Using Advanced Driving Simulation and Vibrotactile Cues to Train Drivers to Interact with Next-Generation Autonomous Vehicles

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1. Introduction

There are six levels of vehicle automation, from Level 0 – no automation to Level 5, fully autonomous [1]. According to several projections, the majority of vehicles on the road will be at intermediate levels for the next several years, meaning that vehicle-to-human takeover will be required in cases where the systems can no longer function due to design limitations, such as under poor weather conditions or in a construction zone [2], [3]. As shown in Fig. 1, the takeover process consists of signal response and post-takeover phases, which involves multiple steps, including perceiving the takeover requests (TOR), moving hands and foot to prepare for manually controlling the vehicle, asesssing information in the driving environment, strategizing maneuvering plans, and executing actions. The process generally lasts a few seconds and could be very challenging if drivers are engaged in non-driving-related tasks [4] that utilize visual and auditory resources that results in them being out-of-the-loop. In this case, Multiple Resource Theory (MRT) [5] posits that drivers' ability to process critical warning information, i.e., a TOR presented via the visual/auditory channels, may be negatively impacted. Therefore, information in the driving environment, that should be acknowledged by drivers, could be conveyed in a more available sensory channel, i.e., the tactile modality. However, given that information presented in the tactile channel can appear in many (complex) formats with different associated meanings [6], [7], it is critical to assess drivers' ability to comprehend meaningful tactile patterns and determine its effectiveness on drivers' takeover performance.

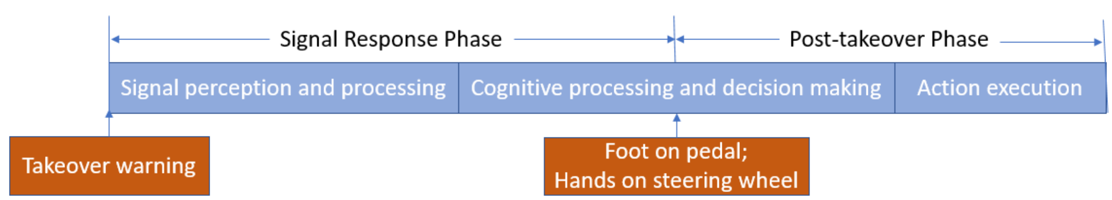

Fig. 1. The takeover model (from [8])

The goal of this project was to investigate the effects of meaningful tactile patterns on automated vehicle takeover performance. In particular, vibrotactile devices were embedded into the seat pan and seatback of a medium-fidelity simulated vehicle. The patterns represented two formats: informative (i.e., communicating the status of surrounding vehicles or obstacles) and instructional (i.e., commanding particular maneuvering actions such as driving into left/right lanes).

Participants were required to complete a series of takeover events, where meaningful tactile patterns served as takeover requests.

2. Methods

Forty volunteers from Purdue University (IRB Protocol #: 1802020214) participated in this study (mean age = 23 years, range: 19 – 30). All participants possessed a valid U.S. driver's license. Experiment equipment included: a medium-fidelity driving simulator, miniSim, developed by the National Advanced Driving Simulator (NADS) (Fig. 2), and a seat embedded with a total of 14 C-2 tactors (Fig. 3, 1'' × 0.5'' × 0.25'' piezo-buzzers developed by Engineering Acoustics, Inc.).

Fig. 2. Experimental setup (the picture is from [8])

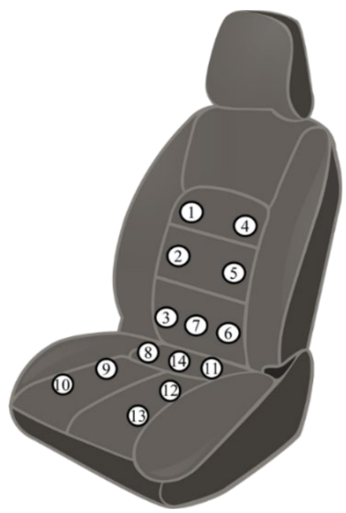

Fig. 3. Distribution of tactors

Participants were required to ride in a simulated SAE Level 3 automated vehicle in the middle lane of a three-lane highway at 60 mph. They did not have to drive since the automation was on. Occasionally, a construction zone appeared ahead of the subject vehicle. In this case, the subject vehicle would send a takeover request (TOR) using meaningful tactile patterns; for example, an instructional tactile pattern would serially vibrate tactors #s 11 → 14 → 8 (seat pan) or #s 6 → 7 → 3 (seatback) to instruct drivers to move into the right adjacent lane in order to avoid both the construction zone as well as an approaching vehicle behind from the left adjacent lane. In contrast, an informative tactile pattern would serially vibrate tactors #s 11 → 12 → 13 (seat pan) or #s 6 → 5 → 4 (seatback) to indicate the same action (see Fig. 4 for one example scenario). After receiving the pattern, drivers were required to follow the information represented in the pattern to take over and manually control the vehicle as they would in real-life driving until they passed the construction zone. Afterwards, they needed to move back to their original (center) lane and reactivate the automation. A baseline signal pattern (3, 6, 8, and 11 vibrated altogether on both the seatback and seat pan, i.e., for takeover warning purposes only) was used to compare performance metrics in this condition to those in the meaningful tactile patterns and locations. Takeover performance was measured using the TOR response time (i.e., time between the presentation of the tactile signal and time to start braking), TOR information processing time (i.e., time between the onset of the tactile signal and time to initiate a lane change), and maximum resulting acceleration (i.e., takeover comfort or quality during the manual driving phase [9]). Additionally, drivers' perceived usefulness and satisfaction ratings on tactile patterns were also measured [10].

