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Driver response times to auditory, visual, and tactile take-over requests: A simulator study with 101 participants

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Abstract— **Conditionally automated driving systems may soon be available on the market. Even though these systems exempt drivers from the driving task for extended periods of time, drivers are expected to take back control when the automation issues a so-called take-over request. This study investigated the interaction between take-over request modality and type of non-driving task, regarding the driver's reaction time. It was hypothesized that reaction times are higher when the non-driving task and the take-over request use the same modality. For example, auditory take-over requests were expected to be relatively ineffective in situations in which the driver is making a phone call. 101 participants, divided into three groups, performed one of three non-driving tasks, namely reading (i.e., visual task), calling (auditory task), or watching a video (visual/auditory task). Results showed that auditory and tactile take-over requests yielded overall faster reactions than visual take-over requests. The expected interaction between take-over modality and the dominant modality of the non-driving task was not found. As for self-reported usefulness, auditory and tactile take-over requests yielded higher scores than visual ones. In conclusion, it seems that auditory and tactile stimuli are equally effective as take-over requests, regardless of the non-driving task. Further study into the effects of realistic non-driving tasks is needed to identify which non-driving tasks are detrimental to safety in automated driving.**

Keywords— Human-machine interaction; highly automated driving; visual displays; auditory displays; tactile displays

I. INTRODUCTION

Automated vehicles are a key topic in the transportation industry. It is foreseen that automated driving will improve safety, increase driver comfort, and decrease environmental impact. Several autonomous busses have been tested on the road in Greece, Spain, and The Netherlands [1]. Major vehicle manufactures but also non-automotive companies such as Google and Uber have invested in the development of automated cars. Within the next 2–5 years, the first conditionally automated cars may be introduced on the market [1],[2],[3].

The SAE-standard-J3016 [4] defines conditional automated driving (Level 3 automation) as a system that takes care of both longitudinal and lateral driving within a certain operational domain (e.g., the highway). When a conditionally automated driving system is activated, the driver is not required to monitor the system continuously and is allowed to engage in non-driving tasks. However, when the automation reaches its functional limits (e.g., the end of the highway, or when it cannot handle a certain situation), it alerts the driver that he/she has to take back control. During the take-over process, the driver needs to shift his/her attention to the driving scene, take back physical control of the steering wheel, and interpret the situation in order to implement an appropriate response [5],[6],[7].

Many prior studies have investigated the driver response to auditory take-over requests. For example, Gold et al. [8] used a beep as take-over request, whereas Melcher et al. [9] evaluated a bimodal (i.e., auditory-visual) take-over request. More recently, tactile stimuli have been shown to be effective as take-over requests [10]. Non-driving tasks, such as reading and making a phone call engage mainly the visual and auditory perceptual modalities. Hence, visual and auditory warning signals, which are traditionally used in cars, might not be optimally effective as take-over requests.

We expected that the effectiveness of take-over requests can be improved when the take-over request is presented in a modality that differs from the modality that is used by the non-driving task. According to Wickens et al. [11] presenting a warning signal via a 'free' modality increases sensitivity, probably resulting in faster reaction times and fewer misses. Similarly, a study by Mohebbi et al. [12] found that tactile warnings induced faster reaction times than auditory ones while performing an auditory non-driving tasks.

A literature overview [13] reported that reaction times to visual, tactile, and auditory stimuli average at 190 ms, 155 ms, and 150 ms, respectively. However, it should be noted that various moderator variables, such as stimulus intensity, may affect these findings.

The aim of this paper was to investigate the interaction between take-over request modality and modality of the non-

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driving task. The reaction times of three warning modalities (visual, auditory, and tactile) was investigated while drivers were reading, making a phone call, or watching a video. We hypothesized that tactile take-over requests are effective regardless of the non-driving task (because the tested tasks do not employ the tactile senses). Similarly, it was hypothesized that auditory take-over requests are faster than visual ones when the driver is reading. Finally, visual warnings were expected to yield faster reaction times than auditory ones when the driver is making a phone call.

II. Method

A. Experimental setup

Participants: A total of 101 participants (31 females, 70 males), divided into three groups, took part in this study. Their ages ranged from 17 to 39 years (Table I). Thirty-six participants wore corrective lenses (25 spectacles, 11 contact lenses) and all participants had normal hearing. Furthermore, 56 participants never drove in a driving simulator before. Participants provided written informed consent.

