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A user study of directional tactile and auditory user interfaces for take-over requests in conditionally automated vehicles

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ABSTRACT

General introduction of unconditionally and conditionally automated vehicles is expected to have a highly positive impact on the society, from increased accessibility to mobility and road traffic safety, to decreased environmental and economic negative impacts. However, there are several obstacles and risks slowing down the adoption of this technology, which are primarily related to the human–machine interaction (HMI) and exchange of control between the vehicle and the human driver. In this article, we present key takeaways for HMI design of take-over requests (TOR) that the vehicle issues to inform the driver to take over control of the vehicle. The key takeaways were developed based on the results of a user study, where directional tactile-ambient (visual) and auditory-ambient (visual) TOR user interfaces (UI) were evaluated with regards to commonly used take-over quality aspects (attention redirection, take-over time, correct interpretation of stimuli, off-road drive, brake application, lateral acceleration, minimal time-to-collision and occurrence of collision). 36 participants took part in the mixed design study, which was conducted in a driving simulator. The results showed that drivers' attention was statistically significantly faster redirected with the auditory-ambient UI, however using the tactile-ambient UI resulted in less off-road driving and slightly less collisions. The results also revealed that drivers correctly interpreted the directional TOR stimuli more often than the non-directional one. Based on the study results, a list of key takeaways was developed and is presented in the conclusion of the paper. The results from this study are especially relevant to the TOR UI designers and the automotive industry, which tend to provide the most usable UI for ensuring safer end efficient human-vehicle interaction during the TOR task.

1. Introduction

Assisted or automated driving is gradually becoming a reality. Automated vehicles are expected to have highly positive impact on the society (Pettigrew et al., 2018; Montgomery, 2018; Stern et al., 2019; Hulse et al., 2018; Jing et al., 2021; Acheampong et al., 2021), such as to reduce the overall carbon footprint, increase driver, cyclists and pedestrian safety, increase mobility of the elderly, disabled and children, improve car sharing possibilities, etc. However, before one could enjoy unconditional automated driving experience in any driving environment, a series of intermediate stages, the so called "conditionally automated" driving phases, have to be implemented. As early as in 2014 (revised in 2018), the Society of Automotive Engineers (SAE) ranked the different levels of automated driving on a scale from 0 to 5 (SAE International, 2018), where level zero (L0) represents a fully manual drive and level five (L5) represents a fully automated or autonomous drive. Manual drive is in L1, and even more L2, (assisted levels) complemented with advanced driver assistance systems (ADAS), while L3 and L4 (conditional levels) represent a gradual transition to fully automated drive.

Due to the rapid development of driving automation, the coexistence of manual and different levels of automated driving can be expected. Currently, the transition to the third level, also called "conditionally automated driving," is in progress. It allows fully automated driving only in specific driving environments, e.g., on the highway. Meanwhile, the driver can shift his or her attention to other, secondary tasks, e.g., control the air conditioning, take or make phone calls or watch a movie. When the vehicle encounters a critical situation, which the automated system cannot resolve, it initiates a take-over request (TOR). The driver is then responsible for a quick and effective reaction (take-over, TO) in order to resolve the critical situation. Examples of such situations include (ordered by increasing urgency (Bazilinskyy et al., 2018):

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- the need to change a lane or exit highway to reach the required destination,
- at least one lane closed due to traffic collision or construction works,
- an unpredicted situation (roadblock, accident, …) right in front of the vehicle.

As pointed out by Melcher et al. (Melcher et al., 2015), there are two key challenges in designing TORs: (1) timing determination, i.e. how much time is needed for a successful TO, and (2) design of a useful (effective, efficient, satisfactory (Frøkjær et al., 2000) user interface (UI). Adequate design of UIs for driver TO is of crucial significance not only for the driver's well-being and satisfaction but also for driving safety, economy, and general acceptance of automated vehicles.

1.1. Related work on TOR parameters

When a conditionally automated vehicle can no longer perform the dynamic task of driving, the driver must intervene within a limited amount of time, which is referred to as *take-over request lead time (TORlt)* (Eriksson and Stanton, 2017). TORlt is in our study defined as the lead time from a take-over request due to a critical event, such as a stranded vehicle until the time of impact if the driver does not take any action. Eriksson and Stanton conducted a review of commonly used TORlt in research (Eriksson and Stanton, 2017). Their results revealed that different TORlts did not affect drivers' reaction times significantly. Gold et al., however, showed that with a shorter TORlt, the driver's reactions are usually faster, but their performances are generally worse in quality (Gold et al., 2013). The results of a study performed by You et al. (You et al., 2018) showed that the reaction time and TO performance is also affected by the modality of the secondary task the driver is engaged in prior a take-over request. For example, when presented with a TORlt of 6 s, every driver which was engaged in an auditory (voice chat) secondary task could perform a TO, while not everyone was able to perform a TO even when the TORlt was prolonged to 8 s when engaged in a visual secondary task (reading).

The take-over time (TOT) – the time between TOR and the actual take-over (also: *reaction time*), can be further divided into shorter time periods (Zeeb et al., 2015). Zeeb et al. suggested a theoretical model of TOT, which consists of a period of gathering information (e.g., gaze direction change) and their cognitive processing which results in situational awareness. The model is stated to be in line with Endsley's theory of situational awareness (Endsley, 1995), stating that one must be aware of a situation before taking any action. Therefore, the reaction time strongly depends on the time needed to (re)gain situational awareness. After the driver becomes aware of the situation, another cognitive task is introduced – decision making (Zeeb et al., 2015), see Fig. 1. The recorded actual TOTs in past research studies have been usually between 2 and 3.5 s long (Eriksson and Stanton, 2017). Naujoks et al. performed a user study (Naujoks et al., 2014) and Zhang et al. performed an extensive literature review (Zhang et al., 2019) where they both found out that shorter TOTs are associated with higher urgency of the situation. Deng et al. have even built a cognitive model based on a queue network (QN-ACTR) that predicts the length of the TOT, which could be used in development and evaluation stages of TOR UI design (Deng et al., 2019).

1.2. Related work on TO user interfaces

The second most important issue, raised by Melcher et al. (Melcher et al., 2015), is the design of an adequate UI for TOR issued by the vehicle, which include:

- determining the appropriate UI modality,
- determining the appropriate information to transfer,
- taking drivers' personal characteristics and current state into account.

