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



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## 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. In this simulator study, we measured drivers' braking behaviour 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 ( $\geq 6$  s), participants in the occlusion condition stopped too early and at variable positions on the road as compared to the control condition. In the occlusion condition, participants were likely to apply an intermediate brake pedal depression, whereas in the control condition participants more often applied low or high pedal depressions. The results are interpreted in light of a distance estimation test, in which we found that participants underestimated the actual distance by 70%.

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## 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 behaviour

Despite its fundamental role in driving safety, drivers' braking behaviour is not well understood. Several attempts to explain braking behaviour have used locomotion theories. According to these theories, the control of locomotion is

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'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, 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, 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:

$$\Delta u(t) = k_p(a^*(t) - a(t)) \quad (1-1)$$

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 acceleration is a function of the current speed ( $v(t)$ ) and current distance ( $d(t)$ ) to the target:

$$a^*(t) = \frac{v^2(t)}{2d(t)} \quad (1-2)$$

### 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<sup>2</sup>. However, it is very well possible to brake harder (e.g., 6 m/s<sup>2</sup>) and thereby avoid the collision, or to wait until the lead vehicle is 50 m ahead and subsequently brake with a constant 4 m/s<sup>2</sup> 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) confirms 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 (1951) model 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:

$$\frac{d}{D} = \frac{A}{A + D} \quad (1-3)$$

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 magnifies the collision hazard and therefore reduces the collision risk.

#### 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, Milgram, & Blaauw, 1984; 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 manoeuvres 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 et al. (1984) introduced the concept of time to line crossing (TLC), which represents the time that drivers can neglect the steering task until the vehicle crosses 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 behaviour. They found that lack of preview resulted in abrupt and coarse steering corrections, reduced steering precision, and increased the number of road departures.

While attempts have been made 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), the visual demand of braking has not yet been determined. We aimed to investigate to which extent the absence of visual information during the course of braking affects drivers' braking behaviour. 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

In the current driving simulator study, we 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 manoeuvres 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. We expected participants to brake sooner and harder when the brake scene is

occluded, as participants rely on the shortened perceived distance at the start of the braking trial, especially for large TTA values.

We also examined whether the braking pattern changes when participants use a variable versus fixed brake onset. 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, where the effect of TTA on braking behaviour per se is investigated.

## 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 (Fig. 1). 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.

### 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 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. 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 carrying out the braking tasks. Thirteen participants reported they used cruise control at least once or twice a year (Table 2).

### 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 Fig. 2 for an overview of the stages of the experiment). Upon arrival, participants read and signed the consent form. The form informed participants 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.



Fig. 1. NADS Minisim driving simulator.

**Table 1**

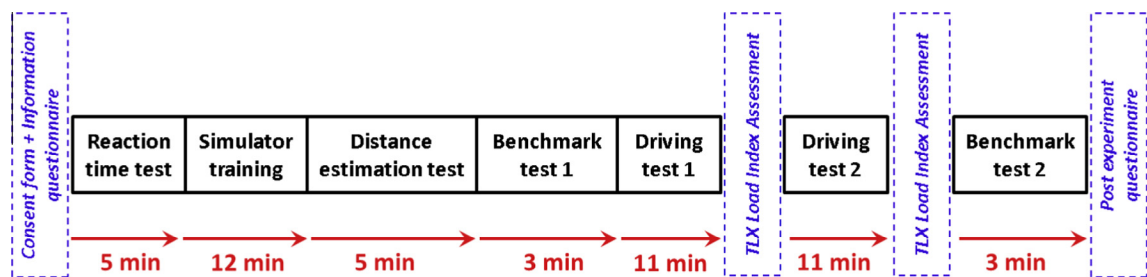
Distribution of the participants based on per-week and per-year driven distance.

D1 = average mileage per week (in km)	D1 < 10	10 ≤ D1 < 100	100 ≤ D1 < 1000	D1 ≥ 1000	
Number of participants	4	13	7	0	
D2 = average mileage per year (in 1000s of km)	D2 < 0.1	0.1 ≤ D2 < 1	1 ≤ D2 < 10	10 ≤ D2 < 100	D2 ≥ 100
Number of participants	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

**Fig. 2.** 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.

### 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  $1366 \times 768$  pixels. Each test consisted of 10 trials, of which the first 5 were considered as warm-up trials 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 min (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. 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 (Fig. 3) and remained visible for 7 s. The participants verbally had to 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 s 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 m in no discernible order. 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.

