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Comparing spatially static and dynamic vibrotactile take-over requests in the driver seat

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ABSTRACT

Vibrotactile stimuli can be effective as warning signals, but their effectiveness as directional take-over requests in automated driving is yet unknown. This study aimed to investigate the correct response rate, reaction times, and eye and head orientation for static versus dynamic directional take-over requests presented via vibrating motors in the driver seat. In a driving simulator, eighteen participants performed three sessions: 1) a session involving no driving (Baseline), 2) driving a highly automated car without additional task (HAD), and 3) driving a highly automated car while performing a mentally demanding task (N-Back). Per session, participants received four directional static (in the left or right part of the seat) and four dynamic (moving from one side towards the opposite left or right of the seat) take-over requests via two 6 × 4 motor matrices embedded in the seat back and bottom. In the Baseline condition, participants reported whether the cue was left or right, and in the HAD and N-Back conditions participants had to change lanes to the left or to the right according to the directional cue. The correct response rate was operationalized as the accuracy of the self-reported direction (Baseline session) and the accuracy of the lane change direction (HAD & N-Back sessions). The results showed that the correct response rate ranged between 94% for static patterns in the Baseline session and 74% for dynamic patterns in the N-Back session, although these effects were not statistically significant. Steering wheel touch and steering input reaction times were approximately 200 ms faster for static patterns than for dynamic ones. Eye tracking results revealed a correspondence between head/eye-gaze direction and lane change direction, and showed that head and eye-gaze movements where initiated faster for static vibrations than for dynamic ones. In conclusion, vibrotactile stimuli presented via the driver seat are effective as warnings, but their effectiveness as directional take-over requests may be limited. The present study may encourage further investigation into how to get drivers safely back into the loop.

1. Introduction

1.1. Highly automated driving and take-over maneuvers

Highly automated cars may be introduced on public roads within the next 5–10 years (ERTRAC Task Force, 2015). In highly automated driving, the car drives itself for most of the time, but the driver must intervene when the automation provides a take-over request (Gasser et al., 2012). How to get a human operator back into the control loop after a period of passive monitoring is a classical issue in human factors science (Bainbridge, 1983) that has become pertinent in the automated driving domain (e.g., Gold and Bengler, 2014; Kerschbaum et al., 2015; Zeeb et al., 2015).

When the automation provides a take-over request, the driver has to get back into the control loop by 1) shifting his/her attention to the road, 2) cognitively processing the traffic situation and selecting an appropriate action, 3) repositioning him/herself in order to take back control of the vehicle, and 4) implementing the action via the steering wheel and/or pedals (Gold et al., 2013; Petermeijer et al., 2015; Zeeb et al., 2015). Most take-over requests in previous studies have been alarms that inform the driver that he or she has to take back control (e.g., Banks and Stanton, 2015; Gold et al., 2013; Melcher et al., 2015). A take-over request may be designed in such a way that it does not only warn the driver that a take-over is required, but also assists him/her in the aforementioned 'shifting of attention' and 'cognitive processing and action selection' phases. Lorenz et al. (2014), for example, proposed a head-up display that

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indicated safe or unsafe 'corridors' on the road after a take-over request.

1.2. The potential of vibrotactile take-over requests

In the future, the driver of a highly automated car may be permitted to engage in non-driving tasks such as eating, resting, or talking on the phone, and empirical studies indicate that drivers are likely to do so (Llaneras et al., 2013; Merat et al., 2012). Visual and auditory warnings may not be suitable as take-over requests in highly automated driving: When drivers are no longer required to look at the road, they are likely to miss visual indications on the dashboard or on a head-up display. Similarly, auditory warnings might go unnoticed when engaging in non-driving tasks such as talking to passengers or listening to music.

Because vibrotactile stimuli do not have to be in the driver's visual field, they are a viable complement to auditory and visual displays for assisting a driver in a take-over scenario. By presenting take-over requests in a multimodal manner, the redundancy of the warning is increased and consequently the probability of misses is reduced (Wickens et al., 2012; Hancock et al., 2013). Prewett et al. (2012) found in a meta-analysis that vibrotactile warnings yield performance advantages (e.g., faster reaction times) when added to a baseline task or to visual cues. Furthermore, in a previous simulator study, it has been shown that visual and vibrotactile warnings combined yielded faster reaction times than visual-only take-over requests (Petermeijer et al., 2016).

In order to assist a driver in a maneuver, an interface should be able to convey more information than a binary warning. Visual and auditory displays are traditionally considered more suitable for communicating semantics than tactile displays (Baldwin et al., 2012). Nonetheless, tactile displays are suitable for providing directional information (Van Erp et al., 2005) or simple messages using so-called tactons (i.e., by encoding the information in terms of the frequency, timing, intensity, and/or location of the vibrotactile stimulus; Brewster and Brown, 2004). Similarly, vibrotactile displays may be useful to convey directional information (e.g., steer right or left) to the driver during a take-over request.

1.3. Static and dynamic directional cues in vibrotactile warnings

One approach to assist the driver in the take-over procedure could be to provide a directional cue, that is, to embed "directional information into the tactile warning signals in order to orient the driver's spatial attention in different locations" (Meng et al., 2015, p. 336; see also, Gray et al., 2014; Ho et al., 2005; Petermeijer et al., 2015). Vibrotactile stimuli with directional cues have been studied in a variety of driving applications, including lane keeping assistance (Beruscha et al., 2010), blind spot warning (Morrell and Wasilewski, 2010), and rear collision warning systems (Ho et al., 2005). Hwang and Ryu (2010) provided directional cues via the steering wheel, and participants were asked to react by turning the steering wheel left or right towards the side of the vibration. They found an average correct response rate of about 90%, with an average response time of 2 s.

