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RESEARCH ARTICLE

In-Vehicle Human Machine Interface: Investigating the Effects of Tactile Displays on Information Presentation in Automated Vehicles

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ABSTRACT **Background:** Semi-autonomous vehicles still require human drivers to take over when the automated systems can no longer perform the driving task. **Objective:** The goal of this study was to design and test the effects of six meaningful tactile signal types, representing six driving scenarios (i.e., navigation, speed, surrounding vehicles, over the speed limit, headway reductions, and pedestrian status) respectively, and two pattern durations (lower and higher urgencies), on drivers' perception and performance during automated driving. **Methods:** Sixteen volunteers participated in an experiment utilizing a medium-fidelity driving simulator presenting vibrotactile signals via 20 tactors embedded in the seat back, pan, and belt. Participants completed four separate driving sessions with 30 tactile signals presented randomly throughout each drive. Reaction times (RT), interpretation accuracy, and subjective ratings were measured. **Results:** Results illustrated shorter RTs and higher intuitive ratings for higher urgency patterns than lower urgency patterns. Pedestrian status and headway reduction signals were associated with shorter RTs and increased confidence ratings, compared to other tactile signal types. Lastly, among six tactile signals, surrounding vehicle and navigation signal types had the highest interpretation accuracy. **Conclusion:** These results will be used as preliminary data for future studies that aim to investigate the effects of meaningful tactile displays on automated vehicle takeover performance in complex situations (e.g., urban areas) where actual takeovers are required. The findings of this study will inform the design of next-generation in-vehicle human-machine interfaces.

INDEX TERMS Human–machine interface, tactile displays, automated driving, takeover request.

I. INTRODUCTION

Autonomous vehicles come with great benefits, such as increased traffic safety, mobility, energy savings, and reduction of fuel emissions [1]. Although there is a push towards fully autonomous vehicles (SAE Level 5) [2], current automation technology, such as SAE Level 3 automation, is not perfect. For example, SAE Level 3 automation may fail to perform the driving task in many driving conditions (e.g., encountering erased lane markings or in poor visibility), which would prompt the vehicle to abruptly request the driver to manually take over control of the vehicle in a limited matter of time [2]. This two-phase (signal response and post-takeover), three-step takeover process (Fig. 1) entails first perceiving and processing the takeover request and then needing to quickly shift their attention while becoming aware of their surroundings and assessing the situation, then moving their hands and feet back to the driving position to manually

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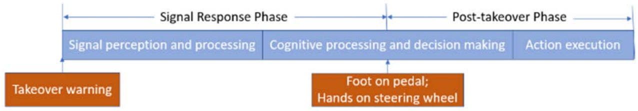

FIGURE 1. The Takeover Model ([3]; adapted from [6]).

takeover control of the vehicle, in an effort to execute a strategic steering/maneuvering decision, under a short vital period of time [3], [4], [5], [6].

The takeover process may be more complex if drivers are engaging in non-driving-related tasks (NDRTs) such as reading or texting at the time of takeover, which could lead to higher cognitive workload and longer reaction times to takeover requests and potential threats [7], [8] and can ultimately result in a driver's possible failure to successfully take over. The criticality of this process could then be further exacerbated when sensory information in the driving environment is overwhelming, leading to an overload in the drivers' sensory channels. For example, drivers need to reorient (pay attention to the road) and regain situation awareness during the takeover process [6], [9], [10]. However, a takeover in complex environments such as urban areas that are already filled with a plethora of visual and auditory information to be perceived and processed, e.g., the status/location of surrounding/oncoming obstacles/objects, including but not limited to vehicles, pedestrians, traffic signs/signals, all of which may lead to the overstimulation of a drivers' visual and auditory resources. There lies a need for a reliable human-machine interface (HMI) that utilizes idle sensory modalities while being cognizant in not adding to the driver's cognitive workload and instead helping drivers quickly connect the information in the driving environment and aid them in cognitive processing and decision making. Multiple resources theory [11] suggests that tactile displays may be a good option as the tactile modality may be more available than visual and auditory modalities in a data-rich driving environment.