### 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 s. 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 for either responding 'at' or '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 (Fig. 4), and (2) maintain the vehicle in the centre 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 road in all the experiments was 3.66 m.

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 ended 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, also 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 first author of this work instructed and observed the participants' compliance in following the instructions.

In both the occlusion and control tests, the time available for braking was changed by manipulating the trigger time of the braking trial. The braking trials were triggered (i.e., by a beep or occlusion onset) at four different TTA intervals before the stopping target: 2, 4, 6, and 8 s. 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 centre of the vehicle to the centre of the circular patch that indicated the stopping target. The two driving tests included four trials per TTA distance. Hence, each of the occlusion and control tests included 16 brake trials where the participants brought their vehicle to a full stop. The travelled distances between two subsequent stopping targets on the road was between 415 and 659 m. The sequence of the trials did not have a recognizable order for the participants. The sequence was also different between the control and occlusion conditions.



Fig. 3. Screenshot of the distance estimation test, the distance represented in this picture is 20 m.

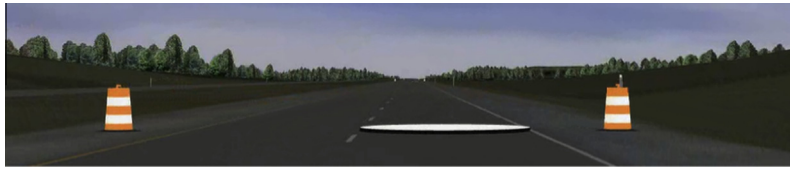


Fig. 4. View of the stopping target of the braking trials in the main driving tests.

### 2.3.6. Benchmark tests

A benchmarking test was conducted before and after the main driving tests (Fig. 2). The participants had to stop their vehicle four times at a target position on the road while approaching with 27 m/s. However, 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 possible learning effect in the simulator environment. 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 also included four items that asked about feeling of risk and self-confidence. 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*.

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 of 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 occlusion or beep sound and the initial brake input of the participant.  $T_{rt}$  is a measure of reaction time to the brake trigger events of this experiment (cf. 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. The potentiometer reading had been 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. We 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. We also determined that 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 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 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.

$$E = 100\% \frac{d - D}{D} \quad (2-1)$$

*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 between 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 Group 1 (G1,  $n = 12$ ) were told to start braking any time after the braking event triggered, and participants in Group 2 (G2,  $n = 12$ ) were asked to start braking immediately at the event trigger. G1 and G2 were compared using an independent-samples *t*-test ( $df = 22$ ). Because we conducted a large number of statistical tests, we adopted a conservative false positive rate (alpha) of 0.01 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 estimate are reported in Table 3. Results of independent *t*-tests revealed no statistically significant differences between the G1 and G2 participants.

Participants, on average, reported a distance that was consistently about 30% of the true distance (Fig. 5). Accordingly, a linear fit provided a better fit than the curvilinear Gilinsky's model (Fig 5).

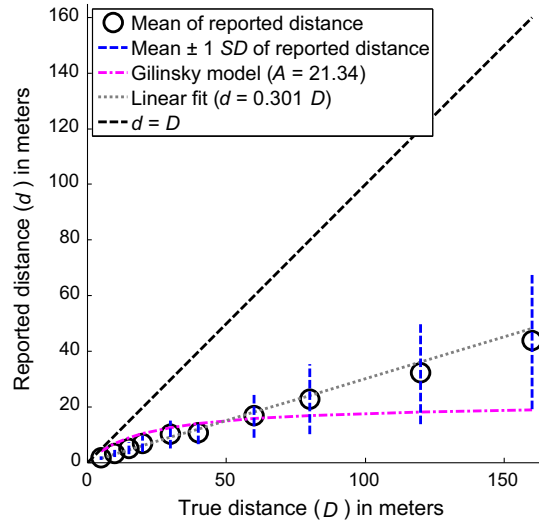
### 3.2. Braking performance and behaviour

Fig. 6 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. Overall, the brake reaction time was faster in the occlusion condition than it was in the control condition ( $p = 0.018$ ,  $t = 2.535$ ). Fig. 7 shows the standard deviations of the brake reaction time among participants. Overall, G2 participants had a more consistent reaction time than G1 participants did, which can be explained by the task instructions for G2 stating that participants should brake directly after the event trigger. The results in Fig. 6 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 G1 group delayed their initial braking response in those cases where there was more time available (i.e., a higher TTA).