Directional cues can be presented by means of static patterns (i.e., stimuli at one location on the human body) or dynamic ones (i.e., a sequence of stimuli at different locations on the body, to simulate a movement), see also Petermeijer et al. (2015) for a categorization of vibration patterns. In a study by Petermeijer et al. (2016), participants did not seem to notice that the static vibrations in the driver seat were provided on the left or right side. Sayer et al. (2005) found similar results to Petermeijer et al.; in their on-road study, several participants had difficulty discriminating static directional cues (i.e., left and right) of vibrotactile stimuli in the seat bottom. Meng and Spence (2015) also noted that static vibrotactile stimuli might be limited in their ability to convey directional cues and argued that "dynamic tactile cues might be used to improve drivers' localization and differentiation to the tactile warnings" (p. 339).

Two recent driving simulator studies showed that dynamic patterns that move towards the driver's torso (using four stimulus locations, namely the two wrists, and two on the waist) evoked faster reaction than away-from-torso cues or static vibrations (Meng et al., 2014; Meng et al., 2015). In Schwalk et al. (2015), participants reported that dynamic vibrations that travelled from the top of the backrest towards the front of the seat bottom were appropriate for signaling driver-to-automation control transitions. Conversely, dynamic stimuli that travelled from the seat bottom to the backrest were regarded as appropriate for automation-to-driver transitions. Thus, based on the available literature, it appears that dynamic vibration patterns hold promise as take-over requests.

1.4. Aim

The aim of this study was to evaluate how accurately humans are able to respond to vibrotactile stimuli in the driver seat. The vibrations (i.e., take-over requests) contained a directional cue to inform the participant that he/she had to change lanes to either the left or the right. We evaluated the correct response rate of static vibrations (i.e., non-moving vibrations that were presented on the left or on the right) and dynamic vibrations (i.e., vibrations that moved to the left or to the right) in a driving simulator experiment. The correct response rate was measured in three conditions: 1) a baseline condition in which the participants were sitting in the simulator but not driving (low mental demand), 2) while participants were driving a highly automated vehicle (medium mental demand), and 3) while participants were driving a highly automated vehicle and engaged in a memory task (high mental demand). In the Baseline condition, participants had to report 'left' or 'right', whereas in the two driving conditions, participants had to make a left or right lane change after having received the directional take-over request. These three conditions were included to infer whether the directional cues were still perceivable if the participants were engaged in a mentally demanding task, for this will likely be the case in real-world take-over scenarios. Driver behavior was further operationalized in terms of take-over time, steering wheel input, and eye and head movements. We hypothesized that dynamic patterns would yield higher correct response rates than static ones, and that the correct response rate of vibrotactile patterns would decrease when the driver is under increased mental demand.

2. Method

2.1. Participants

Eighteen participants (five female) holding a driver license participated in the study. The participants were between 22 and 78 years old ($M = 43.0$ years; $SD = 15.2$ years). Two participants indicated they drove less than 2000 km per year, twelve participants reported a yearly mileage of 5000–20,000 km per year, and the remaining four participants reported a yearly mileage over 20,000 km. Seven participants indicated that they wear glasses or contact lenses when driving, and none reported to be colorblind. Two participants were left-handed. All participants had participated in a driving simulator study at least once before.

2.2. Simulator

The experiment was conducted in a fixed-base simulator, located at Continental, Babenhausen, Germany. The simulator consisted of a BMW 5-series chassis in front of three projectors that

Fig. 1. Top: Driving simulator used in this study. Bottom: The visual display shown on the instrument cluster of the simulator. The center showed the speedometer, and on the right side an icon indicated the automation status (blue icon = active; grey icon = inactive). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

provided the front view of approximately 180 ° (Fig. 1). Small TFT-screens acted as rear-view mirrors. A mounted TFT screen and a touchscreen represented the instrument cluster and center console. A four-camera eye-tracking system running at 60 Hz (Smart Eye Pro, version 6.1.13; Smart Eye, 2016) was used to track the participants' head and gaze motion. The participants could toggle the automation on and off by moving the ACC lever either up or down. An icon on the instrument cluster's right side indicated the automation mode (Fig. 1). The simulation ran on SILAB software (WIVW, 2016).

2.3. Vibrotactile seat

Vibrations were presented to the participants via a vibrotactile seat consisting of a Velcro mat that covered 48 eccentric rotating mass motors (Pico Vibe model number: 307-103, dimensions: 9 × 25 mm). The motors were configured into 6 × 4 matrices in the seat bottom and seat back, respectively (Fig. 2). The inter-motor distance was approximately 45 mm between the six rows and 30, 50, and 30 mm between the four respective columns. The voltage to the individual motors was controlled using three Pulse Width Modulator (PWM) controllers, which in turn were controlled by an Arduino Mega connected to the server of the driving simulator.

2.4. Static and dynamic vibration patterns

Participants were provided with static or dynamic vibrations, which contained a left or right directional cue (Fig. 2). Furthermore, vibration patterns were presented at either the seat bottom or the seat back. Thus, there were four static patterns (i.e., 1: back left, 2: back right, 3: bottom left, and 4: bottom right) and four dynamic patterns (i.e., 5: back moving left, 6: back moving right, 7: bottom moving left, and 8: bottom moving right). The motors, when activated, vibrated at approximately 60 Hz.

