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Take-over again: Investigating multimodal and directional TORs to get the driver back into the loop

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ABSTRACT

When a highly automated car reaches its operational limits, it needs to provide a take-over request (TOR) in order for the driver to resume control. The aim of this simulator-based study was to investigate the effects of TOR modality and left/right directionality on drivers' steering behaviour when facing a head-on collision without having received specific instructions regarding the directional nature of the TORs. Twenty-four participants drove three sessions in a highly automated car, each session with a different TOR modality (auditory, vibrotactile, and auditory-vibrotactile). Six TORs were provided per session, warning the participants about a stationary vehicle that had to be avoided by changing lane left or right. Two TORs were issued from the left, two from the right, and two from both the left and the right (i.e., nondirectional). The auditory stimuli were presented via speakers in the simulator (left, right, or both), and the vibrotactile stimuli via a tactile seat (with tactors activated at the left side, right side, or both). The results showed that the multimodal TORs yielded statistically significantly faster steer-touch times than the unimodal vibrotactile TOR, while no statistically significant differences were observed for brake times and lane change times. The unimodal auditory TOR yielded relatively low self-reported usefulness and satisfaction ratings. Almost all drivers overtook the stationary vehicle on the left regardless of the directionality of the TOR, and a post-experiment questionnaire revealed that most participants had not realized that some of the TORs were directional. We conclude that between the three TOR modalities tested, the multimodal approach is preferred. Moreover, our results show that directional auditory and vibrotactile stimuli do not evoke a directional response in uninstructed drivers. More salient and semantically congruent cues, as well as explicit instructions, may be needed to guide a driver into a specific direction during a take-over scenario.

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1. Introduction

1.1. Highly automated driving and the importance of take-over requests

Research in automated driving is on the rise. Many car manufacturers, OEMs, universities, and federal research institutes are now developing and testing automated driving systems. There appears to be a consensus that fully automated cars will be prevalent on public roads by the year 2030 (Kyriakidis et al., 2015; Underwood, 2014), yet some experts have argued that it will take many more decades before fully automated driving becomes ubiquitous (Shladover, 2015).

Before full automation ('level 5 automation'; SAE International, 2014) is technically feasible, conditional ('level 3') and high ('level 4') automation will probably be deployed. At levels 3 and 4, the automation is not perfectly capable and reliable, meaning that the driver will sometimes have to take back control. If the automation recognizes that it is unable to handle a traffic situation, it provides a warning, also called a take-over request (TOR).

The take-over process is an important topic in human factors research. A substantial number of researchers have studied how drivers behave after receiving a TOR (Clark and Feng, 2015; Gold et al., 2013; Lorenz et al., 2014; Louw et al., 2015; Merat et al., 2014; Mok et al., 2015; Petermann-Stock et al., 2013; Payre et al., 2016; Telpaz et al., 2015; Walch et al., 2015; Zeeb et al., 2015; for reviews see De Winter et al., 2014; Lu et al., 2016). The time buffer

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within which the driver has to perform a steering manoeuvre or a braking action can range from long (e.g., upcoming highway exit) to short (e.g., accident happening in front of the vehicle). In emergency scenarios, in which the time buffer is short, it is important that the TOR causes the driver to resume control as quickly and safely as possible. For example, the automation may provide a take-over request when it cannot handle an impending collision, such as when a stationary obstacle is present on the road. It is then up to the driver to take over control and execute a proper maneuver, such as to evade a stationary object on the left or right.

1.2. Auditory and vibrotactile TORs

In manual driving, information is typically presented to the driver via visual displays (e.g., low fuel indicator) and auditory displays (e.g., navigational instructions). Auditory and vibrotactile displays have the advantage over visual displays of being 'gaze-free', which means that the information can be detected by the driver irrespective of head or eye position (Meng and Spence, 2015; Stanton and Edworthy, 1999; Stokes et al., 1990). During highly automated driving, the driver is likely to be occupied with non-driving activities. Therefore, auditory and vibrotactile stimuli are promising as TORs (Bazilinskyy and De Winter, 2015).

Vibrations are a relatively underused modality in the automotive industry (Meng and Spence, 2015) but are gaining interest (for a review, see Petermeijer et al., 2015). For example, BMW (2015) and Mercedes-Benz (2015) have introduced a vibrating steering wheel for lane departure warnings, whereas Citroën (2007) and Chevrolet (General Motors, 2014) have introduced a lane departure warning system that provides vibrations in the driver seat. Compared to vibrations on the steering wheel, seat vibrations are a promising means of conveying TORs to the driver, because the driver of an automated car will usually be in contact with the seat but not with the steering wheel (Petermeijer et al., 2016).

1.3. Multimodal feedback

Psychophysics research has shown that multimodal warnings (i.e., combinations of visual, auditory, and vibrotactile stimuli) are perceived as more urgent than their unimodal constituents (e.g., Van Erp et al., 2015). In a self-report questionnaire among 1692 respondents investigating the public opinion on visual, auditory, and vibrotactile displays during highly automated driving, it was found that people are more likely to prefer a multimodal TOR when the urgency of the takeover is higher (Bazilinskyy et al., 2016). Consistent with these findings, driving simulator research has shown that a combination of visual, auditory, and vibrotactile TORs led to higher perceived urgency and perceived alerting effectiveness than the corresponding unimodal warnings (Politis et al., 2014).

Multimodal warnings not only enhance subjective urgency, but also elicit faster reaction times than unimodal warnings. Burke et al. (2006) found in a meta-analysis of 43 studies on various types of human-machine interaction that visual-auditory and visual-tactile feedback yield faster reaction times than visual feedback alone. An experimental study by Diederich and Colonius (2004) found that trimodal stimuli (vibration, light, & tone) consistently evoked faster reaction times than bimodal stimuli, which in turn were faster than unimodal ones. Additionally, a review by Spence and Santangelo (2009) concluded that multimodal stimuli are more effective in capturing a person's attention than unimodal ones, especially when the person is engaged in a concurrent attention-demanding task.

Although the benefits of multimodal feedback are well established, such benefits are not necessarily obtained in manual driving with a driver assistance system. A driving simulator study by Tijerina et al. (1996) on a lane departure warning system concluded that a bimodal auditory-vibrotactile display "may be a source of overload to a driver", whereas a study in a driving simulator by Lees et al. (2012) found that bimodal auditory-visual cues yielded higher reaction times than auditory-only cues. In another simulator study investigating warnings when Adaptive Cruise Control (ACC) exceeded its functional limits, Lee et al. (2006) observed brake reaction times that were 400 ms *slower* for a combination of a visual warning, auditory warning, vibratory seat, and brake pulse feedback compared to a visual-auditory warning. A detrimental effect of a multimodal warnings may occur when the cues from the different sources are semantically, temporally, and/or spatially incongruent, as a result of which they are perceived as a series of cues rather than a single cue (Diaconescu et al., 2011; Talsma et al., 2010).