Traditionally, most of the drivers depend largely on visual modality for gathering the required information (Cellario, 2001). However, multimodal UIs in driving have been widely studied, most often as warning signals for critical driving events (e.g., a vehicle in front suddenly braking) or vehicle malfunctions (Politis et al., 2014). Many studies reported that multimodal warnings provoked faster response times (e.g., braking) (Ho et al., 2007; Ho and Spence, 2005; Liu, 2001) or higher accuracy of the desired action (Ferris et al., 2006; Oskarsson et al., 2012). Additionally, such warning UIs also provided faster responses to more urgent warnings (Politis et al., 2014) and when the stimuli came from the direction of the critical event (Ho et al., 2005).

When comparing different UI modalities for TORs, Petermeijer et al. showed that shorter take-over times were achieved when using auditory or tactile interfaces compared to visual interfaces (Petermeijer et al., 2017). Auditory and tactile interfaces seemed to be equally effective. A review by Zhang et al. revealed that using an auditory or a tactile interface in combination with a visual interface provides a shorter TOT compared to using only visual interface (Zhang et al., 2019). Borojeni et al., however, found that the combination of a tactile and an auditory UI does not generally improve TOT (except in urgent TO scenarios), but reduces drivers' effort (Borojeni et al., 2017). Wan and Wu, argumented that the driver's visual and auditory channels are already overloaded and distracted during secondary tasks, and in their study proposed a tactile UI for TOR with alternating vibrations in drivers' back support and seat (Wan and Wu, 2018). Tactile interface (sudden unexpected jerk/brake) was also used by Melcher et al., who showed that if drivers were given enough time to react, the modality of the UI did not influence the TOT. Borojeni et al. further showed that ambient interfaces (cues by changing ambiental light) can also help achieving shorter TOTs (Borojeni et al., 2016). Lastly, Politis et al. and Petermeijer et al. showed that multimodal interfaces perform better for making a TOR (Politis et al., 2015; Petermeijer et al., 2017), with similar conclusions also obtained by Naujoks et al. when comparing visual and auditory-visual interfaces (Naujoks et al., 2014).

In the search of appropriate TOR stimuli, Borojeni et al. evaluated shape-changing and vibro-tactile steering wheel (Borojeni et al., 2017).

Fig. 1. Take-over time, divided into shorter periods: gaze switching, situation awareness and decision making. It consists of mental (situation awareness, decision making) and physical (gaze switching, establishing motor readiness) processes.

Their results showed that tactile cues only reassured drivers of their decision. However, a more recent study of the impact of vibrational patterns on TOT revealed the most effective position of tactile actuators is in the driver's seat or at the lower part of the backrest (Wan and Wu, 2018). Petermeijer et al. demonstrated that a tactile interface is only effective as a warning, while its ability to provide spatial information is limited (Petermeijer et al., 2017). Lv et al. have recently successfully used intelligent haptic torque in the steering wheel to also provide spatial information and assist the guidance to the predicted direction (Lv et al., 2021). Different patterns of ambiental cues, used by Borojeni et al., did not affect the TOT (Borojeni et al., 2016). Language-based warnings (visual text information, speech and speech tactons (Brewster and Brown, 2004)performed equally well compared to abstract warnings (e.g., sound beeps) and were therefore recommended in non-critical situations due to being less annoying (Politis et al., 2015).

To understand and take into consideration the driver's opinion in the design of a TOR UI, Bazilinskyy and de Winter conducted a survey which investigated auditory interfaces in automated driving. The results revealed that drivers have positive attitude towards TOR auditory warnings (Bazilinskyy and de Winter, 2015). In a wider crowdsourcing survey, when compared to unimodal visual, auditory or tactile TORs, a multimodal TOR was the most preferred in very urgent TO situations (Bazilinskyy et al., 2018). Deo and Trivedi recently proposed a model to predict driver TO readiness based on observable cues, which could provide real-time adaption of UI to the driver (Deo and Trivedi, 2020). Similarly, Perello-March et al. proposed a driver state monitoring system to determine whether the driver is ready to take over (Perello-March et al., 2021). Kyriakidis et al. additionally stated that up to SAE level 4, every vehicle should inform the driver about its capabilities and operational status (Kyriakidis et al., 2019).

1.3. Related work on TO quality aspects

Drivers' reactions after the TO are less often covered in research studies (Zeeb et al., 2016). The majority of them, however, recommend that, in addition to the TOT and overall success (or collision), the quality of a TO should also be considered when designing TOR UI (Zeeb et al., 2016; Köhn et al., 2019; Radlmayr et al., 2018; Kim and Yang, 2020; Gold et al., 2018). In that regard, measurements of the deviation from the centre of the lane (Zeeb et al., 2016), the lateral accelerations (Zeeb et al., 2016; Kim and Yang, 2020), the maximal acceleration (longitudinal control) (Kim and Yang, 2020) and drivers' cognitive load (Kim and Yang, 2020; Melnicuk et al., 2021) were most often considered by the researchers. Gold et al. noticed statistically significant differences in performance among the drivers that braked and those that did not (Gold et al., 2018). Melnicuk et al. introduced a novel method to determine stabilisation time as an indicator of a TO quality based on driver's cognitive load (Melnicuk et al., 2021).

Although You et al. observed longer TOTs with drivers engaged in a visual secondary task during the automated mode (You et al., 2018), many studies state that the type of a secondary task (e.g. reading news, watching a movie, making a phone call) does not affect the TOT (Petermeijer et al., 2017; Zeeb et al., 2016; Wu et al., 2020; Jazayeri et al., 2021). However, the overall quality of a TO is deteriorated for distracted drivers, which is manifested in larger lane deviations (Zeeb et al., 2016). Müller et al. argue that TOT is correlated with the amount of mental workload a secondary task imposes to the driver, which can significantly vary among different tasks (Müller et al., 2021). While some studies state the age does not influence the TOT (Zhang et al., 2019; Körber et al., 2016), others show that this is not true when the driver is engaged in a secondary task prior to TOR, with engagement in a secondary task resulting in delayed reactions times of older drives (Wu et al., 2020). Kaye et al., on the other hand, found out that young drivers' TOT is not affected by the use of a hand-held mobile phone for performing a secondary task (Kaye et al., 2021). Previous studies revealed that older drivers also tend to react more safely – brake more often and maintain a longer time-to-collision (Körber et al., 2016). Stephenson et al. also explored older adults' autonomic arousal and found that safety–critical events (such as TORs) may narrow their visual attention and elevate arousal mechanisms (Stephenson et al., 2020). Furthermore, increasing the level of automation does not seem to decrease driving performance; on the contrary, it may even provide a safer drive among drivers with limited experience with the technology (Weaver et al., 2020).

