing the intake questionnaire (10 minutes).

2. Simulator Training (10 minutes)
Task: Follow a lead vehicle at a safe distance and match the speed of the lead vehicle. The lead vehicle brakes at different deceleration rates. Your task is to slow down your own vehicle **with controlled braking** to avoid collision with the lead car and position your vehicle at a minimum acceptable safe distance for yourself. The brake light of the lead car is on.

3. Driving Tests A (20 minutes)
Task: Drive your vehicle at a set speed of 60 MPH while following a lead car. The lead car maintains a set distance from your vehicle, and suddenly slows down at certain moment of the scenario. When the lead car brakes, your task is to slow down your own vehicle **with controlled braking** to avoid collision with the lead car and position your vehicle at a minimum acceptable safe distance for yourself. The brake light of the lead car is on.

4. Driving Tests B (20 minutes)
Task: Similar to Driving Test A. The only difference is that the brake light of the lead car is off.

5. Driving Tests C (20 minutes)
Task: Similar to Driving Test A. The only difference is that when the lead car starts to brake, the scene is occluded (i.e. the screen turns off) for a short period. You should start braking **after the occlusion clears** (i.e. the screen turns back on). The brake light of the lead car is off.

6. Filling out the Post Experiment Questionnaire (10 minutes)

Note for Training and Driving Sessions
- In between driving tasks A, B and C, you will also fill a NASA TLX task load questionnaire.
- In all braking responses, try to control the brake force and avoid slamming on the brake.
- The orders of experiments A, B and C will randomly be changed among the participants.

Appendix A: Experimental Materials of Chapter 2

- In Driving tests A and B: you can start braking at any time after the lead starts braking.
- In Driving test C: You should start braking at any time after the end of the occlusion.
- Drive swiftly but safely, as you do in normal driving conditions.
- Always try to keep your car accurately centered in the right lane; do not change lanes.
- In driving sessions, A, B and C, you should maintain your speed at 60 MPH except the short period after the slowing down and braking of the lead vehicle.
- Keep your right foot on the gas pedal before the start of the brake.

Simulator sickness

Driving in a simulator may sometimes cause simulator sickness symptoms such as headache and nausea. These symptoms resemble car sickness or motion sickness on a boat. If you start to feel uncomfortable in any way, we advise that you immediately withdraw from this experiment. You are able to stop your cooperation in the experiment whenever you wish, without any personal negative consequences. Please inform the experimenter of any uncomfortable feeling immediately.

Compensation

You will receive $12 CAD / hour (total: $30 CAD for 2.5 hours) as a token of appreciation for your participation at the end of this study.

Confidentiality

All information obtained during the study will be held in strict confidence. You will be identified with a study number only, and this study number will only be identifiable by the primary investigator. No names or identifying information will be used in any publication or presentation or will be transferred outside the investigators of this study.

Please be advised that we video-record the experimental trials with four small web-cameras. One camera will be pointed at you, one will capture the steering wheel, one the pedals, and the final camera will capture the overall scene. We will use two other cameras on and near the dashboard to track and record where you are looking during the experiment. The videos will only be seen by the investigators and their research collaborators. Faces will be blurred in any video used in public presentations.

Participation

Your participation in this study is voluntary. You can choose to not participate or withdraw at any time. You will be compensated for your time at $12 CAD / hour rate. Feel free to ask any questions during the experiment. If you read all the above items and have no further questions at this moment please proceed to the following:

Consent

I have had the opportunity to discuss this study and my questions have been answered to my satisfaction. I consent to take part in the study with the understanding that I may withdraw at any time. I have received a signed copy of this consent form. I voluntarily consent to participate in this study.

Date : ………………………………

Participant Name : ……………………………… Participant Signature: ………………………………

Further Questions

If you have any questions about this study after the experiment, please contact:

Mehdi Saffarian: Phone: 647.825.3358, Email: mehdi.saffarian@mail.utoronto.ca

You may also contact the Ethics Review Office at ethics.review@utoronto.ca or 416-946-3273, if you have questions about your rights as a participant.

