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A study using two linked driving simulators

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Concurrent audio-visual feedback for supporting drivers at intersections: A study using two linked driving simulators

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A B S T R A C T

A large portion of road traffic crashes occur at intersections for the reason that drivers lack necessary visual information. This research examined the effects of an audio-visual display that provides real-time sonification and visualization of the speed and direction of another car approaching the crossroads on an intersecting road. The location of red blinking lights (left vs. right on the speedometer) and the lateral input direction of beeps (left vs. right ear in headphones) corresponded to the direction from where the other car approached, and the blink and beep rates were a function of the approaching car's speed. Two driving simulators were linked so that the participant and the experimenter drove in the same virtual world. Participants ($N = 25$) completed four sessions (two with the audio-visual display on, two with the audio-visual display off), each session consisting of 22 intersections at which the experimenter approached from the left or right and either maintained speed or slowed down. Compared to driving with the display off, the audio-visual display resulted in enhanced traffic efficiency (i.e., greater mean speed, less coasting) while not compromising safety (i.e., the time gap between the two vehicles was equivalent). A post-experiment questionnaire showed that the beeps were regarded as more useful than the lights. It is argued that the audio-visual display is a promising means of supporting drivers until fully automated driving is technically feasible.

1. Introduction

1.1. Intersection safety

Intersection driving has long been a safety concern (Surti and McCarthy, 1969; Williams, 1927). At present, 44% of all registered road traffic casualties in the Netherlands occur at intersections, three quarters of which are urban crashes (SWOV Institute for Road Safety Research, 2014). Similarly, in the United States, approximately 36% of crashes occur at intersections (Choi, 2010).

Intersection safety can be studied from a system perspective, in which crashes are postulated to result from a causal net that includes aspects of licensing, road norms, compatibility between infrastructure and other road users, as well as broad social, political, and economic factors (Read et al., 2013; Salmon et al., 2016). The present study tackled the issue of intersection safety by focusing not on these system factors but on the sharp end of human fallibility (cf. Reason, 1990).

Various in-depth studies offer insight into the cognitive and behavioural aberrations prior to crashes. For example, an analysis of 167 crossroad crashes found that sight obstruction (40%), distraction (32%), and masked stimuli (26%; in particular sun glare) were the three most common errors (Staubach, 2009). Najm et al. (1994) reviewed the causal factors of intersection crashes, and found that at unsignalised intersections, 22% of straight crossing path crashes were caused by driver inattention, 37% by the looked-but-did-not-see phenomenon, 16% by sight obstruction, and a further 12% by misjudgement of gap or speed. Werneke and Vollrath (2012) reviewed a number of in-depth studies and concluded that perceptual and recognition errors were major contributing factors to crashes at intersections. Choi (2010) reviewed the causes of 756,570 intersection-related crashes and found that inadequate surveillance (44%) and false assumptions of other's action (8%) were the two most common causes, while these factors were rare in non-

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intersection-related crashes (7% and 2%, respectively). Similarly, Räsänen and Summala (1998) identified two main factors leading to crashes: failure to detect the other road user versus unjustified expectations about the other road user's intentions (see also Sandin, 2009). Braitman et al. (2007) found that failure to yield right of way was the dominant error category at intersections, with inadequate search/detection occurring in 76% of cases, and inadequate evaluation (i.e., seeing the other vehicle but misjudging its intentions) occurring in 20% of the cases.

In sum, the literature suggests that drivers at intersections need help to improve their situation awareness, that is, not only to perceive other road users, but also to comprehend and predict the other road users' intentions. Staubach (2009) recommended that technology “should support the driver in assimilating information, e.g. by the use of sensors and cameras which help to recognize other vehicles in oncoming traffic or cross-traffic” (p. 1026). Similarly, in a user needs survey related to advanced driver assistance systems (ADAS), 82% of the respondents ($N = 1049$) indicated a (great) need for a blind spot warning at uncontrolled intersections in an urban environment (Van Driel and Van Arem, 2005).

1.2. Existing solutions for improving intersection safety

Traditionally, safety at intersections has been addressed by means of black spot treatments, installation of traffic lights, or other modifications to the road infrastructure such as the introduction of roundabouts, priority rules, road signage, or speed limits (e.g., Elvik et al., 2009; Gugerty et al., 2014). Another solution is to offer the warning *inside* the driver's car.

A number of recent studies have tested in-vehicle warning systems for intersection driving, typically yielding improved stopping behaviour at intersections (Brown et al., 2005; Chen et al., 2011). However, the results are not unequivocally positive. Particularly informative is a test-track study by Neale et al. (2007), in which the authors tested a variety of infrastructure-based warnings (dual flashing light, simulated rumble strip [tactile feedback], LED-enhanced stop sign) and in-vehicle warnings (tonal auditory warning, “STOP” verbal warning, brake pulses, or soft braking). Their experiment showed that the STOP warning and the braking interventions were effective in preventing stopping violations at intersections. However, the infrastructure-based warnings were highly ineffective, possibly because the visual warnings were at a farther distance from the driver than the in-vehicle warnings, and therefore less conspicuous when being visually distracted. The tonal auditory warning was not effective either. The effectiveness of tactile and auditory warnings is well established in forward collision warning systems (Bao et al., 2012; Ho et al., 2007; Kramer et al., 2007) or road departure crash warning systems (Sayer et al., 2007), but with these systems the required response is obvious: the driver has to brake or steer back to the road. When approaching intersections, however, the driver's task is complex because the driver has to scan for impending traffic and subsequently determine what to do. Neale et al. (2007) explained: “It is likely that the tonal auditory warning was not sufficiently explicit to aid the driver in understanding the situation and performing the appropriate action.” (p. 141).

The above observations are in line with a review by Abbink et al. (2012), which argued that drivers should be supported by real-time continuous feedback, because warnings and advisory systems are suboptimal when it comes to supporting situation awareness and keeping drivers ‘in the loop’. Specifically, the problem is that binary warnings are either on or off, while the objective risk level (e.g., relative speed, time to collision) and the required driver control inputs (i.e., throttle and brake pedal position) are typically a continuous function of time. Thus, with warnings it is possible to achieve level 1 situation awareness (perception: is there another car?), but it may be difficult to achieve level 2 (comprehension: where is the other car coming from?) and level 3 (projection: will the other car cross the intersection?) situation awareness (cf. Endsley, 1995).

Moreover, for binary warnings, there is the unresolvable problem of the trade-off between false alarms and misses (Parasuraman et al., 1997). In other words, for a given alarm threshold, there may be situations where the driver thinks that the warning came too early, and there will be situations where the warning came too late. An early warning may be annoying and even cause the driver to disengage the warning system, while a late warning may reduce safety (Neale et al., 2007; Parasuraman and Riley, 1997).

1.3. The audio-visual display under investigation

In the present study, no classic warning signal or decision support was offered. Our approach combines principles from the promising research field of spatial and looming warnings (Ho et al., 2013), by monotonically mapping the speed and direction of an approaching car onto an audio-visual display. This approach may be beneficial compared to binary warnings because the driver is continuously informed about the degree and direction of the hazard. Through the visualization and sonification of the state of the approaching road user, the participant may intuitively build situation awareness, which in turn may facilitate appropriate decision-making about whether to maintain speed or slow down.

For the visual modality, blinking lights on the speedometer were used, and for the auditory modality a pulse train of beeps, similar to a parking sensor or Geiger counter, was implemented. It is well established that perceived urgency increases with beep rate (Baldwin and Lewis, 2014; Haas and Casali, 1995; Van Erp et al., 2015). Moreover, it has been found that auditory feedback can be effective for conveying directional information (Bronkhorst et al., 1996) and for continuously assisting car drivers in keeping the car on the road in the absence of visual feedback (Bazilinskyy et al., 2016; Powell and Lumsden, 2015; Verbist et al., 2009). Driving is primarily a visual task (Sivak, 1996), and auditory feedback is thought to be beneficial especially in situations where the visual system is overburdened (Stanton and Edworthy, 1999).