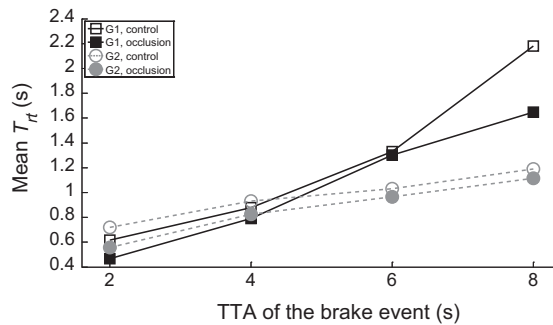
The results of the maximum brake pedal displacement (Fig. 8) show that participants pressed the brake less deeply when the urgency of the braking event was lower, that is, when TTA was higher ( $p < 0.001$ ,  $t = -12.811$ ). The maximum brake displacement was also larger in the control condition as compared to the occlusion condition ( $p = 0.001$ ,  $t = 3.756$ ). Furthermore, there was a TTA 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:

**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).

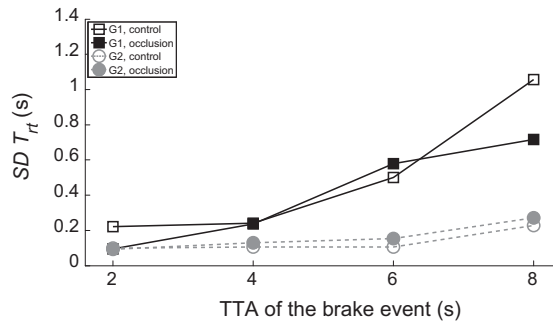
	RTa (ms)	RTv (ms)	E (%)
Mean G1 (SD)	214 (39)	308 (46)	-68 (12)
Mean G2 (SD)	212 (24)	301 (28)	-72 (12)
$t(df = 22)$ G1 vs. G2	0.154	0.471	0.961
$p$ -value G1 vs. G2	0.879	0.643	0.347



**Fig. 5.** Means and means  $\pm 1$  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%.

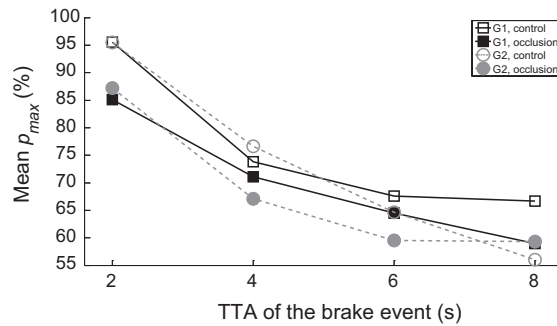


**Fig. 6.** Mean brake response time as a function of the time to arrival (TTA), occlusion, and experimental group (G1 = braking at any time after the occlusion/beep; G2 = braking immediately at the occlusion/beep).

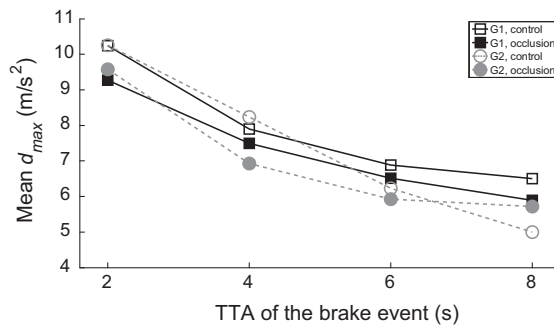


**Fig. 7.** Standard deviation (SD) among participants ( $N = 12$  per condition) of the mean brake response time, as a function of the time to arrival (TTA), occlusion, and experimental group (G1 = braking at any time after the occlusion/beep; G2 = braking immediately after the occlusion/beep). The standard deviation is a measure of inter-individual differences.

$t = 0.818, p = 0.422$ ), 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. The maximum deceleration of the vehicle reveals an almost identical pattern as the maximum pedal displacement (Fig. 9).