TABLE I. Details of the participants

Group	**N**	**Mean age (years)**	**Gender (♀/♂)**
Video	35	25.5	12/23
Phone call	33	24.2	9/24
Reading	33	24.3	10/23
Total	**101**	**24.7**	**31/70**

Apparatus: The study was conducted in a static driving simulator consisting of a full vehicle BMW 6-Series mock-up. Three projectors provided a front view of approximately 180 degrees, and three other projectors provided the views for the rear-view mirrors. Engine and road noise were played back via the car speakers, and low level frequency vibrations were presented via a bass-shaker in the driver seat. An eye tracking system (Smart Eye) recorded the participants' eye movements. The software SILAB from WIVW [14] simulated the driving environment and recorded relevant driving variables. A conditionally automated driving system was able to take over longitudinal control (i.e., driving at a constant speed of 120 km/h) and lateral control (i.e., driving in the lane center) tasks. A 9.7 inch tablet (Samsung Galaxy Tab A) was mounted on the center console for presenting the visual non-driving tasks (see Fig. 1).

Automation status: An icon on the top center of the instrument cluster indicated the current automation status (Fig. 2). A bell sound played when automation became available. The automation could be engaged and disengaged by pressing a diamond-shaped ACC button. The participant could also override the automation by braking or turning the steering wheel.

Fig. 1. Interior of the driving simulator. The top left figure shows the vibration mat in the driver seat. In the top right figure the LEDs are configured in the call-session, namely two red LEDs on the dashboard beyond the steering wheel, and one above the tablet (indicated by red rectangles). The tablet can be seen on the center console and in the bottom left figure. The bottom right shows the instrument cluster and LED on the dashboard above the steering wheel.

B. Experimental design

Procedure: Participants started the experimental procedure with reading and signing an instruction/consent form, followed by a general demographic questionnaire asking for age, gender, visual aids while driving, hearing ability, and prior experience with driving in a simulator. Next, the participants performed a 4-minute familiarization session. Then, the experimental session started, which lasted approximately 12 minutes. The experiment ended with a subjective assessment using an acceptance questionnaire [15]. In total, an experiment lasted at maximum 30 minutes per participants. Participants were asked to conform to the German traffic laws and were told that they would experience six take-over requests. Moreover, participants were asked to perform the non-driving tasks when the automation mode was active, until a take-over request was presented.

Fig. 2. Icons indicating the automation status (gray = disabled; blue = available; green = active; red = take-over).

Non-Driving Tasks: Each participant performed one of three non-driving tasks, namely:

- Video (visual/auditory task): Participants were asked to watch the first episode of "Brooklyn Nine-Nine" (Fox Broad-casting Company) on the tablet. The video was remotely paused by the experimenter when a TOR was presented.

- Call (auditory task): A phone call was simulated by the "Twenty Questions Task". The participants were asked to find out, through yes/no questions, which animal the experimenter had selected. Participants could talk hands-free via an intercom system in the simulator.
- Reading (visual task): On the tablet, four articles out of the German newspaper "Die Zeit" were presented. The participants could scroll down with the touchscreen of the tablet.

Driving scenario: The familiarization session and experimental sessions were conducted on a two-lane motorway with a speed limit of 120 km/h. Both sessions started and ended at a rest stop. After driving manually for a short period, the participants were asked to activate the automation as soon as it was available. Oncoming traffic, separated by a median strip, as well as traffic in driving direction was present. Most traffic maintained the speed limit, but occasionally vehicles would overtake the participant's vehicle. The interval of driving in automated mode between each TOR varied between 90 s and 120 s.

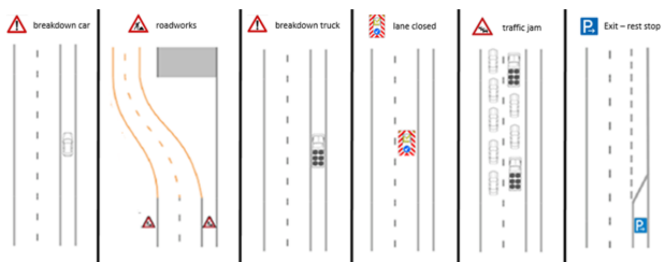

Fig. 3. Illustrations of the six take-over scenarios, adapted from [16].

Take-Over Scenarios: Each participant experienced six different take-over scenarios (Fig. 3). In two scenarios ("breakdown car" and "breakdown truck"), a vehicle was standing still on the hard shoulder. In the "lane closed" scenario, a sign closed off the right traffic lane. A fourth scenario ("roadworks") included roadworks with a speed limit of 80 km/h. In another scenario ("traffic jam") the driver arrived at the tail end of a traffic jam (with vehicles driving 3 km/h) and therefore had to brake. After a while, the traffic jam accelerated back to 120 km/h. The final take-over scenario ("exit – rest stop") included an off-ramp towards a rest stop. The session ended when the participant arrived at the rest stop. All take-over scenarios were non-urgent, meaning that the time-to-collision (to the beginning of the road works, off-ramp, or stationary vehicles) at the moment of the take-over request was greater than 10 s. The six scenarios were always presented in the same order for all participants (Fig. 3). The familiarization session included three take-over scenarios: breakdown car, lane closed, and exit – rest stop.

