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The Design of a Vibrotactile Seat for Conveying Take-Over Requests in Automated Driving

Sebastiaan M. Petermeijer[1(✉)], Paul Hornberger[1], Ioannis Ganotis[1],
Joost C.F. de Winter[2], and Klaus. J. Bengler[1]

[1] Lehrstuhl Für Ergonomie, Technische Universität München,
Boltzmannstraße 15, 85747 Garching, Germany
{petermeijer,bengler}@tum.de
[2] Department of Biomechanical Engineering, Delft University of Technology,
Mekelweg 2, 2628 CD Delft, The Netherlands
j.c.f.dewinter@tudelft.nl

Abstract. The driver of a conditionally automated car is not required to permanently monitor the outside environment, but needs to take over control whenever the automation issues a "request to intervene" (i.e., take-over request). If the driver misses the take-over request or does not respond in a timely and correct manner, a take-over could result in a safety-critical scenario. Traditionally, warnings in vehicles are conveyed by visual and auditory displays, though recently it has been argued that vibrotactile stimuli could also be a viable approach to present a take-over request to the driver. In this paper, we present a vibrotactile seat designed to convey dynamic vibration patterns to the driver. The seat incorporates 48 vibration motors (eccentric mass rotation) that can be individually controlled. One 6×4 matrix, with an average inter-motor distance of approximately 4 cm, is located in the seat back and one in the seat bottom. The DC-voltage to the motors is controlled by three Pulse Width Modulation (PWM) drivers, which in turn are controlled by an Arduino microcontroller. A study with 12 participants was conducted to investigate (1) at which vibration intensity participants find a vibratory stimulus annoying and whether this threshold changes over time, (2) how well participants are able to discriminate vibratory stimuli as a function of spatial separation, and (3) which of six dynamic vibration patterns are regarded as most satisfying. Results showed that participants' annoyance threshold reduced when they were repeatedly exposed to vibrotactile stimuli. Second, the percentage of correct responses in the two-point discrimination test increased significantly with increasing inter-stimuli distance (i.e., from 4 to 20 cm). Third, participants seemed to be more satisfied when more motors were activated simultaneously (i.e., more spatial overlap). Overall, the results suggest that participants are well able to perceive vibrotactile stimuli in the driver seat. However, the results suggest that repetitive exposure to vibrotactile stimuli may evoke annoyance, a finding that should be taken into account in future designs of vibrotactile displays. Future studies should investigate the possibility to convey complex messages via the vibration seat.

Keywords: Vibrotactile interface · Conditionally automated driving · Human factors

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1 Introduction

1.1 Conditionally Automated Driving and the Take-Over Process

Conditionally automated driving may be introduced on public roads within the next decade [1, 2]. SAE International defines “conditional automation” as automation that controls the driving task, with the expectation that the driver takes back control when a “request to intervene” is presented [3]. This means that the driver will be allowed to take his hands and feet off the steering wheel and pedals, and may engage in non-driving tasks such as reading or making a phone call.

A take-over request is presented to the driver when the automation reaches its operational limits. Examples of such situations are when the automation enters a complex traffic situation it cannot solve, when a sensor has failed, or when rules and regulations require human involvement in the driving task. After receiving a take-over request, the driver is expected to take back control in a timely and safe manner. In this process the driver performs the following four temporally overlapping actions: (1) shifting the attention towards the road, (2) cognitively processing the current traffic situation and selecting an appropriate action, (3) repositioning him/herself to take back control (i.e., feet on pedals and hands on steering wheel), and (4) performing the selected action [4–7].

Gold et al. [5] presented drivers with an auditory-visual take-over request, and found that the eyes-on-road reaction time (i.e., time to shift of attention back to the road) was on average 0.8 s. Furthermore, drivers made a steering or braking action after 2.1 or 2.9 s for lead times (i.e., TTC at the moment of the take-over request) of 5 and 7 s, respectively. Thus, shorter lead times yielded faster response times. However, shorter lead times also yielded a diminished take-over quality defined as the level of lateral and longitudinal accelerations. A well-designed interface could assist the driver not only to react faster to the take-over request, but also to improve the take-over quality.

