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To Inform or to Instruct? An Evaluation of Meaningful Vibrotactile Patterns to Support Automated Vehicle Takeover Performance

Gaojian Huang, *Member, IEEE*, and Brandon J. Pitts, *Member, IEEE*

***Abstract*—Automated vehicles may occasionally require drivers to take over. The complexity of the takeover process warrants the design of effective human–machine interfaces that assist drivers in regaining control, especially when the visual and auditory sensory modalities are occupied. Vibrotactile displays, which can represent information about the status, direction, and position of driving environment elements, have been suggested as one promising approach, but their effectiveness to aid in takeover transitions has not been fully evaluated. This study investigated the effects of meaningful tactile signal patterns, used as takeover requests, on automated vehicle takeover performance. Forty participants rode in a simulated SAE Level 3 automated vehicle and completed a series of takeover tasks with two tactile pattern formats, i.e., informative (which displayed status information of surrounding vehicles) and instructional (that displayed the appropriate takeover maneuver), and three in-vehicle locations (seat back, seat pan, and a seat back and seat pan combination). Takeover response options included lane changes only or brake applications followed by changing lanes, depending on the locations of surrounding vehicles. Results indicate that only meaningful instructional tactile signals, in either the seat back or seat pan, were associated with worse takeover response time and maximum resulting acceleration compared to signals without any patterns. Additionally, tactile information presented on the seat back was perceived as the most useful and satisfying. Findings from this study can inform the development of next-generation human–machine interfaces that utilize tactile stimulation in a wide range of environments with automation.**

***Index Terms*—Automated driving, haptics, human–machine interfaces, tactile displays, takeover.**

I. Introduction

MANY ongoing global efforts exist to develop autonomous vehicles. Between 2021 and 2030, the market demand for these vehicles is projected to increase from approximately 6000 to four million units [1]. However, the majority of these automobiles will be semi-autonomous [2], [3], [4], e.g., SAE Level 3 [5], meaning that human drivers will still be needed to intervene or takeover control of the vehicle in particularly difficult driving conditions (e.g., road construction and poor visibility) [6]. The process to take over from an automated vehicle consists of both a signal response and a post-takeover phase [7], which involves perceiving and processing a takeover request (TOR), regaining environment and situation awareness, physically moving hands and feet to vehicle controls, mentally planning maneuvers, and executing the plan (Fig. 1).

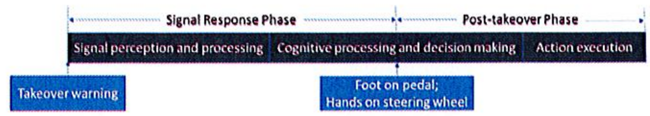

Fig. 1. Takeover process model ([7] adapted from [8] and [9]).

This short (estimated to take, on average, 2.7 s for the signal response phase [10]), but critical, process can become especially complex when the driving environment contains many static and dynamic elements that need to be processed by the driver. For example, in the presence of high traffic, not only do drivers need to know the lane position and speed of their own vehicle but they also need to comprehend characteristics of the external environment, such as the position and status of surrounding vehicles, road geometry, speed limits, and other road signs. In addition, if drivers are engaged in non-driving-related task (NDRTs), such as texting, watching a movie, reading a book, or composing emails [11], the takeover process can become even more difficult to execute. This is because, according to multiple resource theory [12], drivers' ability to perceive TORs presented in visual or auditory form can be inhibited if the driver is already attending to visual and/or auditory elements in the driving environment and engaging in NDRTs that also utilize the visual and auditory modalities. In these cases, a display that conveys critical information that must be acknowledged for a successful takeover in a different and more available modality, i.e., the tactile channel, may best assist drivers during such a complex takeover process.

Several experiments have demonstrated various benefits of employing tactile cueing within human–machine systems,

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Purdue University Institutional Review Board, Application No. 1802020214, and performed in line with the IRB Protocol.

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which include faster processing speeds compared to visual and auditory cues, improved situation awareness, and increased accuracy of spatial information interpretation (e.g., [13], [14], and [15]). This is, in part, due to the ability of tactile cues to convey information about various parameters, e.g., status (such as urgency) (e.g., [18] and [20]), direction (e.g., [21]), and position/location (e.g., [22]). For example, Huang and Pitts [7] evaluated single visual (V), auditory (A), and tactile (T), bimodal VA, VT, and AT, and trimodal VAT signals, as SAE Level 3 automated vehicle takeover alerts and found signals containing a tactile component to be associated with faster response times compared to those that did not. With respect to situation awareness, Pielot et al. [19] used tactile cueing to represent to players, in a 3-D multiplayer virtual game, the location of their teammates (i.e., the distance between players) and found participants with tactile cueing to have a higher level of situation awareness compared to those without tactile cues. Similarly, in aviation, Prinet et al. [13] investigated the effects of tactile spatial cueing on notifying pilots of an intruding aircraft (i.e., its location) along their flight path and found the detection rate to be 100%. Given the many advantages of tactile cueing, researchers have altered the characteristics of tactile stimulation to create meaningful tactile patterns, which are encoded messages that represent meaningful and complex concepts and information [15], [20], [21].

