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The Effects of Vibration Patterns of Take-Over Request and Non-Driving Tasks on Taking-Over Control of Automated Vehicles

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ABSTRACT

Automated vehicles offer the possibility of significantly increasing traffic safety, mobility, and driver comfort, and reducing congestion and fuel emissions. Current automation technology, however, remains imperfect, and in certain situations, automation will still require the driver to suspend non-driving tasks and take back control of the automated vehicle in a limited period of time. During automated driving, drivers engaged in non-driving tasks (e.g., reading, taking a nap) may not perceive the visual or auditory take-over request in a timely nor accurate manner. Therefore, it is necessary to explore the potential of tactile warning further. This study investigates the effects of vibration patterns of take-over requests (six vibration patterns with different orders of the vibration location) and various realistic non-driving tasks (six non-driving tasks: reading, typing, watching videos, playing games, taking a nap, and monitoring the driving scenario on the driving simulator) on driver take-over behavior, and driver trust and acceptance of automated vehicles. Across all non-driving tasks, the fastest response time was observed with Vibration Pattern 5 (order of the vibration location: back–back–seat–seat). The shortest response time and largest minimum time-to-collision (TTC) also were observed when drivers took back control of the vehicle after monitoring the driving scenario. No interaction effects between vibration patterns and non-driving tasks were observed. Potential applications of the results of designing take-over requests in automated vehicles are discussed.

1. Introduction

In recent years, an increasing number of driving assistance systems have been integrated into vehicles, and the task of vehicle driving has become automated at an increasingly frequent rate. In an automated vehicle, the driver can switch his/her attention from driving tasks to non-driving tasks such as reading and texting while the vehicle is operating. However, because automation technology is still imperfect, automated driving capabilities are still largely affected by various driving conditions, such as the weather, and road type. This suggests that vehicles with self-driving automation released in the near future will be limited in capacity, and as a result, resumption of vehicle control may be a challenge due to the "out-of-the-loop" problem. Vehicle automation technology must be able to deliver takeover requests to the driver in a timely and appropriate manner.

Many existing scholarly works have demonstrated the benefits associated with the presentation of visual, auditory, tactile, and even multisensory warning information in terms of alerting and rapidly orienting driver attention towards potential danger (Baldwin, Eisert, et al., 2012; Baldwin, Spence, et al., 2012; Ferris & Sarter, 2008, 2011; Gray, 2011; Haas & Van Erp, 2014; Ho, Spence, & Gray, 2013; Ho, Spence, & Tan, 2005; Ho, Tan, & Spence, 2005; Lee,

Hoffman, & Hayes, 2004; Lee, McGehee, Brown, & Reyes, 2002; Liu & Jhuang, 2012; Meng, Ho, Gray, & Spence, 2015a, 2015b; Meng & Spence, 2015; Spence & Ho, 2008a, 2008b, 2009). Visual and auditory interfaces have been the most common modes of communication between humans and machines, and research around the effects of visual and auditory interfaces on human behavior in the vehicle is extensive (Lif et al., 2014; MacLean & Hayward, 2008; Petermeijer, De Winter, & Bengler, 2015). In the past decade, the potential utility of tactile interfaces has been increasingly investigated, and focus has been placed on potential areas of application of tele-operation (MacLean & Hayward, 2008), aviation (Lif et al., 2014), and military (Van Erp, Veltman, Van Veen, & Oving, 2003). Recently, tactile interfaces have been adopted in the automotive market, including the active gas pedal by Nissan Infinity (Mark Mulder, Abbink, Van Paassen, & Mulder, 2011), lane departure warning systems by Citroën and BMW (Spence & Ho, 2008b), driver awareness package by GM (Luft, 2013), and a forward collision warning system by Kia (Lopez, 2012). In existing research involving haptic driver assistant systems specifically, tactile stimuli were typically used in warning systems, whereas force actuation was used on the steering wheel and/or pedals in guidance systems (Petermeijer,

Abbink, Mulder, & De Winter, 2015; Petermeijer et al., 2015). Despite these developments, designs of tactile interfaces are still in their infancy, and tactile interfaces are still an underutilized opportunity for presenting information in vehicles (Jones & Sarter, 2008).