1.4. Directional warnings

In most of the available research in automated driving, the TORs are provided in a nondirectional manner, meaning that the warning is used for alerting the driver without conveying any extra information. In particular, many studies on the take-over process have used a nondirectional auditory TOR (e.g., a double beep) often in combination with a nondirectional visual notification (e.g., Damböck, 2013; Gold et al., 2013; Melcher et al., 2015; Naujoks et al., 2014; Naujoks et al., 2015; Radlmayr et al., 2014).

Several researchers have demonstrated the potential of directional warnings in manual car driving, whereby the location of the warning signal indicates a location or direction to which the driver needs to focus his/her attention (Weller et al., 2013; Zarife, 2014; Zhang et al., 2015). For example, Gray et al. (2014) tested a forward collision warning system that used vibrotactile stimili that were linked to the closing velocity and which travelled upward or downward on the human body using three tactors. Nukarinen et al. (2015) tested left/right directional visual cues versus directional vibrotactile cues provided via eyeglasses and the driver seat in a simulated lane change test. Their results showed that the vibrotactile cues yielded faster response times than the visual cues. Schwalk et al. (2015) provided dynamic directional vibrotactile cues via the driver seat, which participants rated as appropriate for TORs, whereas Telpaz et al. (2015) provided seat vibrations that made drivers aware of surrounding traffic during automated driving. More generally, research in a variety of applications areas has demonstrated the effectiveness of visual, auditory, and vibrotactile directional cues regarding reaction times and situation awareness (Houtenbos et al., 2017; Naujoks and Neukum, 2014; Prewett et al., 2012).

One issue in the design of left/right directional warnings is that a distinction can be made between an ipsilateral mapping, requiring the driver to steer in the direction of the stimulus (i.e., steer towards the right when the stimulus comes from the right), and a contralateral mapping, requiring the driver to steer away from the direction of the stimulus. Early studies investigating directional cueing in abstract laboratory environments found that ipsilateral mapping yields faster reaction times, a phenomenon also known as the spatial stimulus-response compatibility effect (e.g., Simon et al., 1970; Umiltá and Nicoletti, 1990). However, in realistic driving scenarios, in which there is a dangerous situation and the driver is able to visually assess the driving scene before responding, a contralateral mapping has been found to yield faster reaction times (Beruscha et al., 2010; Müsseler et al., 2009; Straughn et al., 2009; Wang et al., 2007). This is also the approach used in the majority of lane departure warning systems (Meng and Spence, 2015).

Manual and automated driving are different with respect to the role of the driver, and to our knowledge, the effects of directional auditory or vibrotactile warnings have not been investigated in a highly automated driving context. One particular difference between warnings in manual driving (e.g., lane departure warnings, forward collision warnings) and warnings in automated driving (TORs) is that the latter warnings may occur when the driver is not engaged in the driving task at all. In automated driving, the driver may be performing a distracting non-driving task, and should be able to effectively reclaim control and intuitively interpret the directional feedback within a matter of seconds. At present, it is unknown whether directional auditory or directional vibrotactile cues have the potential to guide a driver towards a left or right direction in a take-over scenario.

1.5. Aim of the study

The aim of this study was to evaluate drivers' reaction times and self-reported usefulness and satisfaction of unimodal (i.e., auditory or vibrotactile) versus bimodal (i.e., auditory-vibrotactile) TORs. Furthermore, this study aimed to investigate whether the directionality of the TOR (left, right, or nondirectional) evokes a spontaneous ipsi- or contralateral response. That is, we investigated whether uninstructed drivers execute an ipsilateral or a contralateral response in situations where both responses are valid for avoiding a collision. In our experiment, the drivers of the highly automated car were biomechanically, visually, and cognitively engaged with a secondary task (Surrogate Reference Task [SuRT]; ISO/DTS 14198, 2012) prior to receiving the TOR. The consistency of the participants' steering reaction to the directional TOR after this period of distraction is informative about whether directional feedback is effective in guiding action.

2. Method

2.1. Participants

Twenty-four participants (16 male; 8 female) holding a driver's license participated in the experiment. The participants were students and employees of the Technical University of Munich, and were between 24 and 35 years old ($M = 27.9$ years; $SD = 3.0$ years). Their mean driving experience was 10.1 years ($SD = 3.1$). Four of the participants reported a mileage of 1–1000 km, 9 participants reported a mileage of 1001–5000 km, and 11 participants reported a mileage of 5001–25,000 km in the past 12 months (Table S5). Twelve participants had participated in more than five previous driving simulator experiments. Eight participants reported wearing glasses or contact lenses while driving a car, and none of the participants reported colour blindness. One participant was left-handed.

2.2. Simulator

The study was conducted in a fixed-base driving simulator consisting of a complete BMW 6 Series (Fig. 1). The front (ca. 180 deg) and rear views (perceivable via the rear mirrors) of the environment were presented using six LCD projectors (Technical University of Munich, 2015). Mounted LCD screens represented the dashboard and on-board computer. Road noise and engine noise were played back, and low frequency vibrations were provided in the driver seat via a bass speaker. The participant could override the automation by braking or turning the steering wheel. The automation could be engaged and disengaged by pressing a diamond-shaped ACC button on the steering wheel. Pushing the brake pedal with more than 25% depression or steering so that the deviation from lane centre was greater than approximately 0.5 m would also disengage the automation. No visual indication of the automation status was provided.