Appendix A.2: Information Questionnaire

1. Number - A or B?

2. How old are you?

☐

3. What is your gender?

○ Male
○ Female
○ Other
☐

4. Do you have a normal or corrected-to-normal vision?

○ Yes
○ No

5. Do you wear glasses or contacts when you drive?

○ Yes - Contacts
○ Yes - Glasses
○ I don’t wear glasses or contact lenses when I drive

6. Do you have an active driving license?

○ Yes
○ No

7. If so what type of drivers license do you have?

○ G1 or G1 equivilant
○ G2 or G2 equiviliat
○ G or G equivilant

8. Which year you obtained your first driving license?
☐

9. On average, how often do you drive?

○ Less than 1-2 times per year
○ More than 1-2 time per year but less than once per month
○ More than once per month but less than once per week
○ More than once per week but less than once per day
○ At least once per day

10. On average, how long you drive per week?

○ More than 1,000 kilometers
○ Less than 1,000 kilometers but more than 100 kilometeres
○ Less than 100 kilometers but more than 10 kilometeres
○ Less than 10 kilometers

11. On average, how long you drive per year?

○ More than 100,000 kilometers
○ Less than 100,000 kilometers but more than 10,000 kilometeres
○ Less than 10,000 kilometers but more than 1,000 kilometeres
○ Less than 1,000 kilometers but more than 100 kilometers
○ Less than 100 kilometers

12. How many times you drove in a simulator before? (If never used a simulator enter 0)

13. How often do you drive with Cruise Control?

○ Less than 1-2 times per year
○ More than 1-2 time per year but less than once per month
○ More than once per month but less than once per week
○ More than once per week but less than once per day
○ At least once per day

14. How often you play video game?

○ Less than 1-2 times per year
○ More than 1-2 time per year but less than once per month
○ More than once per month but less than once per week
○ More than once per week but less than once per day
○ At least once per day

15. How often you ride a bicycle?

○ Less than 1-2 times per year
○ More than 1-2 time per year but less than once per month
○ More than once per month but less than once per week
○ More than once per week but less than once per day
○ At least once per day

16. Is English your first language?

○ Yes
○ No

17. Are you right handed?

○ Yes
○ No

18. Do you use your right foot to operate the gas and brake pedal?

○ Yes, I use my right foot to operate both pedals
○ No, I use my both feet to operate both pedals

19. Are you color blind?

○ Yes
○ No

20. Are you allergic or sensitive to adhesive or alcohol?

○ Yes
○ No

21. Have you experienced irreversible hearing loss?

○ Yes
○ No

22. Do you frequently experience migraine headaches?

○ Yes
○ No

23. Do you experience motion sickness?

○ Yes
○ No

24. Do you experience claustrophobia?

○ Yes
○ No

25. Are you pregnant?

○ Yes
○ No

26. Rate the following:

I have good steering skills (for instance in cycling or computer games)

Completely disagree 1 2 3 4 5 6 7 8 9 10 Completely agree

Appendix A.3: NASA TLX workload assessment

W1-Mental Demand: How mentally demanding was the task?

Very Low   Very high

W2-Physical Demand: How physically demanding was the task?

Very Low   Very high

W3-Temporal Demand: How hurried or rushed was the pace of the task?

Very Low   Very high

W4-Performance: How successful were you in accomplishing what you were asked to do?

Perfect   Failure

W5-Effort: How hard did you have to work to accomplish your level of performance?

Very Low   Very high

W6-Frustration: How insecure, discouraged, irritated, stressed, and annoyed were you?

Very Low   Very high

During this experimental condition:

P1- I had a feeling of risk.

Strongly disagree   Strongly agree

P2-I think I drove more safely than the average participant.

Strongly disagree   Strongly agree

P3-I found the driving task easy.

Strongly disagree   Strongly agree

P4-I felt confident in my own capability to act appropriately.

Strongly disagree   Strongly agree

Appendix A.4: Post-Experiment Questionnaire

Q1. Did you use any particular strategy while performing **with no brake light and with no occlusion** scenario (circle one)? YES NO

If yes, please explain your strategy briefly in the space below:

Q2. Did you use any particular strategy while performing **with no brake light and with occlusion** scenario (circle one)? YES NO

If yes, please explain your strategy briefly in the space below:

Q3. Did you use any particular strategy while performing **with brake light** scenario (circle one)?