A static pattern was provided by three vibration pulses (500 ms on/off intervals) in two columns (i.e., 12 motors) (Fig. 3). A dynamic pattern was provided by activating the columns in succession from the left to the right, or vice versa. A column was active for 200 ms and every 100 ms an adjacent column activated, creating a pattern that moved from one side to the other with a maximum of two columns vibrating at the same time.

2.5. Experimental design

A within-subject design was used to evaluate the effect of the vibration type (i.e., static vs. dynamic) and mental demand (i.e., low, medium, and high). Each participant executed three sessions: 1) Baseline, 2) HAD, and 3) N-Back. The Baseline session was completed first, and the HAD and N-Back sessions were counterbalanced across participants. Per session, the participant experienced the eight vibration patterns (four static ones and four dynamic ones, see Section 2.4) in counterbalanced order.

1) The Baseline session (low mental demand): The eight vibration patterns were presented to the participant in the driver seat while no virtual simulation was running. After each pattern, the participant was asked to fill out three multiple-choice questions regarding the location and direction of the pattern: 'I felt the vibration (1a. *in the seat bottom*, 1b. *in the seat back*, 1c. *in the whole seat*; 2a. *on the left side*, 2b. *on the right side*, 2c. *on both sides*; 3a. *travelling to the left*, 3b. *travelling to the right*, 3c. *not travelling*).
2) The HAD session (medium mental demand). The participant drove a highly automated vehicle on the highway and experienced eight take-over requests via the vibrotactile seat. The take-over request warned the driver of a stationary vehicle ahead. The participant was instructed to change to the left or right lane according to the directional cue of the vibration pattern. If the vibration pattern was static, the participant had to change lanes towards the same side as the vibration was presented. In case of a dynamic pattern, the participant had to change lanes to the side the vibrations were moving towards. Note that the take-over request was only presented via the vibrotactile seat; no additional auditory or visual warning was presented.
3) The N-Back session (high mental demand). This session was the same as the HAD session, but the participant performed an additional N-Back task when the vehicle was driving automatically. The N-Back task is a widely used technique for imposing mental demands in automated driving research (e.g., Gold et al., 2016; Radlmayr et al., 2014; Louw et al., 2016). In our study, the participant performed a 2-Back task as specified by Mehler et al. (2011). A pre-recorded female voice uttered random digits between 0 and 9 with an interval of 2.25 s between the presentation of each digit. The participant had to repeat the number that was uttered two digits before the current digit. The task automatically started approximately 700 m after the start of the session, and 900 m after every take-over request. The N-Back task stopped automatically when a take-over request was presented. The N-Back was used to investigate the effect of a mentally demanding non-driving task on the correct response rate and reaction times.

2.6. Driving scenario

During the HAD and N-Back sessions, the participants drove in highly automated mode on a three lane highway, with lane widths of 3.75 m. At the start of the session, the simulated vehicle was parked at the side of the road. The participant was asked via intercom to merge onto the highway and activate the automation when driving in the middle lane. The automation kept a speed of 120 km/h and stayed in the center of the lane. During each session, the participant received eight take-over requests, which were approximately

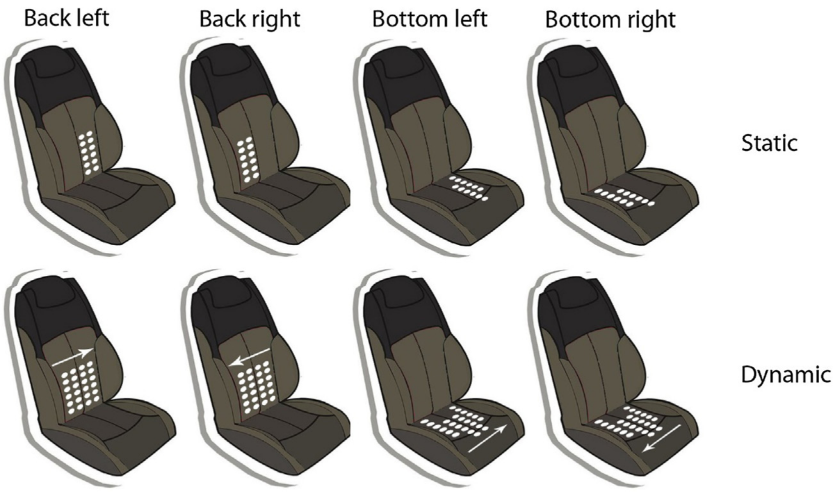

Fig. 2. Vibration locations in the seat back and seat bottom. Top: The vibration locations for the four static patterns. Bottom: The vibration locations for the four dynamic patterns.

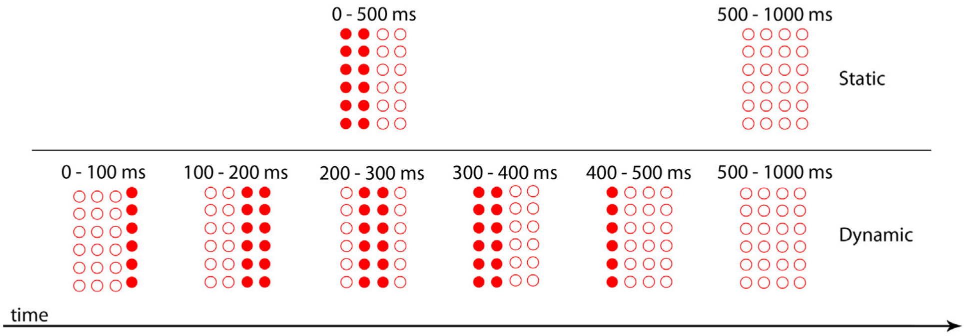

Fig. 3. Schematic of the temporal and spatial configuration of static and dynamic patterns with a 'left' directional cue. One dot represents a single vibration motor. The filled circles represent active motors and the empty circles represent inactive motors.

