# Design of On-body Tactile Displays to Enhance Situation Awareness in Automated Vehicles

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***Abstract*—Fatalities with semi-automated vehicles typically occur when users are engaged in non-driving related tasks (NDRTs) that compromise their situational awareness (SA). This work developed a tactile display for on-body notification to support situational awareness, thus enabling users to recognize vehicle automation failures and intervene if necessary. We investigated whether such tactile notifications support "event detection" (SA-L1) or "anticipation" (SA-L3). Using a simulated automated driving scenario, a between-groups study contrasted SA-L1 and SA-L3 tactile notifications that respectively displayed the spatial positions of surrounding traffic or future projection of the automated vehicle's position. Our participants were engaged in an NDRT, i.e., an Operation Span Task that engaged visual working memory (WM) resources. They were instructed to intervene if the tactile display contradicted the driving scenario, thus indicating vehicle sensing failures. On a single critical trial, we introduced a failure that could have resulted in a vehicle collision. SA-L1 tactile displays of potential collision targets resulted in less subjective workload on the NDRT than SA-L3, which indicated the vehicle's future actions. These findings and qualitative questionnaire suggest that the simplicity of SA-L1 display required less mental resources, which allowed participants to better interpret sensing failures in vehicle automation.**



***Index Terms*—Automated Driving, Situation Awareness, Tactile Feedback, Non-driving-related-task (NDRT), Driver Behavior, Takeover request**


## I. Introduction

Driving automation has transformed how we use and interact with our cars. Continued progress in automation will not only improve driving safety but is expected to enable the user to perform non-driving related tasks (NDRTs; e.g., reading) [1]. The Society of Automotive Engineering (SAE) defines six levels of vehicle automation. Beyond fully manual vehicles (SAE 0), function-specific systems such as Adaptive Cruise Control are dominant (SAE 1). Popularized so-called "self-driving" vehicle (e.g., Tesla Model 3) continue to require the vehicle user to monitor the road (SAE 2) and truly automated driving solutions can take place without driver oversight under specific driving modes (e.g. low speed traffic jam, closed campus operations; SAE 4) or under any condition (SAE 5). SAE 3 poses the greatest challenge to engineering as it specifies shared responsibility between the automated vehicle (AV) and its user, whereby the user is considered to be the fallback system when the vehicle fails to monitor the driving environment accurately. In fact, AV fatalities currently occur because users treat SAE 2 vehicles like SAE 3 vehicles and, hence, are unable to serve as an effective fallback system [2]. There is an inherent risk in shared responsibility between users and AVs (SAE 1-3), because they allow users to possess a false belief of the AV's responsibilities and capabilities [3].

Although users of SAE 2 vehicle are expected to monitor the driving environment, they are typically engaged with NDRTs instead [1]. Here, activities such as working, smartphone browsing, gaming and more, are likely NDRTs when driving in an AV [4]. When users are highly engaged in NDRTs, they suffer from a loss of Situational Awareness (SA) to the surrounding traffic. SA refers to the ability to perceive elements of the environment, comprehend their meaning and predict their status in the near future [2]. If the driver is engaged in NDRTs, this would mean disengaging from one task and engaging back into driving-related tasks. Low SA in such situations typically results in a delayed and insufficient response by the user when a takeover request (TOR) is expected and in increased mental workload [5]. Therefore, to omit accidents, Semi-automated vehicles (SAE 1-3) users must retain some SA to intervene when vehicle automation fails.