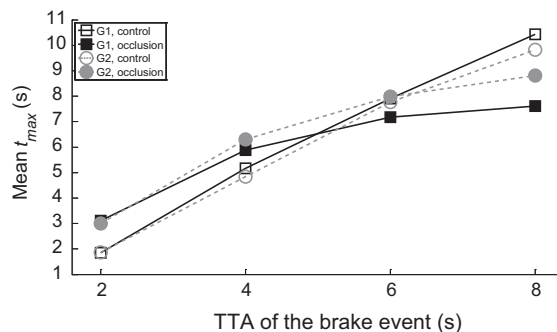
**Fig. 8.** Mean maximum brake pedal displacement as a function of the time to arrival (TTA), occlusion, and experimental group (G1 = braking at any time after the occlusion/beep; G2 = braking immediately after the occlusion/beep).



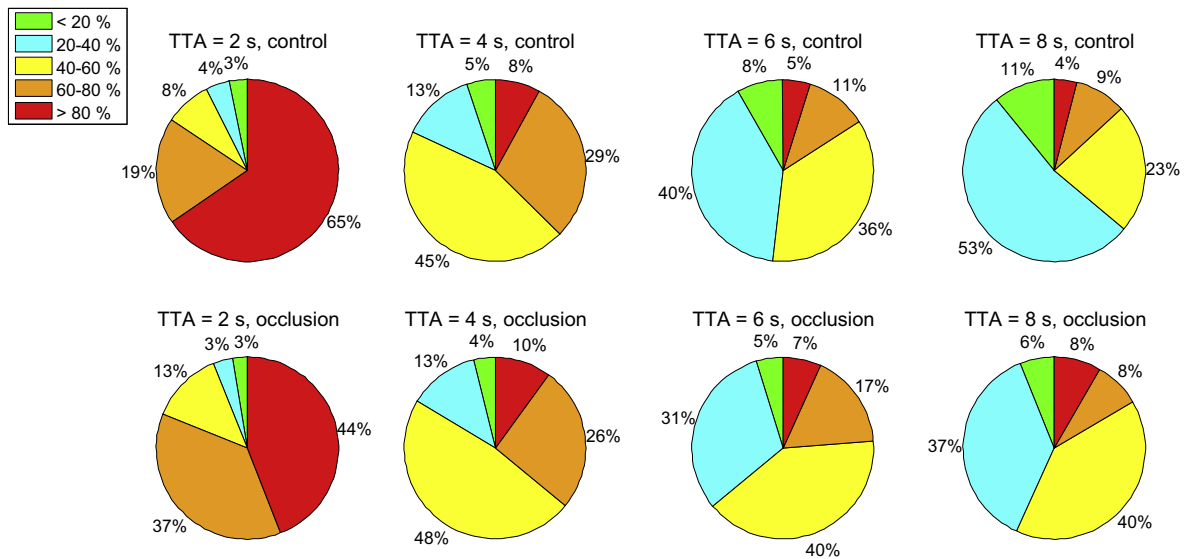
**Fig. 9.** Mean maximum deceleration as a function of the time to arrival (TTA), occlusion, and experimental group (G1 = braking at any time after the occlusion/beep; G2 = braking immediately after the occlusion/beep).

Fig. 10 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 G1 versus G2 ( $p = 0.641$ ,  $t = -0.473$ ). 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 Fig. 10).

As a supplementary analysis, we divided the brake pedal displacement into five equal ranges and subsequently calculated the relative durations of the brake pedal depression within each of the ranges (Fig. 11). Expectedly, it was found that the shorter the TTA, the greater the proportion of severe braking. 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 deeply press the brake pedal (>80%) in the control condition as compared to the occlusion condition. For the brake trials with the longest TTA



**Fig. 10.** Mean maximum brake force time as a function of the time to arrival (TTA), occlusion, and experimental group (G1 = braking at any time after the occlusion/beep; G2 = braking immediately after the occlusion/beep).



**Fig. 11.** 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 G1 (braking at any time after the occlusion/beep) and G2 (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.