2.3. Independent variables

The independent variable was the type of TOR. The TORs were auditory beeps (A), vibrations in the driver seat (V), or their combination (AV). Both directional and nondirectional TORs were provided. In the directional AV TORs, the beeps and the vibrations were provided from the same side (left or right). The TORs did not include a visual notification, because our aim was to study the effectiveness of auditory and vibrotactile feedback while drivers were visually distracted (see Section 2.5 for a description of the

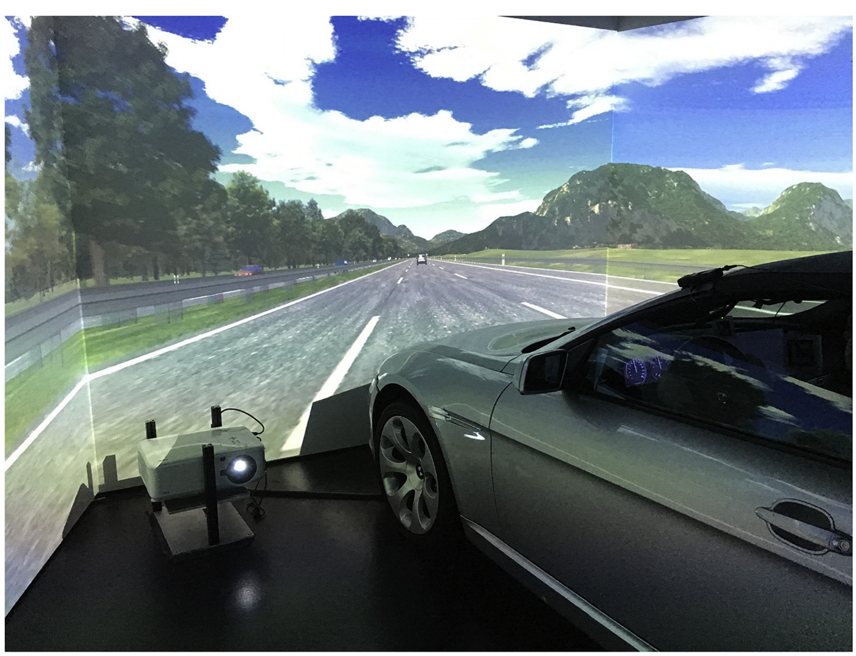

Fig. 1. Driving simulator used in the experiment.

visually demanding secondary task).

An auditory TOR (A) was a single pair of 240 ms beeps of 2700 Hz, with a 100 ms interval between the two beeps. Directional auditory TORs produced the sound from the in-vehicle sound system. Specifically, the sounds were produced from left or right speakers located in the front and rear doors and a subwoofer located in the upper part of the driver seat. Nondirectional TORs were generated from both speakers simultaneously. The loudness of the auditory TOR was 105 dB (measured with Decibel Ultra iOS application).

A vibrotactile TOR (V) was a single pair of vibrotactile pulses having a frequency of approximately 60 Hz, using the same temporal pattern as the auditory TOR (pulse duration = 240 ms, interval between pulses = 100 ms). Twelve vibration motors (Pico Vibe 9 mm, model number: 307-103) were configured in two 3 × 2 matrices on the driver seat back and bottom (Fig. 2). Directional TORs were provided by vibrating the left or right column of motors in the seat back and bottom simultaneously, whereas nondirectional TORs were provided by vibrating all 12 motors. The sound produced by the vibration motors was negligible compared to the engine noise and road rumble of the simulation.

2.4. Driving scenario in experimental sessions

The sessions involved driving on a highway with three 4 m wide lanes. At the beginning of each of the three sessions, the participant's car was positioned in the middle of the three lanes. The participants were asked via the intercom to accelerate to 100 km/h and engage the automation. The automated system controlled both lateral and longitudinal motion at a constant speed of 120 km/h.

In each session, a distance of approximately 21.9 km was driven in about 11.5 min. A total of six stationary cars were positioned in the middle lane, between 3000 m and 4000 m apart. Accordingly, the time interval between the TORs was between 1.5 min and 2 min. When the participant's car was 223 m in front of the stationary car, a TOR was provided. At a speed of 120 km/h, this implies a lead time of about 7 s (see also Gold et al., 2013). All TORs were provided on straight road segments. A video illustration of a TOR is provided as supplementary material.

Fig. 2. Vibration mat on the driver seat of the simulator. Red circles indicate the approximate locations of the vibration motors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

During the entire experiment, there was no other traffic in the participants' direction of travel, so that the participant could avoid the stationary vehicle by changing to either one of the adjacent lanes. Consequently, either an ipsilateral or contralateral response to a directional stimulus were valid. No collisions with objects in the simulated environment (e.g., guardrails or other vehicles) were possible, which means that the participants could drive through these objects.

2.5. Secondary task

The participants were asked to perform the SuRT shown on a 14-inch tablet on the central console, at the position of the car radio. The SuRT is a self-paced task that requires visual search and manual input. The task of the participant was to identify a circle that is larger (target) among other smaller circles (distractors). The participant used a keypad, located next to the handbrake, to select the column of circles that contained the target circle. The target size was 14 mm, the distractor size 12 mm, and the number of columns was 6.

2.6. Procedures and instructions to participants

All participants were given an instructions form describing that the purpose of the experiment was to investigate driving behaviour, subjective experience, and workload for three types of TOR in a highly automated vehicle. Moreover, the form explained that the participants would drive three 12-min sessions, each session with a different TOR (sounds, vibrations, or sound and vibrations combined). The form also introduced the SuRT.

The participants completed an intake questionnaire, after which they proceeded to the simulator, where they adjusted the seat, steering wheel, and mirrors according to their liking. The participants were verbally told how to (dis)engage the automation and how to perform the SuRT. Furthermore, they were asked to focus on the secondary task during automated mode. Participants were instructed that when a TOR was provided, they had to take the steering with both hands and avoid the obstacle. Additionally, they were asked to return to the centre lane and re-engage the automation after having taken over the stationary car. The experimenter also asked the participants to behave as if driving on a real highway in a real car.

After receiving these instructions, participants drove a 3-min familiarisation session in which they practiced how to control the car, (dis)engage the automation, and perform the SuRT. In this session, one nondirectional AV TOR was provided. The participants were not informed that they would be exposed to directional TORs in the forthcoming sessions.

The participants drove three experimental sessions, with one TOR modality (A, V, or AV) per session. Each session featured six TORs: four directional (two from the left, two from the right) and two nondirectional ones. The three conditions (A, V, AV) as well as the directionality of the TORs within a session were randomized between the participants.

Each session was followed by a break of up to 5 min outside the simulator. During this break, the participants filled out a questionnaire on usefulness and satisfaction (Van der Laan et al., 1997) and a NASA Task Load Index (NASA-TLX; Hart and Staveland, 1988). The participants were asked to consider only the TORs (which were presented in either the A, V, or AV modality) when answering the usefulness/satisfaction questionnaire, and all activities during the session when answering the NASA-TLX. After the third experimental session, a post-experiment questionnaire was filled out about participants' preference, perceived urgency, and perceived directionality of the TORs they received during the experiment. The experiment took approximately 1 h per participant to complete.