In driving, the use of meaningful tactile signals has been explored primarily in either an informative or instructional format. For informative signals, tactile displays have been used to represent information in the driving environment and communicate that information to drivers, such as the location and speed of surrounding vehicles (e.g., [25]) or potential collisions with lead vehicles (e.g., [26]). In contrast, for instructional signals, tactile interfaces have been used to command a particular action, such as instructing drivers to slow down or change to a certain lane to avoid danger (e.g., [24]).

Given the complexity and criticality of the components of the automated vehicle takeover process, recent driving studies have begun to exploit the benefits of meaningful tactile signals by applying them as TORs. In general, these studies find both informative and instructional tactile signals to be associated with better takeover performance, e.g., shorter response times to TORs compared to tactile signals used only for warning purposes [24] or vehicles without a tactile display at all [22]. For example, Cohen-Lazry et al. [24] compared the effects of meaningful (both informative and instructional) and generic (used only for warning purposes) tactile signals in the signal response phase of the automated vehicle takeover process and reported that instructional signals had shorter response times to TORs compared to informative and generic signals. However, this study did not compare post-takeover driving performance metrics to understand how well participants controlled the vehicle under the different types of tactile signals. In addition, their takeover scenarios only required participants to drive into the left or right adjacent lanes on a two-lane highway. It did not involve a decision-making step, in terms of vehicle maneuvering action selection, since there was only one available response option at a time. In contrast, Telpaz et al. [22] compared takeover performance during the signal response and post-takeover phases both with and without tactile feedback (employed only in the informative format). Here, after regaining control of the vehicle, drivers needed to move into the lane that presented fewer collision risks when two lane-change options were available. Their findings show that drivers had faster reaction times and better vehicle speed control with the informative tactile interface than without any feedback. However, this study did not compare the effects of informative and instructional formats nor how quickly drivers made maneuvering decisions.

Two research gaps not addressed by the limited number of studies that have examined meaningful tactile signals as TORs relate to the effects of informative and instructional tactile signals on 1) decision-making performance (such as information processing time), when drivers have multiple maneuvering options (e.g., lane-change or brake), and 2) takeover performance (such as response time and post-takeover driving quality) throughout the entire takeover process.

The location of in-vehicle tactile stimulation (particularly seat back versus seat pan) can also impact takeover performance, as partially explained by the stimulus-response compatibility phenomenon [25]. This review suggests that if tactile stimuli presented to different parts of the body do not map spatially onto or directly correlate with information in the driving environment, the processing speed of that stimuli may be negatively impacted. In prior automated driving studies, meaningful tactile interfaces have been embedded into both the seat pan and seat back of vehicles (e.g., [26] and [27]). Wan and Wu [27] compared six tactile patterns that were presented on either the seat pan or the seat back, or a mix of both locations, and found that sequential tactile signals, i.e., those first presented on the seat back then on the seat pan, had shorter takeover response times compared to other static patterns. However, the tactile signals in their study did not have an associated meaning other than warning drivers of the need to take over. Petermeijer et al. [26], on the other hand, compared the effects of different instructional tactile patterns in both the seat back and the seat pan as TORs, but the influence of location was not analyzed in their study. What remains unknown is what (combinations of) locations of tactile information would best support drivers' takeover performance in terms of transition response time and quality.

This study took steps to address the aforementioned gaps in the literature by using vibrotactile signals to create informative and instructional displays embedded into the seat pan and seat back of a simulated vehicle to support drivers in complex takeover situations. To this end, we developed an experiment wherein participants rode in an SAE Level 3 vehicle and completed a series of takeover tasks using both types of tactile displays and three in-vehicle locations (i.e., seat back, seat pan, and seat back and seat pan baseline). We expected that both informative and instructional tactile interfaces would result in better takeover performance in terms of response and information processing times as well as improved takeover quality compared to tactile signals without patterns. Similarly, tactile signals presented in the seat back were hypothesized to

Fig. 2. Experiment setup—the video (non-driving-related task) was located in the bottom corner of the main screen.

Fig. 3. Distribution of tactors in the seat back and seat pan.

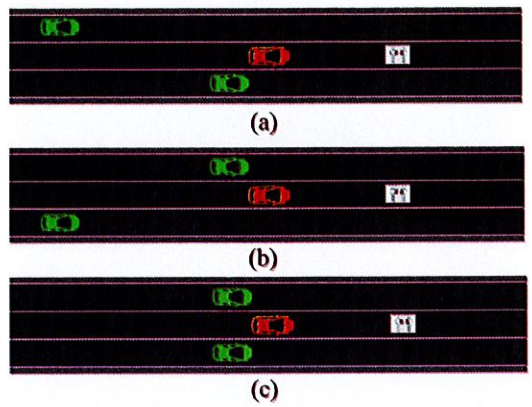


Fig. 4. Three possible takeover actions for the subject vehicle (red) based on the location of surrounding vehicles (green) and the obstacle ahead (grey icon). (a) Drive into the left lane. (b) Drive into the right lane. (c) Slow down, then move into a lane.

be associated with better takeover performance compared to the seat pan [22], [24], [26], [27].

II. Methods

A. Participants

In total, 40 participants (24 males and 16 females) were recruited to take part in this study. All participants were college students, with an average age of 23.1 years (range: 19–30). The self-reported number of years of driving experience was 5.7 years (range: 1–13). Participants were required to possess a valid U.S. driver's license and have a normal or corrected-to-normal vision, no known disorders or injuries that affect tactile sensitivity, and no known susceptibilities to motion sickness. The compensation rate was $40/h. This study was approved by the Purdue University Institutional Review Board (IRB Protocol #: 1802020214).