2. Contribution

Although quite a lot has already been discovered, there are still numerous challenges that need to be addressed regarding the design of TOR UI. Since visual UI is traditionally used and already present in every vehicle (e.g., dashboard), we believe it is reasonable to assume its usage for issuing a TOR. However, it is still an unanswered question which modality should be used in combination with the visual UI. Most types of UI stimuli seem effective as warnings, however, it is not clear, whether and how much additional information (e.g., spatiality) could be beneficial for the driver performing a TOR. While a SAE L1 vehicle may or may not, every SAE L2 vehicle already includes emergency braking as a mechanism to prevent collisions (SAE International, 2018). This braking manoeuvre is however only used as a last resort, providing a large (almost momentarily) deceleration and jerk. A quality TO should however provide a better driving experience and ensure safe driving continuity. Most studies, however, only consider the take-over time (TOT) (Zeeb et al., 2016), ignoring the other valuable indicators of TO quality.

The aim of the presented user study is to evaluate directional multimodal auditory-ambient (sound beeps – auditory stimuli – with ambient light, presenting vehicle's state – visual stimuli) and tactile-ambient (vibrations in driver's seat – tactile stimuli – with ambient light, presenting vehicle's state – visual stimuli) output user interfaces for TOR in terms of take-over quality. Therefore, the primary research question of this paper is:

"Which of the two studied TOR UIs performs better in terms of TO quality?".

and the second research question is:

"Do directional TOR stimuli have a significant impact on TO quality?".

Considering the related work, we hypothesize that tactile-ambient UI may perform better in terms of TO quality as the drivers' tactile input channel is usually not as occupied as auditory input channel. Secondly, we hypothesize that directional stimuli would perform significantly better than non-directional stimuli.

Based on the findings from the study, we make assumptions on how to make even better (more effective, efficient and satisfactory) UI. Our main contribution to science is a list of *key takeaways* which could facilitate the development process of TOR user interfaces that include directional tactile or auditory stimuli.

The rest of the paper is organized as follows: in the section Materials and Methods, the design and technical setup of the conducted user study is presented. In the Results section, comparison and modelling results are graphically presented. Discussion interprets the results by TO quality indicators and summarizes them in a list of key takeaways. The Conclusion provides highlights of the overall process and application of results.

3. Materials and methods

The presented user study had a mixed design: between subject comparison for two modalities of the UI and within subject (repeated measures) for their directionality (directional vs. non-directional).

Two random groups (Group A and Group T) of participants were formed to study the between subject effects:

- **Group A** only used auditory-ambient (visual) multimodal output interface,
- **Group T** only used tactile-ambient (visual) multimodal output interface.

The two different types of TO situations included:

- partial roadblock (indicated by directional UI, the driver could avoid the obstacle by turning left or right),
- full roadblock (indicated by non-directional UI, the driver had to brake to avoid collision with the obstacle).

The used directional UIs provided stimuli form either left or right side (e.g., left or right speaker), corresponding to the location of the roadblock. Non-directional UIs provided stimuli from left and right side simultaneously (e.g., both left and right speakers).

The evaluation of the interfaces was based on multiple measured parameters that represent different TO quality aspects. They are presented in detail in subsection 2.5.

3.1. Technical set-up

The experiment was conducted at the University of Ljubljana in a high-fidelity driving simulator (manufactured by Nervtech, d.o.o., Trzin, Slovenia) ('Nervtech Simuation Technologies', 2019) with AV Simulations's Scanner Studio (AV simulation, Boulogne, France) ('AVSimulation SCANeR studio', 2020) and Nervtech's proprietary software for simulation control and data logging. The simulator (see Fig. 2) consists of three curved full-HD screens covering driver's field of view of approx. 160°, a racing car seat, Fanatec (Fanatec, Endor AG, Landshut, Germany) steering wheel (ClubSport Wheel Base V2.5 ('Fanatec ClubSport Wheel Base V2.5', 2020)and a three-pedal set (ClubSport Pedals V3 ('Fanatec ClubSport Pedals V3', 2020). To obtain deeper insight into driver's physiological responses and to detect the driver's gaze (on or off-road), an eye tracking device (Tobii Pro Glasses 2 (Tobii Pro AB, Stockholm, Sweden) ('Tobii Pro Glasses 2 wearable eye tracker', 2015) was used.

The driving scenario was the same for each participant and consisted of approximately 20-minute driving on a three-lane foggy highway with low traffic (see Fig. 3a). When the vehicle arrived to a situation it could not resolve (see Fig. 3b or Fig. 3c), it initiated a TOR with a lead time (TORlt) of 6 s, based on the findings of (Eriksson and Stanton, 2017). Current lead time was calculated by dividing the current distance between the driver's vehicle and the roadblock with the current speed of the driver's vehicle (i.e., 110 km/h in autonomous driving mode). There were six such situations during the drive, with 3–5 min of automated driving in between them. During autonomous mode, the vehicle always drove on the middle lane. Both two full roadblocks consisted of stranded or broken down vehicles occupying all three driving lanes and emergency lane (Fig. 3b), while partial roadblock only occupied two of the driving lanes (Fig. 3c): two partial roadblocks occupied the middle and the left lane, two partial roadblocks occupied the middle and the right lane. The duration of the automated driving was chosen based on a study by Feldhütter et al. who concluded that the duration of automated driving did not show to influence the TO performance (Feldhütter et al., 2017) and a study by Bourrelly et al. who suggested a series of short automated driving periods (Bourrelly et al., 2019).

Fig. 2. Nervtech™ high-fidelity driving simulator at the University of Ljubljana, Faculty of electrical engineering.

The TOR user interface consisted of three different modalities:

- *Auditory output interface*: stereo speaker set behind the simulator displays. The stimuli was a Boeing 747 cabin altitude warning sound (intermittent horn with a period of 300 ms, 50% duty cycle, main audio frequencies 246 Hz, 750 Hz and 1250 Hz) ('Cockpit Alarm Sounds And Warnings', 2020).
- *Tactile output interface*: a 2 by 3 array of tactors (DC vibration motors with 12000 rpm) was fixed onto the car seat, controlled by a custom-made controller via serial connection (COM port), see Fig. 4a. Each line of three tactors (left and right) could be activated separately. Wan and Wu showed that the best positions for tactile interface are the bottom of the backrest and the seat (Wan and Wu, 2018). Since the simulator used in our study comes with a sports seat, where the backrest is curved, the vibrations could not be felt if tactors were placed on the backrest. Therefore, we chose to place them only on the seat.
- *Ambient (visual) output interface*: An RGB LED strip was fixed under the dashboard, which was shown on the middle simulator screen (see Fig. 4b), and controlled by the same custom controller as the tactile interface.