2.7. Dependent variables

2.7.1. Objective measures

The direction (left or right) on which participants overtook the stationary vehicle was used to assess whether participants chose that direction more likely based on the directionality of the TOR. Furthermore, reaction times were calculated to assess how quickly participants provided steering or braking input after receiving a TOR. The following reaction times were calculated:

(1) Steer touch: absolute steering wheel velocity greater than 1 deg/s. During automated driving, the steering wheel hardly moves. An absolute steering velocity of 1 deg/s was the minimum value which could be reliably attributed to human input. Accordingly, the steer-touch reaction time was regarded as a measure of how quickly participants touched the steering wheel after receiving the TOR.
(2) Steer initiate: absolute steering wheel angle greater than 0.25 deg. This 0.25 deg threshold represents the minimum that could be reliably detected by the steering sensor as being different from the steering angles that were measured during automated driving. This measure may represent the initiation of a steering action or stabilization movement. Out of the 376 registered lane changes, 287 (i.e., 74%) lane changes were made in the same direction as the steering wheel angle when it first exceeded the 0.25 deg threshold.
(3) Steer turn: absolute steering wheel angle greater than 2 deg. The 2 deg threshold was used to represent the initiation of a 'conscious' steering action (Gold et al., 2013). Gold et al. reported that steering angles under this threshold are used to stabilize the vehicle and do not generate notable acceleration forces. The fact that steering actions greater than 2 deg correspond to conscious steering actions was confirmed by the results of the present experiment. Out of 376 registered lane changes, 371 were made in the same direction as the direction of the steering wheel when it first exceeded a 2 deg threshold after a take-over request. In other words, participants made a steering correction in the opposite direction in only 1% of the cases (5/376).
(4) Car avoid: absolute deviation from the lane centre greater than 1.00 m.
(5) Lane change: absolute deviation from the lane centre greater than 2.00 m.
(6) Brake: pedal depression greater than 0%. Similar to the steer-touch reaction time, the brake reaction time represents the initial movement of the brake pedal.
(7) Steer touch or brake: the minimum of the brake time and steer-touch time.

2.7.2. Self-report measures

Table S1 shows the intake questionnaire and the coding of the responses. The first part of the questionnaire (Q1–Q13) contained general questions about gender, age, driving experience, accident history, vision quality, and handedness. The second part (Q14–Q20) measured the participant's driving style using the violations scale of the Driver Behaviour Questionnaire (DBQ) as in De Winter (2013). Q21 asked about past experience with driving simulator experiments, and the remaining questions (Q22–Q25) polled the participants' preference and perceived urgency of auditory TORs, vibrotactile TORs, visual TORs, and combinations thereof. The intake questionnaire was offered in digital form.

A questionnaire on usefulness and satisfaction (Van der Laan et al., 1997) was offered in paper format. The mean usefulness score was determined across the following five items: 1. useful–useless; 3. bad–good; 5. effective–superfluous; 7. assisting–worthless; and 9. raising alertness–sleep-inducing. The mean satisfaction score was determined from the following four items: 2. pleasant–unpleasant; 4. nice–annoying; 6. irritating–likeable; and 8. undesirable–desirable. All items were on a five-point Likert scale. Sign reversals were conducted for items 1, 2, 4, 5, 7, and 9, so that a higher score indicates higher usefulness/satisfaction.

The NASA-TLX questionnaire included the following six aspects of workload: mental demand, physical demand, temporal demand, performance, effort, and frustration. All aspects were marked on a 21-tick horizontal bar with anchors on the left (0% = very low) and right (100% = very high) sides. For the performance item, the anchors (0% = perfect) and (100% = failure) were used. The questionnaire was offered in an online software application provided by Sharek (2011).

Table S2 shows the questions of the post-experiment questionnaire and the corresponding coding of the responses. Q2–Q5 were identical to Q22–Q25 of the intake questionnaire, in order to detect eventual changes in the participants' perception on the different TOR modalities after these were experienced during the experiment. The post-experiment questionnaire was offered in digital form.

2.8. Statistical analyses

Comparisons of the independent variables between the conditions were conducted using a repeated measures analysis of variance. In addition, paired comparisons between the three conditions (A vs. V, A vs. AV, & V vs. AV) were conducted using paired *t*-tests, with a significance level of 0.01. A low significance level was used to minimize the probability of false positives.

3. Results

3.1. Missing data

The driving simulator did not store data for the first two participants, and during the A and V conditions for the third participant. For one participant, the AV condition was excluded because the automation drove at a speed that was different from the target speed of 120 km/h. Therefore, the effective sample size for all conditions was 21. Additionally, for one participant in the AV condition, the third take-over manoeuvre was excluded because the automation did not drive in the middle lane. Moreover, for one participant in the AV condition, the first take-over manoeuvre was excluded because the participant was already pressing the brake when the TOR was provided. The total number of take-overs included in the analysis was therefore 126, 126, and 124 for the A, V, and AV conditions, respectively.

3.2. Take-over direction

Table 1 shows that almost all participants overtook the car on the left side, regardless of the direction of the TOR and regardless of TOR modality (A, V, or AV). Fig. 3 shows the mean deviation from the lane centre for all take-overs, separated into overtaking manoeuvres on the left lane versus the right lane. The black vertical line represents the location of the stationary vehicle. It can be seen that in the AV condition the drivers increased their lateral position slightly earlier than in the two unimodal conditions.

Table 1
Number of take-overs as a function of take-over request (TOR) modality, TOR direction, and participant's lane change direction.

TOR direction	Participant's lane change	A	V	AV
Left	Right	3	2	5
None	Right	4	3	6
Right	Right	4	2	7
Left	Left	39	40	37
None	Left	38	39	34
Right	Left	38	40	35
Total		**126**	**126**	**124**

Note. A = Auditory, V = Vibrotactile, AV = Auditory & vibrotactile.

3.3. Reaction times

The participants successfully evaded the stationary obstacle in all cases. The steer-touch and steer-initiate reactions were faster for the AV condition than for the V condition (Table 2). Fig. 4 shows the mean steering wheel angle across all take-overs, distinguishing between TORs in which the participant braked (bottom figure) or not (top figure). It can be seen that the steering reaction in the AV condition starts earlier compared to the unimodal ones, which is in line with the results in Table 2 and Fig. 3. There were no statistically significant differences between the three conditions regarding the reaction times for steer-turn, avoiding the car, changing lanes, and braking.