B. Apparatus/Stimulus

1) Driving Simulator: A medium-fidelity driving simulator, miniSim (uiowa.edu), developed by the National Advanced Driving Simulator, Coralville, IA, USA, was used to conduct this study. The simulator has three 48-in screens that display the main driving environment and one 18.5-in screen that was used as the dashboard to present information about the subject vehicle, such as speed. Other simulator accessories include a steering wheel, foot pedals, a control panel, and an adjustable seat. All data were collected at 60 Hz. The experiment setup is presented in Fig. 2.

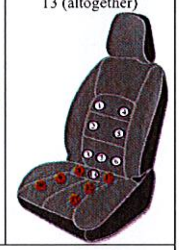
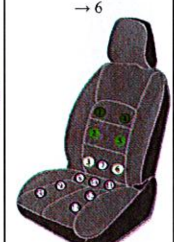
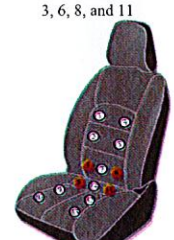
2) Vibrotactile Apparatus and Signal Patterns: A total of 14 C-2 tactors (1" × 0.5" × 0.25" piezo buzzers developed by Engineering Acoustics, Inc., Casselberry, FL, USA) were used in this study. Seven tactors were placed in the seat pan and the other seven tactors were located on the seat back. The vibration frequency of each tactor was set to 250 Hz. The arrangement of tactors is presented in Fig. 3. The minimum distance between each tactor was 3.5 in (maximum distance = 5.5 in) [28], [29].

Based on the driving scenarios, the tactile display represented the following three different types of actions that drivers needed to make.

1) Drive into the left lane (to avoid a possible collision with the lead vehicle and with the vehicle located in the right blind spot [see Fig. 4(a)].
2) Drive into the right lane (to avoid a possible collision with the lead vehicle and with the vehicle located in the left blind spot [see Fig. 4(b)].
3) Slow down, then move into a lane (to avoid a possible collision with the lead vehicle and with vehicles in both the left and right blind spots [see Fig. 4(c)].

As shown in Table I, for the informative signal format, the vibration pattern was used to represent the status of surrounding vehicles. For example, if a car was approaching the subject vehicle behind from the left adjacent lane and the subject vehicle needed to move into the right adjacent lane, then the tactile pattern simulated movement by vibrating, in a serial fashion, tactor locations 6 → 5 → 4 on the seat back, or 11 → 12 → 13 on the seat pan. If two vehicles in both left and right adjacent lanes were approaching at the same time, then all six tactors vibrated simultaneously (i.e., tactor numbers 1–6 for the seat back or tactor numbers 8–13 for the seat pan). For the instructional signal format, on the other hand, to instruct the driver to avoid an approaching vehicle in the left blind spot, the sequential pattern 6 → 7 → 3 was played on the seat back, or 11 → 14 → 8 was presented on the seat pan. To communicate that vehicles were behind in both the left and right blind spots, the signal pattern was serially 1 → 2 → 3 and 4 → 5 → 6 (two arrays of patterns vibrated at the same time) on the seat back, or 10 → 9 → 8 and 13 → 12 → 11 (two arrays of patterns vibrated at the same time) in the seat pan. Also, tactor numbers 3, 6, 8,

TABLE I
MEANINGFUL (INFORMATIVE AND INSTRUCTIONAL) TACTILE PATTERNS FOR SEAT BACK AND SEAT PAN LOCATIONS (VIBRATION SEQUENCE IS PRESENTED AS "A → B → C," INDICATING THAT TACTOR A VIBRATED FIRST, FOLLOWED BY TACTOR B AND THEN TACTOR C)

0 - 645 ms 0 - 215 ms	216 - 430 ms	431 - 645 ms
Informative		
Lane change - move to left (seat back): 3 → 2 → 1 	Lane change - move to right (seat back): 6 → 5 → 4 	Brake (seat back): 1, 2, 3, 4, 5, and 6 (altogether) 
Lane change - move to left (seat pan): 8 → 9 → 10 	Lane change - move to right (seat pan): 11 → 12 → 13 	Brake (seat pan): 8, 9, 10, 11, 12, and 13 (altogether) 
Instructional		
Lane change - move to left (seat back): 3 → 7 → 6 	Lane change - move to right (seat back): 6 → 7 → 3 	Brake (seat back): 1 → 2 → 3 and 4 → 5 → 6 
Lane change - move to left (seat pan): 8 → 14 → 11 	Lane change - move to right (seat pan): 11 → 14 → 8 	Brake (seat pan): 10 → 9 → 8 and 13 → 12 → 11 
Baseline: 3, 6, 8, and 11 		

and 11 vibrated altogether on both the seat back and pan as the baseline TOR, which had no spatial meanings. In this baseline case, drivers needed to devise an appropriate maneuvering plan based on cues in the driving environment without any guidance from the system.

All signal patterns lasted for a duration of 645 ms and vibrated at a frequency of 250 Hz [30]. When three tactors vibrated in a sequential pattern, the duration of each individual tactor was 215 ms for meaningful patterns (which, in total, adds up to 645 ms). But, for the baseline TOR stimulus, all tactors vibrated for 645 ms. These locations, timing, and arrangements of signal patterns were developed based on previous studies (e.g., [23], [28], and [30]) as well as in-lab pilot studies that evaluated the effectiveness of each signal pattern.