1.2 Vibrotactile Displays in Conditionally Automated Driving

With the introduction of conditionally automated cars, the role of the driver shifts from an active controller to a passive supervisor. That is, the driver does not directly control the car for most of the driving time, resulting in human factors issues, such as a loss of situational awareness [8]. How to get a disengaged operator effectively back into the loop after a prolonged period of passive monitoring is an extensively studied topic in the field of human factors [9].

The introduction of conditionally automated driving has major consequences for the design of displays in the car. Non-driving tasks, such as reading or talking on the phone, are generally visually or auditory demanding. Accordingly, it has been argued that traditional visual and auditory displays might be ineffective [10]. Vibrotactile feedback is considered an attention-capturing feedback modality that is relatively underutilized in driving [10–13]. Accordingly, vibrations could be used to complement auditory and visual warnings in order to provide a redundant warning.

Previous studies have investigated vibrotactile feedback manual driving on the steering wheel (e.g., forward collision warning system) [14], the gas pedal (to encourage ecological driving) [15], or the driver's seat (e.g., lane departure warning system) [16]. In conditionally automated driving, the possibilities for presenting vibrotactile stimuli are limited, because the driver is not required to touch the steering wheel and pedals anymore. The seat and seatbelt are evident choices for presenting vibrotactile stimuli to a driver. Still, one cannot ignore the possibility that drivers of conditionally automated cars sometimes leave their seat, for example, to grab something from the backseat [17, 18], which could make them miss a signal.

This paper considers that vibrotactile stimuli are comprised of four basic coding dimensions, namely: (1) location, (2) amplitude, (3) timing (on/off pattern), and (4) frequency of the vibrations [19, 20]. Each of the four dimensions can be static (i.e., not changing over time) or dynamic (i.e., changing over time) [7]. Accordingly, a spatially static pattern is a vibration presented at one location, whereas a dynamic pattern changes location as a function of time. The four dimensions can be used to create distinguishable vibration patterns. For example, providing a stimulus at a certain location can provide a directional cue [10, 21]. A spatially dynamic pattern can provide the illusion of a moving stimulus (analogous to the phi-phenomenon [22]), and an increase of amplitude or a reduction of inter-stimulus interval can increase perceived urgency [23]. Location and timing are considered to be more suited for encoding information than frequency and amplitude [20, 24], and see [24] for an overview of tactile perception, vibrotactile technologies, and applications. In this paper, the term 'intensity' is used for a combination of frequency and amplitude of the vibrations.

1.3 Use Cases of a Vibrotactile Seat in Conditionally Automated Driving

In a meta-analysis, Prewett et al. [25] found that for basic reaction time tasks, vibrotactile stimuli elicit faster reaction times than visual stimuli and equally fast reaction times as auditory stimuli [16]. Schwalk et al. [26] showed that, among six spatially dynamic vibration patterns, a pattern that moved from the top of the seat back towards the front of the seat bottom was judged by participants as the most adequate one to convey a take-over request.

During the take-over process, vibrotactile displays could be used not only as a warning, but also to assist the driver in the first two phases (i.e., shift of attention and cognitive processing) of the take-over process. Meng and Spence, for example, argued that in-vehicle vibrotactile stimuli are promising as spatial warning signals [10]. Straughn, Gray, and Tan [27] showed that it is possible to direct the driver's attention towards the left or right by means of a directional vibrotactile warning. A directional take-over request (i.e., a vibration on the left or right side of the seat) could be used to indicate the direction of a potential danger zone, assisting the driver to direct his/her attention and interpret the traffic situation.

It might also be possible to communicate complex messages to the driver by means of vibrations. For example, an approaching car in the blind spot of the driver could be represented by a dynamic pattern. In this case, the location of the car is mapped to a certain vibration location in the seat (e.g., when the car approaches, the vibration moves accordingly). The mapping of a vibrotactile stimulus to a certain location has also been called "tactification" [28], which is analogous to "sonification" for auditory stimuli.

As mentioned above, vibrations can have a looming effect by increasing the frequency or decreasing the inter-pulse interval. Looming vibration patterns could support the driver in making a fast and accurate decision.

1.4 Aim of This Study

This paper presents the design of a vibrotactile display that presents spatially and temporally dynamic vibration patterns in the driver's seat. Moreover, this paper presents a small psychophysics study to evaluate the first prototype of the seat.