According to the framework of levels and stages of automation proposed by Parasuraman et al. (2000), our display features a high level of automation when it comes to the information-acquisition stage, but no automation at the decision-selection and action-implementation phases. Thus, our approach critically differs from some intersection decision-support systems that have been tested recently (Becic et al., 2012; Caird et al., 2008; Creaser et al., 2007; Dotzauer et al., 2015). With our display, the driver is continuously informed but has to decide himself whether or not to cross, thereby preventing overreliance, which may occur with otherwise promising decision-support systems (Dotzauer et al., 2015) or autonomous emergency brake systems (Banks and Stanton, 2017).

1.4. Linked driving simulators

We tested the audio-visual display in a driving simulator, which allowed for safe driving conditions and accurate measurements of the state of the vehicles in relation to the road infrastructure. In our research, the approaching car was not controlled by a computer algorithm, but by an experimenter driving in the same virtual world using a second simulator. The reason for linking two simulators was that our prior research showed that computer-controlled cars yielded highly repetitive behaviours at intersections (Houtenbos, 2008).

The need for linked driving simulators was found to be especially pertinent in situations where the aim was to measure how participants behave if the computer-controlled car does not follow the traffic rules. To illustrate, if the computer-controlled car comes from the right and is programmed to stop (which is inconsistent with the right-of-way rule), a deadlock occurs: the participant has to decide between waiting and violating the traffic rule by crossing first, and the computer-controlled car has right of way but is programmed to not take it. In human-human interactions, one of the two cars eventually crosses first, and the decision is made based on equivocal 'informal traffic rules' (Björklund and Åberg, 2005). Such situations, in which aspects of rule breaking, free will, and informality are important determinants, are difficult to code into simulator software. Although it is possible to let a computer-controlled car emulate non-normative anthropomorphic decision-making behaviours, for example by making the decision to cross the intersection based on relative speed and position, or an accumulated 'impatience level' (Doniec et al., 2008; Lacroix et al., 2009), this may cause the participant to recognize and adapt to the computer's logic, and is still rule-based behaviour and so fundamentally contradicts the principle of informal traffic rules. Thus, by using a human experimenter who drove the second car, we retained aspects of higher-level controllability (i.e., whether the approaching car adheres to the right-of-way rules or not) while lower-level decision-making and control are non-deterministically human.

1.5. Aim of the present study

This study aimed to assess the effectiveness of an audio-visual display that sonifies and visualizes the speed and direction of an approaching car at intersections, as compared to not using the display. The display was tested in seven uncontrolled intersection situations that differed in terms of whether the other car was absent (18% of the intersections) or present (82%), came from the left (50%) or right (50%), and behaved in a way that was consistent (82%) or inconsistent (18%) with the right-of-way rule. At each intersection, buildings of different topology blocked the line of sight while the participant was approaching the intersection. Furthermore, both the participant and the experimenter always drove straight ahead, which is consistent with epidemiological work by Bougler et al. (2005), showing that the 'straight crossing path' is the most frequent type of crash at intersections (with other dominant categories being the left-turn 'opposite direction' and the left turn 'lateral direction' conflicts). In light of the causes of crashes at intersections (Section 1.1), the seven situations span the range of possibilities where the approaching road user is difficult to perceive and sometimes behaves unexpectedly.

Many researchers agree that there are two main and competing goals that road users have in traffic: getting to a destination in the least amount of time (traffic efficiency) and doing so in a safe manner (safety) (Hale et al., 1990; Laureshyn et al., 2010; Stevanovic et al., 2013), and it has been said that ADAS have the potential to optimize both these factors (Maag et al., 2012). Accordingly, in the evaluation of our audio-visual display, we used measures of speed for both the participant and the experimenter, as well as a measure of safety, namely the time gap between the two vehicles (cf. Van der Horst, 1990). We expected that the display would yield increased speed *and* improved safety with respect to unaided driving.

In a study investigating the effects of visual and auditory feedback on driving behaviour, De Waard et al. (1999) found that although participants' driving behaviour improved (i.e., behaviour was more law abiding), a side effect was an increase in mental effort. Indeed, a risk of many in-vehicle technologies is that they may increase workload and cause distraction (Lee, 2007). In order to determine the effect of the visual-auditory display on effort and acceptance, self-report questionnaires were used in the present research (Van der Laan et al., 1997; Zijlstra, 1993). Here, we hypothesized that the display would be highly accepted and not increasing effort as compared to driving without the display.

2. Materials and methods

2.1. Participants

Thirty-three persons were recruited from a participant database of the Dutch Institute for Road Safety Research (SWOV) and via an advertisement in a local newspaper. Participants were advised not to take part if they tended to get car sick, as nausea is a known side effect of simulator use (Dziuda et al., 2014). Participants were required to have had their driving licence for at least 5 years and to have driven at least 5000 km in the previous year. Eight participants dropped out prematurely due to simulator sickness. The remaining 25 participants (7 females, 18 males) who completed the experiment were between 25 and 70 years old ($M = 51.1$, $SD = 12.9$) and had had their license between 6 and 52 years ($M = 30.1$, $SD = 13.4$). Five participants reported driving 5000–10,000 km/year, 6 reported 10,000–15,000 km/year, 3 reported 15,000–20,000 km/year, and 11 reported more than 20,000 km/year. Participants were compensated with 20 Euro.

2.2. Driving simulators

Two fixed-base simulators were used (Green Dino classic model, see Fig. 1). One simulator was driven by the participant and the other by the experimenter (first author). The simulators were connected so that the drivers encountered each other in the same virtual world. The participant and experimenter steered, accelerated, and braked themselves, while gear changing was automated. The virtual world of each simulator was shown by means of three LCD projectors mounted above the simulator cabin. One projector provided a front view with a resolution of 1024×768 pixels, and two projectors provided the left and right views, respectively, both with a resolution of 800×600 pixels. Together, the three projectors provided a 180-degree field of view to the driver (Fig. 1). The dashboard, interior, and mirrors were integrated into the projected image. Engine and wind sounds were provided through headphones. Force feedback was provided on the steering wheel according to the aligning torque of the front wheels. Motion feedback was provided through vibration elements in the steering wheel and seat.

2.3. Audio-visual display

An audio-visual display informed the participant about the speed and direction of the experimenter's car approaching the intersection. The display became active when the experimenter was 67.5 m before the centre of the intersection. The line of sight was blocked by buildings on the left and right corners. The buildings were placed in different ways, yielding different degrees of visibility. Across all 1800 intersection encounters of the experiment (25 participants * 4 sessions * 22 intersections per session), the experimenter's car could be seen when the participant was, on average, less than 68.9 m before the intersection (min = 19.4 m, max = 118.4 m, $SD = 22.3$ m). In 48.2% of the 1800 encounters, the participant received the audio-visual feedback already before the experimenter's car could be seen (47.4% for display off; $n = 900$; 48.9% for display on; $n = 900$).