The properties of tactile signals, including frequency, amplitude, duration, rhythm, body location, and spatiotemporal patterns (Brewster & Brown, 2004), must be thoroughly understood before they may be used appropriately to convey information to a driver. Auditory signals in the ranges of 20–20,000 Hz are perceivable. However, the sensitivity of human skin to the frequency of tactile signals is much lower. Generally speaking, humans can perceive vibrations in the range of 20–1,000 Hz, but maximum sensitivity occurs in the range of 150–300 Hz (peak at ~250 Hz) (Gescheider, Bolanowski, Pope, & Verrillo, 2002; Gescheider, Bolanowski, & Verrillo, 2004; Gunther & O'Modhrain, 2003). Existing studies have also examined the discrimination of vibration frequencies using tactors on the fingertips or forearms of the body. For example, Sherrick (1985) concluded that humans could only differentiate among five levels of vibrational frequency in the range of 2–300 Hz. Rothenberg, Verrillo, Zahorian, Brachman, and Verrillo (1977) showed a discriminability of seven steps on the forearm and to 10 steps on the fingertip between 10 and 90 Hz. Pongrac (2008) found seven differentiable levels between 100 and 700 Hz. Štrbac et al. (2016) found that subjects could discriminate four frequency levels between 4 and 100 Hz. Moreover, a change in vibrational amplitude can lead to a change in perception of the frequency (Brewster & Brown, 2004). Given a certain vibrational frequency, sensitivity to the frequency will increase with increasing vibrational amplitude (Morley & Rowe, 1990).

Amplitude, or the intensity of the stimulation, can also convey information. Gunther (2001) found that vibrations ranging from 0.4 to 55 dB are perceivable, and vibrations ranging from 0.4 to 2.3 dB are only just noticeable difference of intensity detected by humans. Perception deteriorates above 28 dB (Sherrick, 1985), and pain occurs with any frequencies above 55 dB (Gunther & O'Modhrain, 2003). As well, researchers have found that no more than four different intensities may be discriminated at any one time, meaning that four or less intensities should be in use (Ballard & Hessinger, 1954).

In addition to interaction effects between vibration amplitude and frequency on sensitivity, interaction effects between amplitude and different body parts were observed (Wilska, 1954). Wilska (1954) found that maximum sensitivity to vibration occurred on human fingertips. The lowest levels of sensitivity to vibration occurred on the belly and thigh areas. Weinstein (1968) also found that the hallux and fingers possessed greater pressure sensitivity thresholds than anywhere else on the body, whereas the facial area possessed the lowest thresholds. Of note is that vibration motors should not be placed on or near the head as this can cause vibrations to be felt in the ears, resulting in unwanted sound (Gunther & O'Modhrain, 2003; Spirkovska, 2005).

The ability of accurate localization of tactile stimuli also varies among different body parts. Humans generally experience difficulty differentiating between two tactile stimuli activated in different locations within the same body part when the distance between the two stimuli is lower than a threshold (Weinstein, 1968). Researchers have suggested that the distance between two tactile stimuli must be considered when conveying information using spatiotemporal patterns. Studies conducted around providing directional information with a number of motors being activated in certain patterns in the seat and/or seat back have affirmed that finding (Tan, Gray, Young, & Traylor, 2003; Van Erp & Van Veen, 2001, 2004). However, few studies exist around the effects of vibration patterns of tactile warnings on driver behavior, especially in automated vehicles (Telpaz, Rhindress, Zelman, & Tsimhoni, 2015).

Duration of tactile information (duty cycle) can be used to encode information. Tactile stimuli shorter than 0.1 s are perceived as taps or jabs, whereas stimuli of longer duration, when combined with gradual attacks and decays, are perceived as smoothly flowing tactile phrases (Gescheider, Bolanowski, & Verrillo, 1974; Gunther, 2001; Spirkovska, 2005). Generally speaking, shorter inter-pulse interval could produce the perception of greater urgency, and thus, shorter response time (Chancey, Brill, Sitz, Schmuntzsch, & Bliss, 2014; Pratt et al., 2012; Zheng & Morrell, 2010).

In automated vehicle settings, it is also important to note that certain practical constraints must be circumvented in order for tactile interfaces to be effectively utilized, despite their advantages over modalities. First, the tactile stimuli have to be presented from those surfaces in the automated vehicle that the driver is already in contact with, such as the seat belt (Chun et al., 2013; Ho, Reed, & Spence, 2007; Ho, Tan, & Spence, 2006) and the driver's seat (Drew & Hayes, 2012; Fitch, Hankey, Kleiner, & Dingus, 2011; Lee et al., 2004). Tactile warning from the steering wheel (Chun, Han, Park, Seo, & Choi, 2012; Chun et al., 2013; Tijerina, Johnston, Parmer, Pham, & Winterbottom, 2000) or the gas/brake pedals (De Rosario et al., 2010; Lee, McGehee, Brown, & Nakamoto, 2007; Lloyd, Wilson, Nowak, & Bittner, 1999; Max; Mulder, Mulder, Van Paassen, & Abbink, 2008) used in traditional human-driven vehicles may not work effectively. As automated vehicles enable drivers to take full control of the vehicle, they can engage in non-driving tasks. The effectiveness of tactile warnings may also be reduced if the driver wears thick clothing (McGehee & Raby, 2002; Spence & Ho, 2008b).