Display interfaces have been proposed to support the SA of users. Typically, they rely on auditory, such as hazard-related cues [6], or visual signals, such as visual ambient displays [7]. However, a surfeit of visual and auditory information that compete with NDRTs' requirements [4] could limit their effectiveness. Therefore, tactile displays have been proposed instead [8]. Tactile displays, which communicate information of the surroundings with vibrating actuators, have several advantages over auditory or visual displays. First, tactile stimuli are known to direct user attention faster and decode spatial information better than other modalities [8]. Second, they perform better in direct comparison with other sensory modalities to support intervention in critical scenarios [9]. Third, tactile stimuli are

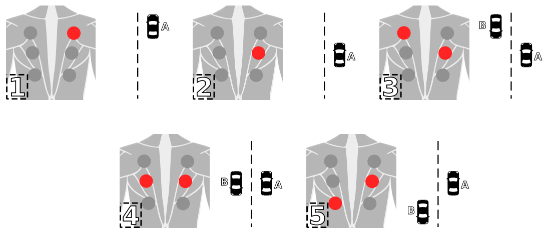



Fig. 1: SA-L1 display: Tactile information is rendered according to the AV's perception of surrounding cars.

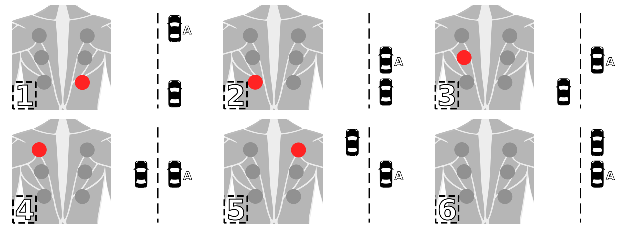



Fig. 2: SA-L3 display: Tactile information is rendered according to future positions of the automated car.

also well-liked by drivers [10].

How can one design tactile displays for AVs? At lower levels of automation (i.e., SAE 1), vibrotactile stimuli could be displayed through the brake pedal [10] or the steering wheel [11]. However, AV users drivers are unlikely to touch these controls at higher levels of automation [12]. Therefore, tactile displays could be integrated into the seat or worn while driving, directly communicating to the driver's body. Integrated tactile displays can suffer from lack of contact to the body or may present spatial information ambiguously (e.g. the driver may mistake a push on the rear-seat for a signal). Therefore, research on tactile displays has moved towards wearable tactile displays that directly encode information on the user's body.

Even if tactile displays are suitable for supporting user SA in the AV context, the information that they should communicate remains unclear. According to Endley's model of SA, SA allows drivers to detect potential risk (Level 1; SA-L1), comprehend it (Level 2; SA-L2), and to anticipate the consequence of its manifestation (Level 3; SA-L3) [2]. Even tough such levels are highly interdependent, they are functionally distinct [**?**]. Operationally speaking, designing tactile displays for comprehension might lead to ambiguity as opposed to displaying either collision targets or future actions of the AV. In this study, we ask: Should AV users be informed of the AV's "perception" of its surroundings (SA-L1) or what the AV will do (SA-L3)?

Functional independence of SA levels allows for two alternative predictions. If the AV user retains some perceptual awareness of the driving scene (SA-L1) even while performing NDRTs, then displaying non-redundant information on the AV's future behavior with tactile cues (SA-L3) would allow the user to directly evaluate the AV's potential actions and reject erroneous actions more effectively. On the other hand, if the driver is minimally aware of the surrounding traffic (i.e., SA-L1), then displaying the vehicle's "perception" of potential risks is necessary prior to evaluate whether or not the AV is likely to act erroneously. The preferred tactile display could be determined by looking at user success in intervening when the tactile display conflicts with reality and the perceived workload of NDRTs. Therefore our research question is: Should we design on-body tactile displays in AVs for SA-L1 or SA-L3 ?

## II. Study Aims

The goal of this study is to compare two on-body tactile displays designed to enhance SA of AV users at either Level 1 or Level 3 SA. These new displays were evaluated in terms of how well they support an emergency intervention and user SA. A tactile display designed for SA-L1 communicates the AV's perception of headway and oncoming vehicles, namely the spatial positions of neighboring traffic relative to the user's vehicle.Instead, a SA-L3 tactile display communicates the AV's projection of future events. Thus, it communicates the intended maneuver of the vehicle. We evaluated the two tactile displays on four aspects, namely (I) performance in a driver-initiated emergency intervention, (II) overall subjective workload (NASA-TLX) [13] and (III) self-reported situational awareness (Situation Awareness Rating Technique; SART) [14]. We supplemented these with (IV) a qualitative questionnaire on the tactile displays.