Pedal depression range	TTA 8 s vs. 2 s	Control vs. Occlusion	G1 vs. G2	Control vs. Occlusion per TTA			
				TTA = 2 s	TTA = 4 s	TTA = 6 s	TTA = 8 s
$T_{<20}$ (%)	<b><math>p &lt; 0.001</math></b> $t = 5.245$	<b><math>p = 0.001</math></b> $t = 3.809$	$p = 0.079$ $t = 1.840$	$p = 0.057$ $t = 2.006$	$p = 0.183$ $t = 1.372$	$p = 0.011$ $t = 2.785$	<b><math>p = 0.001</math></b> $t = 3.736$
$T_{20-40}$ (%)	<b><math>p &lt; 0.001</math></b> $t = 9.166$	<b><math>p = 0.002</math></b> $t = 3.544$	<b><math>p = 0.004</math></b> $t = -3.242$	$p = 0.210$ $t = 1.290$	$p = 0.884$ $t = 0.147$	$p = 0.018$ $t = 2.544$	<b><math>p = 0.002</math></b> $t = 3.489$
$T_{40-60}$ (%)	<b><math>p &lt; 0.001</math></b> $t = 5.626$	<b><math>p = 0.005</math></b> $t = -3.111$	$p = 0.084$ $t = 1.810$	$p = 0.123$ $t = -1.599$	$p = 0.664$ $t = -0.440$	$p = 0.216$ $t = -1.271$	<b><math>p = 0.001</math></b> $t = -4.039$
$T_{60-80}$ (%)	<b><math>p &lt; 0.001</math></b> $t = -4.296$	<b><math>p = 0.008</math></b> $t = -2.895$	$p = 0.195$ $t = 1.336$	$p = 0.011$ $t = -2.753$	$p = 0.693$ $t = 0.400$	$p = 0.053$ $t = -2.043$	$p = 0.730$ $t = 0.349$
$T_{>80}$ (%)	<b><math>p &lt; 0.001</math></b> $t = -10.111$	$p = 0.287$ $t = 1.090$	$p = 0.571$ $t = -0.575$	<b><math>p = 0.002</math></b> $t = 3.252$	$p = 0.714$ $t = -0.371$	$p = 0.371$ $t = -0.912$	$p = 0.306$ $t = -1.047$

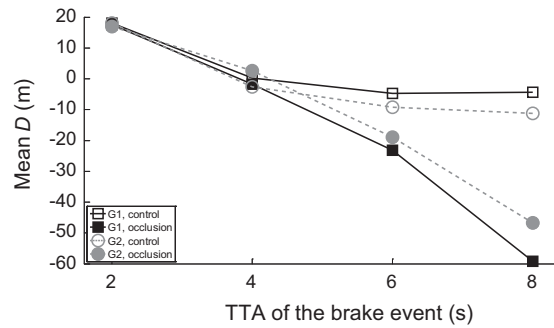
*Note.* The table shows the time to arrival (TTA) effect (TTA = 8 s vs. TTA = 2 s), visual effect (control vs. occlusion condition), and group effect (G1 who were braking at any time after the occlusion/beep vs. G2 who were braking immediately at the occlusion/beep). The table also shows the control versus occlusion effect for each TTA value separately.

$p < 0.01$  is indicated in bold.

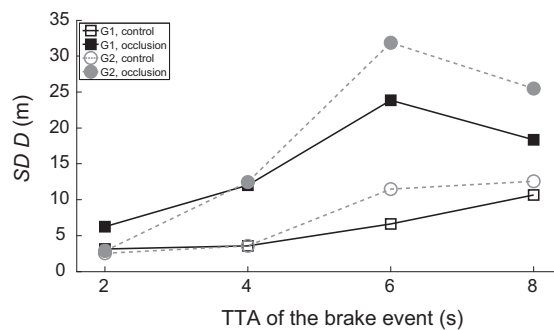
(TTA = 8 s), the relative duration of <40% braking was larger during the control condition than during the occlusion condition. This trend was reversed for the 40–60% range. In summary, in the occlusion condition participants were likely to apply intermediate brake pedal displacements, whereas in the control condition participants were more likely to operate the brakes in the extreme ranges.

Fig. 12 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 effects. The results in Fig. 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, participants in the control condition stopped later than participants in the occlusion condition, only for TTA = 6 s and TTA = 8 s (Fig. 12). In the occlusion condition, participants stopped too late in 99% of the trials for TTA = 2 s and in 8% of the trials for TTA = 8 s (with stopping too late defined as being more than 12 m beyond the centre of the white circle).