YES NO

If yes, please explain your strategy briefly in the space below:

Considering the following tasks during braking: **(A) Keeping the vehicle centered in a lane** and **(B) Avoiding collision with the following car**

Please answer the following questions:

Q4. When you performed **with brake light** scenario:

I. **(A)** was more difficult than **(B)**
II. **(A)** was less difficult than **(B)**
III. **(A)** was as difficult as **(B)**

Q5. When you performed **with no brake light and with occlusion** scenario:

I. **(A)** was more difficult than **(B)**
II. **(A)** was less difficult than **(B)**
III. **(A)** was as difficult as **(B)**

Q6. When you performed **with no brake light and with no occlusion** scenario:

I. **(A)** was more difficult than **(B)**
II. **(A)** was less difficult than **(B)**
III. **(A)** was as difficult as **(B)**

Q7. Do you workout (circle one)? YES NO

If yes, please mention what sports you play:

Q8. Compared with others your age, how would you rate your overall VISION? (If you wear glasses or contacts, rate your corrected vision when you are wearing them)

Excellent Good Average Fair Poor

Q9. Please indicate how you consider your leg strength (circle one)?

Lower than average average above Average

Q10. On a scale of 1 to 10, with 1 being "very unsafe" and 10 being "very safe", how safe a driver do you think you are?

Very unsafe 1 2 3 4 5 6 7 8 9 10 Very safe

Q11. In the past five years, how many times have you been stopped by a police officer and received a WARNING (but no citation or ticket) for a moving violation (i.e. speeding, running a red light, running a stop sign, failing to yield, reckless driving, etc.)?

Q12. In the past five years, how many times have you been stopped by a police officer and received a CITATION OR TICKET for a moving violation?

Q13. In the past five years, how many times have you been in a VEHICLE CRASH where you were the driver of one of the vehicles involved?

Appendix B: Experimental Materials of Chapter 3

Appendix B.1: Consent Form

Location of the experiment:	University of Toronto, Department of Mechanical and Industrial Engineering 164 College Street, Roseborough Building, Room 313
Investigators:	Professor John W. Senders (Thesis Advisor), Mehdi Saffarian (PhD Candidate)
Duration of the experiment:	Less than 90 minutes

Dear participant,

The goal of this research is to investigate how drivers use visual information of a simulated driving scenario to control their brakes. The results of this experiment will be statistically analyzed and published in a scientific paper. All results will be treated anonymously and only used for research purposes.

Simulator controls

The experiment will be conducted in a fixed-base driving simulator with 180-degree field of view. You are able to control the simulated car with the steering wheel, gas pedal, brake pedal and cruise control system. Gear-changing is always automatic.

Test conditions

In this experiment you will complete the following stages:

7. Reading the contest form and completing intake questionnaire (10 minutes)

8. Reaction Time Measurement (5 minutes)

Task: Follow the instructions and react (click the mouse) as fast as possible

9. Training Session with the Simulator (10 minutes)

Task: Familiar yourself with the simulator control and its driving conditions

10. Distance Estimation Test (10 minutes)

Task: Verbally estimate the distance from your seat to the back of the vehicle in front (in meters or feet, whichever you are more convenient with)

11. Driving Tests A and B: two main driving sessions with the task of braking behind a vehicle right after hearing a beep OR after occlusion (30 minutes)

Task: Avoid collision with the stopped vehicle in front; bring the car to stop at 2 meters behind the stopped vehicle (2 meters is indicated with a cone during the driving)

12. Post Test Questionnaire (5 minutes)

Note for Training and Driving Sessions

- Drive swiftly but safely; avoid collisions with the car in front.
- Always keep your car accurately centered in the right lane; do not change lanes or overtake.
- In driving sessions, cruise control should be activated and set at 60 MPH. You don’t need to press the gas pedal.
- Keep your right foot on top of the gas pedal before the start of the brake but do not press the gas pedal.
- After braking, cruise control is no longer activated. At the start of the next trial, make sure to reactivate cruise control and check its set speed. The experimenter can help you with that.

Simulator sickness

Driving in a simulator may sometimes cause simulator sickness symptoms such as headache and nausea. These symptoms resemble car sickness or motion sickness on a boat. If you start to feel uncomfortable in any way, we advise that you immediately withdraw from this experiment. You are able to stop your cooperation in the experiment whenever you wish, without any personal negative consequences. Please inform the experimenter of any uncomfortable feeling immediately.

Compensation

You will receive $13 CAD / hour (total: $20 CAD for 90 minutes) as a token of appreciation for your participation at the end of this study.