## III. Implementation of On-Body Tactile Displays

Our system projects the road situation in the upper region of the participant's back by tactile feedback. Previous work placed actuators on the driver's seat [**?**]. In contrast, we display direct feedback via a vibrotactile vest that stimulates the user's upper-back allowing for flexible prototyping and adaptation to the user's anatomy.

### A. Tactile display

As a new tactile analogy, the AV's status on the road was encoded into tactile information by mapping the two lanes of the road as an actuator matrix (2x3) in our vest. As in [15], we used a spatially compatible pattern. This approach provides more accurate and faster responses [16] than a spatially continuous signal, which may cause discomfort, a higher habituation rate, and increased workload [17]. Our pattern is also dynamic, as dynamic patterns [18] have been shown to yield higher preference and recognition rates in comparison to non-dynamic patterns. The lower right actuator represents the AV (users' car) and its position on the road (see Figure 1). Information related to a nearby 'sensed' vehicle is rendered in the remaining actuators. The stimuli are rendered only when a different vehicle is within a distance of 300 m from the AV. Other vehicles are displayed in relation to the AV position (bottom right). The stimuli deactivate after a successful overtake. The activation parameters for the remaining actuators depends on whether it is targeted to support SA-L1 and SA-L3, respectively:

*SA-L1*: the information encoded in the tactile feedback describes the position of the other sensed vehicle(s) on the road (see Figure 1). In the absence of oncoming cars on the left lane, the vibration rendered on the top and the middle right actuator gives information about the car in front (see Figure 1: Signal 1 and 2). When the automated car begins to overtake, the actuators deactivate unless a car is oncoming on the left lane. In such a case, the device renders the signals 3, 4, and 5 (see Figure 1) to inform the position of the oncoming vehicle.

*SA-L3*: the information displayed describes a projection in the future and based on user's AV route: for example, waiting behind vehicle A before overtaking, and then switching to the left lane (see Figure 2). In contrast to SA-L1, we only render information about the participant's AV. Therefore, tactile stimulation will remain at position 1 (see Figure 2: Signal 1) when another vehicle is passing in oncoming traffic until the left lane is free. Otherwise, the user's AV will overtake and the tactile display observes the sequence of Figure 2.

## IV. User Study

The current study employed a between-groups design to manipulate the factor of *SA display* across two levels (SA-L1 vs SA-L3). Participants were engaged in a NDRT (i.e., Working Memory Operation Span Task [19]).Twenty-five participants voluntarily participated, but 4 participants were be excluded from the analysis due to technical errors or health issues. This resulted in 12 participants who experienced the SA-L1 tactile display and 9 participants, the SA-L3 tactile display ($M_{age} = 23.86$, $SD_{age} = 2.24$). They self-reported driving a mean mileage of 846.9 km per year ($SD = 137.7$), and their mean driving experience was 4.19 years ($SD = 2.05$). All participants provided written informed consent and received monetary compensation of 10 euros. Data are available on the DaRUS Open Data platform, at this link: https://doi.org/10.18419/darus-2824 and Virtual Reality simulated driving scenarios on GitHub[1].

### A. AV Driving Scenario

The driving simulation was modeled after [20]. Participants were the fallback system of a SAE Level 3 vehicle and could use an emergency foot-pedal to disrupt vehicle automation if it failed to respond to neighboring traffic appropriately. To maintain vigilance, participants were instructed that the AV could initiate takeovers, which did not actually occur.

The AV traveled on a two-lane road. A trial always began with the appearance of either a headway vehicle that traveled slower (36 km/hr) than the AV (108 km/hr) or an oncoming vehicle (108 km/hr) on the opposing lane. If the AV encountered a headway vehicle, it would perform an overtaking maneuver via the opposing lane. However, it would slow down and delay overtaking if it detected an oncoming vehicle on the opposing lane. Oncoming traffic could also occur in the absence of headway vehicles. These three encounters posed no danger to the AV user and were repeated seven times each in random order, resulting in a total of 21 trials without the need for user intervention. After the 21 trials, the experiment ended with one critical scenario, namely the AV overtakes the headway vehicle and fails to detect an oncoming vehicle.