1.5 min apart. At the moment that the take-over request was presented, a stationary car appeared 223 m in front of the participant's car (i.e., in the middle lane), and the automation was automatically deactivated. At a speed of 120 km/h this corresponded to a lead time of about 7 s (for studies using the same take-over parameters see Gold et al., 2013; Gold et al., 2016; Petermeijer et al., 2016). All take-over requests were provided on straight road segments, which meant that no immediate action of the participant was needed to stabilize the car in its lane. The participant had to brake and/or steer to avoid colliding with the stationary car ahead.

Between the take-over requests, the participant's car travelled past two or three slower moving vehicles on the right lane, whereas a faster moving vehicle on the left lane overtook the participant's car. No traffic was around the participant's car when a take-over request was presented.

2.7. Procedure and instructions

At arrival, the participant was presented with written instructions and a consent form. After signing the consent form the participant completed an introductory questionnaire with questions about the participant's gender, age, driving experience, driving style, past experience in driving simulators, and presumed preference and perceived urgency of auditory, visual, and vibrotactile take-over requests.

Next, the participant performed the Baseline session in which he/she experienced all eight vibration patterns. Then, the eye-tracking system was calibrated, and the participant drove a training of 2 min to familiarize with the simulator, a take-over request, and how to reactivate the automation. After approximately 1 min of driving in the training session, the N-Back task automatically started. A total of 20 digits were presented, after which the participant received a dynamic vibrotactile take-over request in the back of the seat, requesting the participant to change lanes to the left.

Next, the participant performed the HAD and N-Back sessions (in counterbalanced order) in the driving simulator with a 5 min break in between. To verify whether the N-Back task provided additional workload, the participant completed a NASA Task Load Index (NASA-TLX) after each of the two driving sessions. After all three sessions were completed, the participant completed four questionnaires: (1) a questionnaire on acceptance (Van der Laan et al., 1997) concerning the static patterns, (2) the same acceptance questionnaire but now for the dynamic patterns, (3) a User Experience Questionnaire (UEQ) concerning the tactile seat, and (4) a questionnaire that presented the same questions about take-over request modality as the introductory questionnaire. This final questionnaire was used to evaluate whether the participants' preference had changed after actually experiencing vibrotactile take-over requests.

The participant was instructed in writing and verbally at the beginning of the first driving session to keep the hands and feet off the steering wheel and pedals and not to intervene unless the automation provided a take-over request. When a take-over request was presented, the participant had to place the hands back on the steering wheel, perform the necessary safety checks, and avoid colliding with the car ahead by braking and/or steering. The participant was also asked to focus on the N-Back task when the automation was active during the N-Back session and to stop doing the N-Back task in case of a take-over. The participant was also informed that during a take-over procedure there would be no traffic around. Lastly, the participant was asked to change lanes according to the directional cue in the vibration pattern and to reactivate the automation after having passed the stationary car and being back in the middle lane.

2.8. Dependent variables

2.8.1. Objective measures

The correct response rate of the patterns was defined as the percentage of vibrotactile warnings in which the participants correctly identified the directional cue of the vibration pattern. In the Baseline session, an answer was marked as correct when the participant indicated the correct side (for static patterns) or direction (for dynamic patterns) in the multiple-choice question. During the driving sessions, a response was marked as correct when the participant made a lane change to the same side as the vibration pattern's side or direction.

The following measures of reaction time were used to assess how quickly the participants took back control of the vehicle after a take-over request: (1) Steer-touch: absolute steering wheel angle greater than 0.25 deg. This 0.25 deg threshold was used in an earlier study by Petermeijer et al. (2016) as a measure of how fast participants touched the steering wheel after the take-over request; (2) Steer-turn: absolute steering wheel angle greater than 2 deg. The 2 deg threshold was used to represent the initiation of a steering action (2.0 deg was also used by Gold et al., 2013); (3) Lane change: absolute deviation from the lane center greater than 1.875 m (i.e., half a lane width).

The gaze heading represents the left/right angle between the eye-gaze vector and a vector pointing forwards to the simulator screen. Similarly, the head heading is the left/right angle of the orientation of the head with respect to a vector pointing forwards to the simulator screen. The gaze and head heading were analyzed to investigate whether static or dynamic vibrotactile warnings evoke faster gaze reactions towards a certain direction. The eye-tracking data were filtered with a fourth-order low-pass Butterworth filter having a cut-off frequency of 5 Hz.

2.8.2. Self-report measures

All questionnaires were offered in a paper format in German language. The raw NASA-TLX included six items, namely, mental demand, physical demand, temporal demand, performance, effort, and frustration. All items consisted of a 21-tick horizontal bar with anchors on the left (i.e., low/good) and right (i.e., high/poor) sides (Vertanen, 2016).

The acceptance questionnaire was offered to determine the perceived usefulness and satisfaction of static and dynamic vibration patterns. The 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 satisfaction score was determined by the following four items: 2. pleasant – unpleasant, 4. nice – annoying, 6. irritating – likeable, 8. undesirable – desirable. All items were on a five-point scale. Sign reversals were performed for items 1, 2, 4, 5, 7, and 9, so that higher scores indicate a higher usefulness/satisfaction score.