C. Driving Scenario

Participants rode in an SAE Level 3 automated vehicle in the center of a three-lane highway at a speed of 60 mph. A leading vehicle constantly drove 7 s ahead of the subject vehicle [31], [32]. Also, two vehicles maintained a steady distance of 176 ft behind the subject vehicle in both the left and right adjacent lanes. A construction zone could appear ahead of the subject vehicle (which was in the middle lane) at any point during the drive. When this happened, the subject vehicle would issue a TOR in one of the seven tactile formats, indicating the need to take over. At the same time, the lead vehicle would immediately stop in front of the construction zone, leaving a 7 s lead time for drivers to make action plans and complete the takeover (i.e., either switch into another lane immediately or brake, then change into another lane).

To execute the takeover, participants first needed to tap on the brake to deactivate the automation, then move their hands to the steering wheel and their feet to the brake/gas pedal. After resuming manual driving, two types of responses were available: change lanes (drive into either the left lane or right lane) or apply the brakes (slow down to allow the two trailing vehicles to pass the subject vehicle first) and then change lanes, based on the locations of the two vehicles behind [see Fig. 4(a)–(c)]. These two response types were intended to represent real-world driving when an obstacle is present ahead, and drivers were instructed to either move into adjacent lanes or apply brakes first (then switch to another lane) to avoid a collision (a decision that needed to be made based on the distances between the subject vehicle and surrounding vehicles). For the lane-change response, participants needed to directly switch to the lane with the most available space after processing the tactile notification as well as the information in the driving environment. During the entire manual driving period, they were expected to maintain good driving performance (i.e., 60 mph and remain centered in the lane) as they would in manual driving. After passing the construction zone, all drivers needed to immediately move back to the middle lane and reactivate the automation by pressing a button on the steering wheel. For the brake response scenario, participants needed to decrease their speed (to avoid colliding with the lead vehicle), wait until the trailing vehicles in both adjacent lanes passed their vehicle, and then move into either

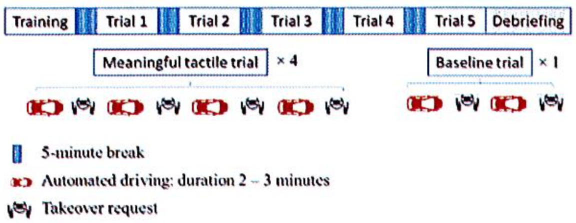


Fig. 5. Diagram of experiment blocks.

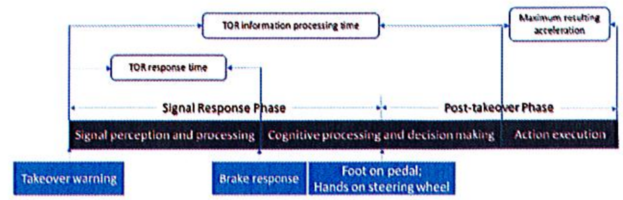


Fig. 6. Illustration of time and driving-related dependent measures in a takeover process model.

the left or right lane (depending on space availability). Similar to the lane-change response, after changing lanes, drivers were asked to maintain good driving until they passed the construction zone and moved back to their original lane. Then, they needed to reactivate the automation.

D. Procedure

Participants first signed the consent form, acknowledging their agreement to participate in the study. Next, a pre-experiment questionnaire was administered to collect demographic information. Then, participants performed a 15-min training session. During the first part of this training, tactile patterns were presented to participants in the absence of a driving session to teach them the meanings of each pattern. Half of the participants were only exposed to informative signals and the other half experienced only instructional signals (a between-subject study design). After successfully interpreting all tactile patterns, they then participated in the second part of the training, where they practiced takeover procedures and manually drove the vehicle with all takeover tactile patterns and locations.

For the actual experiment (see Fig. 5), 18 takeover trials were completed, with an interval of 2–3 min between each takeover event [31], [33]. Correspondingly, 18 TORs, that is, 16 meaningful tactile signals and 2 baseline signals, were presented. A total of 8 out of the 16 meaningful tactile signals were presented in the seat back and the remaining 8 were presented in the seat pan. Additionally, half of the takeover trials required immediate lane changes (i.e., lane-change response), while the other half needed a brake response first (i.e., brake response) and then a lane change. To prevent fatigue due to the number of takeover tasks, the 18 takeover trials were divided into five blocks, where the 16 meaningful tactile patterns were in four blocks, and the two baseline patterns were in one block. A 5-min break was given between each of the two blocks, during which time participants also completed a short questionnaire about their subjective perception of the signal patterns and their locations, which was used to assess the "usefulness" and "satisfaction" of the signals. All signal locations and response types were randomized, and the block sequence and signal information types were counterbalanced across participants. To divert participants' attention away from the road (which prevented participants from preparing for the takeover task in advance), a TED talk video was played during each block, which utilized the visual and auditory modalities, but would not interfere with the tactile channel. The experiment lasted approximately 80 min. After the experiment, participants completed a 10 min. debriefing session where they reported their experiences in the study.