Previous research has demonstrated the benefits of tactile displays as an assistive HMI in a large body of research, which has shown that tactile displays significantly improved decision making with faster cognitive processing/response speeds, while reducing cognitive workload [4], [8], [12], [13], [14], [15], [16], [17], improving situation awareness [18], and enhancing vehicle handling [19], [20]. For example, a study conducted by Van Erp and Van Veen [13] demonstrated that a vibrotactile display consisting of eight vibrating tactors attached to the driver's seat during a simulated drive, resulted in reduced workload for both normal and high workload groups (particularly in the high workload condition) compared to a visual display. Moreover, Chiossi, Villa, Hauser, Welsch, and Chuang [18] illustrated the effects of tactile displays on supporting situation awareness. This study investigated and compared the ability of on-body tactile notifications, that either presented spatial information (status/location) of surrounding traffic or future projections of the position of the automated vehicle, to assist drivers in sensing failures in vehicle automation while engaging in NDRTs. It found that notifications presenting spatial information on surrounding traffic required fewer mental resources, which allowed participants to interpret sensing failures in vehicle automation with higher accuracy and lower mental workload. In addition, Telpaz, Rhindress, Zelman, and Tsimhoni [19] studied a haptic seat that presented spatial information of approaching vehicles and found that participants who had a haptic seat showed shorter reaction times in scenarios requiring lane changes than participants with no haptic seat.

Given the advantages of tactile cueing, researchers started focusing on changing characteristics (e.g., rhythm, duration, intensity) to create meaningful tactile patterns to represent complex driving scenarios during a takeover. A recent review article summarized studies that used tactile displays as the HMI in automated vehicles and categorized the studies into either instructional signals (i.e., instructions for drivers to maneuver their own vehicles) or informative signals (i.e., representing spatial location/status of approaching vehicles/pedestrians/obstacles in the environment) [21]. Examples of instructional signals include navigational [12], [13], [14], [22], [23], [24], and speed regulation cues [25], [26]; and informative signals include the status/location of surrounding vehicles [19], [20], [27], [28], being over the speed limit [14], headway reductions [4], [8], [15], [16], [17], [29], [30], [31], [32], [33], [34], and the status/location of pedestrian in the surrounding environment [18], [35]. For instance, Scott and Gray [16] ran a study that compared tactile, visual, and auditory warnings for rear-end collision prevention (i.e., informative signals) during a simulated drive, using a higher urgency pattern that had 200 ms, with an 800 ms pause per second. They found that drivers with a tactile warning had significantly shorter response times than drivers without a warning or drivers with visual warnings. Here, the tactile display was conveyed via three tactors fastened on a waist belt and positioned on the driver's abdomen to simulate a driver's seatbelt. Moreover, a study conducted by Chang, Hwang, and Ji [14] compared tactile, visual, auditory, and multimodal displays during a simulated drive, which gave navigational information (i.e., instructional signals) such as left, right, and straight, along with a speed limit warning. This study conveyed tactile warning signals via three types of patterns: 1) 12 tactors attached to the driver's seat were activated in sequential bursts of 120 ms with a 510 ms pause from back to front to represent "proceed straight", 2) one tactor on both the left and right sides of the seat were attached to represent the "go left" or "go right" signals and presented 158 ms bursts with a pause of 46 ms, and 3) four tactors were placed on the seat back to represent the speed limit warning presenting two 726 ms bursts with a pause of 78 ms. The study found faster response times for the tactile and multimodal displays in addition to higher satisfaction and lower subjective workload for participants who had a tactile display versus an auditory or visual one. However, these papers only used one type of signal and/or pattern for only one information presentation purpose (i.e., either instructional or informative, but not both). In other words, differences in performance under the effects of meaningful tactile signal type and pattern (in different perceived urgencies) have not been extensively studied. Here, perceived urgencies were manipulated by varying signal durations and interstimulus intervals (i.e., pause periods between bursts) [6], [36], [37], [38]. Thus, it is still unclear whether multiple meaningful or complex tactile patterns can be used altogether (i.e., only activated for corresponding driving scenarios) to communicate the needs of takeover and convey more information to help the takeover task and be reliably and intuitively identified by drivers.

Therefore, the goal of this study was to design and test the effects of signal types representing six most representative driving scenarios, i.e., navigation, speed, location/status of surrounding vehicles, over the speed limit, headway reductions, and pedestrian status, based on previous studies (e.g., [13], [14], [15], [16], [18], [19], [20], [22], [23], [24], [35], [39]), on drivers' perceptions and performance during automated driving.

II. METHODS

A. PARTICIPANTS

Sixteen volunteers participated in this study, ranging between the ages of 18 - 27 years (mean age = 19.9, standard deviation (SD) = 2.6), i.e., ten males (mean age = 20.8, SD = 3.0) and six females (mean age = 18.5, SD = 0.6). The average number of years of driving experience was 2.9 (SD = 2.3). All participants were college students and were required to have a valid driver's license, have a normal or corrected-to-normal vision, and experience no cognitive/neurological impairments to the sense of touch. All participants were given 2-hour of class credits as compensation for their time. This study was approved by the San Jose State University's Institutional Review Board (IRB Protocol ID: 21208).