[1] https://github.com/FrancescoChiossi/Supporting-SA-in-AV

(a) Setup1

(b) Setup 2

Fig. 3: The experiment set-up. The experiment is conducted in a fixed-base driving simulator displaying the automated driving simulation. The secondary task is running on a mounted tablet in a comfortable position.

### B. Working Memory Operation Span Task

A WM operation span task was chosen as the NDRT [19]. This is a standardized task that recruits WM resources as described in [21]. This task alternately required the participants to verify the correctness of a mathematical equation and to memorize the presented items(i.e., letters). This provided for two dependent measurements: accuracy in the operation task termed Attention Interference (AI) (e.g. evaluation of the correctness of the equations), and the accuracy in reporting the letters termed Working Memory Interference (WMI). SA-L1 participants reported an AI accuracy of 94.8% and WMI accuracy of 82.1 % while SA-L3 accuracy of 92.1% and 85.4%, respectively. No significant differences were detected between the tactile displays for NDRT performancee either for AI ($t(17) = 1.444$, $p = .219$) and WMI ($W = 37$, $p = 0.22$).

### C. Apparatus

The simulation system features two major components; an AV simulation (see Figure 3), used for control and visualization, and a vibrotactile vest that provides directly a on-body tactile display.

*1) AV simulation:* The driving simulation was programmed with Unity 3D Version 2019.1, which was presented via a low-fidelity driving simulator with a steering wheel and foot pedals, and an LCD widescreen (42", resolution: 1920x1080 pixels, 60Hz). The NDRT was presented on a Samsung Galaxy Tab S3 tablet (9.7", resolution:2048x1536, 60Hz) with adjustable positioning, next to the simulator seat. (see Figure 3b).

*2) Vibrotactile vest:* Vehicle-to-human communication was mediated by a vibrotactile vest with six stimulation points (see Fig. 4b). The device was built on top of a commercial posture corrector, so it was ergonomically designed to be in contact

(a) Vibrotactile vest

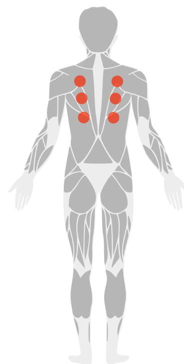

(b) Stimulated areas

Fig. 4: Tactile Setup: Red boxes on the vibrotactile vest highlight the position of the vibrotactile actuators, yellow boxes highlight the position of the processor and battery. Red circles show stimulated regions of the back, all of them placed on the upper back.

with the back of the user. Six linear resonant actuators (LRA; Pimoroni DRV2605L) were placed inside the vest, spaced 55 millimeters in the upper back (see Fig. 4a), slightly above the just noticeable difference tactile threshold of 45 to 50 mm [22]. LRA drivers guarantee a resonant frequency of 250 Hz during the stimulation, which coincides with Pacinian receptors' optimal sensitivity [23].

### D. Procedure

Upon arrival, participants received a written briefing on the experimental procedure and the assigned feedback condition. Next, they wore the tactile vest and entered the cockpit of the driving simulator. To familiarize with the simulation, participants were presented two blocks of 15 practice NDRT trials with feedback while experiencing six trials of the driving simulation where the AV worked flawlessly. All participants confirmed that they perceived the tactile display. After training, participants completed the experimental session. After completing the driving simulation, the SART, the NASA-TLX, and the qualitative questionnaire were administered.

## V. Results

SA-L1 and SA-L3 tactile display designs were compared in terms of intervention performance, perceived NASA-TLX workload, SA as measured by the SART, and qualitative reports on the distractability of the display, the discernability of tactile signals, and overall acceptance. Classical statistical inference ($\alpha$ = .05) was supplemented with Bayes Factors (BFs). This was done to establish the equivalence of the designs on some of the dependent variables, which amounts to confirmatory testing of the Null-hypothesis [24][2].