Through headphones, the participant was informed by beeps presented to the ear that corresponded to the direction from which the experimenter was approaching. Long low-pitched beeps

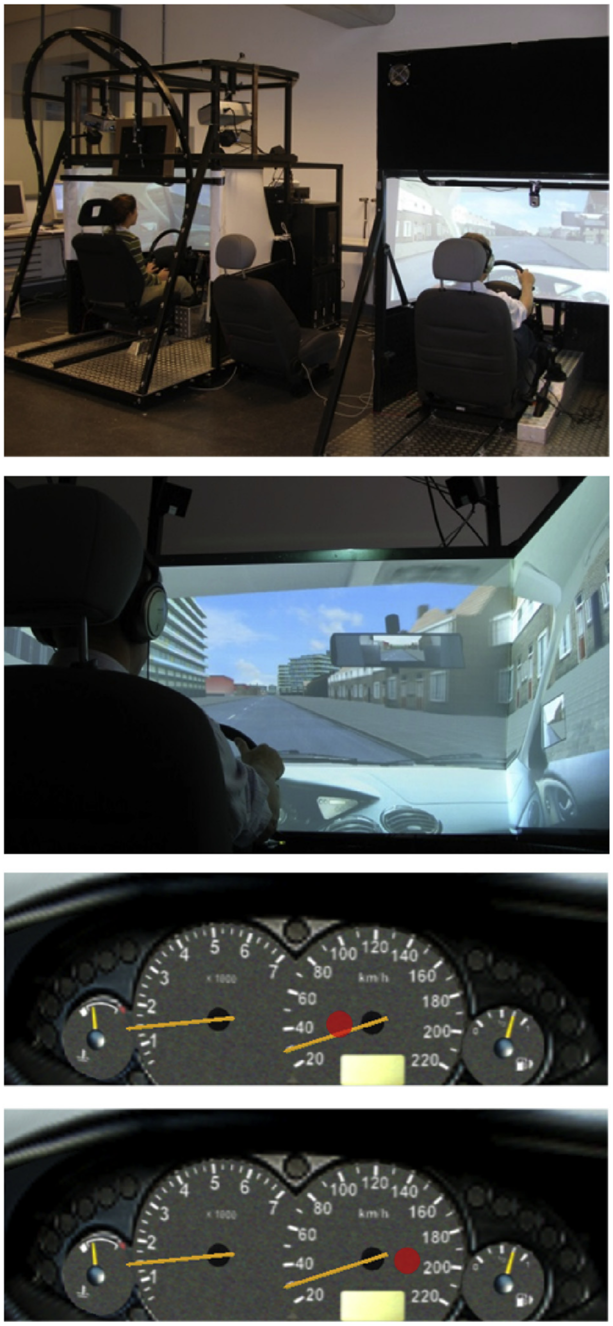


Fig. 1. Top: Two driving simulators (Green Dino; classic model). The left simulator was driven by the experimenter; the right simulator was driven by the participant. Middle: Close-up of the participant's simulator. Bottom: Screenshot of the simulator's dashboard, with approximate location of the flashing red light on the dashboard, when the experimenter approached from the left versus right, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

indicated a slowly approaching experimenter, whereas short high-pitched beeps indicated a rapidly approaching experimenter. Specifically, if the experimenter approached the intersection with a speed of 30 km/h, 0.25-s long samples were played uninterruptedly, each sample containing a beep with a fundamental frequency of 1738 Hz. Thus, at 30 km/h, 4 beeps per second could be heard. The duration of the sample depended on the speed of the experimenter's car as follows: Duration = (0.25 s × 30 km/h)/(experimenter's speed in km/h), which implied that the faster the experimenter was driving, the more beeps were played per second and the greater the fundamental frequency of those beeps (i.e., a sound with higher pitch). For example, when the speed of the experimenter's car was 50 km/h, then the sample duration was 0.15 s (6.7 beeps per second) and the sound frequency was 2897 Hz.

In addition to the beeps, a red flashing light to the left or right of the centre of the speedometer indicated whether the experimenter was approaching from either the left or the right. The flash rate depended on the speed of the experimenter as follows: Time light on = Time light off = (5 km/h)/(experiment's speed in km/h). The lights were projected on the dashboard using a fourth LCD projector. Fig. 1 (bottom) provides an illustration of the approximate positions of the blinking lights in case the experimenter approached from the left or right, respectively. This positioning ensured spatial compatibility with respect to the approaching road user. The dashboard was considered a reasonable location because warnings lights and directional indicators are typically presented on the dashboard as well.

2.4. Intersection situations

Participants completed four sessions, each consisting of the same 10.7 km route with 22 intersections at each of which the participant drove straight ahead. The lane width was 5 m. Each intersection was 35 × 35 m. The experiment was conducted with Dutch citizens, and the road layout and signage represented a typical Dutch city environment. The intersections were all standard Dutch uncontrolled 'priority to the right' situations with no marking of stop lines on any of the four intersections. In the Netherlands, at such intersections without designated priority, a driver approaching from the right has right of way.

When the participant was 242.5 m before the centre of the intersection, the experimenter was spawned with a speed of 50 km/h. If the participant drove faster (or slower) than 50 km/h, the experimenter was spawned farther from (or closer to) the intersection, so that the participant and experimenter encountered each other at the intersection. If a collision occurred between the participant and the experimenter, the participant was automatically placed back 350 m (i.e., directly after the previous intersection) with zero speed. The 350 m distance was large enough for participants to accelerate back to the speed limit of 50 km/h and to approach the intersection again as usual. Collisions were not accompanied by visual or auditory 'special effects' (cf. Hault-Dubrulle et al., 2011, for a driving simulator study in which unexpected crashes were simulated by physical motion and sound). This way there ought to be minimal cognitive or emotional effects of collisions on subsequent driving behaviour.

Seven different intersection situations were encountered by the participants. These situations differed in terms of whether the experimenter approached from the left (L) or right (R), and whether the experimenter behaved consistent (C) or inconsistent (I) with the right-of-way rule, or behaved naturally (N). Together, this yielded the following combinations: (1) Left Consistent (LC), (2) Right Consistent (RC), (3) Left Inconsistent (LI), (4), Right Inconsistent (RI), (5) Vehicle Absent (VA), (6) Left Natural (LN), and (7) Right Natural (RN). Thus, the experimenter approached from the left, with priority to the participant (Situations LC, LI, LN), or from the right, with priority to the experimenter (Situations RC, RI, RN), and always drove straight ahead. In Situation VA, the participant encountered no other road users. Figs. 2 and 3 illustrate the seven intersection situations, including how often they were encountered per session. In sum, both the participant and the experimenter always drove straight ahead, and there was no other traffic besides these two vehicles.

In Situations RC and LI, the experimenter maintained speed. She

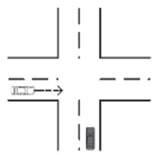
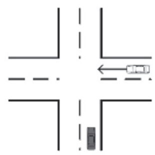
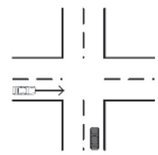
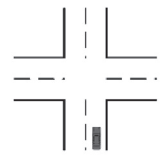
	Left Consistent (LC) (6x per session)	Right Consistent (RC) (6x per session)	Left Inconsistent (LI) (2x per session)	Right Inconsistent (RI) (2x per session)	Vehicle Absent (VA) (4x per session)
					
Participant has right of way?	Yes	No	Yes	No	
Experimenter's behaviour	From left, Slows down	From right, Maintains speed	From left, Maintains speed	From right, Slows down	
Visibility level as determined by the placement of buildings	2 x high 2 x medium 2 x low	2 x high 2 x medium 2 x low	1 x high 1 x medium	1 x high 1 x medium	2 x high 2 x medium

Fig. 2. Intersection Situations Left Consistent (LC), Right Consistent (RC), Left Inconsistent (LI), Right Inconsistent (RI), and Vehicle Absent (VA). Situations LC and RC (each occurring 6 times per session) are consistent with the right-of-way rule. Situation LI (occurring twice per session) is a dangerous situation where the experimenter maintained speed while not having right of way. In Situation RI (occurring twice per session) the experimenter slowed down while having right of way. Situations LN and RN are not shown in this figure, but are analogous to Situations LC and RC, respectively, with the difference that the experimenter behaved 'naturally' rather than always letting the participant go first (as in Situation LC) or always maintaining speed (as in Situation RC). Situations LN and RN together occurred in total twice per session. High, medium, and low visibility refers to buildings that were placed so that the experimenter became visible when the participant was about 85, 60, and 40 m from the intersection, respectively. Situations LN and RN were 'high visibility' intersections.