There were no statistically significant differences between the steer-touch reaction time for 'congruent' responses (i.e., TOR from the left & overtake on the left) and 'incongruent' responses (i.e., TOR from the right & overtake on the left). Specifically, the mean steer-touch reaction times were 1.77 s (SD = 0.50), 1.92 s (SD = 0.53), and 1.70 s (SD = 0.43) for congruent responses, and 1.91 s (SD = 0.50), 1.89 s (SD = 0.53), and 1.67 s (SD = 0.43) for incongruent responses, for the A, V, and AV conditions, respectively (p = 0.298, 0.818, 0.768, for congruent vs. incongruent responses per condition, respectively).

As a supplementary analysis, Fig. 5 shows a scatter plot of the lane change versus steer-touch reaction times for take-overs that involved braking versus no braking. It can be seen that the reaction times in which no braking was involved had considerably smaller standard deviations than the reaction times with braking (SD steer-touch time = 0.49 vs. 0.81 s; SD lane change time = 0.58 vs. 1.57 s). The results in Fig. 5 illustrate that by braking, participants 'buy time' in order to resolve the conflict. Moreover, a learning effect was observed for the percentage of TORs that involved braking and for the mean maximum brake position across TORs, as well as for the reaction time measures (Fig. 6).

3.4. Self-report measures

Table 3 shows the mean NASA-TLX scores with standard deviations in parentheses. No statistically significant differences between the three modalities of TORs were observed. Table 4 presents the mean scores of the usefulness/satisfaction questionnaire with

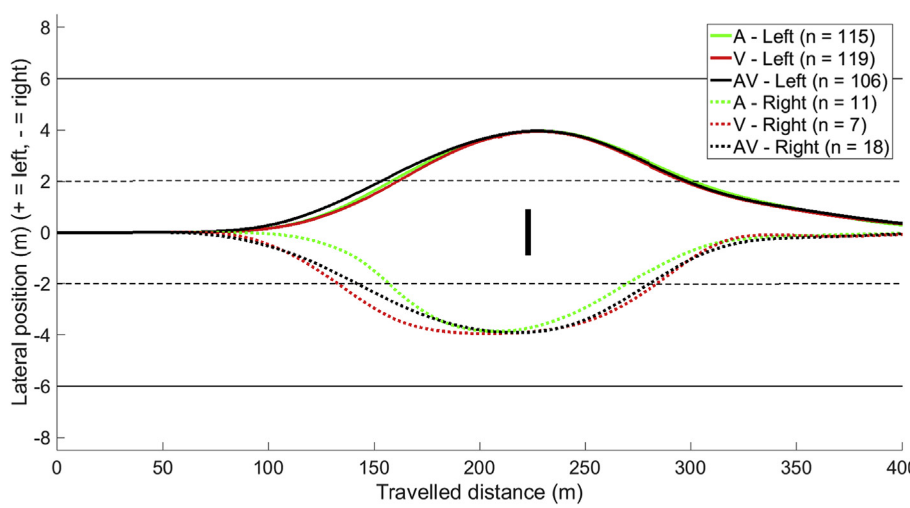

Fig. 3. Mean deviation from the lane centre across all take-overs, for left and right lane changes. A = Auditory, V = Vibrotactile, AV = Auditory-vibrotactile.

Table 2
Mean reaction times with standard deviations in parentheses (N = 21), results of the repeated measures ANOVA, and results of paired comparisons using t-tests.

	A M (SD)	V M (SD)	AV M (SD)	Repeated measures ANOVA	A vs. V p	A vs. AV p	V vs. AV p
Steer touch or brake (s)	1.69 (0.39)	1.80 (0.38)	1.57 (0.38)	F(2,38) = 5.53, p = 0.008	0.013	0.221	**0.005**
Steer touch (s)	1.83 (0.43)	1.92 (0.46)	1.67 (0.48)	F(2,38) = 5.08, p = 0.011	0.151	0.117	**0.002**
Steer initiate (s)	2.00 (0.47)	2.03 (0.43)	1.80 (0.49)	F(2,38) = 4.22, p = 0.022	0.596	0.073	**0.009**
Steer turn (s)	2.91 (0.86)	2.90 (0.89)	2.67 (0.95)	F(2,38) = 2.73, p = 0.078	0.876	0.064	0.047
Brake (s)	1.91 (0.45)	1.88 (0.25)	1.87 (0.46)	F(2,14) = 1.16, p = 0.342	0.191	0.939	0.276
Car avoid (s)	4.57 (0.94)	4.56 (1.08)	4.27 (1.13)	F(2,38) = 1.93, p = 0.159	0.984	0.098	0.124
Lane change (s)	5.22 (0.94)	5.20 (1.08)	4.96 (1.19)	F(2,38) = 1.22, p = 0.307	0.882	0.175	0.230

Note. A = Auditory, V = Vibrotactile, AV = Auditory & Vibrotactile. N = 10, 8, 10 for the brake reaction time for the A, V, and AV conditions, respectively. The repeated measures ANOVA was performed for the 20 participants (8 participants for the brake reaction time) for whom data were available for each of the three conditions. For the paired comparisons, p-values smaller than 0.01 are listed in boldface.

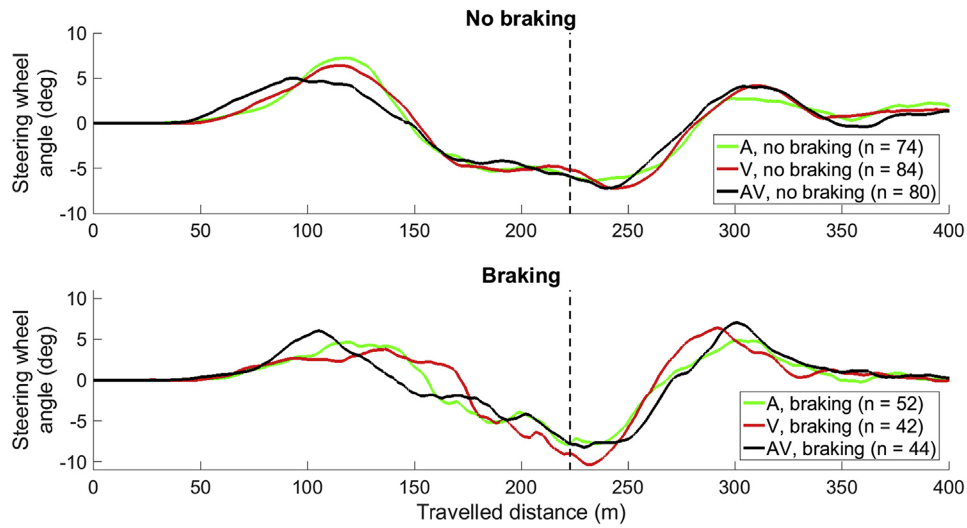

Fig. 4. Mean steering wheel angle across all take-overs for take-overs in which the driver braked (bottom) or did not brake (top). If the participant overtook the car on the right, the sign of the steering wheel angle was reversed. The dotted black line represents the location of the stationary vehicle. A = Auditory, V = Vibrotactile, AV = Auditory & Vibrotactile.