E. Dependent Measures

Takeover performance was measured using both time- and driving-related metrics (see Fig. 6). Time-related metrics included TOR response time and information processing time. TOR response time (in seconds) was measured between the onset of the TOR and the initial contact with the brake pedal [34]. The TOR information processing time (in seconds) was calculated as the time between the presentation of the TOR and the initiation of a lane change (absolute deviation from the lane center more than 6 ft, when the center of the subject vehicle is above the lane marker between the two lanes [29], [35]). Response time indicated how quickly a driver reacted to the tactile TOR, whereas information processing time measured how quickly a person processes the tactile TOR and devises a maneuvering plan.

Maximum resulting acceleration (in m/s^2) was the only driving-related metric used in this study, which is calculated as the square root of the sum of squared maximum longitudinal and lateral accelerations. This variable encompasses a range of longitudinal and lateral vehicle handling-related metrics (e.g., maximum longitudinal/lateral accelerations/positions, mean speed of the vehicle, velocity, and angle of the steering wheel) and has been used in related literature as an indicator of takeover performance (e.g., comfort and quality) (e.g., [33] and [36]). Here, a smaller value indicates better vehicle control and takeover quality.

Additionally, to assess drivers' perceived usefulness of and satisfaction with the tactile patterns and locations, which may provide additional insights on the design of tactile displays, as well as to examine potential relationships between subjective signal preferences and takeover performance, a technology acceptance questionnaire was administered [31], [37]. It consists of nine items using a 5-point Likert scale ranging from −2 to 2. The usefulness score was calculated as the average score of items 1, 3, 5, 7, and 9, whereas the satisfaction score was computed by averaging items 2, 4, 6, and 8. See Table II for a summary.

F. Data Analysis

This study employed a 2 (information type: informative and instructional) × 2 (response type: lane change and brake) × 3 (location: seat back, seat pan, and seat back/seat pan baseline) full factorial design. A linear mixed-effects model was used to compare the effects of information type (a between-subject factor) and response type and signal location (both within-subject factors) on the dependent measures. *Post hoc* comparisons with

TABLE II
AVERAGE USEFULNESS AND SATISFACTION SCORES FOR EACH TOR PATTERN LOCATION

Negative (− 2)	Positive (+2)	Seat back	Seat pan	Baseline
Useless	Useful	1.35	0.88	0.73
Bad	Good	1.13	0.35	0.60
Superfluous	Effective	1.10	0.65	0.63
Worthless	Assisting	1.25	0.98	0.65
Sleep-inducing	Raising Alertness	1.23	1.18	1.10
Overall usefulness score		1.21	0.81	0.74
Unpleasant	Pleasant	0.80	0.18	0.53
Annoying	Nice	0.63	0.18	0.63
Irritating	Likeable	0.60	0.05	0.40
Undesirable	Desirable	0.90	0.10	0.53
Overall satisfaction score		0.73	0.13	0.52

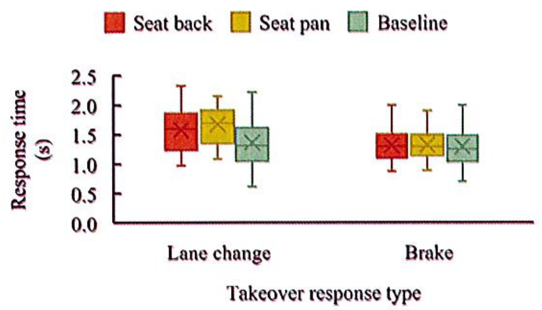


Fig. 7. Response time as a function of TOR location and response type.

Bonferroni corrections were performed to compare means between factor levels. Greenhouse–Geisser estimates were used to correct the degrees of freedom for sphericity tests that were violated. The significance level was set at $p < 0.05$. Partial eta squared (η_p^2) was presented as the effect size.

III. RESULTS

A. Response Time

There was a significant main effect of location ($F(2,\ 76) = 13.418,\ p < .001, \eta_p^2 = 0.261$) and response type ($F(1,\ 38) = 41.047,\ p < 0.001, \eta_p^2 = 0.519$) on response time (see Fig. 7). Specifically, the baseline condition (mean (M) = 1.326 s, standard error of mean (SEM) = 0.052) had the shortest response times compared to the seat back (M = 1.448 s, SEM = 0.041) and the seat pan (M = 1.507 s, SEM = 0.044) locations. Also, drivers in the lane change response type condition (M = 1.542 s, SEM = 0.051) had longer response times compared to brake responses (M = 1.312 s, SEM = 0.038). No main effect of information type on response time was found ($F(1,\ 38) = 0.277,\ p = 0.602, \eta_p^2 = 0.007$).

Two significant interaction effects were found: location × information type ($F(2,\ 76) = 3.237,\ p = 0.045, \eta_p^2 = .078$) and location × response type ($F(2,\ 76) = 10.364,\ p < 0.001, \eta_p^2 = 0.214$). For location × information type, for instructional signals only, the seat back (M = 1.505 s, SEM = 0.058) and the seat pan (M = 1.545 s, SEM = 0.063) locations had longer response times compared to the baseline location (M = 1.297 s, SEM = 0.074). For the location × response type interaction, the baseline condition (M = 1.362 s, SEM = 0.069) had the shortest response

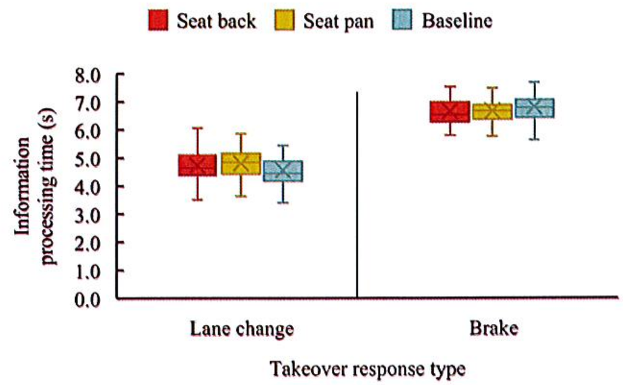


Fig. 8. Information processing time as a function of TOR location and response type.

time compared to the seat back (M = 1.581 s, SEM = .053) and the seat pan (M = 1.684 s, SEM = 0.064) locations, but only for the lane-change response type. No difference was found in brake response type (see Fig. 7).