[2] A default prior of Cauchy = 0.707 was used for all analysis, which amounts to a very weakly informative prior that penalizes BF for especially large differences, i.e., the case of a t-test. A prior sensitivity analysis was performed by varying it from 0.507 to 0.907 in steps of 0.1. Results did not change substantially.

### A. Intervention performance

In the driving scenario, two erroneous types of braking actions were possible: false positives, namely braking in any non-critical situations, and misses, namely no braking in the critical scenario. There were only two false positives throughout all sessions; only two participants used the brake once in a non-critical situation. Therefore false positives were omitted from further analysis. In total, seven out of twelve participants in the SA-L1 and four out of nine participants in the SA-L3 braked in the critical situation. A chi-square test of independence showed no significant association between SA Level and emergency braking, $\chi^2(1, 19) = 0.398$, $p = 0.52$.

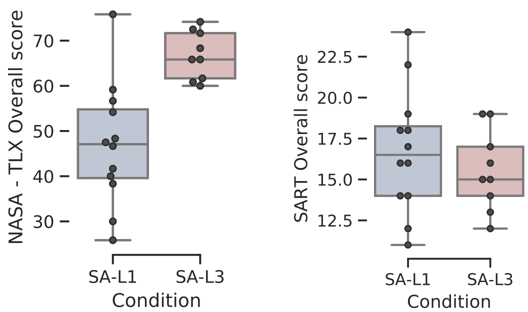
Time To Collision (TTC) was analyzed via a chi-square test of independence which did not significantly differ from the expected frequencies, $\chi^2(1, 19) = 0.43$, $p = 0.50$ for TTC and SA Level. Only three participants successfully intervened to prevent the accident, resulting in a TTC $>$ 1.5 s, all of which were assigned to SA-L1. Bayesian contingency table analyses demonstrated that TTC ($BF_{01}$ = 3.039) did not vary across conditions as the Null-hypothesis is three times as likely as the alternative hypothesis.

### B. Subjective Workload

Workload was measured by NASA-TLX. NASA-TLX scores for the two conditions were normally distributed, as assessed by Shapiro-Wilk's test ($W$ =0.953, $p$ = .391) and submitted to a *t-test*. Participants strongly differed in their perceived workload, $t$(19) = - 4.125, $p$ <.001, $d$ = 1.819. Participants assigned to SA-L1 condition ($M = 47.01$, $SD = 13.53$) reported lower workload than those in the SA-L3 condition ($M = 66.75$, $SD = 5.27$). This large [25] effect of $d$ = 1.81 can be considered substantial and all participants (n = 9) in SA-L3 condition were well above the mean/median of participants in condition SA-L1. Here, a Bayesian $t$ test, indicated evidence for H1: specifically, $BF_{01}$=45.205, which means that the data are approximately 45 times more likely to occur under H1 than under H0. This result indicates very strong evidence in favor of H1 [24] (see Fig. 5a).

### C. Situational Awareness

An independent samples t-test was conducted on SART questionnaire scores to assess Situational Awareness across conditions, given no significant deviation from normality as measured by Shapiro-Wilk test ($W$ = 0.965, $p$ $>$ .05). The test was not statistically significant, $t$(19) = 0.082, $p$=.42 as participants from SA-L1 condition ($M$ = 16.750, $SD$ = 3.817) and from SA-L3 condition ($M$ = 15.556, $SD$ = 2.455) both produced similar overall SA scores. The effect size is defined as small, giving a $r_{rb}$ = 0.167. Lastly, a Bayesian $t$ test, indicated that it was more than twice times as likely that there was no significant difference, $BF_{01}$ = 2.279. Nonetheless, the amount of information in favor of the Null hypothesis was small (see Fig. 5b).




(a) NASA (b) SART

Fig. 5: Overall workload (NASA-TLX score) and Situational Awareness (SART score) perceived by the participants when using the on-body tactile notification display designs. SA-L1 led to significantly less perceived workload than SA-L3.