Confidentiality

All information obtained during the study will be held in strict confidence. You will be identified with a study number only, and this study number will only be identifiable by the primary investigator. No names or identifying information will be used in any publication or presentation. No information identifying you will be transferred outside the investigators of this study.

Please be advised that we video-record the experimental trials with four small web-cameras. One camera will be pointed at you, one will capture the steering wheel, one the pedals, and the final camera the overall scene. We will use two other cameras on and near the dashboard to track and record where you are looking during the experiment. The videos will only be seen by the investigators and their research collaborators. Faces will be blurred in any video used in public presentations.

Participation

Your participation in this study is voluntary. You can choose to not participate or withdraw at any time. You will be compensated for your time at $13 CAD / hour rate. Feel free to ask any questions during the experiment. If you read all the above items and have no further questions at this moment please proceed to the following:

Consent

I have had the opportunity to discuss this study and my questions have been answered to my satisfaction. I consent to take part in the study with the understanding that I may withdraw at any time. I have received a signed copy of this consent form. I voluntarily consent to participate in this study.

Date : ………………………………

Participant Name : ……………………………… Participant Signature: ………………………………

Further Questions

If you have any questions about this study after the experiment, please contact:

Mehdi Saffarian: Phone: 647.825.3358, Email: mehdi.saffarian@mail.utoronto.ca

You may also contact the Ethics Review Office at ethics.review@utoronto.ca or 416-946-3273, if you have questions about your rights as a participant.

Appendix B.2: Post-Experiment Questionnaire

Q1. Do you workout?

Q2. What sports you play?

Q3. Please indicate how you consider your leg strength (circle one)?

Lower than average   average   above Average

Q4. Did you use any particular strategy while performing the braking task <u>without occlusion or beep sound</u> (circle one)?   YES   NO

If yes, please explain your strategy briefly in the space below:

Q5. Did you use any particular strategy while performing the braking task <u>with occlusion</u> (circle one)?

YES   NO

If yes, please explain your strategy briefly in the space below:

Q6. Did you use any particular strategy while performing the braking task <u>with beep sound</u> (circle one)?

YES   NO

If yes, please explain your strategy briefly in the space below:

Considering the following tasks: **(A)** Keeping the vehicle centered in a lane AND **(B)** Stopping the vehicle at a marked position on the road

Please answer the following questions:

Q7. When you did the <u>without occlusion or beep sound</u> scenarios:

I. **(A)** was more difficult than **(B)**
II. **(A)** was less difficult than **(B)**
III. **(A)** was as difficult as **(B)**

Q8. When you did the <u>with occlusion</u> scenario:

I. **(A)** was more difficult than **(B)**
II. **(A)** was less difficult than **(B)**
III. **(A)** was as difficult as **(B)**

Q9. When you did the with beep sound scenario:

I. **(A)** was more difficult than **(B)**
II. **(A)** was less difficult than **(B)**
III. **(A)** was as difficult as **(B)**

Note1. The Information Questionnaire of the experiments reported in Chapters 3 and 4 are identical.

Note2. The NASA TLX workload assessments of the experiments reported in Chapters 1 to 4 are identical.

Appendix B.3: Screenshots of the Distance Estimation Test. Note that the green marker on some of the screenshots was not visible during the experiment.