B. Information Processing Time

Given that information processing time is a function of drivers' maneuvering decisions, the comparison between the two response types is not reported for this measure. No main effect of location ($F(1.64,\ 62.2) = 0.788,\ p = 0.436, \eta_p^2 = 0.020$) nor information type ($F(1,\ 38) = 0.305,\ p = 0.584, \eta_p^2 = 0.008$) was found. Analysis revealed a significant location × response type interaction effect ($F(1.70,\ 64.66) = 4.526,\ p = 0.019, \eta_p^2 = 0.106$). Specifically, the seat pan location (M = 4.821 s, SEM = 0.094) had a marginally longer information processing time than the baseline location (M = 4.563 s, SEM = .105; $p = .093$) for the lane-change response type. No other differences were found (see Fig. 8).

C. Maximum Resulting Acceleration

There was a significant main effect of location ($F(2,\ 76) = 7.178,\ p = 0.001, \eta_p^2 = 0.159$) and response type ($F(1,\ 38) = 8.851,\ p = 0.005, \eta_p^2 = 0.189$) on maximum resulting acceleration (see Fig. 9). *Post hoc* analysis revealed that drivers in the baseline condition (M = 10.82 m/s^2, SEM = 0.079) had a smaller maximum resulting acceleration compared to participants who received signals in the seat back (M = 12.00 m/s^2, SEM = 0.425) and seat pan (M = 11.64 m/s^2, SEM = 0.254). Also, the lane-change response type (M = 12.02 m/s^2, SEM = 0.344) had a larger maximum resulting acceleration compared to the brake response type (M = 10.96 m/s^2, SEM = 0.343). The takeover trajectories of the two response types indicated that after receiving a TOR, even though the initial lane-change time with brake response was longer (as indicated by the later increase of the absolute lane position value in Fig. 10), the overall trajectory of the brake response was smoother than the lane-change response, which is reflected in its smaller maximum resulting acceleration (see Fig. 10). No main effect of

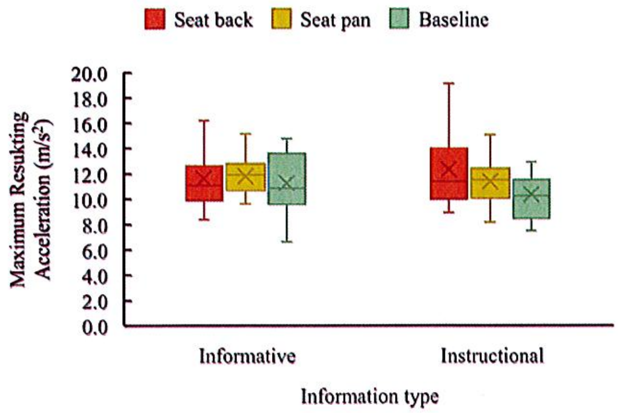


Fig. 9. Maximum resulting acceleration as a function of TOR location and information type.

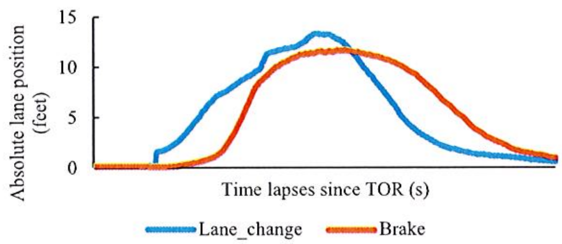


Fig. 10. Takeover trajectories for each response type 20 s after takeover request.

information type on maximum resulting acceleration was found ($F(1,\ 38) = 0.108,\ p = 0.744, \eta_p^2 = 0.003$).

There was also a significant location × information type interaction ($F(2,\ 76) = 3.352,\ p = 0.043, \eta_p^2 = 0.081$). Specifically, with instructional signals, the seat back (M = 12.36 m/s^2, SEM = 0.602) and seat pan (M = 11.44 m/s^2, SEM = 0.360) locations had larger maximum resulting accelerations compared to the baseline location (M = 10.38 m/s^2, SEM = 0.482). But this difference was not present for informative tactile signals.