Take-over requests: Each take-over request was unimodal (i.e., either visual, or auditory, or tactile). Visual warnings were provided via LEDs (light-emitting diodes). The position of the LEDs was adapted according to the non-driving task to make sure the LEDs were in the driver's field of view. In the Video and Reading conditions, two LEDs were placed next to the tablet and one centrally above the steering wheel. In the Call condition, the LEDs were placed the other way round, that is, two LEDs above the steering wheel and one centrally above the tablet. The LEDs flashed twice for 240 ms with an inter-stimulus interval of 100 ms (i.e., the total time of the warning signal was 580 ms). Identical timing parameters were used for the vibrotactile and auditory signals. Two single beeps of 240 ms (inter-stimulus interval: 100 ms) of 2700 Hz served as auditory feedback. The loudness of the beeps was 80.6 dB (measured with the BAPPU-evo from ELK). A vibrating seat as previously used in [17] provided the tactile take-over request. Forty-eight motors located in the seat bottom and back vibrated twice at approximately 60 Hz for a duration of 240 ms (100 ms inter-stimulus interval). Per driving session every modality was presented twice (six in total). The order of take-over request modality ('Tracks' in Fig. 3) was counterbalanced between participants to prevent order effects (Fig. 3).

Variables: The independent variable for the between-subjects design was the non-driving task (Video, Call, Reading). Dependent variables, as used in earlier studies [8],[10],[18], were:

- Eyes-on-road reaction time: the time between the take-over request and the first gaze on the road ahead.
- Steer initiation time: the time between the take-over request and the first turn of the steering wheel, measured as the absolute steering angle > 0.25 deg. The 0.25 threshold represents the smallest angle that could be reliably differentiated from the steering angle during automated driving.
- Steer turn time: the time between the take-over request and the moment that the absolute steering angle exceeded 2.0 deg, representing the first 'conscious' steering action.
- A subjective assessment of the take-over request modality was obtained using a usefulness and satisfaction questionnaire [15]. The questionnaire consisted of 9 items on a 5 point Likert-scale ranging from -2 to +2.

Statistical analysis: The reaction times were tested for significance using a mixed two-way analysis of variance analysis (ANOVA), with the task as between-subjects factor task and the modality as within-subject factor. After this, a *t*-test was used for pairwise comparisons. An alpha value of 0.01 was used to indicate statistical significance.

III. Results

A total of 606 take-over situations occurred in the experiment (i.e., 101 participants * 6 take-overs). Due to eye tracker limitations, the eyes-on-road reaction time could not be computed for all participants. Furthermore, we discarded all reaction times faster than 0.3 seconds. Such fast reaction times could be recorded when the participant was already looking at the road ahead, or when he/she was already touching the steering wheel at the moment that the take-over request was provided.

Regarding the eyes-on-road reaction time, 15%, 94%, and 16% of reaction times were unavailable in the Video, Call, and Read conditions, respectively. The high percentage in the Call

TABLE II. REACTION TIMES PER TAKE-OVER REQUEST MODALITY, ANOVA, AND P-VALUES OF THE PAIRWISE COMPARISONS BETWEEN MODALITIES. V = VISUAL, A = AUDITORY, AND T = TACTILE.

	Visual *M* (*SD*)	Auditory *M* (*SD*)	Tactile *M* (*SD*)	ANOVA	T vs. A *p*	V vs. A *p*	V vs. T *p*
Eyes-on-road (s)	1.94 (1.36)	1.57 (0.49)	1.44 (0.48)	$F(2,132) = 8.09, p < .001$	.056	**.008**	**.003**
Steer initiate (s)	2.29 (1.71)	1.54 (0.63)	1.47 (0.49)	$F(2,196) = 21.82, p < .001$	.301	**< .001**	**< .001**
Steer turn (s)	5.93 (2.59)	5.29 (2.25)	5.48 (2.30)	$F(2,196) = 2.59, p = .195$	.463	.025	.151

condition is due to the fact that participants were already looking at the road, while for the other two tasks they were looking at the in-vehicle display. Therefore, eyes-on-road reaction times for the Call condition were not further analyzed.