Second, in terms of constraints, the perception of tactile stimuli could be influenced by the driver's own body movement. In automated vehicles, drivers are free to occupy themselves with non-driving related tasks, and/or to engage in and switch between different non-driving tasks. This freedom to potentially engage in many tasks may increase the driver's body movement, and, thus, aggravate the vehicle's suppression response. Therefore, the effects of vibration patterns in terms of alerting the driver to system boundary and potential collisions may be influenced by non-driving related tasks. In this study, the interaction effects between vibration patterns and non-driving tasks on drives' vehicle take-over behavior in an automated vehicle environment will be investigated.

The objectives of this research included investigating the effects of vibration patterns as well as the non-driving tasks on

drivers' vehicle take-over behavior when drivers were prompted by the automated vehicle to take control, and identifying the vibration patterns that would produce the fastest driver takeover response across different non-driving tasks.

2. Methods

2.1. Participants

Thirty-six participants (18 males, 18 females) ranging from age 18 to 49 ($M = 25.4$, SD = 7.5) years of age took part in this laboratory session. Their reported years of driving experience ranged from two years to 27 years ($M = 4.6$, SD = 3.5). All participants had normal or corrected-to-normal vision, valid driver licenses, and had driven at least once within the past month. Participants were compensated $10/hour for their study participation. Written informed consent was obtained from all participants before the study began.

2.2. Apparatus

In order to investigate how drivers interacted with automated vehicles, as well as observe their vehicle take-over behavior, a simulated automated vehicle platform was built using OpenDS (see Figure 1). OpenDS is an open source and platform-independent driving simulator software with high performance scene graph-based graphics API (OpenDS), 2016. The driving simulator was installed on a Dell Workstation (Precision T5810, Intel Xeon CPU E5-1607 v3 3.10 GHz). The driving simulator included an adjustable seat, wheel, and pedal supports, Logitech Driving Force GT® steering wheel with force feedback (Logitech Inc., Fremont, CA, USA), a throttle pedal, and a brake pedal. Driving scenarios were displayed on three LCD monitors with 3840 × 1024 pixel resolution.

The simulated automated driving system was capable of taking over full longitudinal and lateral vehicle control for a specific period, during which the driver did not have to continuously monitor the system or the road. When system boundaries were breached, the system could send out a takeover request to the driver with sufficient time to take control over the vehicle. Besides longitudinal and lateral control, the automated driving system was able to perform lane changes, as well as overtake of other vehicles on the road (which moved at slower speeds than the set speed of the subject vehicle). The automated driving system would turn off if the driver steered, or pressed the brake pedal. Additionally, at any point the driver could turn the automated driving system on and off by pushing a button on the steering wheel.

As compared to unimodal displays, multimodal interfaces enable the use of larger information bandwidth to provide more effective support for time-sharing and attention management in complex scenarios, resulting in better task performance (Baldwin, Eisert et al., 2012; Bazilinskyy, Petermeijer, Petrovych, Dodou, & De Winter, submitted; Burke et al., 2006; Oviatt, 1997; Sarter, 2002; Spence & Driver, 1997). In order to effectively draw the driver's attention back from various non-driving tasks under automated vehicle settings, multimodal interfaces were adopted in this study. A green-colored LED strip was installed on the steering wheel, presenting visual information to the driver (see Figure 1). Once the system boundary occurred, the LED would be turned off. A small speaker was placed in front of the participant and provided various sound effects (e.g., engine sounds). In addition, four vibration motors were placed in the seat in a 2 × 2 array, and four more were placed in a 2 × 2 array in the back support (see Figure 2). For each vibration motor, the duration of the vibration was 250 ms, and the duration of inter-vibra-

Figure 1. Simulated automated vehicle platform used by participants in this study.

Figure 2. Haptic seat and the locations of the vibration motors used in the experiment.

tion was 100 ms. The vibration intensity was set according to the guidelines of Ji, Lee, and Hwang (2011).

2.3. Questionnaires

All participants were asked to complete a questionnaire before engaging in driving tasks. The questionnaire solicited participants' demographic information (including age, gender, etc.) and driving history (including estimated cumulative driving mileage, year driver license was first issued, etc.). In addition, the Interpersonal Trust Scale was used as a proxy to collect data as to subjects' personalities in terms of tendency to trust (Rotter, 1967). The score was used as an index of tendency to trust in automated vehicles.