B. APPARATUS/STIMULUS

1) DRIVING SIMULATOR

The experiment was conducted using a medium-fidelity driving simulator. System accessories included a 65-inch Sony TV monitor, Logitech G27 steering wheel/foot pedals, a Cobra Monaco E36 life-size bucket seat, and a seat belt (see Fig. 2).

2) WARNING SIGNALS

The tactile signals were presented by twenty $1'' \times 0.5''' \times 0.25''$ piezo-buzzers (called C-2 tactors developed by Engineering Acoustics, Inc.; represented by the numbered circles on the seat and seat belt in Fig. 3) at a frequency of 250 Hz. Five tactors were attached, across the torso, to the seat belt (e.g., [23], [39]), nine tactors (3 × 3) were installed in the seat back (e.g., [18], [19]), six tactors were embedded to the seat pan in two rows, one row under each thigh (e.g., [14], [36]). There were six signal types (Table 1): navigational (left turn, right turn, U-turn), speed (speed up/slow down), surrounding vehicle location (left, behind, right) and status, over the speed limit, headway reductions (forward collision), and pedestrian status (traveling left-to-right or right-to-left). Example patterns are illustrated in Fig 3.

FIGURE 2. Experimental setup and apparatus.

C. EXPERIMENTAL DESIGN

The experiment employed a 6 (signal type: navigation, speed, surrounding vehicle, over speed limit, headway reduction, pedestrian status) × 2 (pattern: lower urgency, higher urgency) full factorial design. Here, signal type and patterns were within-subject factors. The six tactile signal types, with subcategories, were presented in three locations, i.e., seat back, pan, and/or belt. The six signal types represent the most common takeover scenarios from the literature (see a review, [21]). These signals were designed based on other studies, including the tactile locations, the number of tactors, and vibration intensity and sequence used (see an example design guideline, [36]), as well as a few iterations of in-lab prototype testing. For example, navigational signals had three subcategories, left turn (presented on either belt or back), right turn (presented on either belt or back), and U-turn (presented on either belt or pan). We intentionally presented signals at different locations to eliminate potential location effects, given that previous studies played tactile signals at different locations (e.g., seat back [12], [40], pan [13], [22], [24], and belt [23]) for the same meanings, but the comparisons of locations on takeover performance have not been widely studied. Similarly, speed signals had two subcategories, speed up (presented on either belt or pan) and slow down (presented on either back or pan). Surrounding vehicles approaching signals had three subcategories, approaching from the left side (presented on either back or pan), approaching from behind (presented on back), and approaching from the right side (presented on either back or pan). Both over speed limit and headway reduction signals only had one subcategory to represent speeding (presented on either back or pan) and forward collision (presented on belt), respectively. Finally, pedestrian status warning signals had two subcategories played on the seat belt: traveling left-to-right or right-to-left. Each tactile signal was presented in two patterns: lower and higher urgency. Lower urgency