Each interface's output was different for different types of TO situations – see Table 1. Stimuli was presented from the TOR until the TO action. The TO was defined as the moment when the driver moved the steering wheel for at least 4°, pressed the brake pedal for at least 10% or pressed the dedicated button on the steering wheel (Radlmayr et al., 2014).

3.2. Participants

The study was conducted at the University of Ljubljana, Faculty of Electrical Engineering in Ljubljana, Slovenia, in compliance with the Code of Ethics of the University of Ljubljana, which provides guidelines for studies involving human beings and is in accordance with the Declaration of Helsinki.

Only drivers with a valid driving licence were recruited. Invitations were sent out via the mailing lists of Laboratory of Information Technologies, Faculty of Electrical Engineering, University of Ljubljana. 36 drivers with a valid driving license volunteered for participation in the study, 12 women (33%) and 24 men (67%). Their age distribution was from 18 to 45, with a mean of 26.58 ± 6.96 years old. 27 out of 36 (75%) reported they have never driven a vehicle with an advanced driver assistance system (ADAS) such as automatic cruise control or lane assist.

Drivers were randomly assigned to one of the two groups (Group A and Group T) for between-subject comparison. As Shapiro-Wilk tests of normality showed that age and years-of-driving-experiences distributions within groups were not normal ($p < .001$), we used Mann-Whitney U Test to evaluate the differences in distributions between groups. The test showed that neither age distributions ($U = 118.0$, $p = .16$) nor distributions of years of driving experiences ($U = 125.5$, $p = .25$) appeared significantly different between groups. Additionally, chi-square tests' results showed that neither gender ($\chi^2(1) = 0.50$, $p = .48$) nor level of previous experiences with ADAS ($\chi^2(1) = 0.15$, $p = .70$) or driving

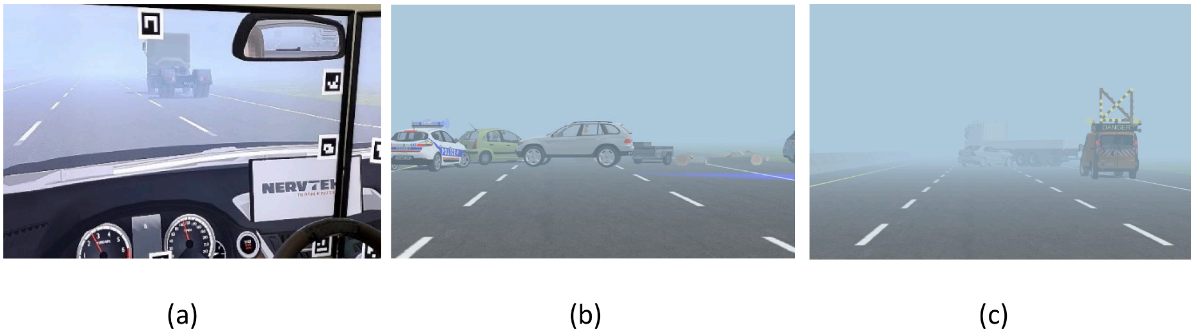

Fig. 3. Driving scenario - foggy highway with low traffic (a),an example of a critical situation that blocked the road and required the driver to take over (b) and an example of a critical situation that only partially blocked the road (c).

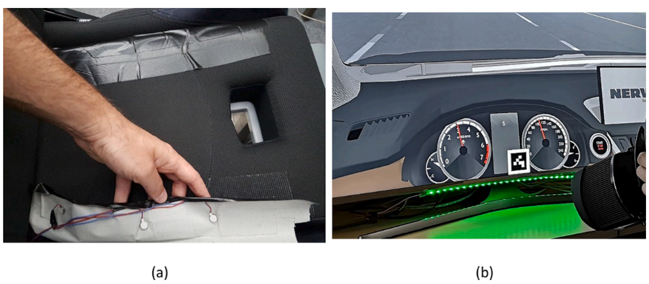

Fig. 4. Tactile and ambient (visual) output user interfaces. The tactile interface was fixed on the car seat in two lines (left and right) of three tactors (a); ambient (visual) interface was an RGB LED strip, fixed under the dashboard on the middle simulator display (b).

Table 1
Types of TOR stimuli outputs, dependent on interface modality (columns) and TO situation type (rows).

TO situation type	Auditory output	Tactile output	Ambient output
Partial roadblock - danger on left	warning sound on left speaker	left line of tactors vibrating	left half of LED strip coloured red
Partial roadblock - danger on right	warning sound on right speaker	right line of tactors vibrating	right half of LED strip coloured red
Road blocked	warning sound on both speakers	both lines of tactors vibrating	whole LED strip coloured red
Automated driving	off	off	whole LED strip coloured green
Manual driving (take over)	off	off	off

simulators ($\chi^2(3) = 4.54$, p =.21) appeared significantly different between groups.

3.3. Tasks

3.3.1. Primary task: ensuring safe driving continuity

Drivers were placed in a conditionally automated vehicle where after some time the driver had to take over the control of the vehicle. Their primary task was to ensure safe transition from automated to manual driving any time the vehicle issued a TOR. The reaction had to be done in a limited amount of time, otherwise the vehicle could collide with the obstacle. After a successful TO and resolution of the critical situation, the driver reengaged the automated driving functionality.

The TO situations included:

- two partial roadblocks with danger on right: drivers had to change from middle to left lane (turn left) to abide the obstacle and avoid collision,
- two partial roadblocks with danger on left: drivers had to change from middle to right lane (turn right) to abide the obstacle and avoid collision,
- two full roadblocks (drivers had to brake and eventually stop the vehicle to avoid collision, then go around the obstacle – drive off the road after conductor's implication to continue with the experiment).

3.3.2. Secondary task: playing a game on a smartphone

The purpose of the secondary task was to visually distract the driver; to keep his eyes off the road as predicted to be a common scenario in level 3 automated vehicles. Drivers were given a smartphone with a Tetris game app (Fast Fun, 2020). They were explicitly asked to focus on the secondary task during autonomous driving periods and had not been informed of when to expect the take-over request.

3.4. Procedure

At participant's arrival, a facilitator of the study briefly described its goals and the expected procedure. After that, an informed consent for signature with detailed procedure and expectations was presented to the participants. Table 2 summarizes the overall procedure.

3.5. Variables

Our primary interest in the study was to analyse the quality of TO with regards to two different modalities and directionalities of user interfaces for TOR. Therefore, we were interested in two independent variables (factors):

- between-subject factor: *UI modality* = {Tactile-ambient, Auditory-ambient},

Table 2
Detailed user study procedure with approximate durations of each activity.