Distance Gap = 160 m

Distance Gap = 120 m

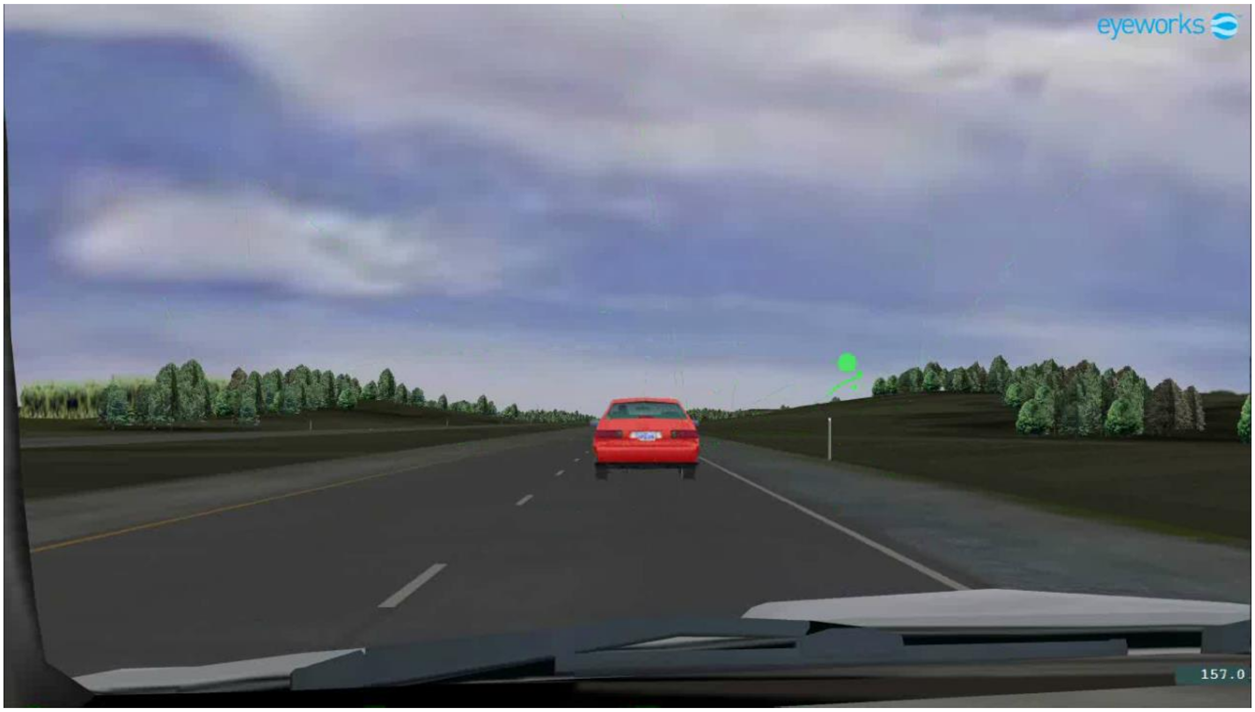
Appendix B: Experimental Materials of Chapter 3

Distance Gap = 80 m

Distance Gap = 60 m

Appendix B: Experimental Materials of Chapter 3

Distance Gap = 40 m



Distance Gap = 30 m

Appendix B: Experimental Materials of Chapter 3

Distance Gap = 20 m

Distance Gap = 15 m

Appendix B: Experimental Materials of Chapter 3

Distance Gap = 10 m

Distance Gap = 5 m

Appendix C: Experimental Materials of Chapter 4

Appendix C.1: Consent Form

Location of the experiment: TU Delft. Faculty Mechanical, Maritime and Materials Engineering (3mE)
Biomechanical Engineering Department (BMechE)
Driving Simulator Lab; room 4A-0-36

Duration of the experiment: 60 minutes

Dear participant,

The goal of this research is to investigate how visibility (presence or absence of fog) and adaptive cruise control (a system that automatically keeps a constant following distance to the car in front) influence driving performance and behavior. The results of this experiment will be statistically analysed and published in a scientific paper. All results will be treated anonymously and only used for research purposes.

Simulator controls

The experiment will be conducted in a fixed-base driving simulator with 180-degree field of view. You are able to control the car with the steering wheel, throttle, and brake pedal. In 50% of the sessions, the adaptive cruise control will be operative, which means that you only have to use the steering wheel. Gear-changing is always automated; do not use the clutch pedal or gear lever.

Test conditions

The experiment consists of one training session, and four test sessions. In the training session you will have an opportunity to experience how each of the test sessions feel. The training session is about 8 minutes and each of the test sessions are about 7 minutes. You will test all the following conditions in random order:

1. Manual car following in clear visibility
2. Automated car following in clear visibility
3. Manual car following in fog condition
4. Automated car following in fog condition

Before each test, you will be informed which test condition will be the next one.

Task instructions

The goal for you is to

- Follow the car in front. The speed of the car in front will vary.
- Drive swiftly but safely; avoid collisions with the car in front
- Always keep your car accurately centered in the right lane; do not change lanes or overtake.
- During the automated driving do not use the brake pedal.

Questionnaire

Between the test sessions, you are asked to step out the simulator, have a break for 3–5 minutes while filling in a short questionnaire about your experienced mental and physical workload.