Fig. 13 shows that intra-individual differences in the distance gap are larger for the occlusion condition than for the control condition. For example, 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 centre of the white circle) was 45% in the control condition, compared to 3% in the occlusion condition.



**Fig. 12.** Mean distance gap as a function of the time to arrival (TTA), occlusion, and experimental group (G1 = braking at any time after the occlusion/beep; G2 = 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.



**Fig. 13.** Standard deviation (SD) of the distance gap as a function of the time to arrival (TTA), occlusion, and experimental group (G1 = braking at any time after the occlusion/beep; G2 = 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

The temporal pattern of the braking manoeuvre (i.e., pedal position, vehicle acceleration, and distance gap to the on-road target) was examined in this section. We calculated the time-locked average of the response across the 12 participants per group (i.e., across 48 trials per each combination of TTA and occlusion/control condition). Because participants ended their brake at different points in time, there are fewer data points to be averaged near the end of each time series. To minimise 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.

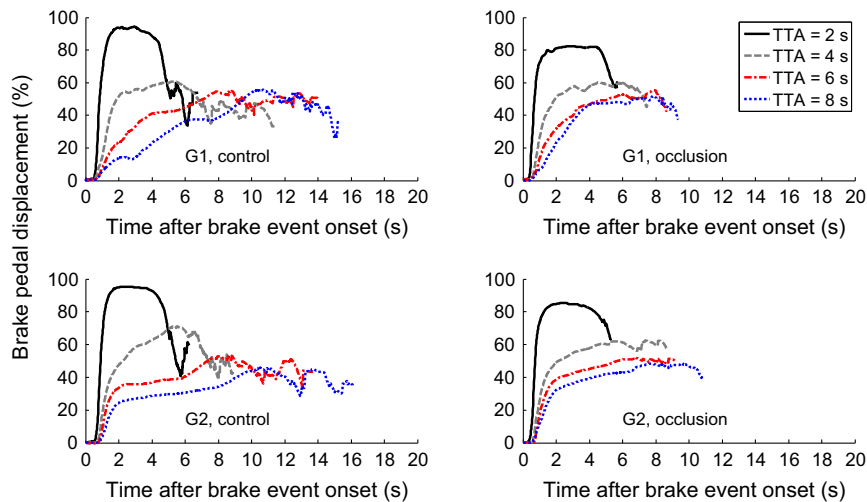
The average braking response when faced with a stopping task with short TTA of 2 s is pulse-shaped with high amplitude. As TTA of the braking event increased, participants responded with a longer and less hard brake depression, which resulted in a longer average deceleration profile and lower levels of average deceleration (Figs. 14 and 15). For TTA = 2 s, participants on average braked less hard in the occlusion condition as compared to the control condition (Fig. 14).

Fig. 16 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 (G1 vs. G2).

### 3.4. Self-report questionnaires

Table 5 shows the results of the NASA TLX and the four additional questions about feeling of risk and self-confidence. Participants found the occlusion condition more demanding than the control condition. The largest effects 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



**Fig. 14.** The average brake pedal displacement of participants during braking trials, as a function of time to arrival (TTA), participant group (G1 vs. G2), and control and occlusion conditions. G1 = braking at any time after the occlusion/beep; G2 = braking immediately after the occlusion/beep.

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’.