### D. *Qualitative Questionnaire*

The questionnaire consisted of nine questions on distractibility of the vest (2), discernability of the tactile patterns (2), acceptance for real-car usage(1), usability (3) and general feedback (1). Regarding distractability, 9 participants affirmed they divided their attention, either constantly having "an eye on the road," of which 6 of them belonged to the SA-L1 condition. Four, across conditions, felt distracted from the tablet task by the tactile stimulation, two of which found the tactile display useful nevertheless. When asked to report display and the discernability of the vibrations, the majority (n = 14) of participants stated that the display of the tactile stimulation was understandable (eight from SA-L1 condition), nevertheless 16 participants (seven from SA-L1 and nine from SA-L3) expressed difficulties in differentiating vibrations from the individual motors and thus discerning the position of other cars or their car. On device acceptance, six participants (two from SA-L1 and four from SA-L3) showed reluctance towards real-world usage. Considering the usability from the tactile display, 13 participants (seven from SA-L1 and six from SA-L3) stated that they entirely relied on the tactile feedback to keep track of the road and did not look on the road often. At the same time, only three participants from the SA-L3 condition stated that they ignored the feedback by the vest because they did not find it reliable. Of the 21 individuals, 16 indicated that they looked less on the road than they would have without the vest. This suggests that the tactile vest could have induced over-reliance on vehicle automation instead of its intended aims, namely to increase SA. Usage preferences were conditional on specific circumstances, e.g., only in AVs or adverse environmental conditions.

## VI. Discussion

Two on-body tactile displays to promote SA in AV users were designed and evaluated. Our displays could either communicate what the AV 'perceives' or how it would 'act', supporting AV users to recognize failures in the vehicle's ability to identify collision targets or to move safely.

Results from the NASA-TLX endorse further development in tactile SA-L1 displays that support the detection of AV errors in identifying the presence or absence of a collision target. SA-L1 and SA-L3 designs were not significantly different from one another in terms of intervention performance or qualitative statements. Still, it is worth noting that all the participants who managed to perform a successful emergency intervention benefited from a SA-L1 display, whilst no SA-L3 display users managed a successful intervention.

Differences in perceived NDRT workload between SA-L1 and SA-L3 designs can be explained by how information is stored in working memory (WM). WM is supported by perceptual processes, long-term memory, and action. It is essential for building and updating an efficient situation model of the driving scene [1]. Our results of increased perceived workload for SA-L3 could reflect that storing information about future possibilities consumes more working memory resources, which results in a demanding user experience with no added safety benefit. Processing SA-L3 information may involve retrieving pattern schemas of potential risk maneuvers, from long-term memory, to support a risk assessment of the AV's anticipated maneuver [2]. This interpretation can be strengthened when looking at our data on emergency braking. Only drivers that used the SA-L1 display successfully managed to brake and avoid a collision. When WM is engaged, drivers may struggle to perceive future behavior of other vehicles, leading to inadequate comprehension and lack of proper takeover [26]. Thus, displays that depict SA-L1 information might only draw on perception and spatial resources [2] of WM rather than WM mechanisms that include long-term memory with schemas of vehicle behavior. Supporting SA-L1 might make drivers less susceptible to NDRTs interference and more attentive to the situation on the road.

Qualitative feedback did not clearly distinguish between our SA-L1 and SA-L3 tactile displays implementations. Nevertheless, more participants who experienced SA-L1 feedback favored adopting tactile feedback as a SA support in a AV context, especially in high-risk situations.

Future work could address some current limitations, concerning the tactile display design and the generalizability of our findings to real-world situations. First, tactile habituation can be problematic if tactile feedback is presented too frequently [27]. Participants experienced the tactile stimuli for approximately 30 minutes in the study, occasionally interrupted by the tablet training blocks. Road trips might be more prolonged, even featuring more than two lanes or critical scenarios so habituation effects could be more common. Second, we report increased workload associated with SA-L3 tactile display. SA-L3 might inherently require more complicated patterns, diminishing user's SA not only of the driving scene but of the tactile feedback itself, which needed to be continuously interpreted. Future work should explore alternative SA-L3 patterns or efficiently deliver information to support scene comprehension (SA-L2). Third, as our results are supported by subjective measures, a multidimensional SA evaluation would benefit from central and peripheral psychophysiological monitoring [28]. This is in line with future implementation in AVs of ubiquitous sensing and integration within the driving experience to infer user's state [29]. Lastly, our study took place a fixed-based simulator without motion cues. Previous studies have shown that AV users can be sensitive to motion trajectories [30] and road bumps [31]. Thus, on-body tactile displays might be more effective in supporting SA in real-world scenarios that provide motion cues.