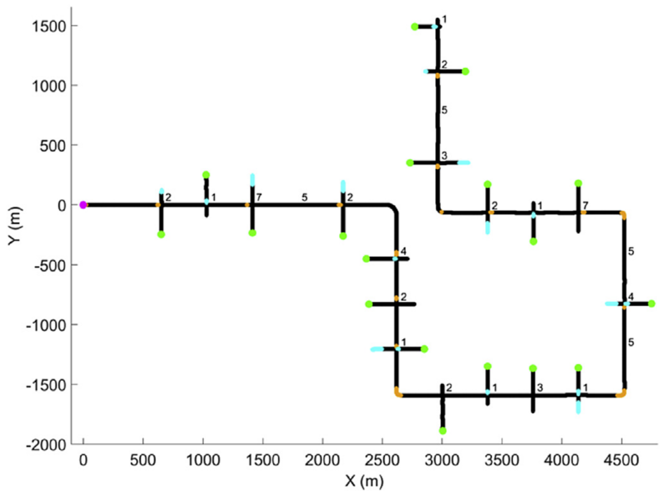


Fig. 3. Top view of the route driven by the participant and experimenter, in one random session. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Magenta = starting point of the participant.
Green = locations where the experimenter was spawned.
Orange = participant's trajectory when he/she drove slower than 30 km/h.
Cyan = experimenter's trajectory when she drove slower than 30 km/h. The situation numbers are indicated next to each intersection. As can be seen, Situation Left Consistent (LC), occurred 6 times, Situation Right Consistent (RC) occurred 6 times, Situation Left Inconsistent (LI) occurred twice, Situation Right Inconsistent (RI) occurred twice, and Situation Vehicle Absent (VA) occurred 4 times. Situations Left Natural (LN) and Right Natural (RN) together occurred in total twice (determined at random; in this case Situation RN occurred twice and Situation LN occurred 0 times).

released the throttle when approaching the intersection, maintaining speed but able to brake if not receiving right of way, and as soon as the participant yielded, she accelerated again. In Situations LC and RI, the experimenter slowed down. Here, the experimenter released the throttle and applied the brakes to come to a standstill at the intersection. Thus, Situations LC and RC are consistent with the right-of-way rule. Situation LI is a potentially dangerous situation where the experimenter maintained speed while not having right of way. In contrast, Situation RI is a potentially inefficient situation. Here, the experimenter slowed down while having right of way; whoever goes first depends on the willingness to wait. Situations in line with the right-of-way rule (Situations LC & RC) were each encountered six times per session, whereas situations that were inconsistent with the right-of-way rule (Situations LI & RI) were each encountered twice per session.

At 2 of the 22 intersections the experimenter did not react strictly according to the priority rule, but naturally, meaning that she behaved in agreement with the right-of-way rule, but also let the relative positions and speeds of both road users determine if she should yield or cross the intersection. In these two conditions, the experimenter approached at random from the left (participant's priority, referred to as Situation LN) or right (experimenter's priority, referred to as Situation RN). To illustrate, in Situation LC, the experimenter always let the participant cross the intersection first. In Situation LN, the experimenter also yielded to the participant, but when it was obvious to her that the situation was safe (e.g., because the participant had stopped or was still far from the intersection) she took right of way. In Situation RC, the experimenter always maintained speed, whereas in Situation RN, the experimenter would brake in case of a looming conflict.

As mentioned above, buildings were positioned at each intersection, obstructing the view of the experimenter's car. Fig. 2 provides an overview of Situations LC, RC, LI, RI, and VA, as well as of the different degrees of visibility in these situations.

2.5. Instructions to participants

After arriving at the laboratory, participants were presented with a leaflet explaining the driving task and the working mechanism of the audio-visual display. The leaflet also mentioned that participants should drive as they normally would and that they should adhere to the speed limit of 50 km/h as much as they could. The leaflet further stated that the experimenter would occupy the other simulator and that she would drive a number of cars that the participant would encounter during the experiment. The participants were advised to stop the experiment if they felt any discomfort. Next, participants signed a consent form, and took their place in the simulator where the experimenter explained the way to operate it.

2.6. Experimental design and procedures

The experiment was of a within-subject design, in which each participant experienced the display and the seven situations an equal number of times (except for Situations LN and RN, which were selected at random, as described above). Participants started with two practice sessions of 4 min each. The first session was driven with the display off, and the second with the display on. When participants indicated they were comfortable to continue, the experiment commenced. Participants started with a session with the display off (Session 1), followed by two sessions with the display on (Sessions 2 & 3), and ended with a session with the display off (Session 4). This 'sandwich' design was applied to determine the robustness of the effect of the display: the comparison between Session 1 (display off) versus Session 2 (display on) assessed the effect of the display when having no prior experience with it, and the Session 4 (display off) versus Session 3 (display on) comparison allowed us to investigate whether the effect of the display disappeared after not using it anymore.

The seven intersection situations were presented in no discernible order per session. Two order sequences (A & B) were used, see Fig. 3 for order sequence A. In Sessions 1, 2, 3, and 4, the order sequences were either A, A, B, B (order condition 1), or A, B, A, B (order condition 2), or B, A, B, A (order condition 3), or B, B, A, A (order condition 4). These four order conditions were randomized across participants. Thus, participants encountered each order sequence (A or B) twice, once with the display off (Session 1 or 4) and once with the display on (Session 2 or 3).

In between sessions, participants took a break for as long as they felt necessary. After each session, including the two practice sessions, participants completed the Rating Scale Mental Effort (RSME; Zijlstra, 1993). After the last session, participants completed a scale designed to assess acceptance of transport telematics (Van der Laan et al., 1997). The acceptance scale was filled out twice: once for rating the beeps and once for rating the lights of the audio-visual display.

2.7. Dependent variables

The simulator recorded the following variables at 50 Hz for the participant's and experimenter's cars: throttle, brake and steer position, speed, and position in the virtual world. In addition, it was recorded, based on a line of sight algorithm, whether participant and experimenter could see each other.

The following variables were calculated per intersection:

Participant crosses first (0 = no, 1 = yes).

Mean speed of the participant (km/h), calculated as follows: 3.6(Distance$_{M2}$−Distance$_{M1}$)/(Time$_{M2}$−Time$_{M1}$).* Here, M1 is the moment when the participant was 150 m before the centre of intersection, and M2 is when the participant was 15 m past the centre of the intersection. The mean speed across the intersection was regarded as a measure of traffic efficiency.

Mean speed of the experimenter (km/h), calculated as follows: 3.6*(Distance$_{M4}$−Distance$_{M3}$)/(Time$_{M4}$−Time$_{M3}$), where M3 is the moment when the experimenter was 150 m before the centre of the intersection, and M4 is when the experimenter was 15 m past the centre of the intersection. Even though the experimenter used no audio-visual display, it would be inadequate to assess only the mean speed of the participant. If a speed increase of the participant comes at the expense of a speed reduction of the experimenter, the net traffic efficiency may well be negative.

Time that the throttle was released. The time that the participant's throttle position was 0%, calculated between M1 and M2. Coasting has been interpreted as a delay in decision-making (Yeo et al., 2010). Accordingly, we regarded pressing the throttle as a measure of traffic efficiency, signifying that the participant was decisive about whether to accelerate or brake. Put differently, we assume that if a driver knows he can maintain speed, he is unlikely to release the throttle, and if a driver knows he has to come to a stop, he is unlikely to apply a coasting period prior to braking.

Time gap(s). The time difference between the moment that the participant's car and the experimenter's car passed the intersection point, which is the coordinate where the lane centres intersected.

In addition the following variables were extracted from the questionnaire data:

Effort (0–150). The RSME is a 150 mm vertical line with nine anchors, from 3 mm (absolutely no effort) to 112 mm (extreme effort) (Zijlstra, 1993).