2 Design of the Vibrotactile Seat

2.1 Requirements of the Vibrotactile Seat

In order to build a vibrotactile seat that can provide spatially and temporally dynamic vibrotactile stimuli, the following functional requirements need to be met:

- The matrix of the motors should cover most of the contact area between seat and driver.
- The timing and intensity should be independently controllable for each vibration motor.

Additionally, for the purpose of evaluating the display:

- The seat should be compatible with different simulators and test vehicles, and therefore the display needs to be able to communicate with different software environments.
- The vibration motors should be easy to replace.
- The locations of the vibration motors need to be reconfigurable.

2.2 Signal Architecture

The vibrotactile seat is developed for use in simulators and test vehicles. The seat consists of three main parts, namely:

- vibration motors, located in the seat bottom and seat back.
- a control unit that controls the intensity and timing of the individual motors.
- software that determines which vibration pattern has to be present to driver and that communicates this information to the control unit. For example, the software may receive information about upcoming road works and determines that the driver should resume control. The software then communicates the take-over request to the control unit, which activates the motors with the appropriate timing and intensity.

2.3 Hardware

Motors. Eccentric rotating mass (ERM) motors produce vibrations by rotating a mass outside a rotation axis. The rotational speed of the motor is controlled by the voltage to the motor. The rotational speed determines the frequency and amplitude of the vibration, which are therefore not independently controllable. The motors that were used in this prototype were Precision Microdrives™ (type: Pico Vibe, model: 307-100) [29].

Motor Matrix. A series of Velcro strips were used to create a mat, which could be placed in the driver's seat (Fig. 1a). The vibration motors were placed between the Velcro strips so that the motors formed two 6 × 4 matrices (i.e., 48 motors in total). One matrix was located in the seat bottom and the other in the seat back (Fig. 1b). Accordingly, the configuration of motors can be changed if needed, and the seat mat is interchangeable between simulators or real vehicles.

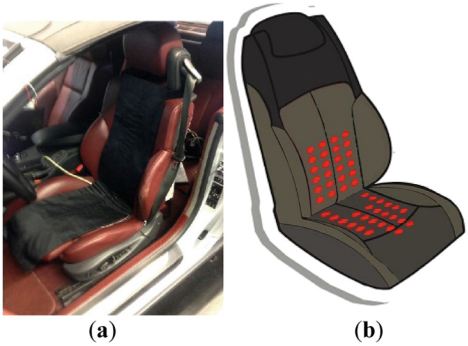


Fig. 1. (a) Vibration mat in the driver's seat of a simulator. (b) Motor configuration in the seat mat, consisting of 6 × 4 matrices in the seat bottom and back

Control Unit. The motors are controlled by three Pulse Width Modulation (PWM)-drivers (Texas Instruments, TLC5940NT) [30], which are connected to an Arduino microcontroller (Arduino Mega 2560) [31]. The PWMs control the motors by a series of on/off pulses, which vary the duty cycle (i.e., percentage of time that the signal is on per cycle). The pulses (de)activate the transistor and consequently control the average DC voltage to the vibration motor. The Arduino in turn can be connected to the software environment through a USB or Ethernet connection (Fig. 2a).

Electrical Circuit. The DC-voltage to the motors is controlled by a PWM signal to a transistor (Fig. 2b). The resistor (R1, 100 Ohm) is connected to the base of a PNP transistor (Q1, P2N2907A). The emitter and collector of the transistor are connected to the ground and a motor (M), respectively. A diode (D1, 1N4001) is connected in parallel with the motor to prevent inductive motor spikes flowing back to the transistor. Power to the Arduino, PWM drivers, and motors is provided by an AC/DC converter (Traco-Power, TXL 100-3.3S), which converts 230 V AC from the power network to 3.3 V DC.