## VII. Conclusions

This work proposed on-body tactile displays to support drivers' SA for driver-initiated emergency takeovers. Two feedback designs delivering information on the AV's "perception" or AV's future state were evaluated. On-body tactile notifications supporting SA-L3 result in a higher workload rather than reducing it. Given the positive feedback received in terms of usability and acceptance, lower-level information, i.e., SA-L1, might be more appropriate via the tactile channel in an automated driving context. Tactile notifications can, therefore, be considered a promising and viable alternative to SA support in automated vehicles.

## VIII. Acknowledgments

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## References

[1] M. Baumann and J. F. Krems, "Situation awareness and driving: A cognitive model," in *Modelling driver behaviour in automotive environments*, pp. 253–265, Springer, 2007.

[2] M. R. Endsley, "Situation awareness in future autonomous vehicles: Beware of the unexpected," in *Congress of the International Ergonomics Association*, pp. 303–309, Springer, 2018.

[3] C. P. Janssen, L. N. Boyle, A. L. Kun, W. Ju, and L. L. Chuang, "A hidden markov framework to capture human–machine interaction in automated vehicles," *International Journal of Human–Computer Interaction*, 2019.

[4] F. Roche, A. Somieski, and S. Brandenburg, "Behavioral changes to repeated takeovers in highly automated driving: effects of the takeover-request design and the nondriving-related task modality," *Human factors*.

[5] F. Tanshi and D. Söffker, "Modeling of takeover variables with respect to driver situation awareness and workload for intelligent driver assistance," in *2019 IEEE Intelligent Vehicles Symposium (IV)*, pp. 1667–1672, IEEE, 2019.

[6] T. J. Wright, R. Agrawal, S. Samuel, Y. Wang, S. Zilberstein, and D. L. Fisher, "Effects of alert cue specificity on situation awareness in transfer of control in level 3 automation," *Transportation research record*, vol. 2663, no. 1, pp. 27–33, 2017.

[7] S. S. Borojeni, L. Chuang, W. Heuten, and S. Boll, "Assisting drivers with ambient take-over requests in highly automated driving," in *8th AutoUI International Conference*, 2016.

[8] M. S. Prewett, L. R. Elliott, A. G. Walvoord, and M. D. Coovert, "A meta-analysis of vibrotactile and visual information displays for improving task performance," *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, 2011.

[9] R. Mohebbi, R. Gray, and H. Z. Tan, "Driver reaction time to tactile and auditory rear-end collision warnings while talking on a cell phone," *Human Factors*, 2009.

[10] H. De Rosario, M. Louredo, I. Díaz, A. Soler, J. J. Gil, J. S. Solaz, and J. Jornet, "Efficacy and feeling of a vibrotactile frontal collision warning implemented in a haptic pedal," *Transportation research part F: traffic psychology and behaviour*, 2010.

[11] D.-B. Vo and S. Brewster, "Investigating the effect of tactile input and output locations for drivers' hands on in-car tasks performance," in *12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 2020.

[12] A. Telpaz, B. Rhindress, I. Zelman, and O. Tsimhoni, "Haptic seat for automated driving: preparing the driver to take control effectively," in *7th AutoUI International Conference*, 2015.

[13] S. G. Hart and L. E. Staveland, "Development of nasa-tlx (task load index): Results of empirical and theoretical research," in *Advances in psychology*, vol. 52, pp. 139–183, Elsevier, 1988.