D. *Subjective Measures*

As shown in Table II, there was a significant main effect of location ($F(2,\ 76) = 5.797,\ p = 0.005, \eta_p^2 = 0.132$) on usefulness score. *Post hoc* analysis showed that participants rated the seat back location as most useful (M = 1.21, SEM = 0.090) compared to the seat pan (M = 0.81, SEM = 0.113) and the baseline (M = 0.74, SEM = 0.138) locations. No main effect of information type ($F(1,\ 38) = 0.023,\ p = 0.880, \eta_p^2 = 0.001$) nor interaction effect on usefulness score were found. Similarly, satisfaction scores were significantly affected by location ($F(1.61,\ 61.32) = 8.794,\ p = 0.001, \eta_p^2 = 0.188$). Here, the seat back was perceived to be most satisfying (M = 0.73, SEM = 0.100) compared to the seat pan (M = 0.13, SEM = 0.152). There were no differences between the baseline location (M = 0.52, SEM = 0.132) and the two other locations (i.e., seat back and seat pan). Finally, no main effect of information type ($F(1,\ 38) = 0.053,\ p = 0.819, \eta_p^2 = 0.001$) nor significant interactions were found.

IV. Discussion

This study investigated the effects of informative and instructional vibrotactile signal patterns embedded into the seat back and seat pan of an automated vehicle on takeover performance. Overall, only meaningful instructional tactile signals, presented in either the seat back or pan, had longer response times and worse takeover quality compared to generic signals that did not assist drivers in making takeover decisions. Also, subjective ratings showed that signals presented in the seat back were perceived as the most useful and satisfying compared to signals presented in the seat pan.

A. *Signal Response Phase*

Takeover performance measures were categorized into time- and driving-related metrics, representing the takeover signal response and post-takeover phases, respectively. In the signal response phase, TOR response time and information processing time were measured. Contrary to our expectations, the baseline condition (i.e., signals without a meaningful pattern) had shorter response times compared to meaningful signals presented in the seat back and seat pan. This finding is consistent with Petermeijer et al. [26], who also found the static signal (equivalent to our baseline signal) to have faster response times compared to signals with patterns. This could be partially explained by the type of information that needed to be processed. Signals without any patterns only served as a TOR or warning signal, while signals in the seat back and seat pan served both as an alert as well as an assistant that conveyed information about surrounding vehicles and instructions on how to maneuver. For meaningful signals, drivers needed additional time to perceive and comprehend the meaning of the signals, which led to a longer response time. Especially for patterned signals, which consisted of three separate tactors vibrating at different times, participants were likely not able to interpret the meaning of the entire message after the activation of only the very first tactor of the pattern, and thus they waited until all vibrations of the signals were complete before responding (after 645 ms). But with the baseline signal, wherein all four tactors vibrated concurrently, drivers could have very quickly interpreted the meaning of the signal within 215 ms, resulting in a faster response.

Alternatively, the baseline condition in our study could have been (inherently) perceived to have a higher intensity, given that four tactors vibrated at the same time (as opposed to being presented in a sequence). In contrast, for meaningful signal patterns used to elicit lane-change responses, only a single tactor vibrated at a time (which accounted for 50% of response types). According to previous studies on tactile perception in driving, higher intensities of tactile stimuli have been associated with higher perceived urgency and faster response times (e.g., [38] and [39]). This explanation may be further highlighted by the finding that drivers had longer response times when making lane-change responses compared to brake responses. Here, either six or two tactors were activated instantaneously for the brake response in informative or instructional signal patterns, respectively. An increase in the number of tactors might have led to higher perceived signal intensity and, thus, a faster response time. To confirm this hypothesis, future work should investigate the effects of signal intensity on response times. If this finding still holds true, then an intra-modal matching task [40], [41], i.e., a process wherein a user is asked to subjectively equate the intensities of tactile signals to that of a different tactile stimulus reference, may be needed to avoid confounding signal intensity with signal pattern and location.

No main effects of TOR location on information processing time were found, which did not meet our expectations. This suggests that the difference between meaningful tactile patterns (in the seat back and seat pan) and the baseline signal only existed for the TOR response time but not for information processing time. In other words, the main effects of meaningful TORs were found only in the initial takeover signal response phase (as measured by response time), but not the entire signal response phase (measured by information processing time). This finding may be explained by the potential benefits of meaningful signals in terms of supporting drivers' decision-making. As reported, the baseline condition was associated with shorter takeover response times (*RT*) compared to meaningful signals (such that $\Delta RT = RT_{\text{baseline}} - RT_{\text{meaningful}} < 0$). However, after this initial takeover signal response phase (i.e., TOR response time, Fig. 6), the time taken to process information about the environment for the meaningful signals (denoted as $\text{IPE}_{\text{meaningful}}$), was shorter than for the baseline signal (i.e., $\Delta\text{IPE} = \text{IPE}_{\text{baseline}} - \text{IPE}_{\text{meaningful}} > 0$). In other words, (informative or instructional) meaningful signals conveyed information about the location and status of the surrounding vehicles as well as about obstacles ahead, which reduced the need for drivers to glean this information for themselves. This ultimately helped drivers more quickly make maneuvering decisions. Here, the time lost in processing meaningful TORs, earlier on in the takeover signal response phase was now made up in the latter part of the takeover signal response phase due to the environmental information communicated to participants. Stated another way, the performance gap in *RT* between meaningful and baseline signals was mitigated by the difference in IPE between meaningful and baseline signals (i.e., $|\Delta RT| \approx |\Delta\text{IPE}|$), resulting in no overall performance difference between the two signal types/locations (represented by the seat back and/or pan) for the entire signal response phase (i.e., TOR information processing time, $RT + \text{IPE}$, Fig. 6).