Appendix C: Experimental Materials of Chapter 4

Risk Measurement

When you hear a beeping sound during driving, please press the touchpad and indicate your perceived risk level at that moment on a scale between 0% (not risky at all) and 100 % (extremely risky). During all sessions, the touchpad installed on your steering wheel will be on and displaying a scale from 0–100.

Simulator sickness

Driving in a simulator may sometimes cause simulator sickness symptoms such as headache and nausea. These symptoms resemble car sickness or motion sickness on a boat. If you start to feel uncomfortable in any way, we advise you to immediately exclude yourself from this experiment. You are able to stop your cooperation in the experiment whenever you wish, without personal negative consequence. If you have any questions, do not hesitate to ask the experimenters for clarification.

If you read all the above items please proceed to the next page.

Date : ………………………………

I confirm that I read and understood this text, and that I participate voluntarily.

Name and signature of the participant

Name : ………………………………
Signature : ………………………………

Appendix C.2: Photos made for different bumper-to-bumper following distances between the participant's car and the lead car in the fog condition.

Following Distance = 6 m

Following Distance = 16 m

Appendix C: Experimental Materials of Chapter 4

Following Distance = 21 m

Following Distance = 26 m

Appendix C: Experimental Materials of Chapter 4

Following Distance = 31 m

Following Distance = 81 m

Appendix C: Experimental Materials of Chapter 4

Following Distance = 161 m

Appendix C.3: Photo of the car following scenario in the clear weather condition

Appendix D: Experimental Materials of Chapter 5

Appendix D.1: Information Form (with RWND group)

Seating position

Please find a comfortable driving position, by moving the seat forwards or backwards.
Raise the lever on the left-hand side under the chair to move the seat.
You must be seated so that you are able to operate the steering wheel and pedals.

The idea of the test is that you try to follow the first car you encounter as good as you can, i.e. you must try to maintain a constant time headway(=the following distance divided by speed).

Controls

The gearbox of the car is fully automated.
The right pedal is the accelerator. If you press it you will drive faster.
The middle pedal is the brake. If you press it you will slow down.
Please use only your right foot to operate the pedals.
The steering wheel is used to move the car to the left or right.

Test

First you will drive a sort of tutorial for 5 minutes, in which you can get to know the simulator, we will not store the data of these 5 minutes.

After this, the actual test will start. The first run of the test you will drive a certain track for 10 minutes on which you must try to follow the preceding car as described above. The test starts when you leave the emergency lane, so do this as fast as possible.

Next, your will get a short break after which you will perform a second run of 10 minutes.

Survey

After the driving session, please fill in the Rating scale Mental Effort questionnaire we will hand you.

N.B.: There is a possibility that you get car sick in the driving simulator, this has happened before in other tests. If this happens to you, let us know and stop with the experiment.
If something weird happens during the test, just keep driving. If you have any questions, ask them directly after reading this information sheet.

Appendix D.2: Information Form (with RWND Group)

Seating position

Please find a comfortable driving position, by moving the seat forwards or backwards.
Raise the lever on the left-hand side under the chair to move the seat.
You must be seated so that you are able to operate the steering wheel and pedals.
The idea of the test is that you try to follow the first car you encounter as good as you can, i.e. you must try to maintain a constant time headway(=the following distance divided by speed).

Controls

The gearbox of the car is fully automated.
The right pedal is the accelerator. If you press it you will drive faster.
The middle pedal is the brake. If you press it you will slow down.
Please use only your right foot to operate the pedals.
The steering wheel is used to move the car to the left or right.

Test

First you will drive a sort of tutorial for 5 minutes, in which you can get to know the simulator, we will not store the data of these 5 minutes.

After this, the actual test will start. The first run of the test you will drive a certain track for 10 minutes on which you must try to follow the preceding car as described above. The test starts when you leave the emergency lane, so do this as fast as possible.

Next, your will get a short break after which you will perform a second run of 10 minutes. In this run we will provide you with an interface to help you to maintain a constant time headway.
In this interface we will show vertical arrows, which indicate the ideal time headway. If the arrows are not visible, it means that you are following the car at the ideal time headway. If the top arrow is visible, then you need to decrease the following distance. If the bottom arrow is visible, it means that you need to increase the following distance. The purpose of the test is to drive in such a way that the arrows are not visible.