2.9. Statistical analyses

Of the dependent measures, we obtained for every session an 18×8 matrix (i.e., participants x vibration patterns). For the correct response rate and usefulness and satisfaction scores, the numbers in the matrix were rank transformed to account for non-normal distributions. For the correct response rate, the differences between the three sessions (i.e., Baseline, HAD, and N-Back) were assessed by mean of a repeated-measures ANOVA. For the remaining measures, the differences between the two types of vibration patterns (i.e., static and dynamic) and between the two driving sessions (i.e., HAD and N-Back) were assessed by means of paired t tests. Additionally, Cohen's d_z was used to describe the size of the within-subject effect (Faul et al., 2007). Effects were declared statistically significant if $p < 0.05$. If multiple effects were compared as a function of travelled distance, a more stringent significance level of 0.01 was adopted.

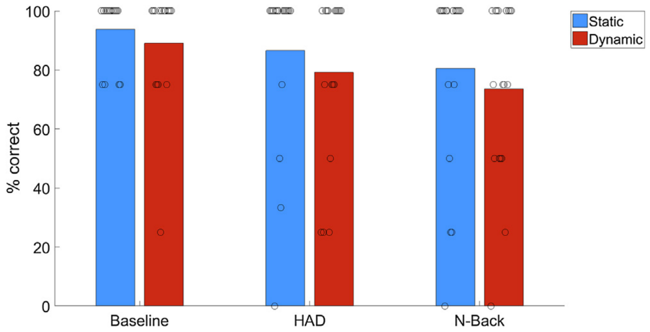

Fig. 4. Mean correct response rate for the static and dynamic patterns per participant. The black markers represent the correct response rates for the individual participants. The mean (*SD*) percentages per condition are as follows: Baseline static: 93.8 (11.2), Baseline dynamic: 89.1 (20.3), HAD static: 86.6 (29.0), HAD dynamic: 79.2 (28.8), N-Back static: 80.6 (32.7), N-Back dynamic: 73.6 (30.3).

3. Results

During the Baseline session, the correct response rates for two participants were not recorded correctly; therefore, these data were imputed with the mean value of the remaining 16 participants. One participant did not evade the stationary car when the first take-over request (HAD session) was presented. Data of this particular take-over maneuver were excluded. Eye-tracking data of three participants were unavailable because of technical difficulties (e.g., because the participant was wearing glasses).

3.1. Correct response rate

During a preliminary analysis, it was found that there were no statistically significant differences between the correct response rates of patterns in the seat bottom and seat back. Therefore, these results have been aggregated, and are not reported separately. Fig. 4 shows the correct response rates for the three sessions and the static versus dynamic patterns. It can be seen that the correct response rate decreases with increased mental demand (i.e., decreasing from Baseline to HAD to N-Back), but these effects were not significantly different, $F(2,34) = 2.01$, $p = 0.149$. There was also no statistical difference between the static and dynamic vibration patterns, $F(1,17) = 3.36$, $p = 0.084$.

3.2. Reaction times

Table 3 shows the reaction times from the moment of the take-over request to the first steering wheel touch and the lane change. Paired t tests yielded no significant effects between the HAD and N-Back sessions ($t(17) = 1.12$, $p = 0.278$; $t(17) = 1.21$, $p = 0.241$; and $t(17) = 1.47$, $p = 0.160$, for steer-touch, steer-turn, and lane change, respectively). However, the reaction times were slightly faster for static patterns than for dynamic patterns ($t(17) = -2.69$, $p = 0.016$; $t(17) = -2.54$, $p = 0.021$; $t(17) = -2.18$, $p = 0.043$, for steer-touch, steer-turn, and lane change, respectively). During the entire study, the brake pedal was applied only five times during a take-over maneuver (twice in the HAD session and three times in the N-Back session).

3.3. Driving variables

Fig. 5 shows the mean lateral position and the mean steering wheel angle across participants as a function of travelled distance for the static and dynamic patterns (left) and for the HAD and N-Back sessions (right). It can be seen that the participants steered around the stationary car, with the steering wheel angle following a pattern that is characteristic of a double lane change. The results in Fig. 5 are consistent with the reaction times (Table 1) in that dynamic vibrations yielded slightly slower lane changes than static vibrations. Specifically, the maximum steering angle is higher and occurs earlier for static vibrations than for dynamic ones. The bottom two plots in Fig. 5 show the p values of paired t tests between the static and dynamic patterns (left) and between the HAD and N-Back condition (right). These graphs are inspired by Manhattan plots (e.g., Tanikawa et al., 2012). High values on the inverted logarithmic scale represent low p values. The p values regarding the dynamic versus static patterns (bottom left) show two peaks that exceed the 0.01 threshold, whereas the p values between the HAD and N-Back sessions (bottom right) exceed this threshold once.

3.4. Eye-tracking data

Fig. 6 shows the mean heading angle of eye-gaze and the head, including the standard deviations across the mean of participants. Shortly after the take-over request, the standard deviation of the gaze heading decreases, suggesting that the participants focused on the road ahead. After this (i.e., from about 50 m after the take-over request was presented), participants shifted their attention to the left or right depending on the direction of the lane change. The second peak in heading occurs when the participants returned to the middle lane. Based on the p values, it seems that both the gaze and head heading for the static patterns diverted earlier towards the left/right than dynamic patterns.