B. Post-Takeover Performance

Post-takeover performance was measured by maximum resulting acceleration. Surprisingly, meaningful signals in both the seat back and seat pan had larger maximum resulting accelerations compared to signals in the baseline condition, indicating a poorer post-takeover quality with meaningful signal patterns. This finding can be explained by different cognitive resources needed to process signal information and develop and perform the driving task during the post-takeover phase. Here, even though drivers spent an equal amount of time processing the signal and information in the environment for both meaningful and baseline signals (indicated by the lack of difference in information processing time between the two signal types), participants likely utilized more and different cognitive resources to decipher meaningful signal patterns, resulting in a reduced capacity to conceptually coordinate a takeover/manual driving strategy [42].

Furthermore, the discovery of an interaction between location and information type showed that the seat back and seat pan only had a larger maximum resulting acceleration compared to the baseline for instructional signals only. A similar effect was also found in time-related metrics, i.e., that patterned signals only had longer response times compared to the baseline location for instructional signals. This indicates that the performance difference in the maximum resulting acceleration and takeover response time measures between the seat back, seat pan, and baseline locations only existed for instructional signals. Specifically, with instructional signals, drivers were commanded to simply follow the guidance of the system to make maneuvers without having to learn about the driving environment. Thus, without additional information about the happenings in the driving environment, drivers might have performed the post-takeover task hastily and with more uncertainty about the surrounding vehicle locations. Also, without feedback on whether their planned vehicle maneuvering decision was accurate, drivers may have experienced a greater amount of workload (e.g., not only from maneuvering the vehicle but also trying to ensure that they had some awareness of the environment). These influences could have degraded their overall takeover quality. Future work can confirm this hypothesis by using eye-tracking to compare drivers' eye gazes on the side and rear mirrors to determine the frequency at which participants checked the surrounding vehicles.

C. Perceived Usefulness and Satisfaction

Subjective ratings of signal information type and location revealed that drivers perceived signals embedded in the seat back to be more useful and satisfying compared to the seat pan. However, no difference in preference was found between the informative and instructional tactile display types. Wan and Wu [27] also compared six vibration patterns that started from one location and then moved to the other locations, e.g., seat back → seat pan → seat back → seat pan or back left → back right → back left → back right, and also found no differences in subjective scores. In their study, patterns initially presented in the seat back had faster response times compared to those in the seat pan, even though all signal patterns were generic (noninformative and noninstructional) and only served as TORs. According to the authors, tactile sensitivity in the back region is higher than for the legs, which may also explain why, in our study, participants reported higher usefulness for signals in the seat back. Additionally, vibrations presented in the seat pan may be more invasive, based on reports from a few participants during the debriefing session. A third explanation could be that during the drive, participants were not required to keep their feet on the control pedals. Thus, their lower-limb postures might not have always been consistent. In cases where their legs were not in direct contact with the seat tactors, their ability to detect tactile stimulation on the seat pan could have been significantly reduced and ultimately more frustrating for drivers. Also, the lack of a difference in subjective ratings between the informative and instructional display types further supports our objective measure findings in that the effects of the two meaningful patterns on the takeover task were observed to be very similar. A more systematic study may be needed to compare preferences between locations that may have tactile stimulation (e.g., seat back, seat pan, seat belt, steering wheel, or pedals), as well as patterns of signals that have various meanings.

D. Limitations

One limitation of the study is that the driving scenario was relatively simple in terms of the number of surrounding vehicles and the complexity of the driving environment, even though drivers had three different maneuvering action options. Once participants were familiarized with the takeover scenarios, they might have been less motivated to collect additional information from the driving environment, as they would in a real-world takeover scenario, since they knew that other road elements in our study did not pose an immediate threat to them. For example, in real-life, drivers need to quickly obtain characteristics of the external environment, such as the speed limits, road conditions, the surrounding vehicle locations and speeds, and/or the cause of the takeover event. But, in our study, drivers only needed to understand the meanings of the tactile cues and avoid prescriptive collisions. Also, the cause of the takeover event was always related to construction. Future research may seek to increase the number and nature of elements in the driving environment, as well as the variabilities in takeover events. Additionally, the accuracy of the information conveyed by the informative and instructional tactile signals was 100%. Follow-up work should vary the reliability of the TORs to examine their impact on drivers' trust and performance. Finally, only college students participated in this study. The inclusion of volunteers from other groups, such as older adults and individuals with disabilities, may enhance the generalizability of findings.

V. Conclusion

This study examined how meaningful vibrotactile patterns, i.e., in informative and instructional formats, embedded into the seat back and seat pan, affected automated vehicle takeover performance. For the instructional signal group only, both meaningful tactile formats (in either the seat back or seat pan location) were associated with worse takeover performance in terms of response time and maximum resulting acceleration compared to generic signals. Additionally, tactile information presented in the seat back was perceived as most useful and satisfying by drivers. The knowledge gained from this work may help to inform how human–machine interfaces are designed, particularly in the context of automated transportation. Even though meaningful tactile patterns are capable of representing information in the driving environment, our study results suggest that more time is likely needed for drivers to process the complexities of the signals, which could pose a potential threat to safety. Also, designers and engineers may consider ways to leverage drivers' preferences by enhancing the presentation of information in the seat back instead of the seat pan. Ultimately, findings from this study can serve as one guide for developing tactile interfaces to be used across a wide range of automated environments.

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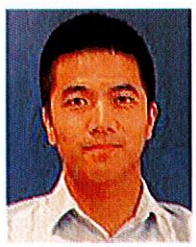

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