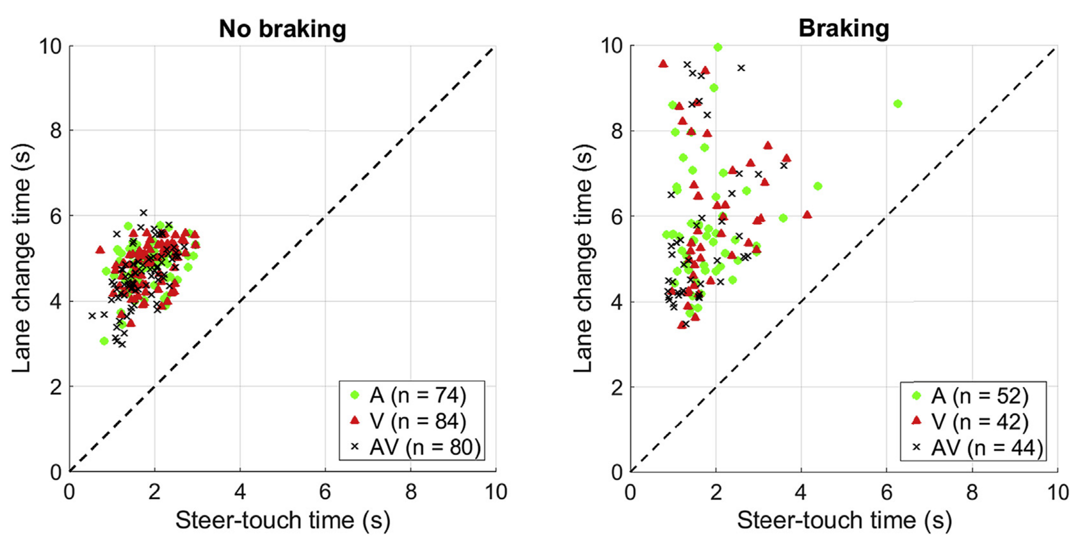

Fig. 5. Scatter plot of lane change time versus steer-touch time, distinguishing between trials in which the participant did not brake (left panel) and trials in which the participants braked (right panel). A = Auditory, V = Vibrotactile, AV = Auditory & Vibrotactile.

standard deviations in parentheses. The bimodal TORs (AV) were more highly rated in terms of usefulness than the unimodal TORs (A & V). Furthermore, A was considered more annoying and unpleasant than V.

Fig. 7 shows the participants' opinion on the use of A, V, and AV TORs for the intake- and the post-experiment questionnaires. A large shift in opinion was observed for the option “Sound message and vibrations message (in any order)”: 5 participants chose this TOR type before the experiment, whereas 12 selected this option after the experiment. None of the participants selected “Visual message”, either before or after the experiment. The figure also shows respondents' opinion from a previous online questionnaire study (Bazilinskyy et al., 2015; $N = 1692$), where similar questions were asked for a scenario with a high level of urgency: a traffic accident happening in front of a highly automated vehicle. It can be seen that the responses from that questionnaire were comparable to the results from the intake questionnaire in the current study (Fig. 7).

The participants were also asked both before and after the experiment whether they considered A, V, and AV TORs as urgent (1 = *Disagree strongly* to 5 = *Agree strongly*). No large differences were found between the pre- and post-experiment responses (Tables S3 and S4). The majority of participants had not perceived that the TORs sometimes came from the left or right: $M_A = 1.88$ and $M_V = 2.00$, on a scale from 1 = *Disagree strongly* to 5 = *Agree strongly*.

4. Discussion

The aim of this study was to investigate the steer reaction time, steering behaviour, and self-reported usefulness and satisfaction scores of auditory, vibrotactile, and bimodal (i.e., auditory-vibrotactile) TORs. We also investigated whether a directional cue (left, right, or nondirectional) of the TORs evoke a consistent contra- or ipsilateral response if drivers are not informed about the presence and meaning of this directional feedback.

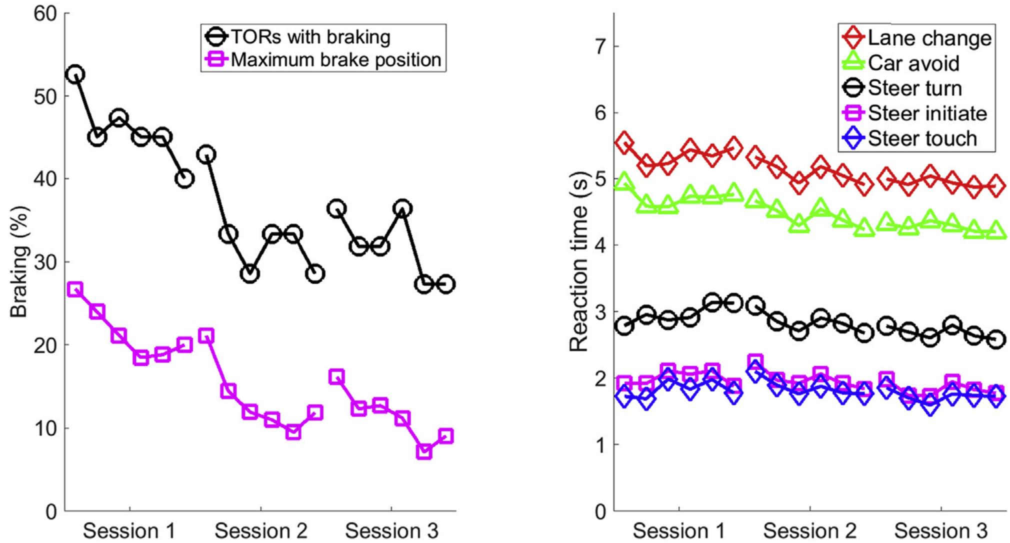

Fig. 6. Left: Percentage of take-over requests (TORs) that involved braking and mean maximum brake position across TORs as a function of the TOR number (3 sessions * 6 TORs per session equals 18 TORs per participant). Right: Mean lane change times, mean car avoid times, mean steer turn times, mean steer initiate times, and mean steer touch times as a function of the TOR number. Markers of the six TORs within the same session are connected by a line.

Table 3
Mean NASA Task Load Index (TLX) scores with standard deviations in parentheses ($N = 18$), results of the repeated measures ANOVA, and results of paired comparisons using *t*-tests.