Activity		Duration (min)
Introduction	Total	15
Experimental environment preparation		5
Brief overview of the study, see Appendix A		2
Signing an informed consent		1
Collecting participant's driving experience and demographic data		2
Attaching eye tracking device, testing connections and calibrating		5
Training procedure	Total	6
Explaining and familiarizing with manual driving, automated driving and TOR UIs (primary task), including practice drive		4
Explaining and familiarizing with the Tetris game (secondary task)		2
Experiment procedure	Total	20
Driving (6 TO events)		20
Post experiment procedure	Total	4
Individual discussion		4
Total session duration		45

- within-subject factor: *UI directionality* = {Directional, Non-directional}.

Based on the reviewed literature in the first section of the paper, we measured the following parameters (dependent variables) as representations of different TO quality aspects. Physiological measurements (e.g., pupil diameter, galvanic skin response, cognitive load) were excluded due to too dynamic conditions of TO actions that resulted in unreliable measurements (Čegovnik et al., 2018; Gruden et al., 2019).

I. *Attention redirection* (Zeeb et al., 2015; Endsley, 2017): the time difference from TOR until first glance on the road (detected with eye tracker),
II. *Take-over time* (TOT) (Gold et al., 2013; Zeeb et al., 2015; Deng et al., 2019; Zeeb et al., 2016; Köhn et al., 2019; Kim and Yang, 2020; Gold et al., 2018; Radlmayr et al., 2014): the reaction time, measured from the moment of TOR until the moment of the actual TO,
III. *Correct interpretation of stimuli*: representing information, if the driver recognized and reacted according to the directionality of TOR stimuli, i.e., braked when the stimuli was non-directional and steered in the correct direction when the stimuli was directional; it is only applicable in the analysis of UI modality independent variable, as UI directionality might be susceptible to the effects of scenario type (partial vs. full roadblock),
IV. *Off-road drive* (Zeeb et al., 2016; Kim and Yang, 2020): representing information if the centre of the vehicle passed the edge or centre line (the red-highlighted area in Fig. 5at least once during manual driving after a TO; it is only applicable in the situations where the drivers had to steer (bypass the partial roadblock). In the situations with full roadblock, off-road drive may sometimes provide a safer manoeuvre since that is the only way to bypass the roadblock;
V. *Brake application* (Kim and Yang, 2020; Gold et al., 2018): representing information if the driver used a brake pedal during the TO; it is also only applicable in the situations with a partial roadblock, as in situations with a full roadblock, the brake application was considered as mandatory,
VI. *Maximal lateral acceleration* (Gold et al., 2013; Zeeb et al., 2016; Kim and Yang, 2020), the measure of possible unwanted lane changes or (lateral) deviations due to sudden oversteering,
VII. *Minimal time to collision* (TTC) (Kim and Yang, 2020; Gold et al., 2018; Körber et al., 2016; Radlmayr et al., 2014; Minderhoud and Bovy, 2001): at every moment *t* of a TO, TTC(*t*presents the time until reaching collision point, assuming constant vehicle speed and acceleration; minimal achieved TTC(*t*) presents a measure of TO quality, where higher value is better;
VIII. *Collision* (Gold et al., 2013; Kim and Yang, 2020; Gold et al., 2018; Radlmayr et al., 2014): representing information if the vehicle encountered a collision (unsuccessful TO).

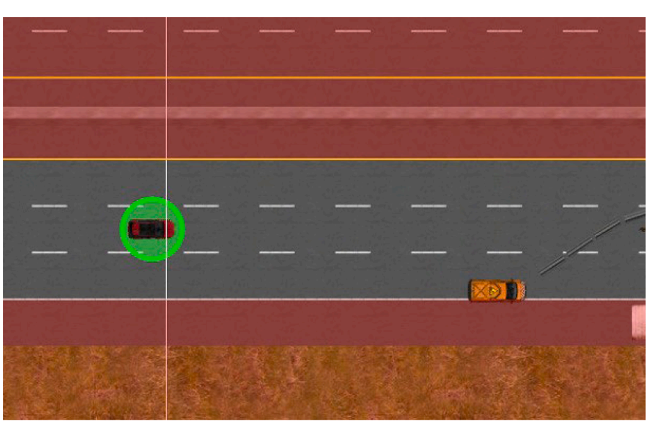

Fig. 5. Representation of off-road drive. If the centre of the vehicle drives in red-highlighted area of the road, the manoeuvre is considered as »off-road drive«. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Mixed model analysis (Seltman, 2018) was performed for every dependent variable. The UI modality and directionality were considered as fixed effects with a possible random intercept and a possible random slope of directionality because of its within-subject nature. Successive TOR occurrence was considered a repeated measure. The trial results were grouped based on subject identification (clustering variable). Different models including or excluding random intercepts and slopes were analysed and compared. The one with the smallest Schwarz's Bayesian Information Criterion (BIC) was selected as the most suitable one. Where not otherwise specified, alpha level of $\alpha = 0.05$ was used.

4. Results

Each session consisted of six TOR events, which in combination with 36 drivers provided a dataset of **216 take-over events** in total. Among them, in 144 TORs the drivers were provided with directional stimuli and in 72 TORs the drivers were provided with non-directional stimuli. Highlights regarding the primary research question are presented in Fig. 6. Detailed results regarding the eight measured TO quality aspects (described in subsection 2.5) are presented in the following subsections.

4.1. Attention redirection

Drivers' attention was measured from the moment of a TOR until the first glance on the road. Our model (BIC = 3077) consists of UI modality, directionality and their interaction as fixed effects. Among them, only UI modality appeared statistically significant with a less strict alpha level of $\alpha = 0.1$, see Table 3. The modelled estimation resulted in 239 (±113) ms quicker attention when using auditory-ambient UI, $t(33.85) = 2.12$, $p = .041$, see Fig. 6a.

4.2. Take-over time (TOT)

The most often studied TO quality indicator is the reaction time, commonly named also as take-over time (TOT). We created a mixed model (BIC = 3549) including UI modality, directionality, and their interaction as fixed effects. No random intercepts or slopes were used. Among the effects, UI directionality appeared to be statistically significant, see Table 4. The estimation showed a significantly faster (489 ± 181 ms) take-over when the driver was provided a non-directional stimuli (requirement to brake), $t(34) = 2.71$, $p = .011$, see Fig. 6b.