After each collision event, the participants were asked to complete a subjective questionnaire regarding their acceptance of the automated vehicle system, which included items around the intensity and the comfort levels of the vibration, the driver's workload when s/he took over control of the vehicle, how comfortable and how safe the participant felt about the automated vehicle, how much the participant trusted the automated vehicle, and the participants' acceptance of the automated vehicle system. After each reading task, the participants completed questions regarding the content of the reading material. After each video-watching task, the participants rated the level of interesting of the video from zero to 10. Before and after the task of taking a nap, participants were instructed to complete the Stanford Sleepiness Scale (Hoddes, Zarcone, & Dement, 1972). Finally, after each instance of vehicle takeover, participants described the vibration pattern they just experienced.

2.4. Driving scenarios

The Test Block was a simulated five-lane freeway environment. The subject vehicle was driving in the middle lane at the speed of 70 mph. Other vehicles drove simultaneously next to the subject car in the same direction. Due to the system boundaries, six different, common collision scenarios in the driver's lane (e.g., traffic accident, a suddenly stopped lead vehicle, an obstacle) represented vehicle takeover scenarios. To avoid the crash, the driver could either slow down or stop on his/her lane, or change to the left or right lane. To make lane changing possible, the adjacent left or right lane was not occupied by any other vehicles. After passing the hazard event, the driver needed to continue the manual driving for a further 1,000 m. In addition to the vehicle takeover scenarios, 18 other potential hazard events were designed that the automated vehicle could handle by itself.

2.5. Secondary tasks

In order to study a realistic case scenario in the automated vehicle setting, where the driver was out of the loop and not monitoring the automated vehicle system, six different non-driving tasks were assigned. They included reading, typing, playing games, and video watching via a smart phone, sleeping, and monitoring the road. These non-driving tasks came from the most common observed passengers' tasks on various modes of public transportation (Gamberini et al., 2013; Guo, Derian, &

Zhao, 2015; Lyons, Jain, Susilo, & Atkins, 2004), and from a large-scale opinion survey on what people in a fully self-driving vehicle would do instead of driving (Sivak & Schoettle, 2015).

2.6. Experiment design and procedures

The current experiment used a two-factor 6 × 6 experimental design, with vibration patterns of the takeover request and non-driving task as independent variables. The vibration patterns had six levels (Pattern 1: seat left–seat right–back left–back right, Pattern 2: back left–back right– seat left–seat right, Pattern 3: seat–back–seat–back, Pattern 4: back–seat–back–seat, Pattern 5: back–back–seat–seat, Pattern 6: seat–seat–back–back). In order for the driver to better differentiate the vibration of the take-over request from the vehicle vibration, vibration motors in the different seat positions were not activated at the same time in any of the vibration patterns. Six non-driving tasks, including reading, typing, watching videos, playing games, taking a nap, and monitoring were implemented. In addition, the optimal lead time 10 s observed in Wan and Wu (Under Review)'s study was used in this experiment. Each subject experienced six hazard events in which they needed to take over vehicle control due to the automated system boundary. The six collision scenarios were randomly assigned to the six hazard events. The six different vibration patterns and six different non-driving tasks were also assigned to the above six hazard events using a balanced incomplete design. This was done so that (1) if the non-driving tasks were disregarded, the arrangement would become six balanced Latin square design, (2) if vibration patterns were disregarded, the arrangement would become six balanced Latin square design, and (3) each pair of ($Pattern_i$, $Task_j$) showed up in the nth event once (Rees & Preece, 1999).

In order to control the learn effect and prevent the driver from responding as soon as any auditory messages or traffic events occurred, a number of events were designed and randomly assigned between two adjacent hazard events. Auditory messages not relevant to any traffic events (e.g., ads, news), normal traffic events (e.g., the emergence and departure of a lead vehicle, vehicles in other lanes, etc.) and potential hazard events which the automated vehicle could handle by itself were randomly inserted between the two hazard events. The time intervals between two adjacent hazard events' locations were randomly assigned to be between 5 and 15 min long. In addition, hazard vehicle/objects would not appear, or were blocked, by lead vehicles. As the takeover request occurred, the hazard vehicle/object would appear and the lead vehicle would change lanes.