As an extra, we will also show a horizontal bar with the degree of acceleration of the preceding car to the right and the degree of braking of the preceding car to the left, so how harder the preceding car brakes or accelerates, how larger the beam becomes.

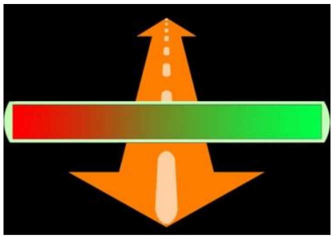


Figure1:The interface

Survey

After the driving session, please fill in the Rating scale Mental Effort questionnaire we will hand you.

Appendix D: Experimental Materials of Chapter 5

N.B.: There is a possibility that you get car sick in the driving simulator, this has happened before in other tests. If this happens to you, let us know and stop with the experiment. If something weird happens during the test, just keep driving. If you have any questions, ask them directly after reading this briefing. During the test we will not answer questions.

Appendix D.3: Intake Questionnaire

Name *(Last, First)*		
Phone Number		
E-mail		
Age		
Gender	☐ **Male**	☐ **Female**
Do you have a license?	☐ **Yes**	☐ **No**
Do you play video games at least 1 hour per week?	☐ **Yes**	☐ **No**
Have you ever driven in a simulator before?	☐ **Yes**	☐ **No**
Year of issue first Drivers' License		
Driving Experience *How often do you drive?*	☐ ***Less than one time per year*** ☐***Monthly*** ☐***Weekly*** ☐***Daily***	
I have good steering skills (for instance in cycling or computer games) Completely disagree 1 2 3 4 5 6 7 8 9 10 Completely agree		
Test code *(to be filled in by experimenter)*	☐ **A**	☐ **B**
Session code *(to be filled in by experimenter)*	☐ **A**	☐ **B**

Curriculum vitae

15 September 1978
Born in Abadan, Iran

Education

1996 – 2000
BSc Mechanical Engineering, University of Tehran

2000 – 2003
MSc Mechanical Engineering, Sharif University of Technology

2006 – 2009
MSc Engineering Management, University of Alberta

Recent Positions

2016-Present
R&D Team Leader, Motum N.V. (Mechelen, Belgium)

2012-2016
Systems Engineer, Freelance Consultant (Toronto, Canada)

2009-2016
Doctoral Fellow, University of Toronto / TUDelft (Toronto, Canada and Delft, the Netherlands)

2012-2015
Communication Instructor, University of Toronto (Toronto, Canada)

Awards and Scholarship

University of Toronto Fellowship (2013-2015)

NSERC Alexander Graham Bell Canada Graduate Scholarship (2011-2013)

NSERC Michael Smith Foreign Study Supplement Award (2013)

Transportation Association of Canada Scholarship (2013)

Propositions belonging to the PhD thesis

Understanding and improving driving performance by removing and adding visual information

Mehdi Saffarian, 10 March 2017

1. Among all driving conditions, the performance of drivers in the most safety-critical driving conditions is the least understood.

2. The distance to objects in the environment is positively correlated with safety, but negatively correlated with performance.

3. The moment one glances away from the road is a more important determinant of driving safety than the duration of that glance.

4. Braking an automobile is not an entirely open loop task, even when the time-available-to-respond is very short (this thesis).

5. In developing automation technologies for driving, the priority should be to automate the most safety-critical driving task.

6. In order to enhance safety, the best use of automated driving technology is not to let the driver supervise the automation, but to let the automation supervise the driver and intervene when the driver is about to crash.

7. Drivers find assistive technologies that enhance their perception and control abilities more useful than technologies that replace those abilities.

8. In driving simulator research, there is a trade-off between fidelity and reproducibility.

9. Simulators are often used to investigate performance in perceptual tasks, but the perceptual validity of simulators is rarely investigated.

10. Compared to tactical and strategic tasks, simulators are better suited for studying operational control tasks.

11. An integration of information theory (to identify critical conditions in the environment), queueing theory (to prioritize critical conditions), and control theory (to mitigate critical conditions) is required for understanding and improving the safety of driving.

Michon, J. A. (1985). A critical view of driver behavior models: what do we know, what should we do? In *Human behavior and traffic safety* (pp. 485–524). Springer.

These propositions are regarded as lending themselves to opposition and as defendable, and have been approved as such by the promotor prof.dr. F.C.T. van der Helm