(a) (b)

Fig. 2. (a) Functional diagram of the vibrotactile seat. Orange lines represent digital connections, whereas grey lines are power connections. (b) Electrical circuit of a single vibration motor that is PWM-controlled

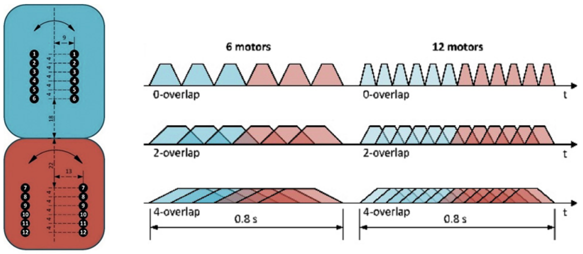
2.4 Participants

Twelve participants, seven men and five women, between 19 and 31 years old ($M = 24.2$, $SD = 3.1$) took part in the experiment. All participants were students or employees of the Technical University of Munich and had a valid driver's license.

2.5 Apparatus

During the experiment, the participants were sitting in the driver's seat of a fixed-base driving simulator. The simulator featured a driver's seat, steering wheel, and three pedals (gas, brake, and clutch). Three 4 K High Definition screens were placed in front of the driver offering him a viewing angle of approximately 160°. The simulator was not running during the experiment, but used solely to provide a realistic driving position of the participant.

For this study, a prototype of the presented vibrotactile seat above was used (for a study with the presented seat see [32]). This prototype version featured 12 vibration motors. The motors were placed in two straight columns of 6 motors (one column of 6



(a) (b)

Fig. 3. (a) Dimensions of the 12 × 1 motor matrix on one side of the seat. The seat mat would be turned over to position the motors on the other side for the second trial. The blue area represents the seat back and the red area represents the seat bottom. (b) Activation sequence of the six vibration patterns that were investigated. Three vibration patterns activated six (*left*) or twelve (*right*) motors in sequence, with an overlap of 0, 2, or 4 motors. Blue: motors located in the seat back. Red: motors located in the seat bottom

motors in the seat back, one column of 6 motors in the seat bottom), with a 4 cm intermotor distance (Fig. 3a). The columns were placed on one side of the seat mat. By turning over the mat, the columns were located on either the left or right side of the seat.

2.6 Procedure

After entering the lab, participants were presented with a consent form, which explained the goal and procedures of the experiment. The study consisted of three parts. The first part was aimed to determine the appropriate vibration intensity for the different motor positions in the seat. The second part investigated the spatial discrimination ability of the participant in the seat back and bottom. The third part concerned the apparent motion of spatially dynamic patterns. Participants were informed that they could leave the experiment at any moment.

Part 1. The PWM duty cycle, and with that the vibration intensity, of a single motor was increased linearly from 0% to 100% over 15 s. The participants were asked to press a button on the steering wheel when they perceived the vibration to be annoying or irritating. When the participant pressed the button or the maximum intensity was reached the vibration would stop.

After a short pause (random between 3 and 6 s), the process was repeated using a different motor. All twelve motors were activated once and the activation order of motors was randomized. Once the participant had received all twelve vibrations, the procedure was repeated but the intensity was inversed. That is, the duty cycle PWM would start at 100% and decrease to 0%. The participants were asked to press the button when the vibration no longer caused any discomfort or irritation.

Part 2. The spatial resolution was investigated using a two-point discrimination test. A pair of motors, both located in either the seat bottom or seat back, was activated simultaneously. The participant was asked to press the button if he/she felt the vibration at two distinct locations. Six motors result in 15 (i.e., [6 × 5]/2) possible motor pairs, which were presented both in the seat back and in the seat bottom (thus 30 pairs in total). All motor pairs where activated once in a random order. The motor pairs were activated at 25% of the duty cycle for 2 s and with an interval of 3 s.

Part 3. Six dynamic vibration patterns were presented to the participant. The patterns differed in the amount of activated motors and in the amount of simultaneously activated motors. A pattern activated either 6 (motor: 1, 3, 5, 7, 9, and 11) or 12 motors (see Fig. 3b) and activated none, two, or four motors simultaneously. All six patterns moved down from the top of the seat back, and forward in the seat bottom. Each vibration pattern lasted 0.8 s.