3.5. Self-report questionnaires

The mean (*SD*) workload across the six scales of the NASA-TLX was 21.7% (16.3%) and 35.7% (15.2%) for the HAD and N-Back session, respectively. A paired t test showed a significant difference between these two sessions, $t(17) = -4.31$, $p < 0.001$, $d_z = -1.02$. Fig. 7 shows that the participants rated the vibrotactile feedback positive in terms of usefulness and satisfaction, but no differences between static and dynamic patterns were found (usefulness: $t(17) = -0.32$, $p = 0.749$, $d_z = -0.08$; satisfaction: $t(17) = -0.12$, $p = 0.906$, $d_z = -0.03$). In the introductory and final questionnaire, 61% and 72% of participants, respectively, reported that take-over requests should be provided by means of vibrations in combination with auditory and/or visual warnings. In both questionnaires 17% of participants reported that take over requests should be provided by means of vibrations only.

4. Discussion

The aim of this study was to investigate the correct response rates, reaction times, and eye/head orientation in response to static and dynamic vibration patterns conveyed via a vibrotactile seat. We conducted a driving simulator experiment with three sessions: Baseline, HAD, and N-Back. The Baseline session was used to measure participants' response rates with low mental demand, whereas the N-Back task imposed extra mental demand on the participant (as confirmed by the results of NASA-TLX).

4.1. The effect of mental demand

The Baseline session yielded the highest average correct response rates (91%), followed by the HAD (83%) and N-Back sessions (77%). Thus, when participants were not engaged in a driving task, they were reasonably well able to distinguish left versus right vibrations, but when mental demand increased, the ability to distinguish the directionality of the vibrotactile stimuli diminished. It should be noted that these differences were not statistically significant.

The reaction times showed no significant differences between the HAD and N-Back sessions (Table 1). The secondary task that the participants performed required cognitive processing and a verbal response; participants did not have to use their hands and did not have to look away from the road. Our findings are in line with a recent study performed by Gold et al. (2016), which also found that take-over times were hardly affected by a mentally demanding non-driving task. In some previous studies, participants lost a large amount of time with disposing objects (e.g., a phone, tablet, or book) or with re-attending to the road. For example, Melcher et al. (2015) found an average reaction time of 3.5 s to a take-over request when participants held a mobile phone. In Gold et al. (2013) and Petermeijer et al. (2016), the participants were performing a Surrogate Reference Task (SuRT) having their eyes diverted from the road, but their hands free, when the take-over request was presented. These two studies reported similar touch-reaction times but substantially higher steer-turn reaction times than the present study. In summary, it appears that biomechanical distraction causes large impairments in reaction times. Visual distraction, on the other hand, does not appear to have an influence on the time to achieve motor readiness (see also Zeeb et al., 2016), but increases the time to get cognitively back into the loop (as operationalized by a 'conscious' steering action). Finally, cognitive distraction (as applied in our N-Back condition) seems to have only minor effects on the reaction times in a take-over scenario.

4.2. Static and dynamic patterns

Static vibration patterns yielded higher correct response rates than dynamic patterns, but the effect was small and not statistically significant. Fig. 4 illustrated the high variability of the correct response rate among participants, both with the static and dynamic patterns.

Contrary to the results of Meng et al. (2014, 2015), static patterns showed significantly *faster* reaction times than dynamic patterns. This discrepancy between our results and those of Meng et al. can be explained as follows. First, in the present experiment the participants had to recognize the directional cue of the vibration patterns in order to make a lane change in the correct direction, whereas in the studies of Meng et al., the participants were instructed to react (i.e., to brake) as quickly as possible when they perceived the vibrotactile warning. It probably takes time for a driver to recognize the direction of the dynamic pattern. To illustrate, the first 200 ms of a dynamic stimulus to the left is hardly distinguishable from a static stimulus to the right; only after 200 ms it becomes clear that the dynamic stimulus moves to the opposite side (see Fig. 3). This potential confusion between vibration onset and direction of travel may be inherent to many types of dynamic vibrations, and could represent a significant drawback as compared to static vibrations. A solution to this confusion in our case would have been to present the dynamic vibrations on one side of the seat only (i.e., the vibrations could travel from left of the center further outward to the left, or vice versa from the right of the center further outward to the right). However, this would have limited the range of travel (and therefore the perceptibility) of the dynamic vibrations, and still does not do away with the fact that by definition it takes time