Acceptance (1–5). The survey consisted of nine five-point scales: 1) Useful … Useless, 2) Pleasant … Unpleasant, 3) Bad … Good, 4) Nice … Annoying, 5) Effective … Superfluous, 6) Irritating … Likeable, 7) Assisting … Worthless, 8) Undesirable … Desirable, 9) Raising-alertness … Sleep-inducing (Van der Laan et al., 1997). Both the RSME and acceptance scales were offered in the Dutch language.

2.8. Statistical analyses

Mean values of the dependent variables were calculated per situation and session. Because the display was presented in the same sequence for all participants (i.e., Session 1 = off, Session 2 = on, Session 3 = on, Session 4 = off), the results are influenced by an experience effect and other carryover effects. Effects were regarded as consistent only if a paired t test yielded $p < .05$ both for Session 1 versus 2 *and* for Session 4 versus 3 ($df = N-1 = 24$ for each t test). This approach is conservative because the effect had to appear when the display was used for the first time (initial exposure effect: Session 1 vs. 2) and had to disappear after it was used (maintenance effect: Session 4 vs. 3). Moreover, this approach effectively applies a significance level (alpha) of $.05^2 = .0025$ if assuming that Sessions 1–4 are independent. Effect sizes between Session 1 versus Session 2 and between Session 4 versus Session 3 were calculated according to Cohen's d_z for matched pairs (Faul et al., 2007).

3. Results

3.1. Main results

Two collisions occurred between participant and experimenter, both in the first session (display off) in Situation LI, which was the hazardous situation where the experimenter maintained speed against the right-of-way rule. Participants took on average 863 s ($SD = 64$), 829 s ($SD = 59$), 814 s ($SD = 55$), and 814 s ($SD = 57$) to complete Sessions 1, 2, 3, and 4, respectively. Table 1 shows the results for the five dependent variables, for each of the seven intersection situations, and for the four sessions.

Table 1
Mean values of the dependent variables, for each of the four sessions and each of the seven situations. Also listed are the p values from a paired t test and corresponding Cohen's d_z effect sizes between Session 1 and 2, and between Session 3 and 4.

Proportion of intersections where participant crossed first						
Situation	**Session 1 (Off)**	**Session 2 (On)**	**Session 3 (On)**	**Session 4 (Off)**	**Session 1 (Off) vs. Session 2 (On) p (d_z)**	**Session 4 (Off) vs. Session 3 (On) p (d_z)**
1. Left Consistent (LC)	1.00	1.00	1.00	1.00	X	X
2. Right Consistent (RC)	0.09	0.06	0.03	0.09	.203 (0.26)	.088 (0.36)
3. Left Inconsistent (LI)	0.08	0.10	0.10	0.04	.714 (-0.07)	.265 (-0.23)
4. Right Inconsistent (RI)	0.58	0.62	0.60	0.58	.425 (-0.16)	.788 (-0.05)
5. Vehicle Absent (VA)	X	X	X	X	X	X
6. Left Natural (LN)	0.85	0.91	0.91	0.84	.430 (-0.19)	1.000 (0.00)
7. Right Natural (RN)	0.03	0.03	0.07	0.00	.337 (0.28)	.334 (-0.26)
Mean of the mean speed of the participant (km/h)						
Situation	**Session 1 (Off)**	**Session 2 (On)**	**Session 3 (On)**	**Session 4 (Off)**	**Session 1 (Off) vs. Session 2 (On) p (d_z)**	**Session 4 (Off) vs. Session 3 (On) p (d_z)**
1. Left Consistent (LC)	46.7	49.4	49.3	47.1	**< .001 (-0.77)**	**.004 (-0.64)**
2. Right Consistent (RC)	42.0	42.2	42.3	42.5	.795 (-0.05)	.620 (0.10)
3. Left Inconsistent (LI)	44.5	43.4	43.9	43.5	.168 (0.28)	.532 (-0.13)
4. Right Inconsistent (RI)	36.8	38.8	38.2	37.1	**.047 (-0.42)**	.437 (-0.16)
5. Vehicle Absent (VA)	47.6	49.6	49.2	47.6	**.001 (-0.74)**	**.007 (-0.59)**
6. Left Natural (LN)	48.1	49.0	49.8	48.3	.966 (-0.01)	**.021 (-0.73)**
7. Right Natural (RN)	42.1	41.5	42.3	42.8	.835 (0.06)	.955 (0.10)
Mean of the mean speed of the experimenter (km/h)						
Situation	**Session 1 (Off)**	**Session 2 (On)**	**Session 3 (On)**	**Session 4 (Off)**	**Session 1 (Off) vs. Session 2 (On) p (d_z)**	**Session 4 (Off) vs. Session 3 (On) p (d_z)**
1. Left Consistent (LC)	35.7	36.7	37.5	36.7	**.035 (-0.45)**	.058 (-0.40)
2. Right Consistent (RC)	48.8	48.8	48.7	48.4	.737 (-0.07)	.087 (-0.36)
3. Left Inconsistent (LI)	49.0	48.8	49.2	49.4	.712 (0.07)	.742 (0.07)
4. Right Inconsistent (RI)	34.4	35.7	35.0	34.8	.177 (-0.28)	.886 (-0.03)
5. Vehicle Absent (VA)	X	X	X	X	X	X
6. Left Natural (LN)	41.3	41.2	40.3	41.2	.789 (0.06)	.953 (-0.02)
7. Right Natural (RN)	49.6	48.8	48.2	48.9	.059 (0.58)	.838 (-0.05)
Mean throttle released time (s)						
Situation	**Session 1 (Off)**	**Session 2 (On)**	**Session 3 (On)**	**Session 4 (Off)**	**Session 1 (Off) vs. Session 2 (On) p (d_z)**	**Session 4 (Off) vs. Session 3 (On) p (d_z)**
1. Left Consistent (LC)	4.99	4.27	4.05	5.03	**.014 (0.53)**	**< .001 (0.80)**
2. Right Consistent (RC)	6.13	5.40	5.59	5.99	**.015 (0.53)**	.116 (0.33)
3. Left Inconsistent (LI)	5.37	5.26	5.78	6.32	.796 (0.05)	.193 (0.27)
4. Right Inconsistent (RI)	7.62	6.86	6.84	8.20	.084 (0.36)	**.031 (0.46)**
5. Vehicle Absent (VA)	3.93	3.34	3.22	4.07	.107 (0.33)	**< .001 (0.75)**
6. Left Natural (LN)	3.91	3.50	2.98	4.29	.607 (0.12)	**< .001 (1.25)**
7. Right Natural (RN)	5.05	5.27	5.83	6.27	.296 (0.30)	.720 (0.09)
Mean time gap (s)						
Situation	**Session 1 (Off)**	**Session 2 (On)**	**Session 3 (On)**	**Session 4 (Off)**	**Session 1 (Off) vs. Session 2 (On) p (d_z)**	**Session 4 (Off) vs. Session 3 (On) p (d_z)**
1. Left Consistent (LC)	2.55	2.64	2.62	2.45	.329 (-0.20)	**.034 (-0.45)**
2. Right Consistent (RC)	5.34	4.74	3.13	2.90	.634 (0.10)	**.048 (-0.42)**
3. Left Inconsistent (LI)	2.51	2.78	2.85	2.59	.109 (-0.33)	**.038 (-0.44)**
4. Right Inconsistent (RI)	2.66	2.68	2.57	2.52	.906 (-0.02)	.643 (-0.09)
5. Vehicle Absent (VA)	X	X	X	X	X	X
6. Left Natural (LN)	2.18	2.27	2.64	2.13	.712 (-0.09)	.053 (-0.60)
7. Right Natural (RN)	2.97	3.02	2.78	2.86	.338 (0.28)	.397 (-0.23)

Note. $N = 25$ ($df = 24$) for Situations Left Consistent (LC), Right Consistent (RC), Left Inconsistent (LI), Right Inconsistent (RI), and Vehicle Absent (VA). N between 14 and 22 (df between 10 and 17) for Situation Left Natural (LN) and Situation Right Natural (RN). The p values were determined with a paired t test (boldface when $p < .05$).