4.3. Correct interpretation of stimuli

Mixed model (BIC = 12.1) for modelling correct interpretation of stimuli (whether the driver correctly recognized and reacted according to the TOR stimuli) included UI modality and directionality as fixed effects, random slope for UI directionality (confirming its within-subject nature) and random intercept. The analysis did not show any statistically significant impact of UI modality, see Table 5. As some scenarios could have affected the drivers' choice of action (e.g., the only safe action to a full roadblock is braking) and therefore confused the interpretation of directionality of stimuli, UI directionality was not further analysed.

4.4. Off-road drive

Almost every off-road drive (27 out of 28) was caused by passing the centre line, which happened in the situations where the drivers had to avoid collision by bypassing the obstacle on the left side. Therefore, the

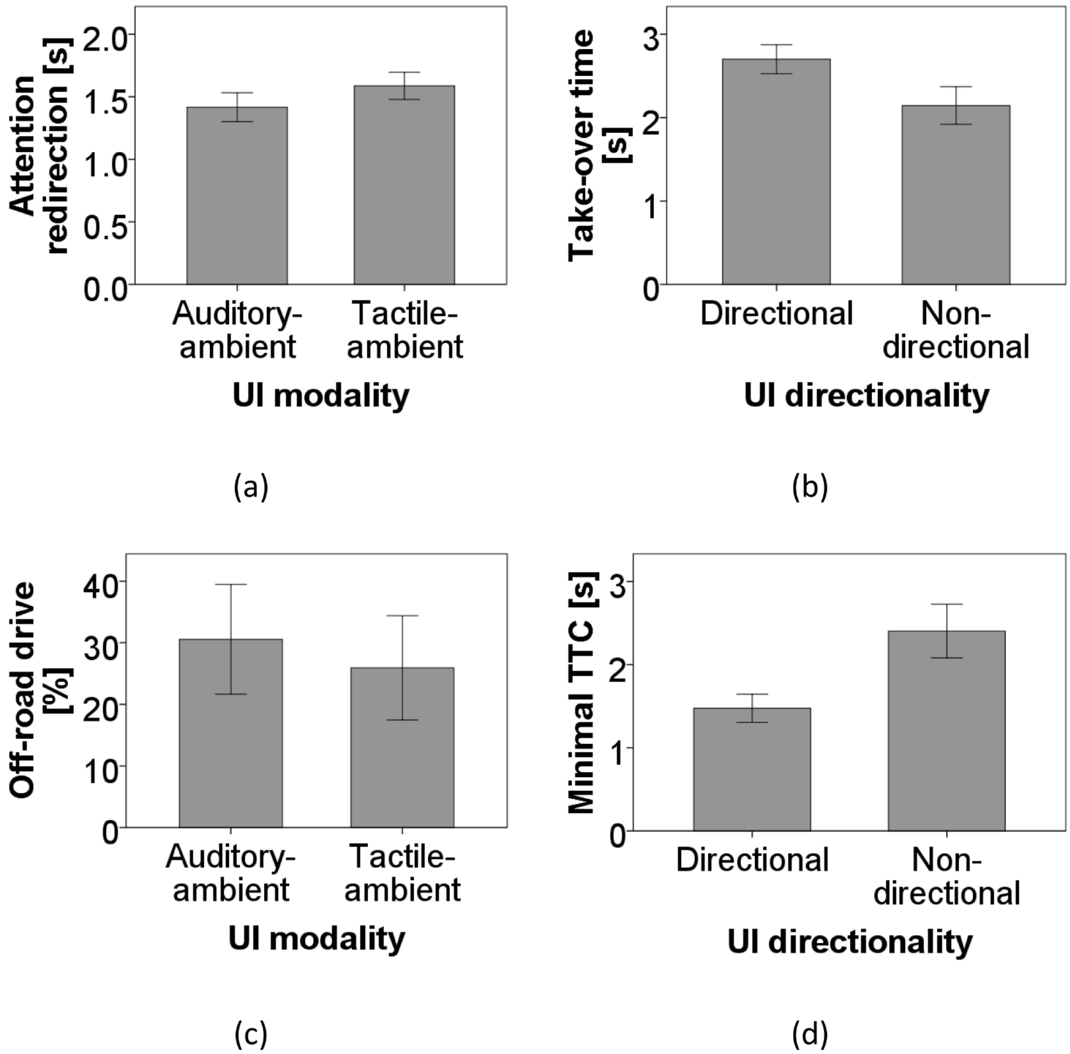

Fig. 6. Histograms of TO quality aspects with respect to the fixed factors (UI modality or directionality) that appeared statistically significant during the mixed model analysis. Error bars present ± 2 standard errors.

Table 3
Type III tests of fixed effects during mixed model analysis for attention redirection as dependent variable.

Fixed effect	Degrees of freedom	F-value	p-value
Intercept	(1, 32.695)	628.284	< 0.001
UI modality	(1, 32.695)	3.869	0.058
UI directionality	(1, 29.262)	0.027	0.870
UI modality * UI directionality	(1, 29.262)	0.117	0.734

Table 4
Type III tests of fixed effects during mixed model analysis for take-over time as dependent variable.

Fixed effect	Degrees of freedom	F-value	p-value
Intercept	(1, 34)	452.874	< 0.001
UI modality	(1, 34)	0.718	0.403
UI directionality	(1, 34)	18.284	< 0.001
UI modality * UI directionality	(1, 34)	0.199	0.658

following results and conclusions were based primarily on driving on the wrong side of the centre lane. No off-road drives were detected among the drivers whose first reactions were in accordance with the TOR stimuli. Among the 28 TOs where off-road drive was detected (19.4% of all TOs), 12 off-road drives happened while using tactile-ambient UI modality and 16 happened while using auditory-ambient UI modality.

Table 5
Type III tests of fixed effects during mixed model analysis for correct interpretation of stimuli as dependent variable.

Fixed effect	Degrees of freedom	F-value	p-value
Intercept	(1, 8.797)	1553.608	< 0.001
UI modality	(1, 1.554)	0.401	0.607
UI directionality	(1, 63.228)	11.028	< 0.001

A mixed model (BIC = 313) consisting of UI modality as a fixed effect and a random intercept showed only slightly fewer (considering a less strict alpha level of $\alpha = 0.1$) off-road drives among the drivers that used tactile-ambient modality of UI, $F(1,54.38) = 3.08$, $p = .085$, see Fig. 6c.

4.5. Brake application

In 82 out of 144 (57%) TO events with a partial roadblock, the drivers applied brake. A mixed model (BIC = 104) consisting of UI modality as a fixed effect did not show any statistically significant effect of UI modality on brake application, $F(1,34) = 0.414$, $p = .524$.

Additionally, in 4 out of 72 (5.5%) TO events with a full roadblock, the drivers did not apply brake at all, i.e., crashed the vehicle without braking intervention.