### 3.5. Learning effects

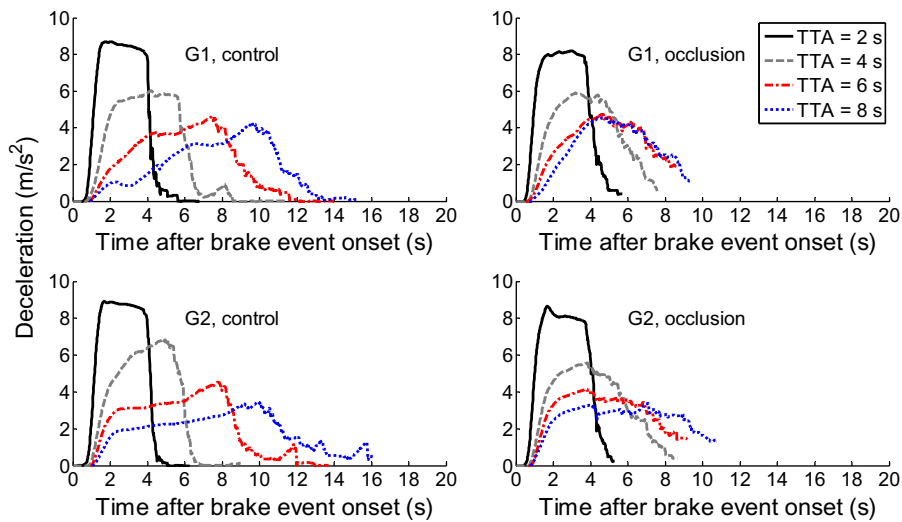
There were several statistically significant differences between the braking behaviour of the two benchmark tests (Table 6). The maximum brake displacement and its occurrence moment did not significantly change between these two benchmark tests. However, during the second benchmark test, participants 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 learning had occurred regarding the control of the brake pedal.

## 4. Discussion

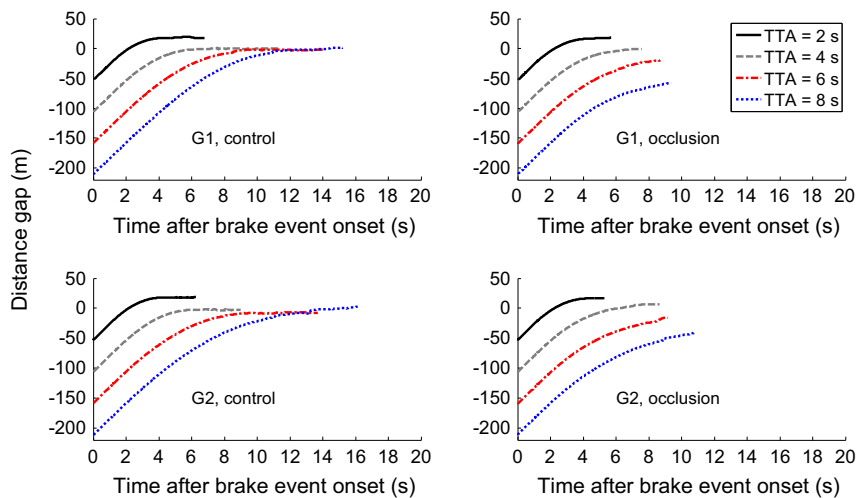
In this experiment we investigated to what extent drivers rely on open loop (i.e., use of the scene memory) versus closed loop (i.e., active compensation of distance and speed with respect to a target) strategies in executing a braking task. To this end, we examined the effect of the presence versus absence of visual information on the characteristics of participants’ brake responses, when they were asked to stop at a target. In half of the trials, we blanked the screen 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 the brake (consistent with Gilinsky’s model of distance perception).

### 4.1. Distance underestimation

Baumberger, Flückiger, Paquette, Bergeron, and Delorme (2005) showed that drivers underestimated the distance by about 5 m 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). Our results indicate that in standstill conditions people underestimate the true distance 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). Hence, we reject the curvilinear Gilinsky model for the simulator for the range of distances examined in this experiment (Fig. 5).



**Fig. 15.** The average deceleration of participants during braking trials, as a function of time to arrival (TTA), participant group (G1 vs. G2), and control and occlusion conditions. G1 = braking at any time after the occlusion/beep; G2 = braking immediately after the occlusion/beep.



**Fig. 16.** The average distance gap of participants during braking trials, as a function of time to arrival (TTA), participant group (G1 vs. G2), and control and occlusion conditions. G1 = braking at any time after the occlusion/beep; G2 = braking immediately after the occlusion/beep.

A recent study by Li, Phillips, and Durgin (2011) sheds light on why the Gilinsky model did not show a good fit on 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 we did in our 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 Gilinsky's (1951) 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 20–30% (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 our research 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. Failure to consider this effect in designing driver support systems (by means of driving simulators) could adversely impact the effectiveness of such systems.