[14] S. J. Selcon and R. Taylor, "Evaluation of the situational awareness rating technique(sart) as a tool for aircrew systems design," *AGARD, Situational Awareness in Aerospace Operations*, 1990.

[15] J. Morrell and K. Wasilewski, "Design and evaluation of a vibrotactile seat to improve spatial awareness while driving," in *2010 IEEE Haptics Symposium*, pp. 281–288, IEEE, 2010.

[16] R. W. Proctor and T. G. Reeve, "Research on stimulus-response compatibility: Toward a comprehensive account," in *Advances in psychology*, vol. 65, pp. 483–494, Elsevier, 1990.

[17] F. Al-Shargie, U. Tariq, H. Mir, H. Alawar, F. Babiloni, and H. Al-Nashash, "Vigilance decrement and enhancement techniques: a review," *Brain sciences*.

[18] M. Schwalk, N. Kalogerakis, and T. Maier, "Driver support by a vibrotactile seat matrix–recognition, adequacy and workload of tactile patterns in take-over scenarios during automated driving," *Procedia Manufacturing*, vol. 3, pp. 2466–2473, 2015.

[19] A. R. Conway, M. J. Kane, M. F. Bunting, D. Z. Hambrick, O. Wilhelm, and R. W. Engle, "Working memory span tasks: A methodological review and user's guide," *Psychonomic bulletin & review*.

[20] S. Faltaous, M. Baumann, S. Schneegass, and L. L. Chuang, "Design guidelines for reliability communication in autonomous vehicles," in *Proceedings of the 10th international conference on automotive user interfaces and interactive vehicular applications*, pp. 258–267, 2018.

[21] T. von der Malsburg, "Py-span-task–a software for testing working memory span.(june 2015)," 2015.

[22] S. Weinstein, "Intensive and extensive aspects of tactile sensitivity as a function of body part, sex and laterality," *The skin senses*, 1968.

[23] X. Evagoras, A. Banu, and P. Nurgeldy, "Audiotactile integration in the pacinian corpusclel's maximum sensitivity frequency range," *Attention, Perception, & Psychophysics*, vol. 82, no. 6, pp. 3250–3257, 2020.

[24] D. van Ravenzwaaij, R. Monden, J. N. Tendeiro, and J. Ioannidis, "Bayes factors for superiority, non-inferiority, and equivalence designs," *BMC medical research methodology*, vol. 19, no. 1, pp. 1–12, 2019.

[25] J. Cohen, "The effect size index: d," *Statistical power analysis for the behavioral sciences*, vol. 2, pp. 284–288, 1988.

[26] K. Mühl, T. Stoll, and M. Baumann, "Look ahead: understanding cognitive anticipatory processes based on situational characteristics in dynamic traffic situations," *IET intelligent transport systems*.

[27] A. P. Van den Beukel, M. C. van der Voort, and A. O. Eger, "Supporting the changing driver's task: Exploration of interface designs for supervision and intervention in automated driving," *Transportation research part F: traffic psychology and behaviour*, vol. 43, pp. 279–301, 2016.

[28] T. Zhang, J. Yang, N. Liang, B. J. Pitts, K. O. Prakah-Asante, R. Curry, B. S. Duerstock, J. P. Wachs, and D. Yu, "Physiological measurements of situation awareness: a systematic review," *Human factors*, 2020.

[29] E. Massaro, C. Ahn, C. Ratti, P. Santi, R. Stahlmann, A. Lamprecht, M. Roehder, and M. Huber, "The car as an ambient sensing platform," *Proceedings of the IEEE*, vol. 105, no. 1, pp. 3–7, 2016.

[30] S. Sadeghian Borojeni, S. C. Boll, W. Heuten, H. H. Bülthoff, and L. Chuang, "Feel the movement: Real motion influences responses to take-over requests in highly automated vehicles," in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*.

[31] S. Mayer, H. V. Le, A. Nesti, N. Henze, H. H. Bülthoff, and L. L. Chuang, "The effect of road bumps on touch interaction in cars," in *12th AutoUI International Conference*, 2018.