The intensity of one motor was modulated to increase in a short amount of time, then was constant, and decreased swiftly. That is, the shape of the stimulus was trapezoidal. The three phases (i.e., increase, constant, and decrease) each represented one third of a single vibration time, see Fig. 3b. For an increasing overlap, the stimulated area on the participant increased as well. It has been shown that humans are more sensitive for larger stimulus areas (i.e., spatial summation [33]). Therefore, the maximum intensity of the vibration was decreased for an increasing overlap. That is, for the 0-, 2-, and 4-overlap the maximum intensity of a single motor was 35, 25, and 20% respectively (illustrated by the height of the trapezia in Fig. 3b). After each vibration pattern the participant was asked to fill out the satisfaction scale of a questionnaire on the acceptance of automotive technology [34]. The scale contained four items on a five-point Likert-scale, ranging from −2 to +2 (1. Unpleasant – Pleasant, 2. Annoying – Nice, 3. Likeable – Irritating, 4. Desirable – Undesirable).

Once a participant had completed the three parts of the experiment, he/she was asked to leave the room. The seat mat was turned over and the trial was repeated with the motors on the other side of the seat. The side (left/right) and order of the three parts were counterbalanced for trials 1 and 2. A single trial took approximately 8 min to complete.

3 Results

The results did not show any significant differences between the left and right side of the seat. Therefore, these results has been averaged, and are not reported separately.

Part I. Figure 4 shows the mean and standard deviations of the vibration intensity (percentage of the PWM-duty cycles) that annoyed the participants. For both the ascending and descending method, the annoyance threshold of second trial was lower than the first (t(11) = 1.96, p = 0.076 and t(11) = 2.21, p = 0.049, respectively). There was no statistically significant difference between seat bottom and seat back.

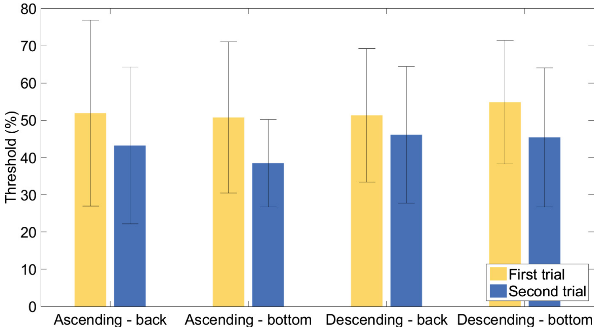


Fig. 4. Means ± standard deviations (N = 12) of the % PWM duty cycles values that annoyed the participants. Ascending = measured when the duty cycle increased; Descending = measured when the duty cycle decreased

Part II. Figure 5 shows the results of the two-point discrimination test. The percentage of correct perceptions (i.e., the participant perceived two separate stimuli) in the seat back increased with inter-motor distance. A two-way ANOVA indicated a significant difference between distances (F(4, 44) = 30.61, $p < 0.01$). Post-hoc analysis revealed that all pairs, except 4/8, 12/16, 16/20 cm, were significantly different ($p < 0.05$, after Bonferroni correction).

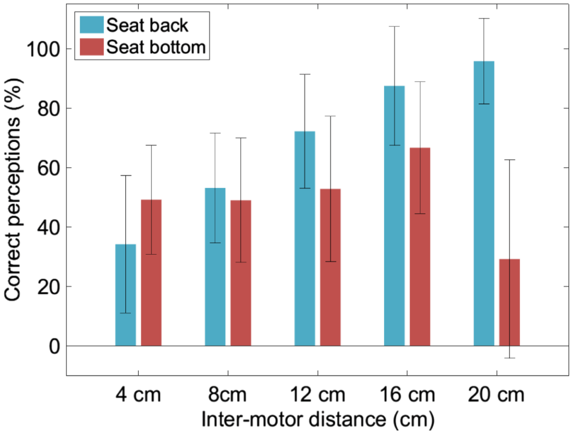


Fig. 5. The mean ± standard deviations (N = 12) of the correct perceptions percentage for two point

The results for the seat back are less clear. The percentages for the 4, 8, 12, 16 cm inter-motor distances are similar, whereas for 20 cm the percentage is considerably lower. A two-way ANOVA indicated there was a significant difference between the groups F(4,44) = 4.07, p = 0.007). The post-hoc analysis showed that the difference between 16 and 20 cm was statistically significant ($p < 0.05$ after Bonferroni correction).