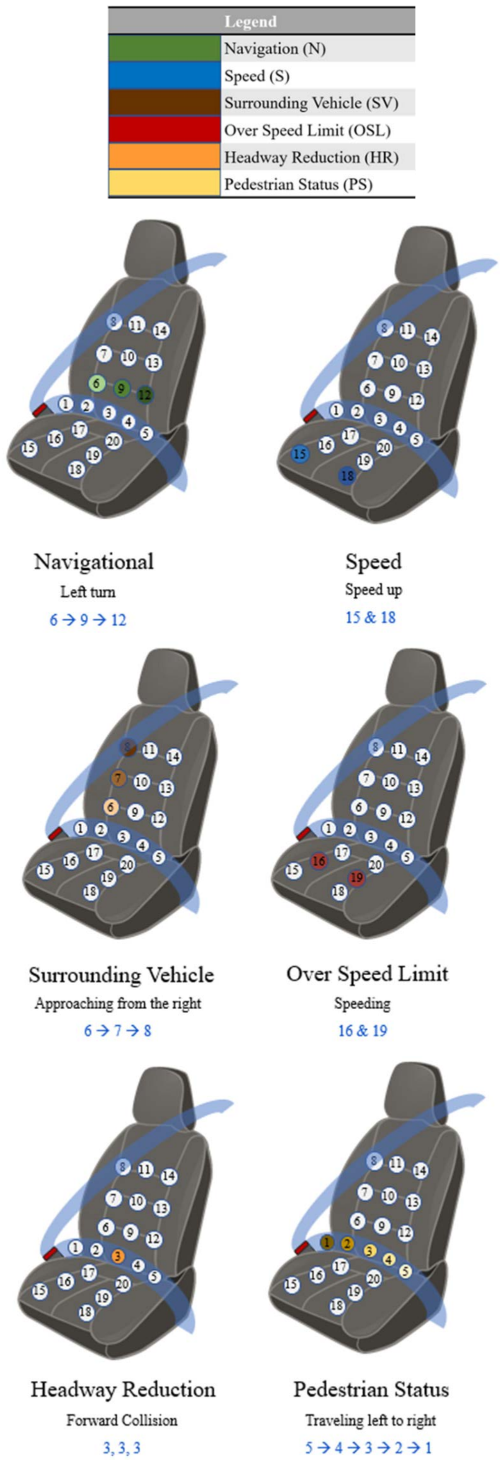

FIGURE 3. Example pattern descriptions for all six warning signal types.

TABLE 1. A summary of tactile signals and patterns used in the study.

Tactor Sequence	Display Location	Warning Signal	Pattern: Lower Urgency	Pattern: Higher Urgency
Instructional (5)				
Navigational Warning Signal (3)				
2 > 3 > 4	Belt	Left Turn	(3x 215ms on)	(3x 107.5ms on)
6 > 9 > 12	Back	Left Turn	(3x 215ms on)	(3x 107.5ms on)
4 > 3 > 2	Belt	Right Turn	(3x 215ms on)	(3x 107.5ms on)
12 > 9 > 6	Back	Right Turn	(3x 215ms on)	(3x 107.5ms on)
3 > 4 > 12	Belt	U-Turn	(3x 215ms on)	(3x 107.5ms on)
15 > 18 > 19	Pan	U-Turn	(3x 215ms on)	(3x 107.5ms on)
Speed Warning Signals (2)				
2 & 4	Belt	Speed Up	(3x 215ms on, 215ms off)	(3x 107.5ms on, 107.5ms off)
15 &18	Pan	Speed Up	(3x 215ms on, 215ms off)	(3x 107.5ms on, 107.5ms off)
6 & 12	Back	Slow Down	(3x 215ms on, 215ms off)	(3x 107.5ms on, 107.5ms off)
17 & 20	Pan	Slow Down	(3x 215ms on, 215ms off)	(3x 107.5ms on, 107.5ms off)
Informative (5)				
Surrounding Vehicles Warning Signal (2)				
12 > 13 > 14	Back (left)	Back Left	(3x 215ms on)	(3x 107.5ms on)
9 > 10 > 11	Back (center)	Back	(3x 215ms on)	(3x 107.5ms on)
6 > 7 > 8	Back (right)	Back Right	(3x 215ms on)	(3x 107.5ms on)
20 > 19 > 18	Pan (left)	Pan, left side, back-to-front	(3x 215ms on)	(3x 107.5ms on)
17 > 16 > 15	Pan (right)	Pan, right side, back-to-front	(3x 215ms on)	(3x 107.5ms on)
Over Speed Limit Warning Signal (1)				
7 & 13	Back	Speeding	(3x 215ms on, 215ms off)	(3x 107.5ms on, 107.5ms off)
16 & 19	Pan	Speeding	(3x 215ms on, 215ms off)	(3x 107.5ms on, 107.5ms off)

patterns entail longer signal bursts and interstimulus interval (ISI) durations [6], [36], [37], [38], i.e., bursts of 215 ms with varying interstimulus interval durations, while higher urgency patterns are comprised of the opposite – shorter warning signal burst durations and shorter ISI durations along with a repetition of the tactile signal, i.e., shorter (half) bursts of 107.5 ms. See Table 1 for a summary of signals and patterns that were designed and examined.

TABLE 1. ***(Continued.)*** **A summary of tactile signals and patterns used in the study.**

HEADWAY REDUCTION (1)				
3, 3, 3	BELT	FORWARD COLLISION	(215MS ON, 4800MS OFF, 215MS ON, 3440MS OFF, 215MS ON, 1200MS OFF) + 1800MS OFF DELAY	(107.5MS ON, 2400MS OFF, 107.5MS ON, 1720MS OFF, 107.5MS ON, 600MS OFF) + 1800MS OFF DELAY
PEDESTRIAN STATUS WARNING SIGNAL (1)				
1>2>3>4>5	BELT	PEDESTRIAN TRAVELING RIGHT TO LEFT	(5X 215MS ON, 2500MS OFF)	(5X 107.5MS ON, 1250MS OFF)
5>4>3>2>1	BELT	PEDESTRIAN TRAVELING LEFT TO RIGHT	(5X 215MS ON, 2500MS OFF)	(5X 107.5MS ON, 1250MS OFF)

The driving task was designed to represent SAE Level 3 automated driving, in a light-traffic environment. Participants completed four separate driving sessions, where in total 120 tactile signals (i.e., twenty signals each randomly repeated three times in two patterns) were presented in four separate blocks. The average time interval between each signal was between 10 – 20 seconds. Participants' reaction times to the signals, their interpretation accuracy, and subjective ratings on the signals were measured. No actual takeover was required.