There are several reasons that can explain the underestimation of distance perception in the driving simulator. The simulator screen represents a two-dimensional picture of the environment, which prevents the use of stereopsis (i.e., depth perception through binocular vision), and consequently, reduces the accuracy of depth perception. Furthermore, the two-dimensional simulator scene lacks the monocular parallax created by the movement of the head with respect to the

**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		<i>p</i> -value G1 vs. G2	<i>p</i> -value control vs. occlusion
	G1	G2	G1	G2		
TLX Mental demand	54 (25)	55 (23)	39 (21)	35 (23)	0.871	<b>&lt;0.001</b>
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	<b>0.005</b>
TLX Frustration	52 (28)	42 (25)	26 (24)	26 (23)	0.534	<b>0.002</b>
I had a feeling of risk during driving (Risk)	33 (29)	45 (35)	19 (21)	22 (24)	0.465	<b>&lt;0.001</b>
I think I drove more safely than the average participant (Safety)	65 (20)	43 (19)	65 (18)	47 (14)	<b>0.006</b>	0.506
This driving task was easy (Difficulty)	44 (23)	40 (23)	70 (20)	56 (22)	0.238	<b>&lt;0.001</b>
I felt confident in my own capability to act appropriately (Confidence)	66 (19)	50 (26)	84 (14)	64 (22)	0.022	<b>&lt;0.001</b>

Note. The table shows means across participants (standard deviations in parentheses), and the *p*-values for comparisons between the two participant groups (G1 vs. G2) 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.

**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 ( $T_{<20}$ ,  $T_{20-40}$ ,  $T_{40-60}$ ,  $T_{60-80}$ ,  $T_{>80}$ ) during the two benchmark tests. The comparison was made between the average data of the four trials per test.

Variable	Benchmark test 1 <i>M</i> ( <i>SD</i> )	Benchmark test 2 <i>M</i> ( <i>SD</i> )	<i>p</i> -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)	<b>0.002</b>
$T_{20-40}$ (%)	21.5 (19.7)	32.4 (14.4)	0.040
$T_{40-60}$ (%)	35.3 (14.5)	29.0 (17.1)	0.121
$T_{60-80}$ (%)	16.1 (10.6)	16.1 (10.0)	0.991
$T_{>80}$ (%)	18.9 (13.8)	6.0 (10.0)	<b>&lt;0.001</b>

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

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. It was expected that in such a short time window, participants rely mainly on their instinct as they 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 influences 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 (Fig. 12). Presumably, for this short TTA, reliance on the visual information available before the brake onset is sufficient.

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 (Fig. 8). 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 (Fig. 6). 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 in the urgent conditions ( $TTA \leq 4$  s), participants cannot detect that they are likely to miss the target and therefore do not feel the urgency to press the brake as far as possible.

When there was ample time available at the start of the braking manoeuvre ( $TTA \geq 6$  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  $TTA \geq 6$  s conditions, participants cannot know when to release and regulate the brake pedal input, and they therefore apply a 'hold' strategy. The interaction effect between the visual condition and TTA (Table 4 and Fig. 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. Contrastingly, the people driving in the control condition were more likely to 'slam' the brakes (at  $TTA = 2$  s) or release the brakes (at  $TTA = 8$  s). Our results are consistent with a study by Andersen et al. (1999) in which participants non-interactively observed a scene of 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 high TTA values ( $TTA \geq 6$  s), the pitfalls of not having access to visual information for braking performance are apparent. 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 (Fig. 8) and reached slightly lower peak decelerations (Fig. 9) than in the control condition, possibly because they did not perceive the looming target.

#### 4.3. The effects of task instructions

Our results showed that imposing the brake onset instructions had little effect on the brake response characteristics. The largest difference between G1 (the group braking at any time after the occlusion/beep) and G2 (the group braking immediately at the occlusion/beep) was obtained in the brake response time itself. The uniform timing (i.e., low SDs, see Fig. 7) among the G2 trials indicates that G2 participants responded as instructed: right after the brake stimulus. In the case of low urgency ( $TTA = 8$  s), G1's average brake onset showed a delay of about 1 s compared to G2 (Fig. 6). The finding that the brake response pattern does not noticeably change when participants use either flexible or fixed brake onset, suggests that it is the urgency of the situation shaping people's behaviour, and to a lesser extent the task instructions.

#### 4.4. Limitations of this research

One limitation of our 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, Raymond, Kemeny, & Berthoz, 2001). A third limitation is that the participants in our study were relatively young, with a mean age of 27 years and two thirds of them 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 our 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 we showed that 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. Our 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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