Part III. Table 1 shows the mean and standard deviation of the satisfaction scores for the 6 dynamic patterns that were presented to the participants. However, there seems to be a trend that the patterns with more overlap received higher satisfaction ratings. A repeated measures ANOVA (F(5,55) = 2.04, p = 0.087) showed that there were no significant differences between the six patterns.

Table 1. Means and standard deviations (N = 12) of the satisfaction score. Scores were on a 5 point-Likert scale with a range from −2 to +2 as in [34]

	0-overlap	2-overlap	4-overlap
6 motors	0.177 (0.989)	0.542 (0.636)	0.833 (0.611)
12 motors	0.354 (0.732)	0.604 (0.832)	0.615 (0.418)

4 Discussion

In this paper, we presented the design of a tactile display that is able to present vibrotactile stimuli with dynamic location, timing, and intensity in the driver's seat. The seat was developed to investigate the potential to use vibrotactile stimuli in conditionally automated driving. The seat can communicate via standard Ethernet and USB-protocols, making it compatible with various software environments. The Arduino software enables the control of the individual motors and the seat mat allows for easy modifications of the motor configuration.

The average annoyance threshold across participants was approximately at a 50% duty-cycle, which, according to the motor specifications, resulted in a vibration frequency and amplitude of approximately 100 Hz and 1.3 g, respectively. During the first part of the experiment, single motors were activated. However, to present dynamic patterns, multiple motors will have to be activated simultaneously. Since larger stimulus areas are perceived more intensely [33], designers of vibrotactile displays should adjust the vibration intensity accordingly. Moreover, results show large variance in the annoyance threshold, indicating large differences between participants, despite the fact that the participant group was homogeneous. It is expected that variance will be even higher in a group that is more representative of the general driving population. If a vibrotactile display would be implemented in future vehicles, the intensity may have to be adjustable in order to avoid annoyance or irritation.

The annoyance thresholds seemed to be lower for the second trial as compared to the first. A trial took approximately 8 min, during which participants received many vibrations in quick succession. Thus, vibrations become annoying if people are frequently exposed to them for a prolonged time. Some participants commented after the experiment that they started to dislike the vibrations towards the end of the experiment.

The results in Fig. 5 showed that the percentage of correct perceptions increases as a function of the inter-stimulus location. Ji et al. [35] found similar results and additionally reported that more intense vibrations yielded higher percentages of correct perceptions. When multiple vibrotactile stimuli are presented simultaneously, the distance should be large enough to distinguish separate locations in order to avoid “tactile clutter” [36]. Remarkably, the perception percentage is low for a distance of 20 cm in the seat bottom. This is probably because there were only two motors 20 cm apart in the seat bottom and back respectively. Therefore, the inter-motor distance of 20 cm was presented 4 (out of 60) times to each participant. Alternatively, the result could perhaps be explained by a phenomenon called “apparent location” [20]. This phenomenon occurs when two stimuli are simultaneously presented at different locations, but are perceived as one vibration in one location. Future experiments should investigate if this could potentially be an issue in the design of vibrotactile displays.

The results in Table 1 seemed to indicate that dynamic patterns with more motors simultaneously active (i.e., larger overlap) were rated as more satisfying. However, there were no statistically significant differences between the patterns. A more thorough investigation into dimensions like overlap and waveform should be performed to explore if these can mitigate annoyance.

Note that during the experiment the participants did not actually drive the simulator nor had to monitor a conditionally automated system. Consequently, they could focus all their attention to detecting the vibrotactile stimuli. Future research should investigate how the effectiveness of vibrotactile displays when the driver is engaged in other tasks, like reading a book or playing with a smartphone.

Tactile warnings might be more effective than visual or auditory stimuli, if the driver is engaged in other tasks. Moreover, the vibrotactile seat could perhaps be used to convey complex information, by directional cues or "tactification" of the stimulus (i.e., the stimulus location is mapped to a physical location in the world). The current design of the seat allows further investigation of such dynamic vibration patterns.

Research is needed on the implementation of multimodal displays in a conditionally automated car. Future experiments should investigate how to complement visual and auditory displays with vibrotactile stimuli, aiming to effectively and safely assisting the driver in the take-over process. Nevertheless, the results of this experiment showed that annoyance could be an issue when vibrations are presented to driver. Interface designers should aim to mitigate annoyance by, for example, making the intensity levels adjustable.

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