	A *M* (*SD*)	V *M* (*SD*)	AV *M* (*SD*)	
Mental demand (%)	38 (26)	37 (29)	34 (24)	
Physical demand (%)	17 (16)	18 (20)	20 (18)	
Temporal demand (%)	35 (25)	31 (26)	32 (23)	
Performance (%)	26 (18)	27 (18)	23 (15)	
Effort (%)	36 (25)	35 (26)	29 (21)	
Frustration (%)	19 (17)	20 (22)	19 (15)	
				Repeated measures ANOVA
Average (%)	28 (17)	28 (17)	26 (15)	$F(2,34) = 1.38$, $p = 0.265$

Note. A = Auditory, V = Vibrotactile, AV = Auditory & Vibrotactile.

Table 4
Mean usefulness and satisfaction scores with standard deviations in parentheses, results of the repeated measures ANOVA, and results of paired comparisons using *t*-tests.

Negative (−2)	Positive (+2)	A *M* (*SD*)	V *M* (*SD*)	AV *M* (*SD*)				
Useless	Useful	1.17 (0.65)	1.04 (0.81)	1.63 (0.49)				
Unpleasant	Pleasant	−0.09 (0.90)	1.00 (0.88)	0.50 (0.72)				
Bad	Good	0.65 (0.78)	0.88 (0.85)	1.00 (0.78)				
Annoying	Nice	−0.17 (0.98)	0.83 (1.09)	0.25 (0.85)				
Superfluous	Effective	1.26 (0.81)	0.92 (0.88)	1.50 (0.51)				
Irritating	Likeable	0.22 (0.80)	0.58 (0.88)	0.29 (0.91)				
Worthless	Assisting	1.09 (0.79)	1.29 (0.62)	1.38 (0.58)				
Undesirable	Desirable	0.22 (0.60)	0.71 (0.86)	0.63 (0.77)				
Sleep-inducing	Raising Alertness	1.04 (0.93)	0.63 (0.82)	1.38 (0.88)				
					Repeated-measures ANOVA	A vs. V *p*	A vs. AV *p*	V vs. AV *p*
Overall usefulness score		1.04 (0.51)	0.95 (0.60)	1.38 (0.43)	$F(2,44) = 4.71$, $p = 0.014$	0.573	<**0.001**	0.013
Overall satisfaction score		0.04 (0.64)	0.78 (0.72)	0.42 (0.63)	$F(2,44) = 7.47$, $p = 0.002$	**0.001**	0.043	0.058

Note. A = Auditory, V = Vibrotactile, AV = Auditory & Vibrotactile. $N = 23$, 24, and 24, respectively. The repeated-measures ANOVA was performed for the 23 participants for whom data were available for each of the three conditions. For the paired comparisons, *p*-values smaller than 0.01 are listed in boldface.

The results showed that all types of TOR were effective in ensuring that participants did not collide with the stationary car. Moreover, the results showed that the reaction times for steer, brake, and lane change were not significantly different between the

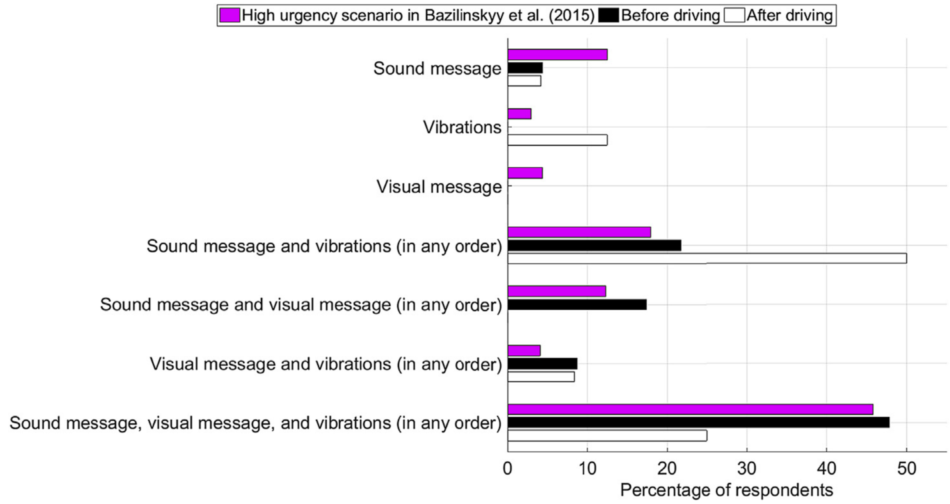

Fig. 7. Participants' opinion on various types of take-over requests (TORs) before ($N = 23$; one missing value) and after ($N = 24$) the experiment. Magenta bars represent the respondents' opinion from a previous online questionnaire (Bazilinskyy et al., 2015) for the question "*What take-over request would you like to receive in this scenario?*", where the scenario was described as "You are driving on the highway in the automated mode and you see a traffic accident happening in front of you. You have little time to take over control".

auditory and vibratory tactile modalities. The similarity of the reaction times for auditory and vibrotactile TORs is consistent with basic psychophysical research on simple reaction times (Woodworth and Schlosberg, 1954). Similarly, previous research in manual driving has found that auditory and vibrotactile warnings yielded equivalent reaction times (e.g., Scott and Gray, 2008); however, there have also been cases where auditory warnings (e.g., Ho et al., 2006) or vibrotactile warnings (e.g., Cao et al., 2010; Mohebbi et al., 2009) yielded the faster reaction times. It seems that the specific task conditions (e.g., auditory demands, such as talking on the phone) and the physical intensity of the stimulus (i.e., vibration amplitude, sound pressure) can explain these differential findings (see Dodonova & Dodonov, 2013 and Jensen, 2006 for overviews of task-related factors that influence reaction times). In summary, the results of the current study show HMI designers that vibrotactile and auditory feedback are both effective in alerting the driver of a take-over request.

Bimodal TORs yielded mean steering reaction times that were about 0.2 s faster than unimodal TORs (Table 2). It should be noted that the differences were statistically significant only for the steer-touch and steer-initiate times, and not for the steer-turn time, car avoid time, lane change time, or brake time. The lack of significant effects may be explained because participants were inclined to grab the steering wheel as quickly as possible, while effects diluted afterwards (i.e., there may be no need to change lanes as quickly as possible, given the fairly large time budget of 7 s). This dilutive effect can be seen when comparing the magnitude of the standard deviations between the steer-touch and steer-initiate time versus the other measures in Table 2. Although the difference in steer-touch times was only 0.2 s, it could have large safety consequences if this effect transpires to evasive manoeuvring or braking in a truly urgent condition. For example, if decelerating with 8 m/s^2, a 0.2 s reaction time advantage implies a speed reduction of 6 km/h, which in turn has strong effects on the probability of surviving a collision (Joksch, 1993). More research is needed to investigate whether multimodal feedback offers safety benefits on roads. Specifically, driving safety is not only determined by take-over time, but also by take-over quality (cf. Radlmayr et al., 2014).