Regarding the steer initiation time, reaction times were unavailable for 1%, 2%, and 3% of the take-overs in the Video, Call, and Read conditions, respectively. For the steer turn time, reaction times were unavailable for 11%, 3%, and 9% of the take-overs, respectively. The high percentages for steer turn time as compared to steer initiation time were due to the fact participants completed some scenarios (e.g., breakdown truck) with a steering amplitude below 2 deg. In case no reaction time was unavailable for a participant for a particular take-over modality, then a mean substitution was performed. Using paired *t* tests, no statistically significant differences between the six scenarios (cf. Fig. 3) were observed for the eyes-on-road time and steer initiation time, likely because the take-over request was issued long in advance of the scenario. Therefore the effect of scenario will not be reported separately.

An inspection of the raw data (Fig. 4) suggests that the take-over modality has an effect on the initial reactions (i.e., eyes-on-road, steer initiation, and steer turn). Table II shows the average reaction times for the three take-over request modalities. The ANOVA indicated that there is a significant difference for the eyes-on-road and steer initiation times. The pairwise comparisons showed that tactile and auditory take-over requests yielded significantly faster reaction times than visual ones. The steer turn times did not show significant differences between the three takeover modalities.

Table III shows the mean reaction times for the three non-driving tasks. The ANOVA showed no significant differences for the eyes-on-road reaction time for this group. No significant differences between the three non-driving tasks were found (Table III).

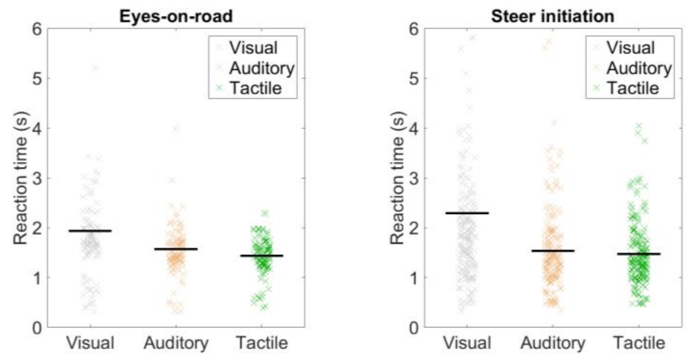

Fig. 4. Mean (black horizontal lines) eyes-on-road and steer initiation reaction time per modality across participants. The crosses show the reaction times per individual take-over request (Eyes-on-road: n = 116, 118, 110, for visual, auditory, and tactile, respectively; Steer: initiation: n = 200, 199, 196 for visual, auditory, tactile, respectively).

The mixed ANOVAs indicated no significant interaction (modality x task) for any of the three reaction times. In other words, the expected effect between non-driving task and take-over modality was not found ($p > .4$).

A Friedman test for the usefulness and satisfaction (Fig. 5) indicated a significant difference between take-over request modalities ($\chi^2(2,200) = 95.17$, $p < .001$ and $\chi^2(2,200) = 43.88$, $p < .001$). Post-hoc analysis showed that for usefulness of tactile and auditory take-over requests were rated significantly higher than visual ones (T vs. A: $p = 1.00$, V vs. A: $p < .001$, V vs. T: $p < .001$). Moreover, the tactile take-over requests were rated as more satisfactory than auditory and visual ones (T vs. A: $p < .001$, V vs. A: $p = .041$, V vs. T: $p < .001$).

TABLE III. REACTION TIMES PER NON-DRIVING TASK, ANOVA, AND *P*-VALUES OF THE PAIRWISE COMPARISONS BETWEEN MODALITIES. C = CALL, R=READING, AND V = VIDEO.

	Video *M* (*SD*)	Call *M* (*SD*)	Read *M* (*SD*)	ANOVA	R vs. C *p*	V vs. C *p*	V vs. R *p*
Eyes-on-road (s)	1.75 (0.79)	- -	1.55 (0.42)	$F(1,66) = 1.63, p = .206$	-	-	.206
Steer initiate (s)	1.94 (0.82)	1.63 (0.74)	1.71 (0.65)	$F(2,98) = 1.63, p = .202$	.628	.105	.209
Steer turn (s)	5.97 (1.49)	5.22 (2.00)	5.49 (1.67)	$F(2,98) = 1.66\ p = .195$	.556	.082	.212