D. PROCEDURE

Prior to the start of the experiment, participants were given an overview of the study and signed the experiment consent form, then they were asked to fill out a pre-experiment questionnaire for demographic information and driving experiences. Moving into the experiment, participants were introduced to a 15-minute training session to learn the driving setup and experiment procedures along with studying the vehicle "manual," which listed all the driving scenarios and their associated vibrotactile signals/patterns. For the actual experiment, participants were informed that the vehicle was an SAE Level 3 automated vehicle that did not require to be in constant manual control, and thus they were asked to keep their hands at their sides and feet off the pedals. To reduce the impact of the tactile (buzzing) sound produced by the tactors, noise cancelling headphones were provided to the participants and worn throughout the experiment. At random, tactile patterns would play on the driver's seat (back or pan) and seat belt. Participants were asked to execute a response (e.g., pressing a button) as quickly as they could as if they would in a real-life takeover, but only after they had an answer for the actual meaning the tactile signal was representing. Once participants pressed the button, they needed to state their interpretation of the signal, and then rate their confidence in their answer and intuitiveness of the tactile signals both on a scale of 1(low) to 5 (high). The interpretation accuracy was also recorded. The study lasted about two hours and was split into four sections to help prevent fatigue. At the end of the experiment, participants filled out a post-experiment questionnaire, which asked questions about their overall experience, and were then debriefed.

E. DEPENDENT MEASURES

The dependent variables were put into three categories: a) reaction time (in milliseconds (ms)), which was the time between the onset of the tactile signal and the moment the participant pressed the button on the dashboard; b) interpretation accuracy, participants were presented with 120 tactile signals (20 signals as shown in Table 1, each randomly repeated three times in two urgency patterns) and were asked to provide an answer after each signal, as to what they felt the tactile signal was communicating, which measured the number of correct answers in each of the 12 conditions (6 signal types × 2 patterns), and c) subjective satisfaction ratings, which were participants' ratings based on the confidence in their answers and intuitiveness of the tactile signals, both on a 5-point rating scale (1 low – 5 high).

F. DATA ANALYSIS

Dependent variables were analyzed using a two-way repeated measures analysis of variance (ANOVA) with tactile signal and pattern as independent variables. For violations of sphericity tests, degrees of freedom were corrected using Greenhouse-Geisser estimates. Bonferroni corrections were applied for multiple comparisons to identify significant differences and interactions between each level. The statistical analysis was conducted using IBM SPSS Statistics 28.0 and evaluated at a significance level of $p < 0.05$. Effect size was presented as partial eta squared (η_p^2).

III. RESULTS

A. REACTION TIME

There were significant main effects of pattern (F (1, 15) = 22.1, p <.001, η_p^2 = .60) and signal type (F (2.59, 38.80) = 22.60, p <.001, η_p^2 = .60) on reaction time. Specifically, the higher urgency pattern had shorter reaction time (mean (M) = 1614.6 milliseconds (ms), standard error of mean (SEM) = 208.7), compared to the lower urgency pattern (M = 1974.0 ms, SEM = 243.1). For signal type, the analysis showed pedestrian status warning signal (M = 920.9 ms, SEM = 137.9) and headway reduction signal (M = 1101.0 ms, SEM = 251.0) had shorter reaction times compared to the other signals, i.e., the surrounding vehicle signal (M = 1987.2 ms, SEM = 253.6), the over the speed limit signal (M = 2230.3 ms, SEM = 311.7), the speed signal (M = 2238.7 ms, SEM = 276.3), and the navigation signals (M = 2287.6 ms, SEM = 252.9). There were no interaction effects between pattern and signal (F (2.90, 43.46) =.42, p =.733, η_p^2 = .027) on reaction time.