3.1.1. Participant crosses first

There were no consistent effects of the display on the yielding percentage. In Situation LC, where the experimenter slowed down according to the right-of-way rule, the participant always crossed the intersection first. In Situations RC, LI, and RN, in which the experimenter maintained speed and/or had right of way, the participant crossed the intersection first in 10% or less of the cases. In the ‘inefficient’ Situation RI, the participant crossed first about 60% of the cases, regardless of whether the display was on or off.

3.1.2. Mean speed of the participant

In Situations LC and VA, the participants drove consistently faster when the display was on compared to when it was off. The mean speed was relatively low in Situations RC, LI, and RN, which were the situations where the participant had to slow down because the experimenter maintained speed and/or had right of way. The mean speed was lowest in Situation RI, which was the situation where the experimenter slowed down while this was not required according to the right-of-way rule.

3.1.3. Mean speed of the experimenter

There were no consistent effects of the display on the experimenter's speed. The mean speed of the experimenter was lowest in Situations LC and RI, which were the situations where she slowed down. The experimenter's speeds were high in Situations RC, LI, and RN, which were the situations where the experimenter maintained speed.

3.1.4. Time that the throttle was released

In Situation LC, the throttle-released time was consistently smaller when the display was on compared to when it was off. The lower throttle released time suggests that participants were more decisive. It can further be seen that, although not always statistically significant, the effect size was of the same direction for all 14 effect sizes reported in Table 1.

3.1.5. Time gap

There were no consistent effects of the display, but the tendency seems to be that driving with the display on yielded larger time gaps than driving with the display off. The time gap was largest in Situation RC, which was the situation where the participant had to slow down in order to give right of way to the experimenter. The time gap was large in this situation because the participant typically accelerated from low speed or standstill.

3.1.6. Effort

The mean RSME scores in the two practice sessions were 52 (display off) and 37 (display on). During the following four experimental sessions, the mean RSME scores were 38 (display off), 30 (display on), 24 (display on), and 28 (display off), where scores of 27, 38, and 58 correspond to 'a little effort', 'some effort', and 'rather much effort', respectively. The difference between the first and second experimental session was significant ($p = .001$), but the difference between the third and fourth experimental session was not ($p = .067$). In other words, this pattern of results suggests that the display gave rise to lower effort scores compared to the display off, but the effects were not significant between the last two sessions.

3.1.7. Acceptance

The beeps were rated more highly than the lights (Fig. 4). The differences between beeps and lights were most evident on items 1, 3, 5, 7, and 9, which are the items about usefulness. The lights received lower ratings than the beeps, and were considered more useless than useful (item 1 in Fig. 4).

3.2. Supplementary analyses

The results in Table 1 showed that participants in Situation LC drove with statistically significantly greater mean speeds and with less coasting when the display was on than when the display was off. However, these descriptive statistics do not provide insight into how the participant and experimenter jointly behaved as a function of each other's speed and distance to the intersection. A supplementary analysis was conducted to gain further insight into this matter.

Fig. 5 shows the participants' trajectories and actions (braking, pressing throttle) in Situation LC. This figure illustrates that the participants always crossed the intersection before the experimenter did (see also Table 1). Additionally, it can be seen that when the display was on, participants more frequently pressed the throttle when they could not yet see the experimenter's car compared to when the display was off. Specifically, this happened in 5% of 300 intersections for display off, and 14% of intersections for display on. In other words, Fig. 5 illustrates that the display facilitated goal-directed driving behaviour when the approaching car was out of sight.

As mentioned above, the visibility differed per intersection

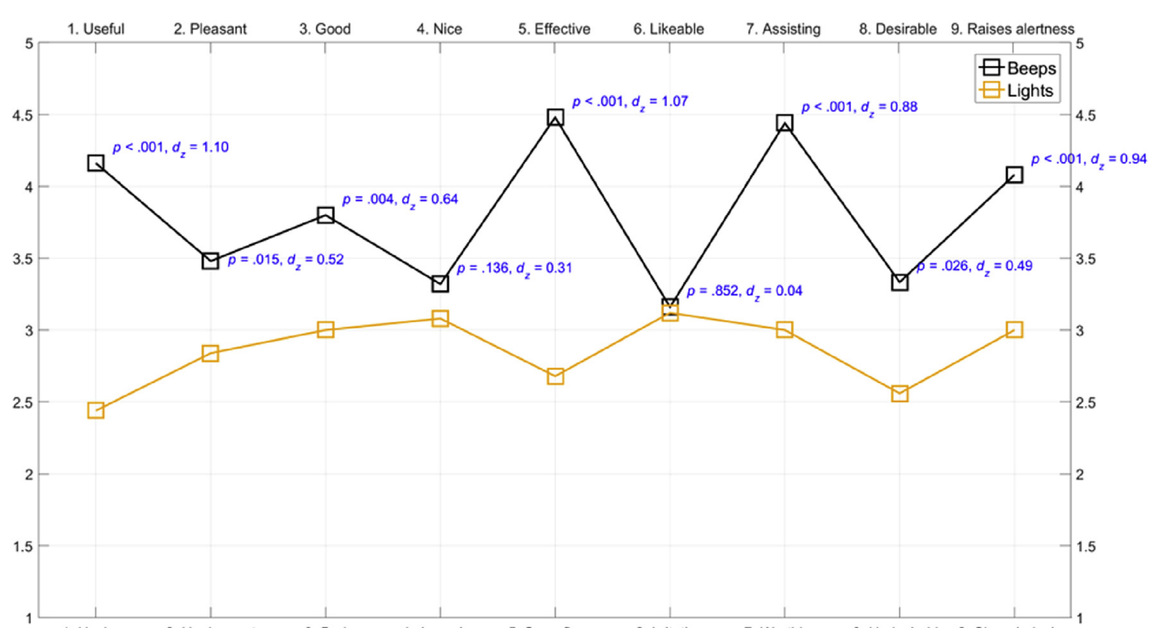


Fig. 4. Mean scores on the acceptance scale. The scores on items 1, 2, 4, 5, 7, and 9 were reversed. The p values were determined with a paired t test between the scores for beeps versus the scores for lights.

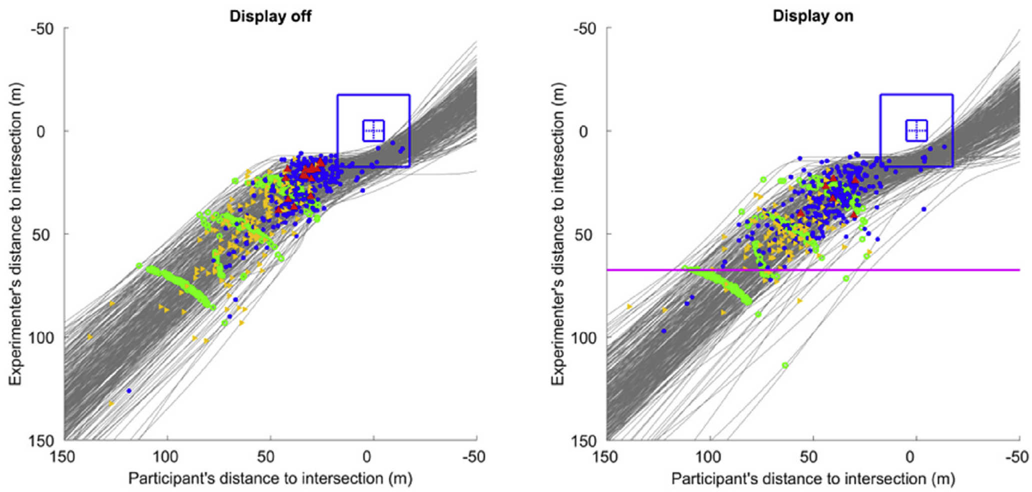


Fig. 5. Distance to the centre of the intersection for the experimenter's car and the participant's car, for Situation Left Consistent (LC; experimenter comes from the left and slows down). The large blue square represents the 35 × 35 m intersection. The four smaller blue squares represent individual lanes (5 × 5 m). For both figures, 300 grey lines are depicted (6 intersections * 2 sessions * 25 participants). The horizontal magenta line in the right figure represents the moment from which the audio-visual display became active. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- Green = moment that participant and experimenter could first see each other (off: $n = 300$, on: $n = 300$).
- Orange = moment that participant first pressed the brakes (off: $n = 127$, on: $n = 96$).
- Red = moment that participant braked harder than 60% (off: $n = 16$, on: $n = 6$).
- Blue = moment of latest throttle depress event that occurred after the participant released the throttle (off: $n = 269$, on $n = 265$). In 15 (display off) and 42 cases (display on) the participant depressed the throttle before the participant and experimenter could see each other.