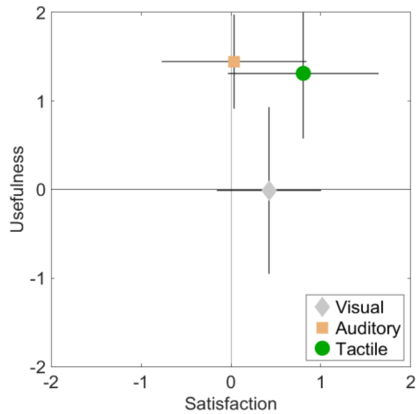

Fig. 5. Mean satisfaction and usefulness scores, with error bars indicating the standard deviation. The mean (standard deviation) of the usefulness score for auditory, visual, and tactile take-over requests was 1.45 (0.53), -0.01 (0.94), 1.31 (0.73), respectively. The mean (standard deviation) of the satisfaction score for auditory, visual, and tactile take-over requests was 0.03 (0.80), 0.42 (0.58), 0.80 (0.83), respectively.

IV. Discussion

This study investigated the interaction between take-over request modality and non-driving task, for the driver's reaction time. It was hypothesized that tasks which predominantly employ a certain modality would yield increased reaction times when the take-over request was presented in the same modality. For example, when the driver makes a phone call, auditory take-over requests were expected to be less effective. 101 participants, divided into three groups, performed one of three non-driving tasks, namely reading, calling, or watching a video.

Results showed that tactile and auditory take-over request yield faster initial reaction times (i.e., eyes-on-road and steer initiation) than visual ones. It is possible that the visual take-over requests (three flashing LEDs) were interpreted as less urgent than the auditory (beeps from multiple speakers) and tactile (vibrations from 48 motors) take-over requests. Additionally, it is possible that participants overlooked the LEDs, despite the fact that they were positioned close to the tablet that was used for the non-driving task. Our results are in line with Politis et al. [19] who also found significantly higher reaction times for visual take-over requests than for tactile, auditory, and multimodal requests (depending on the location of the visual warning).

In our study, the advantage in the initial reaction times seems to diminish in the later stages of the take-over process. That is, the steer turn reaction times do not show any significant differences. Previous studies [10],[18], using the same measures, found similar 'diluting effects'. In order to improve the driver's decision making in the later stages of take-over process, more informative displays (e.g., augmented feedback) may be needed.

Calling yielded 0.31 s and 0.09 s faster steer initiation times than watching a video and reading, respectively. Furthermore, calling yielded 0.75 s and 0.27 s faster steer turn times than watching a video and reading (Table II). However, none of these differences were statistically significant. Similarly, Gold et al. [20] found faster take-over times for non-visual non-driving tasks than for visual non-driving tasks (i.e., on average 0.34 s faster). Moreover, Gold et al. found these results to be significantly different. This may be because Gold et al. used a within-subject design, which has more statistical power than our between-subjects design.

The non-driving tasks in this study were more realistic than abstract tasks such as the N-Back or SuRT, which have been used in other automated driving research. However, in our study, participants were *assigned* a task. Hence, it is debatable how engaged they actually were with the non-driving tasks. Moreover, the non-driving tasks in this study were interruptible without any 'negative' consequences. In reality, videos watched on a tablet or phone will not automatically stop and not all games are easily interrupted. Indeed, in a recent article in Wired, Volvo's head of safety stated "it's not so easy to put the game away" [21]. Also, non-driving tasks rarely employ a single modality and are often a combination of multiple modalities; for example typing an email is a visual-motor task. Future research should investigate the effect of more realistic non-driving tasks on take-over performance.

The expected interaction between the take-over modality and the predominant modality of the non-driving task was not found in our study. Thus, it seems that adapting the modality of the take-over request to the modality of the non-driving task will only have a limited effect on the driver's initial reaction times. Other factors, like the take-over requests modality [10], the complexity of the scenario [22], or whether the non-driving task is hands-free [20] seem to have a larger influence on the reaction times.

As for subjective acceptance and satisfaction, tactile take-over requests outperformed the auditory and visual ones. The results on the usefulness scale seem to reflect the results of the reaction times. That is, visual stimuli were rated as less useful than auditory and tactile stimuli. Moreover, on the satisfaction scale, the tactile stimuli outperformed the auditory stimuli. This could have been caused by the urgent nature of the tone (i.e., high pitched and relatively loud). Indeed, an example of a participant's open comment regarding tactile feedback "a pleasant way to take-over [...] which was perceived immediately" and auditory take-over requests "it is not a comfortable tone, but definitely effective".

In conclusion, the modality of the take-over request has a substantial effect on take-over times, but the type of non-driving task does not. There was no statistically significant interaction between these two variables either. Auditory and tactile stimuli were more effective take-over requests than visual ones. Future research should further investigate the effect of realistic non-driving tasks on take-over performance.

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