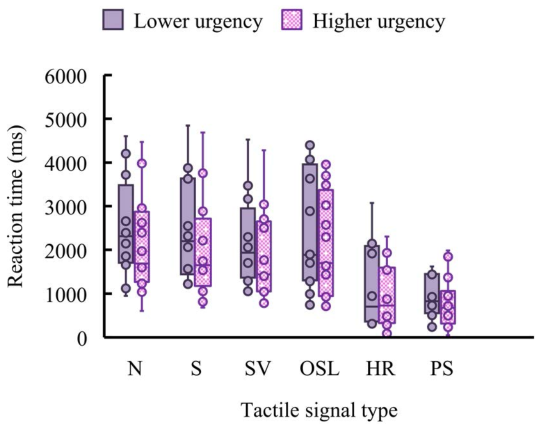

FIGURE 4. Boxplot of reaction time, as a function of tactile signal type and pattern (Navigation (N), Speed (S), Surrounding Vehicles (SV), Over the Speed Limit (OSL), Headway Reduction (HR), Pedestrian Status (PS)).

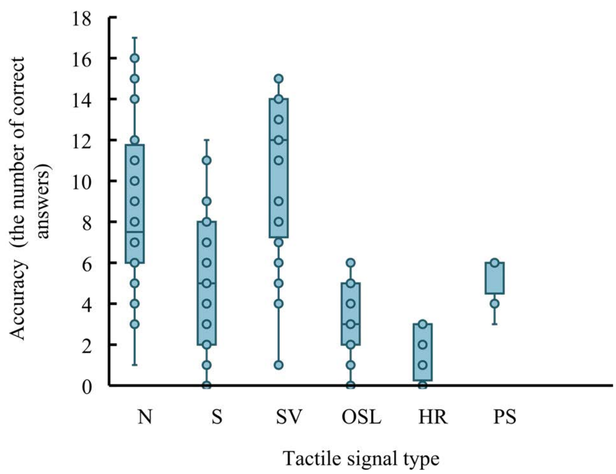

FIGURE 5. Boxplot of interpretation accuracy as a function of tactile signal type (Navigation (N), Speed (S), Surrounding Vehicles (SV), Over the Speed Limit (OSL), Headway Reduction (HR), Pedestrian Status (PS)).

B. ACCURACY

There was also a significant main effect of signal type (F (3.49, 52.33) = 25.87, p <.001, η_p^2 = .63), but not for patterns (F (1, 15) =.484, p =.497, η_p^2 = .031), on interpretation accuracy. For signal type, surrounding vehicles (M = 10.31, SEM =.997) and navigation (M = 8.53, SEM =.904) signals had higher accuracy compared to the other tactile signals, i.e., the speed signal (M = 5.16, SEM =.916), the pedestrian status warning signal (M = 4.81, SEM =.528), the over the speed limit signal (M = 3.31, SEM =.452), and the headway reduction signal (M = 2.13, SEM =.324). No difference between the higher urgency (M = 5.79, SEM = .440) and lower urgency (M = 5.63, SEM =.534) patterns were found. Additionally, there was no interaction effect between pattern and signal type (F (2.6, 39.21) = 1.09, p =.359, η_p^2 = .068) on interpretation accuracy.

C. SUBJECTIVE SATISFACTION

1) CONFIDENCE RATINGS

There was a significant main effect of signal type (F (2.48, 37.15) = 9.16, p <.001, η_p^2 = .379), but not for patterns

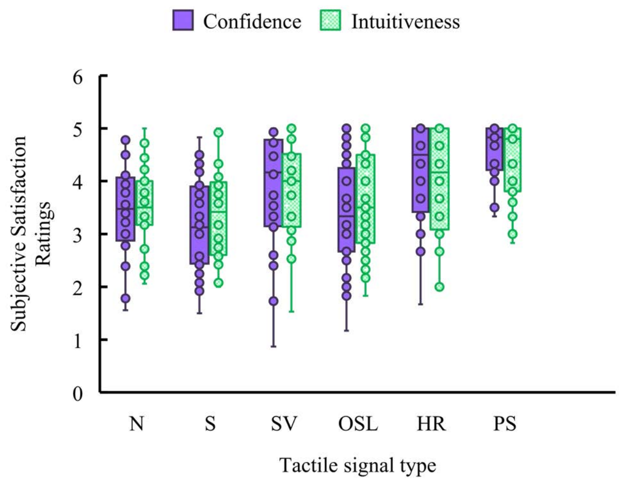

FIGURE 6. Boxplot of subjective satisfaction ratings (i.e., confidence and intuitiveness) as a function of signal type (Navigation (N), Speed (S), Surrounding Vehicles (SV), Over the Speed Limit (OSL), Headway Reduction (HR), Pedestrian Status (PS)).