because buildings blocked the line of sight. Because the degree of visibility of the experimenter's vehicle may interact with the effects of the audio-visual display, a follow-up analysis was conducted. Fig. 6 shows the speed of the participants' car at the moment the experimenter's car could just be seen, for each of the situations. For Situations LC and RC, there was no noteworthy difference in the participant's speed between the display on versus off if the visibility of the intersection was high (i.e., a high distance to intersection when the experimenter became visible). However, if the visibility was low (i.e., a small distance to intersection) in Situation LC (the situation in which the participant could maintain speed), the display facilitated an *increase* of speed as compared to the display off, in line with the results shown in Fig. 5. Conversely, for Situation RC (which was the situation where the participant had to yield to the experimenter), the display facilitated a *reduction* of speed, which can be explained by the fact that participants received information about the fact that the experimenter maintained speed already before the experimenter's car could be seen. Specifically, when the experimenter became visible in Situation RC, the participant's speed was less than 20 km/h in 21 cases when the display was on, and in only 2 cases when the display was off (see Fig. 6). For Situations LI, RI, LN, RN, there were no clear differences between the display on and off, which may be because the overall visibility was high at these intersections. In summary, as with Fig. 5, Fig. 6 shows that the display was particularly effective in guiding action when the approaching road user could not yet be seen.

4. Discussion

We investigated the effectiveness of an in-vehicle display that provided real-time information about the approach speed and direction of another road user at intersections. In this research, two driving simulators were connected so that the participant encountered a human experimenter in the same virtual world, an approach that is relatively rare but gaining popularity in human factors research (Hancock and De Ridder, 2003; Lehsing et al., 2015; Muehlbacher et al., 2014; Oeltze and Schießl, 2015; Preuk et al., 2016). This linked-simulator method allowed for realistic behaviours of the road users, while retaining adequate control over the intersection situations.

The results of the experiment showed that in Situations LC and VA participants drove faster when the display was on compared to when it was off. This effect was robust despite the presence of a learning curve in the data. That is, the mean speeds during Situations LC and VA were significantly lower in Session 4 (display off) than in Session 3 (display on), despite the fact that there was a session-on-session trend to increase speed (i.e., Session 4 was completed 49 s faster than Session 1, and Session 3 was completed 15 s faster than Session 2).

The speed-increasing effect of the display can be explained as follows: In Situation LC, the display provided information that the experimenter was slowing down. The participant could therefore know that he/she could safely maintain speed, especially when the experimenter's car could not yet be seen (Figs. 5 and 6). In Situation VA, the experimenter's car did not appear. In Sessions 2 and 3 (display on), the VA situations were the only situations in which no audio-visual information was provided, and so the *absence* of audio-visual information offered knowledge that the participant could safely maintain speed. In other situations, the participant *had* to slow down because the right-of-way rule specified so (Situations RC, RI, RN), or because the experimenter took right of way against the rules (Situation LI). In summary, participants seemed to use the information provided by the display in order to improve their driving efficiency. The mean speeds were slightly higher in situations where the participant could legitimately continue driving through the intersection.

The display resulted in increased driving speeds in Situations LC and VA, but did not have a negative effect on the speed of the experimenter's car. Moreover, the display did not compromise the time gap (which we used as a proxy measure of safety) between the two vehicles. In fact, in Situations LC, RC, and LI the time gap was larger in Session 3 (display on) than in Session 4 (display off).

The auditory information was rated more highly than the visual information, which is in line with other research on in-vehicle

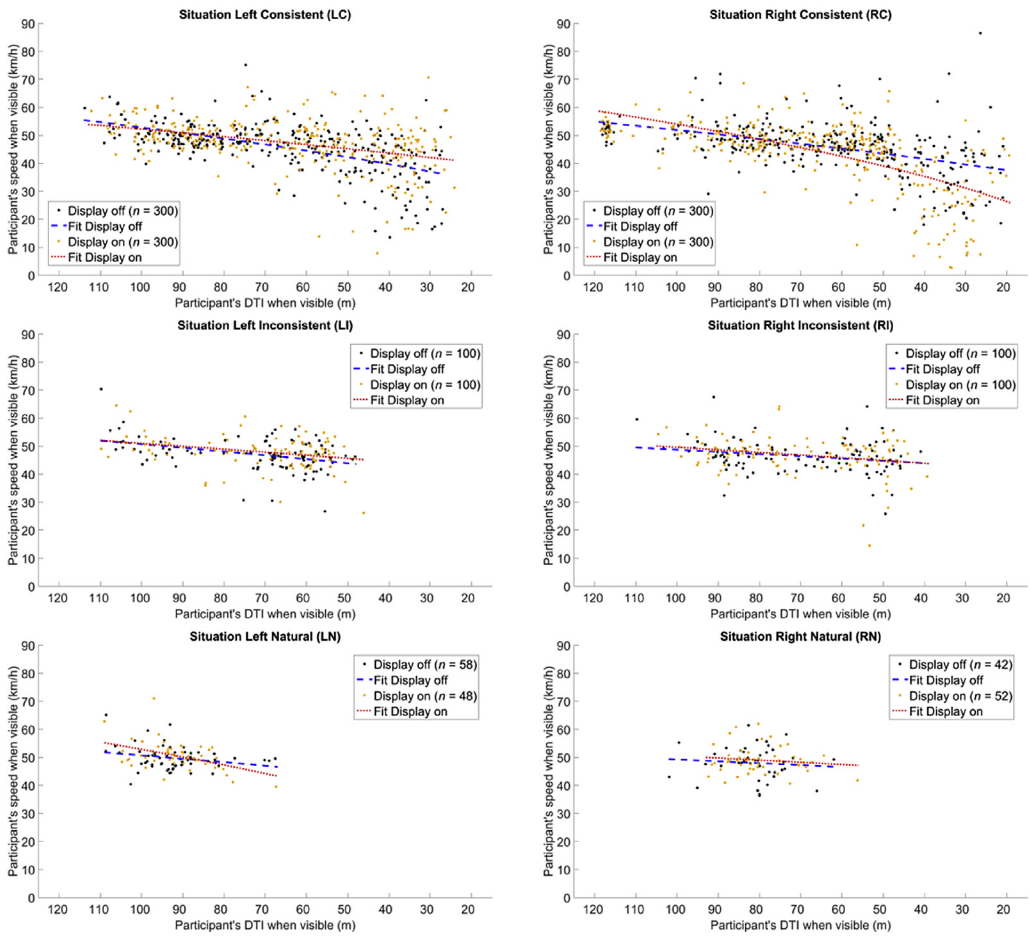


Fig. 6. The participant's speed at the moment that the participant could see the experimenter versus the participant's distance to the intersection (DTI) at the moment the participant could see the experimenter, for Situations Left Consistent (LC), Right Consistent (RC), Left Inconsistent (LI), Right Inconsistent (RI), Left Natural (LN), and Right Natural (RN). Each data point corresponds to an individual intersection encounter. Also shown is a fit through the data points for illustrative purposes. The fit is of the equation: speed = $(b^2+2*a*\text{DTI})^{0.5}$, representing the instantaneous speed as a function of travelled distance given a constant deceleration (a) and initial speed (b), according to Newtonian mechanics.