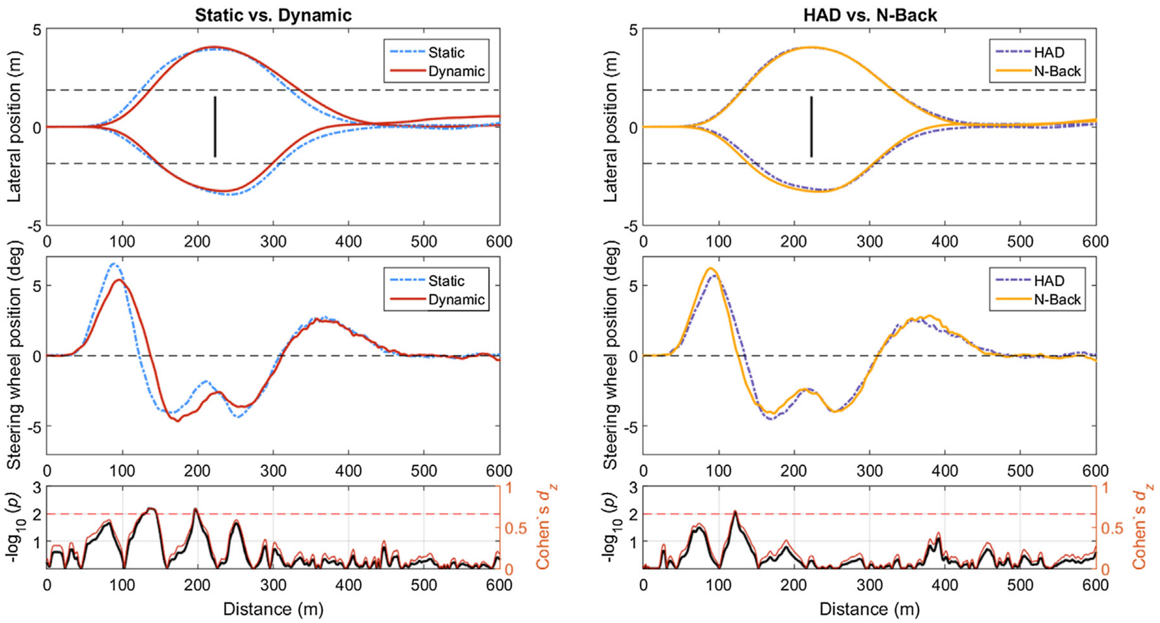

Fig. 5. Top: Mean lateral position of the vehicle across participants as a function of travelled distance since the take-over request (the take-over request was presented at a distance of 0 m). The vertical line at 223 m represents the stationary car in the middle of the lane. The horizontal dashed lines at 1.875 m and −1.875 m represent the lane markings on the road. Middle: The mean steering wheel position in degrees. If the lane change was made to the right, the values were inverted. Bottom: *p* values of paired *t* tests for the steering wheel angle. The horizontal dashed line in the bottom plots indicates a *p* value of 0.01.

Table 1

Means and standard deviations (in seconds) of the reaction times and effect sizes (Cohen's d_z) between conditions.

	HAD		N-Back		Cohen's d_z	
	Static *M* (*SD*)	Dynamic *M* (*SD*)	Static *M* (*SD*)	Dynamic *M* (*SD*)	Static vs. Dynamic	HAD vs. N-Back
Steer-touch (s)	1.95 (0.41)	2.10 (0.58)	1.80 (0.40)	2.07 (0.62)	−0.633	0.264
Steer-turn (s)	2.15 (0.45)	2.29 (0.60)	1.97 (0.46)	2.25 (0.65)	−0.599	0.286
Lane change (s)	4.31 (0.49)	4.48 (0.65)	4.13 (0.54)	4.40 (0.67)	−0.515	0.347

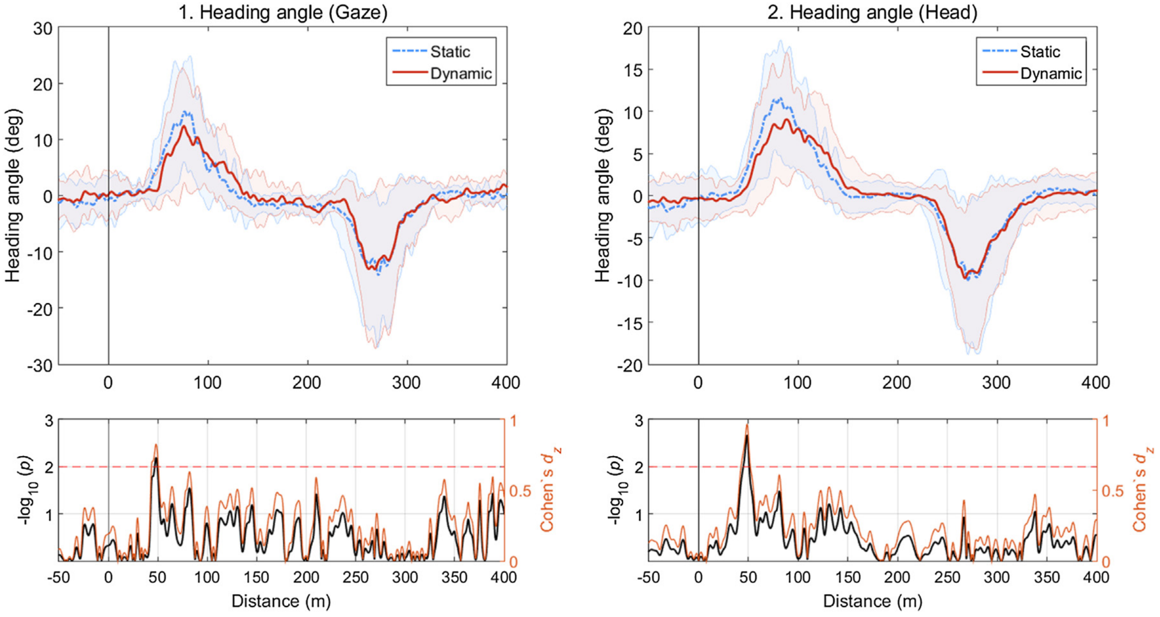

Fig. 6. Top plots: mean gaze and head heading as a function of travelled distance since the take-over request (the take-over request was presented at a distance of 0 m). The shade represents the mean ± 1 standard deviation across the mean of participants. A heading of zero implies that the participant was looking straight ahead, and a positive value indicates that the participant was looking to the left. If the lane change was made to the right, the values were inverted. Bottom plots: *p* values of the *t* test between dynamic and static patterns. In all plots, the vertical line at a distance of 0 m indicates the moment of the take-over request. The horizontal dashed line in the bottom plots indicates a *p* value of 0.01.