4.6. Maximal lateral acceleration

Mixed model (BIC = 3316) consists of UI modality, directionality and their interaction as fixed effects and no random effects. It, however, did not indicate any statistically significant factor, see Table 6.

4.7. Minimal time to collision (TTC)

Three of all the generated mixed models (see Table 7) achieved similar BIC values. The simplest (also has the lowest BIC) is model C, consisting only of the UI directionality. It shows that directionality has a statistically significant effect on minimal TTC, $F(1,35) = 25.89$, $p < .001$, which is 893 ms ± 175 ms higher in cases where non-directional stimuli was provided, $t(35) = 5.09$, $p < .001$, see Fig. 6d.

4.8. Collision

Collision is without doubt the most unwanted outcome of every TO. We observed that all collisions occurred in situations, where the drivers were required to brake (stop the vehicle before the roadblock).

The mixed model (BIC = 92) consisted only of UI modality as a fixed effect, without random effects. It did not reveal any statistically significant influence of the UI modality on the collision, $F(1,34) = 1.15$, $p = .29$. From the 18 TOs that ended with collision (8.3% of all), 7 occurred while using tactile-ambient and 11 occurred while using auditory-ambient UI modality. It should be noted that the relatively high (potentially unsafe) number of collisions (8.3%) was expected since the simulation had been designed to provoke extremely critical situations.

5. Discussion

The presented results offer interesting insights and explanations of drivers' reactions and performance during the TO considering the diverse TO quality indicators. More importantly, they also reveal many aspects that should be taken into consideration during the design of a TOR UI.

Although some authors assume that drivers' visual and auditory input channels are already occupied in vehicles and therefore try to explore other modalities (i.e., tactile modality) to increase performance (Borojeni et al., 2017; Borojeni et al., 2016), we have confirmed that the use of auditory modality is the fastest way to grab driver's ***attention***. On the other hand, it seems that the ***take-over time (TOT)*** depends primarily on the directionality of the information as it turned out that non-directional stimuli provoked faster reactions. We assume this happened because the drivers who only received a warning (non-directional stimuli) did not have to process any additional information or perceived it as more urgent information and therefore simply applied the brake. This is in accordance with Politis et al. (Politis et al., 2014) and Borojeni et al. (Borojeni et al., 2017) who observed shorter reaction times with increasing urgency of warning signals. However, it was proven that TOT itself is not sufficient to determine the TO quality (Zeeb et al., 2016).

In general, most of the drivers ***correctly interpreted the stimuli*** (93.1%) as they correctly recognized its (non–)directionality and acted accordingly (steer or brake). To further enhance correct recognition of non-directional TOR stimuli, its meaning should be better communicated to the drivers through a specific UI-based training procedure. Although Petermeijer et al. demonstrated that tactile interfaces were limited in their ability to provide spatial information (Petermeijer et al., 2017), we did not observe any significant negative effect of using tactile or auditory interfaces providing also directional information. We found significantly larger ***minimal TTC*** (resulting in better TO quality) in situations where non-directional stimuli were used. We believe that, in line with Politis et al. (Politis et al., 2014), the subjectively perceived urgency in TO situation significantly impacts the TO quality and it seems that directional stimuli were not perceived as urgent as non-directional stimuli. Therefore, when fast but not necessarily intense driver's reactions are required, a non-directional TOR UI seems more appropriate but in combination with an automatic speed-adapting manoeuvre. Contradictory to Borojeni et al., who reported significantly lower minimal TTC while using a tactile UI compared to auditory UI (baseline) (Borojeni et al., 2017), we found no statistically significant effect of UI modality on minimal TTC. As they discussed, their tactile cues might not had been perceivable by the participants at the time the auditory stimuli were present.

We detected slightly less ***off-road*** drives when using tactile-ambient UI modality for TO warnings. It seems that both modalities (tactile-ambient or auditory-ambient) have their own advantages and disadvantages. Almost all off-road drives happened in the situation when drivers were required to move to the left lane, i.e., the faster lane in Slovenia. It seems safer for the drivers to steer the vehicle to the opposite lane, still staying on the driving area, than to drive on the wrong side of the edge line, which can in practice be even gravel or grass-paved road shoulder. It seems somehow surprising that in some situations the drivers did not ***apply brake*** at all. Similar to our observations, Gold et al. also noticed significant performance issues among drivers that had not applied brake (Gold et al., 2018). Körber et al. state that only older, experienced drivers had tend to often apply brake (Körber et al., 2016). Additionally, Petermeijer et al. observed that by applying brake, drivers gained additional time to properly resolve the critical situation (Petermeijer et al., 2017). Therefore, our suggestion would be for the vehicle to automatically slow down while the driver should take over lateral coordination of the vehicle (partially take over). Longitudinal coordination could be taken over simultaneously or afterwards.

The last, and probably the most important, TO aspect is the fact whether the driver was involved in a ***collision***. Fewer collisions were observed when using tactile-ambient TOR UI (39%) compared to auditory-ambient TOR UI (61%). The difference was however not statistically significant, probably due to relatively small overall number of detected collisions for conducting statistical analysis (18 occurrences). In general, 18 collisions out of 216 TORs (8.3%) should not be acceptable for the industry of automated vehicles. To compare, a large study of naturalistic driving by Dingus et al. noticed 69 crashes out of 9125 (0.76%) reported events (Dingus, et al., 2006). However, our simulation was designed to provoke extremely critical situations that would not often occur while driving and such outcomes were expected. They are also similar to those, obtained by Gold et al., who observed 17 collisions out of 213 TO events (Gold et al., 2016) or Körber et al., who observed 17 collisions out of 216 TO events (Körber et al., 2016). We assume that the used lead time (TORlt) of six seconds is sufficient in situations which can be resolved by only steering the vehicle away from the obstacle, but might be too short if the driver is expected to completely stop the vehicle, similar conclusions were made by Gold et al., who also observed

Table 6
Type III tests of fixed effects during mixed model analysis for maximal lateral acceleration as dependent variable.

Fixed effect	Degrees of freedom	F-value	p-value
Intercept	(1, 34)	136.176	< 0.001
UI modality	(1, 34)	1.822	0.186
UI directionality	(1, 34)	1.248	0.272
UI modality * UI directionality	(1, 34)	1.932	0.174

Table 7
Different mixed models for the analysis of effects on minimal TTC.

Model	Fixed effects	Random effects	BIC
A	UI modality, directionality, interaction	none	715.1
B	UI modality, directionality	none	715.6
C	UI directionality	none	714.6

no collisions in situations that were easier to handle with (in their case, lower traffic density) (Gold et al., 2016). Therefore, a TOR UI designer may also consider multiple TORlts for different kinds of situations.