One of the goals of this study was to determine whether directional feedback without any prior instructions about the directionality caused drivers to follow the direction of the feedback. The results showed that almost all participants overtook the stationary car on the left, regardless of the directionality of the TOR. This result is consistent with German traffic rules stating that overtaking on the right is prohibited on highways, and suggests that rules and habits are dominant performance-shaping factors regarding whether a driver steers to the left or right. The post-experiment questionnaire showed that only a few participants reported to have noticed that feedback was directional (Table S6). These findings may be attributable to a lack of saliency of the directionality of the stimuli, or by the cognitively engaging secondary task (SuRT). Future studies should investigate whether more salient cues, instructions, or a higher level of semantics might allow the driver to perceive directional cues in a TOR. In more recent work (Petermeijer et al., 2017) we found correct left/right response rates in the order of 80%–90% after participants had been trained and instructed about the meaning of directional vibrotactile stimuli. In order to improve drivers' responsiveness to directional feedback, future research could investigate the effectiveness of verbal warnings (e.g., "left!", "right!", see Gold et al., 2015). Such directional voice cueing is also used in traffic alert and collision avoidance systems (TCAS), a technology that is mandatory in most airplanes. Another promising solution for object avoidance is to use continuous force feedback on the steering wheel, an approach that may work both when the driver touches and when the driver releases the steering wheel. This approach, also known as haptic shared control or haptic steering guidance, has been previously shown to support effective left/right steering decisions in a head-on collision scenario (Della Penna et al., 2010). Yet another strategy is to apply small oscillatory movements on the steering wheel to prime the driver to steer in a particular direction (Navarro et al., 2007; Navarro et al., 2010).

Our results further suggest that the initial steering reaction represents only a portion of the behaviours that occur in a conflict resolution scenario. For example, we showed that drivers can increase their own temporal demands by braking (Fig. 5), and that they become more efficient at resolving the conflicts with increasing experience (Fig. 6, see also Young, 2000). This latter finding is in line with research showing that practice and mental model forming are crucial determinants of the use of automated driving systems (Beggiato et al., 2015).

Several limitations have to be considered when interpreting the results of this experiment. First, participants experienced a high number of TORs per time unit (i.e., every 1.5–2 min), and each take-over scenario was identical (i.e., no other road users, time budget of 7 s, and a stationary vehicle in the middle lane). The high consistency and low level of ambiguity may explain why none of the participants missed a TOR or crashed into the stationary car. Future studies on driving behaviour in a take-over scenario should consider that unsuspecting drivers are unlikely to react quickly and consistently. For example, an on-road study into drivers' reactions to truly unexpected events found that drivers reacted in 2.5 s on average (Summala, 1981), which is considerably higher than professional drivers' average reaction time of 0.84 s to system failures of automated vehicles on the roads (Dixit et al., 2016). Our approach has advantages from a statistical viewpoint because we obtained as much as 125 reaction times for each of the three TOR conditions. According to our literature survey, over 70 studies have been published on take-over performance in highly automated driving, yet almost all of them included only one TOR per experimental condition. An exception is Young (2000), who found a learning effect in a critical event scenario that required a braking intervention, with 16 of 44 participants applying the brakes in trial 1, and 36 of 44 participants in trial 2. Similarly, Hergeth et al. (in press) found that the take-over time reduced from the first to the second TOR. In our study, we established learning curves across as much as 18 TORs.

Second, although simulators are useful tools because they offer safety and a high degree of controllability of the environment, by definition simulators have limited fidelity (Boer et al., 2015; De Winter et al., 2012). Our simulator had a realistic visual projection with a large field of view, but did not provide vestibular motion feedback. It is known that participants brake harder and more abruptly in simulators than in real cars, especially when the simulator has no motion platform (Boer et al., 2000; De Groot et al., 2011; Siegler et al., 2001). Klüver et al. (2016) found that drivers showed higher standard deviation of lateral position (SDLP) in fixed base simulators than in moving simulators and in a real car (i.e., a violation of absolute fidelity because of the discrepancy in SDLPs). However, these authors showed that the fixed base simulators were still useful for assessing the distractive effect of secondary tasks (i.e., a confirmation of relative fidelity). Another factor is that our experiment occurred in the summer period with high temperatures in the lab. Because the air conditioning in the car was not functional and the car windows were closed, it is possible that the observed reaction times may have been slower than reaction times in real cars that are equipped with air conditioning (but see Teichner, 1954 claiming that ambient temperature has little to no effect on reaction times). On the other hand, it is also possible that the haptic seat or auditory warnings are actually more difficult to detect in real cars, due to environmental noise and vibrations that may be more intense on the road than in the simulator.

Vibrotactile TORs were rated as more satisfactory than auditory TORs, which is consistent with results of Stanley (2006) and Calhoun et al. (2005) on haptic and auditory warnings. Moreover, multimodal TORs were rated as more satisfactory than auditory ones. The questionnaire data showed that participants became more appreciative towards TORs they were exposed to (Fig. 7). These results per se do not imply that multimodal TORs are preferred over visual TORs; participants may have rated the vibrotactile and multimodal TORs highly for the reason that they had experienced them in the experiment.

Finally, the participants were mostly researchers and students from the Technical University of Munich, many of whom had previously participated in driving simulator studies and were familiar with the principles of highly automated driving. Further research could investigate the effects of TORs in different samples of the driving population. Note that it is likely that drivers of future highly automated cars will also be familiar with the technology in their cars, and so testing naïve participants may not be a recommended approach either.

In summary, our results showed that multimodal TORs yielded a faster steer-touch times and higher self-reported satisfaction than unimodal TORs, and the directional cue evoked no spontaneous contra- or ipsilateral response of the drivers. Our results complement the literature on multimodal warnings in general (Bazilinskyy et al., 2015; Burke et al., 2006; Diederich and Colonius, 2004; Oviatt, 1999; Petermeijer et al., 2015; Van Erp et al., 2015) and suggest that in a take-over scenario, a TOR should be multimodal rather than unimodal.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.apergo.2017.02.023.

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