Fig. 7. Mean scores across participants on the usefulness and satisfaction items, ranging from −2 to +2. The error bars show the standard deviation across participants.

to be able to distinguish the direction of travel of a dynamic vibration. Second, Meng et al. presented the vibrations on the wrist and waist in order to achieve a movement towards or away from the body. They found that 'towards the body' vibrations elicited significantly faster reaction times than static patterns, but 'away from the body' cues did not. The directional cues in the present study first moved towards and then moved away from the torso's midpoint, possibly rendering the 'towards the body cue' ineffective. A third explanation for the long reaction times to dynamic vibrations could be that the number of activated motors in the first 100 ms of the dynamic pattern was half of to the static pattern. Humans are more sensitive to vibrations that stimulate a larger area, an effect also known as spatial summation (Geschneider et al., 2002). Collectively, these three points are worth considering by designers of dynamic vibrotactile warnings.

Static and dynamic vibrotactile patterns also yielded differences regarding the participants' orienting behavior (Fig. 6): the static patterns evoked a faster gaze and head reaction towards the direction of the lane change. A comparison of Figs. 5 and 6 shows that the steering movement appears to lag about 30 m (corresponding to about 1 s at 120 km/h) behind the eye and head movement, which is in line with Gold et al. (2013) who found that the gaze reaction time was about 1 s faster than the hands-on time.

Generally, before the take-over request, the gaze heading showed a large deviation around zero (Fig. 6, right). Shortly after the take-over request, the average heading angle around zero and the drop in heading angle standard deviation indicate that the participants focused on the road ahead. These results are in line with a study by Morando et al. (2016) which analyzed gaze data during naturalistic driving. These authors found a similar shift of attention towards the road ahead after a Forward Collision Warning (FCW) was produced. After attending to the road, participants gazed into the same direction as the lane change (Fig. 6). This may be a manifestation of the fact that drivers tend to look where they steer (Wann and Swapp, 2000) or it may be a consequence of the fact that drivers scanned the mirrors or adjacent lane to see whether it is free. In summary, participants' eye movement showed a pattern of re-attending to the road followed by looking into the direction of steering, with static take-over requests yielding faster reactions than dynamic ones.

4.3. Vibrotactile stimuli to complement visual and auditory displays

The reaction times of the participants seemed to be unaffected by additional mental demand, which indicates that the vibrotactile stimuli were effective as warnings. However, the correct response rates of the present experiment ranged between 74% and 94%, with large individual differences. These response rates may be insufficient for safe driving if one of the two lanes is blocked. As indicated by Schwalk et al. (2015) "under real conditions in public traffic the recognition rates should be close to 100%, especially when it comes to crucial warnings" (p. 1434). Thus, it seems that unimodal vibrotactile take-over requests, as implemented in the present experiment, are not suitable for conveying semantic information, like 'change lanes to the left'. Presumably, symbols (e.g., arrows) or voice commands may be more effective as semantic messages. Salzer et al. (2011), for example, found correct response rates of approximately 74% for a unimodal vibrotactile stimulus presented via eight motors located on the participant's thigh. The correct response rate increased to 95% when a multimodal stimulus (i.e., vibrotactile, auditory, and visual) was presented. Moreover, correct response rates of 99% were found for unimodal visual stimuli. However, in Salzer et al., the participants' task was to react to the stimulus as quickly as possible by pressing a button, after which they indicated the direction of the vibration on a touch-screen. Presenting additional visual information during a take-over scenario, which requires considerable visual attention to the road, might be less effective.

Previous studies (e.g., Lif et al., 2014; Van Erp et al., 2002 Van Erp et al., 2005) have found vibrotactile feedback with directional cues to be effective in assisting an operator in performing a task. However, in these studies the vibrotactile feedback assisted the operator in a primary task (e.g., hovering a helicopter), whereas in the present study the vibration patterns were presented during a transition of control. Possibly, the drivers in our experiment were busy with cognitively processing the traffic situation, which may have diminished their ability to recognize the patterns.

It may be possible to improve the vibration patterns so that they yield higher correct response rates. Consistent with recommendations by Jones and Sarter (2008), our motors were placed at inter-motor distances (30 or 50 mm laterally and 45 mm longitudinally) that were larger than the two-point discrimination threshold (10 mm for successive vibrations on one's back; Eskildsen et al., 1969). In our study, the dynamic pattern travelled a distance of about 210 mm. Patterns with an even larger travelling distance, like front to back, might be easier to recognize. Schwalk et al. (2015) showed that the correct response rate for a pattern that moved from the front of the seat bottom towards the top of the seat back was better recognized than patterns travelling in the opposite direction. Elsewhere, Schwalk et al. (2016) showed an increased correct response rate for static vibrations when a smaller number of motors was activated (i.e., one column of activated motors on the left instead of two). Further adjustments of the frequency, amplitude, location, and timing of the patterns might improve the correct response rates of static and dynamic warnings.

5. Conclusions and recommendations

The vibration patterns used in this study were effective as a warning to prompt drivers to quickly reclaim manual control, but participants did not reliably detect the directional cue that was embedded in the stimulus. Furthermore, static patterns yielded faster reaction times than dynamic patterns. Based on these findings, vibrotactile feedback may be a valuable supplement to auditory and visual displays, but we recommend that directional instructions in a take-over scenario should not be provided by means of a vibrotactile seat alone.

Future studies should investigate how the four dimensions of vibrotactile stimuli (i.e., frequency, amplitude, location, and timing) should be tuned to make directional cues easier to recognize. In our study, the participants received a high number of take-over requests, each with an identical road obstruction. This may have allowed them to prepare to the vibrotactile stimuli. In reality, the take-over requests will be more variable and occur with lower frequency. To investigate whether the present results generalize to real driving conditions, long driving sessions with rare safety-critical events are required.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.aap.2016.12.001.

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