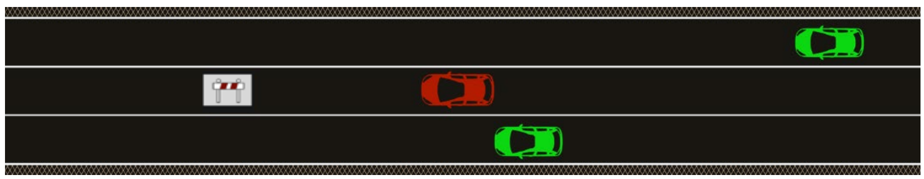

Fig. 4. One example takeover scenario: subject vehicle (red) needed to move into the right adjacent lane to avoid both the construction zone (grey icon) and an approaching vehicle behind from the left adjacent lane (green vehicle)

3. Results

For TOR response time, meaningful tactile patterns on either the seatback or seat pan had the longer response times compared to the baseline condition. This finding may be due to the amount of information that needed to be processed. For example, meaningful tactile patterns convey not only warning information (i.e., the need to takeover), but also information about the driving environment as well as instructions for maneuvering the vehicle. Thus, drivers could have needed more time to process this information compared to only warning information in the baseline tactile condition.

No main effects of signal information type (informative vs. instructional) nor location (seatback and pan) on information processing time were found, suggesting that the differences observed in response times between meaningful and baseline signals did not sustain throughout the information processing phase. One possible reason for this finding could be that the differences in TOR response time were mitigated overtime in the signal response phase. In other words, the effects of TOR information type or location were only shown during the attention capturing phase. Once drivers perceived the need to takeover, they might no longer rely on the signals to process the information.

With respect to maximum resulting acceleration, meaningful tactile signals presented on the seat back and pan had a larger value compared to the baseline signal, indicating a poorer takeover quality. Further analysis revealed that this difference only existed when the signal was instructional (i.e., commanding maneuvering actions). One possible explanation for this phenomenon is that drivers might have had lower situation awareness [11] when presented with instructional signals, since they only followed the command without fully processing the information in the driving environment. On the other hand, drivers with informative signals may learn more about the driving environment, resulting in higher situation awareness and better overall takeover control.

Finally, drivers perceived tactile patterns presented on the seatback to be more useful and satisfying compared to the seat pan. One possible reason could be that drivers considered vibrations in the seat pan to be more invasive (based on participants' self-reports) than in the seat back [12].

4. Significance and impact

The findings of this project contribute to the literature in human-machine interface (HMI) and haptics, which could be used to guide future research involving complex automated systems. Results may also aid research communities in informing models of human perception and performance that can generalize to other environments, such as aviation.

This study also has broader implications for the design of various HMIs in complex domains, such as provide engineers and designers with guidelines for designing HMIs to facilitate effective information communication between operators and systems.

5. Where might this lead?

The meaningful tactile patterns used in this study only represent two types of information presentations in automated systems. Future work may design other types of patterns that can convey more complex information and messages similar to how human communicates in verbal language, to enable humans to make decisions when their visual and auditory channels are occupied. Secondly, this work can be expanded to assess the use of tactile displays in other application domains, such as aviation and healthcare. Finally, the participants in this study were all college students. Follow-up work may seek to include participation from other potential user groups, such as the aging population and individuals with disabilities.

6. Publications Stemming from the Fellow's Efforts

Huang, G., & Pitts, B. J. (In preparation). Effects of Meaningful Tactile Signaling in Automated Vehicle Takeover Performance (the title is subject to change). Targeted journal: *Transportation Research Part C: Emerging Technologies*

Huang, G., Hung, Y. H., Proctor, R. W., & Pitts, B. J. (In preparation). Exploring the Relationships Between Age, Autonomous Vehicle Acceptance, and Self-perceived Driving Ability: A Crowdsourcing Study (the title is subject to change). Targeted journal: *Transportation Research Part C: Emerging Technologies*

Huang, G., Hung, Y. H., Proctor, R. W., & Pitts, B. J. (2021). Non-Chronological Age Factors and Self-perceived Driving Abilities: A Survey Study of Autonomous Vehicle Acceptance. *Technology, Mind and Society Conference*. (Accepted)

7. How did the Fellowship make a difference?

The Fellowship enabled me more flexibility to work full-time on my own research instead of serving as a graduate research/teaching assistant. Even though the COVID-19 pandemic impacted some milestones of this research, namely the recruitment of older adult drivers, permission was given by the Link Foundation Fellowship office to proceed with only younger adults. This particular challenge helped me to grow as a scholar because I was required to strategize and implement contingency plans. Overall, I gained incredible research experiences and ultimately became a better researcher as a result of being a Link Foundation Fellow. I will continue my research program at San Jose State University as an Assistant Professor.

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