auditory displays (Nees and Walker, 2011). Auditory feedback is 'gaze free' meaning that it can attract a person's attention regardless of the orientation of the eyes and head (Meng and Spence, 2015; Stanton and Edworthy, 1999). The lights were presented on the speedometer, which seemed a sensible location for presenting directional and speed-related information. However, the results of the acceptance questionnaire showed that the blinking lights on the speedometer were regarded as a rather useless feature of the audio-visual display. In their study on collision warnings at intersections, Werneke and Vollrath (2013) compared visual warning locations in a head-up display (central: on the own driving lane versus peripheral: towards the right, where the critical incident was initiated), and found that the peripheral warning received a lower favourability rating. In our study, the visual information was placed even more peripherally (on the speedometer rather than through a head-up display). In order to notice the visual information, drivers were required to direct their visual attention to the speedometer. It takes a certain amount time (about 0.5–1.0 s) to glance in the direction of the speedometer (Dingus et al., 1989; Mourant and Rockwell, 1972; Wittmann et al., 2006), which is valuable time lost in a safety critical situation. Therefore, it is recommended to test more conspicuous head-up augmented-reality feedback for future applications (see also Caird et al., 2008; Manca et al., 2015; De Groot et al., 2013; Zimmermann et al., 2014).

Several limitations have to be considered when interpreting the results of this experiment. First, the audio-visual display was tested in a driving simulator, and therefore did not allow for eye contact or gestures. Kemeny and Panerai (2003) pointed out that there is important contribution of vestibular feedback in distance perception, prompting a re-evaluation of the role of visual-vestibular interaction in driving simulation studies. It is known that people brake harder in a simulator than they do in a real car, especially when the simulator does not provide vestibular motion feedback (Boer et al., 2000; De Groot et al., 2011). Furthermore, in our experiment, about a quarter of the participants (8 of 33) dropped out because of simulator sickness, and their data were not used in the analyses. Such dropout rates are not uncommon in simulator research, especially in city driving tasks where occurrences of visual-vestibular conflict are likely (Mourant and Thattacherry, 2000; Park et al., 2006). We advised participants to not continue driving if they experienced symptoms of simulator sickness, and all eight dropouts left the experiment early (either in the training session, or in Session 1 or 2), suggesting that the remaining participants were not severely affected. Despite their drawbacks, simulators have clear advantages for low-cost human factors research (Lawson et al., 2016). With a simulator, the states of road users are always known with perfect accuracy, whereas it is challenging to obtain accurate information with instrumented vehicles (Santos et al., 2005).

Second, it is possible that the experimenter unknowingly influenced the results by driving with different safety margins in Sessions 2 and 3 (display was on) than in 1 and 4 (display was off). However, we argue that it is unlikely that such experimenter bias has caused the observed effects. In Situation LC, the experimenter always came to a halt, and in Situation VA, the experimenter did not appear at all, yet the strongest effects were observed in these two situations (Table 1).

Third, for the sake of simplicity and controllability, the visual-auditory display was tested in situations where drivers were instructed to go straight ahead at each intersection and where a single other driver approached from the intersecting road. Of course, ordinary driving involves other types of manoeuvres at intersections than just driving straight. It is yet to be determined how to design a sonification display for complex situations, such as a left-turn gap acceptance conflict, or situations with vulnerable road users, with ambient sounds (e.g., horn honking, vehicles with sirens), or with sounds from other in-vehicle technology (e.g., route navigation device, ADAS). As a first step, future research could investigate whether the display would work when there are two other road users approaching the intersection, and how to sonify a vehicle that makes a left or right turn. Humans have strong selective attention abilities when it comes to the auditory modality ('the cocktail party effect', see Shinn-Cunningham, 2008), suggesting that appropriate solutions are viable for complex traffic situations.

Fourth, participants drove faster when the display was on compared to when it was off, which raises some concerns about misuse in case of technological failure. The speed-enhancing effect of the display was particularly strong in the VA situation. Here, some participants may have assumed that the absence of evidence is evidence of absence (*argumentum ad ignorantiam*), which is a dangerous assumption in real-life cases if the sensor fails to detect the approaching car. However, these overreliance concerns are probably less severe compared to overreliance on automated driving, in which the human is not in the loop and therefore has no opportunity to react within a short time frame (cf. Flemisch et al., 2008).

Fifth, it is acknowledged that we developed the display under the assumption that providing drivers with task-relevant information enhances situation awareness and decision-making. Although the display was effective in the simulator, in real traffic it may put unreasonable responsibilities on drivers, and may be seen as (yet another) technological gadget in the cockpit. Recent research emphasizes the need for a more system-based approach to intersection safety, in which the perspectives of different road users, training and licensing, enforcement, as well as organisational, political, societal, and economic factors are considered (Cornelissen et al., 2015; Salmon et al., 2016; Stefanova et al., 2015). We agree that the present study represents only part of the causal chain leading to crashes, and various other aspects, such as the effects of road infrastructure, are worthy topics of investigation (Campbell et al., 2012). At the same time, there are diminishing returns on pursuing more systemic influences when it comes to creating tractable crash countermeasures (De Winter 2014; Reason, 1999). Although it is true that regulatory and societal factors have important influences on crashes at intersections, the same could be said of any inadvertent event, and this knowledge by itself is not specific enough to be able to develop or implement remedial measures (Reason, 1999). A strength of our study is that it addressed the proximal contribution to crashes (i.e., 'human error'), and that we established causal and empirical relationships between the display and driver behaviour.

Finally, one may wonder what it takes to implement an audio-visual display in a real car. Within a few decades, cars will be able to drive automatically, at least part of the time (Underwood, 2014). In order to estimate the state of other road users, automated driving systems will rely on vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communication (Dey et al., 2016; Kamalanathsharma and Rakha, 2016). Our audio-visual display has to use the same type of sensors and V2V/V2I communication as automated vehicles do (Dogan et al., 2004), with the difference that the driver remains in control of the steering wheel and pedals. Although automated driving is promising for road safety (Mui and Carroll, 2013; Thrun, 2010), concerns exist that it causes out-of-the-loop problems such as low workload and loss of situation awareness (Endsley and Kiris, 1995; Young and Stanton, 2007). As pointed out by Hancock (2015), "if you build vehicles where drivers are rarely required to respond, then they will rarely respond when required" (p. 138). The human-centred audio-visual display, which continually informs and involves the driver, is regarded as promising until wholly automated driving is technically feasible (see also Banks and Stanton, 2016; Billings, 1991).

The present results might be particularly relevant for older drivers because they are overrepresented in crashes at intersections (e.g., Davidse, 2007; Dukic and Broberg, 2012; Oxley et al., 2006; Skyving et al., 2009). Psychological reasons that have been found for this overrepresentation are that intersections impose high visual and cognitive demands, resulting in search and detection errors (Braitman et al., 2007; Dukic and Broberg, 2012). Because older persons are becoming increasingly mobile, ways to help them in complex driving situations are becoming increasingly relevant.

5. Conclusions

In conclusion, by means of a linked-simulator experiment, we tested a real-time audio-visual display that provided task-relevant feedback about the presence, direction, and speed of another road user, even when this road user could not yet be seen. The results showed that the display resulted in greater traffic efficiency while not reducing safety, and that the auditory component of the display was rated as more useful than its visual counterpart.

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