(F (1, 15) =.546, p =.472, η_p^2 = .035), on confidence ratings. For signal type, the post-hoc analysis showed that pedestrian status warning signal (M = 4.35, SEM =.260) and headway reduction signal (M = 4.01, SEM =.311) had higher confidence rating compared to the surrounding vehicle signal (M = 3.79, SEM =.269), the navigational signal (M = 3.45, SEM =.183), the over the speed limit signal (M = 3.32, SEM =.248), and the speed signal (M = 3.14, SEM =.221). No difference between the higher urgency (M = 3.70, SEM =.205) and lower urgency (M = 3.65, SEM =.224) patterns were found. Also, there was no interaction effect between signal type and pattern (F (5, 75) = 1.14, p =.345, η_p^2 = .071) on confidence ratings.

2) INTUITIVE RATINGS

Finally, there was a significant main effect of signal type (F (2.81, 42.155) = 3.83, p =.018, η_p^2 = .203), and pattern (F (1, 15) = 7.40, p =.016, η_p^2 = .330), on intuitive ratings. Specifically, pedestrian status warning signal (M = 4.16, SEM =.280) had the highest intuitiveness rating compared to the other warning signals, i.e., the headway reduction signal (M = 3.89, SEM =.272), the surrounding vehicle signal (M = 3.87, SEM =.204), the over the speed limit signal (M = 3.58, SEM =.227), the navigational warning signal (M = 3.51, SEM =.154), and the speed signal (M = 3.33, SEM =.207). Also, the higher urgency pattern had higher intuitive ratings (M = 3.82, SEM =.177) compared to the lower urgency pattern (M = 3.62, SEM =.188). There was no interaction effect between pattern and signal type (F (3.04, 45.60) =.998, p =.403, η_p^2 = .062) on intuitive ratings.

IV. DISCUSSION

This study investigated the effects of meaningful tactile signal type and pattern on reaction time, information interpretation accuracy, and subjective satisfaction during semi-autonomous driving. Findings include shorter reaction times and higher intuitive ratings when the signal pattern was in higher urgency compared to lower urgency. Also, when the signals were pedestrian status warning and headway reduction, reaction times were shorter, and confidence ratings were higher compared to other tactile signal types. Finally, surrounding vehicle signal and navigation signal types showed higher interpretation accuracy compared to the other four signal types.

A. TACTILE SIGNAL TYPES

Regarding tactile signal types, pedestrian status and headway reduction signals had shorter reaction times and higher subjective ratings (i.e., confidence and intuitiveness) compared to the other warning signals. These findings indicate that meaningful signals related to pedestrian status and headway reduction designed in this study were intuitive and straightforward to be processed and interpreted by drivers. Especially for the pedestrian status signal, the findings were in line with previous research in spatial and distance detection of people in the surrounding environment while engaging in a highly demanding task [35]. Specifically, Pielot, Krull, and Boll [35] embedded six equally spaced tactors onto a belt that was placed around participants' waists during a 3D gaming experience. Each tactor corresponded to a direction in distal space to assist players in detecting and tracking the various movements of multiple people in the surrounding environment using vibrotactile signals. The study found that people equipped with tactile displays had improved situation awareness, with faster and more accurate information processing, and higher certainty, than those who did not have a tactile display. The findings from our study and the literature on pedestrian status signals demonstrated that tactile displays could be a promising approach to representing the status/location of people in the surrounding environment, especially since humans have the ability to code more than the four cardinal directions (i.e., north, east, south, west) [13], [23], [43].

For the headway reduction signal, the results were also consistent with previous studies where signals representing forward collision warnings changed in rhythm and duration, leading to faster reaction times [15], [29], [30] and higher subjective ratings (i.e., intuitiveness and confidence) [35], [36]. A possible explanation for this finding may be in the location and pattern of the single tactor placed on the navel (i.e., in front of the drivers' internal frame of reference), which may have helped draw their attention in the forward direction [23], as previous research has shown that humans tend to judge spatial locations of objects in the environment and to themselves relative to their body in a horizontal 360-degree span [13], [22] and are most sensitive to motion that is head-on compared to motion in other directions [30]. Alternatively, the tactile patterns of the headway reduction signal had increasingly shorter ISI as the signal progressed to give the perceptual impression of faster apparent motion in the oncoming head-on collision [30], which may have led to participants reacting faster to these tactile signals.