Prior to forming the key takeaways, some limitations, imposed by the study design, have to be considered.

1) Simulation always introduces several limitations in comparison to the real-world experiments. However, a big majority of driving studies are typically performed in simulators as they provide safe, robust, and highly controllable experimental environment. We faced the drivers with critical situations on the road, which could never be safely performed in real world. Eriksson et al. even conducted a comparative study and found strong positive correlations between on-road and the simulator driving conditions during take-over requests (Eriksson et al., 2017). Nevertheless, the simulator used in our study provides highly realistic and immersive driving experience and therefore provokes very realistic drivers' responses to different critical and stressful situations.
2) In factorial designs, the traditional methods for determining the appropriate sample size (power analysis) drastically underestimate the required sample needed to power an interaction (Bartlett, 2019). Wang et al. had proposed a novel method to estimate sample size based on the mean squared error curve and determined that 30 drivers should be the acceptable sample size for driving safety evaluation studies in driving simulators (Wang et al., 2019). A limitation of our study design is that while repeated measures do increase the power for within-subject effects and interactions, the power for between-subject variables decreases compared to completely random designs with the same number of participants (Donmez et al., 2006). It is therefore possible that some between-subject effects were not detected.
3) The non-directional stimuli used in our study may have been misunderstood by the drivers. Our non-directional stimuli should be associated with the absence of specific directionality of the obstacle (which is represented by a full roadblock), not necessarily with the absence of information (e.g., system malfunction). As such, directional stimuli had to be presented in partial roadblock scenarios, while non-directional stimuli had to be presented in full roadblock scenarios. Other than that, the partial and full roadblock scenarios were the same. We would therefore recommend the drivers to complete even more specific UI training prior to driving a conditionally automated vehicle.
4) Our study was designed to provide some design considerations or key takeaways regarding directional tactile and auditory TOR. Key takeaways, developed from the results, are therefore limited to designing UI modality and directionality; not the whole concept of human–machine interaction process during TO.
5) One might wonder, why the vehicle would only provide a TOR to the driver and not slow down itself, if it had detected the roadblock. Provided takeover use cases may seem unrealistic but, in our opinion, mainly due to the safety reasons. A realistic use case of such scenarios would be, for example, when the primary sensing technologies malfunction and a backup system is unable to directly interfere with lateral or longitudinal coordination of the vehicle. However, we acknowledge the problem of broader generalization of the results.

Considering the above discussion, we summarized the research results in a ***List of key takeaways***:

- Both auditory and tactile UI modalities are important:
  - ▪ auditory modality should be used to achieve faster attention redirection,
  - ▪ tactile modality seems to cause slightly less off-road drives and collisions,
  - ▪ when combined, tactile stimuli should provide a non-directional warning, while auditory stimuli could provide directional information.
- Stimuli directionality should be chosen regarding the concrete TO situation:
  - ▪ non-directional stimuli (less information) provoke a faster TOT,
  - ▪ directional cues provide less off-road drives but they seem ineffective in time-critical situations due to the increased cognitive load.
- Automatic speed-adapting (braking) manoeuvre should be implemented:
  - ▪ gradual automatic speed reducing prior to the actual TO,
  - ▪ it is unclear, if the vehicle should help the driver also after the TO – it is possible that the driver loses the feeling of having everything "under control".
- UI specific training procedures should be completed before usage:
  - ▪ teach the drivers how to react on a TOR.

6. Conclusion

The extensive research in the field of human–machine interaction in vehicles indicates that it is merely impossible to design a "universally best" TOR UI. The most appropriate answer to our primary research question would therefore be, that each of the two studied TOR user interfaces showed their own advantages and disadvantages with regards to TO quality. Consequentially, multimodal TOR UIs seem like the most appropriate and safe solution. Our results showed that non-directional stimuli are perceived as more urgent and therefore contribute to faster reactions, while directional stimuli contribute to overall TO quality when fast braking reactions are not necessary.

A relatively high number of collisions observed in our and related studies indicates that a significant attention should be given to ensure a safe transition from secondary task prior to global introduction of conditionally autonomous vehicles. Automatic brake application and adaption of speed can without doubt be an efficient addition to better and safer TOR. However, its automatic application after the driver actually takes over can be questionable. It is also an interesting question how vehicle should react if the driver only touches and turns slightly the steering wheel - should the vehicle anticipate a full TO or should it continue assisting the driver? Should partial TOs – only lowering the vehicle automation level – also be considered instead? Those questions are focusing on the very critical time period after the TO is successfully performed and therefore open an interesting area for future research. In the future research we propose to investigate also a suitable time boundary between the time when automation can still afford to let the driver decide on the most appropriate action or measure and the time when a qualitative (not only as a last resort) TO should be performed automatically.

CRediT authorship contribution statement

Timotej Gruden: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Visualization, Writing – original draft. **Sašo Tomažič:** Funding acquisition, Project administration, Resources, Supervision. **Jaka Sodnik:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Validation, Writing – review & editing. **Grega Jakus:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Supervision, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

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Appendix A

Brief overview of the study (Read aloud to every participant)

Welcome and thank you for your willingness to participate in our user study designed to evaluate the user interfaces, sensors, and hardware of our driving simulator. We will definitely not be evaluating your driving skills, only the performance of the simulator.

At the beginning, you will receive a consent form and two questionnaires to help us analyse the data. Your answers and the data collected during the drive are completely anonymous and cannot be linked to your identity. You will then sit in the simulator and be asked to put on the glasses that will track your eyes.

Your vehicle will be conditionally automated, meaning it will drive autonomously and only ask you to take over in unexpected situations. During the initial, training phase, you will be able to test the vehicle. We will not collect any data in the meantime. During the training phase, you can try all three ways to take over the vehicle: by turning the steering wheel, by pressing the brake pedal and by pressing the "AUTO" button on the steering wheel. During manual driving, the vehicle will ask you to activate autonomous driving mode by pressing the "AUTO" button if it is off. During normal autonomous driving, the LED strip below the centre screen is coloured green. In unexpected situations, depending on the situation (located left, right or undefined), the corresponding part of the LED strip where the vehicle expects danger is coloured red. In addition, a sound beep / vibration in the car seat will be presented on the corresponding side.

While driving, you will be asked to play the game "Tetris" on your mobile phone. Try to achieve the best score.

The training will be followed by a drive of about 20 minutes, during which you should try to behave as you would in a real vehicle with the aforementioned features.

At the end, you will be presented with two further questionnaires to conclude your cooperation.

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