Regarding accuracy, navigation and surrounding vehicle signals had the highest accuracy compared to the other signal types. These results are in accordance with previous research that used vibrotactile warning signals to represent spatial/navigational directions in the driving environment during semi-autonomous driving, leading to increased accuracy of information interpretation of directional signals [12], [19], [20], [24], [39], [44]. One likely explanation may be that drivers have become more familiar with navigation and surrounding vehicle signals in their day-to-day driving experience (e.g., blind spot warnings as surrounding vehicles signal; and GPS/mobile apps for navigation purposes). Even though these signals are generally applied via different sensory channels (i.e., visual and auditory), they may be more capable of processing the same type of information [11]. Follow-up studies may conduct, for example, semi-structured interviews or focus groups to gain more insights in this regard.

B. HIGHER URGENCY VS. LOWER URGENCY PATTERNS

As described in Methods, higher urgency patterns consist of two shorter warning signals, while lower urgency patterns are longer warning signals. Overall, the higher urgency pattern significantly reduced reaction time, by 359.4 ms on average, and had higher intuitive ratings, compared to lower urgency patterns. This finding is consistent with previous research in that participants tended to prefer signals (i.e., measured subjectively) with shorter ISI durations compared to longer ISI durations [6], [36], [45], [46]. For example, Pratt *et al.* [45] investigated whether scalable levels of perceived urgency could be achieved utilizing tactile signals by measuring the changes between the vibrotactile pulse rate and its relationship to perceived urgency and annoyance ratings. That study found that faster pulse rates (shorter ISI) resulted in signals being perceived as having higher urgency. In our study, we also found that shorter burst durations and ISI durations were correlated with faster reaction times (with objective data). One possible explanation for this result could be that the shorter burst and ISI durations create a sense of urgency [6], [37], [38], [45], [46], which helped drivers quickly process and comprehend the signal information (measured by reaction times). Alternatively, the signal duration could be the cause of the differences between the higher and lower intensities. In our design, the higher urgency patterns were shorter in overall duration time compared to the lower urgency patterns. The shortened time duration allowed drivers to start processing the signal meaning and return their attention to the driving environment earlier, thus reacting faster to distal stimuli.

C. LIMITATIONS AND FUTURE WORK

There are a few limitations of this study. First, participants in experienced a total of 120 signals under six warning signal types and two different types of patterns. Although our goal was to compare the tactile signals and patterns, and we gave participants 5-15-minutes of uninterrupted time to practice the tactile signals and divided the experiment into four separate blocks to prevent participants from experiencing fatigue, this may not have been the most appropriate approach to represent a real-life semi-autonomous drive, as drivers would not commonly receive a constant wave of signals presented every 10-20 seconds. Future work may investigate the effects of tactile displays in a more immersive environment as opposed to a driving simulator and with various takeover scenarios (e.g., under different weather and traffic conditions). Similarly, our study did not ask participants to perform actual takeover tasks since this was not the main goal of the study. Follow-up studies may extend this study by measuring takeover performance (e.g., maximum lateral and longitudinal accelerations) during semi-autonomous driving. In addition, even though we grouped the six signal patterns into instructional and informative signals, we did not directly compare the effects of the information type on task performance. Future studies may design both informative and instructional signal types to represent the same takeover scenarios and compare their effects on takeover performance. Moreover, research has shown that demographic information such as age or gender may cause individual differences in task performance. For example, older adults who may be experiencing cognitive and psychomotor declines may have slower and more variable reaction times compared to younger adults [47], [48], [49]. However, our participants only represented college students between the ages of 18-27. Future studies may include a wider range of ages, including both older and middle-aged drivers with varied driving experience.

V. CONCLUSION

This study examined the effects of meaningful tactile signal type and pattern on reaction time, information interpretation accuracy, and subjective satisfaction during semi-autonomous driving. The results showed shorter reaction times and higher intuitive ratings for higher urgency patterns, compared to lower urgency patterns. In addition, pedestrian status warning and headway reduction signals were associated with shorter reaction times and higher confidence rating, compared to other tactile signal types (i.e., the surrounding vehicle, the over the speed limit, the speed warning, and the navigation signals). Moreover, surrounding vehicle and navigation signal types were correlated with higher accuracy of information interpretation compared to the other four signal types. Lastly, this study has shown that participants may be able to interpret multiple meaningful tactile displays in a continuous driving task. Follow-up studies may continue examining the interpretation speed and accuracy in more realistic settings. The findings of this study will be used as preliminary data for future studies that aim at investigating the effects of meaningful tactile displays on automated vehicle takeover performance in complex situations (e.g., urban areas), where actual takeover performance will be measured, and may inform the design of next-generation in-vehicle human-machine interfaces.

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