Upon arrival to the study session, participants were asked to sign a consent document and fill out questionnaires regarding demographic characteristics, driving history, and personality. Participants were then briefed on the operation of the driving simulator, as well as how to turn the automation driving system on and off. Next, they completed a Practice Block to familiarize themselves with the driving simulator and the automated driving system. They were also asked to drive in the middle lane unless they had to overtake a slow lead vehicle or an obstacle in the middle lane. The 10-min scenario in the Practice Block was similar to the Test Block scenario. To ensure a high automation confidence and, therefore, intense activity in the non-driving tasks, the subjects were told that the system was flawless, that

they could withdraw themselves completely from the driving task, and that the automation did not require their assistance or any monitoring unless they received a tactile request for vehicle takeover from the system. Such a takeover request would occur when the vehicle reached a system boundary, and the lead time would be long enough for the subject to comfortably take control over the vehicle. As soon as they received the request, subjects were instructed to put their hands back on the steering wheel, place their foot on the gas pedal, and take over manual control of the vehicle.

2.7. Measurements

The OpenDS driving simulator automatically collected data around driving time elapsed (s), longitudinal and lateral speed (km/h), longitudinal and lateral acceleration (m/s^2), and distance (m). With such data, each participant's take-over reaction time, minimum time-to-collision (TTC), maximum lateral acceleration, and maximum longitudinal deceleration in each hazard event were calculated. Takeover reaction time was the shorter one between the time of first steer (the amount of time between the point at which the take-over request occurred and the first steering input greater than 2° was applied) and the time of first pedal pressing (the amount of time between which the take-over request occurred and the first pedal input greater than 10% was applied) (Radlmayr, Gold, Lorenz, Farid, & Bengler, 2014).

In addition to objective data quantifying the drivers' vehicle control inputs, subjective measures including the perceived vibration intensity of the take-over request, the driver's workload during vehicle take-over, and levels of trust and acceptance of the automated vehicle were collected.

2.8. Data analysis

Initially, a generalized linear model (GLM) analysis was conducted. The analysis included objective measures (including crash rate, response time, minimum TTC, maximum lateral acceleration, and maximum deceleration) and measures of engagement in non-driving tasks as dependent variables. Gender, driving experience, annual mileage, subjects' alertness at the start of automated driving, personality, and order were selected as covariates to investigate the effects of vibration patterns of the takeover request and vibration patterns on driver takeover behavior. Afterward, a GLM analysis was conducted using subjective measures (perceived vibration intensity, workload of taking over control, trust on the automated vehicle, and the acceptance of the automated vehicle) as dependent variables, and gender, driving experience, annual mileage, subject's alertness at the start of the automated driving, personality, and order as covariates. This allowed the researchers to also examine the effects of vibration patterns and non-driving tasks on participants' subjective opinions as to the automated vehicle system.

Pattern 1: seat left-seat right-back left-back right
Pattern 2: back left-back right- seat left-seat right
Pattern 3: seat-back-seat-back
Pattern 4: back-seat-back-seat
Pattern 5: back-back-seat-seat
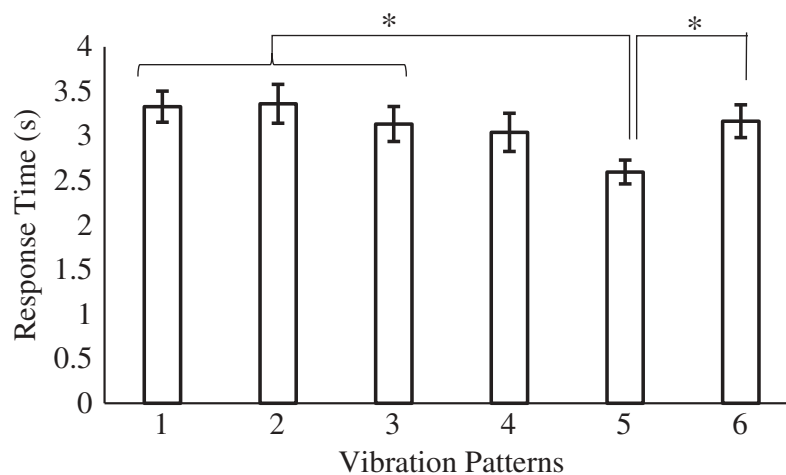Pattern 6: seat-seat-back-back

Vertical bars indicate Mean ± 1S

Figure 3. Main effect of vibration patterns on response time.

3. Results

3.1. Objective measures

Results indicated a significant effect of the vibration patterns on response time ($F(5,174) = 2.582$, $p = .028$) (see Figure 3). HSD post-hoc test suggested that Vibration Pattern 5 (back–back–seat–seat) ($M = 2.59$, $SD = .08$) generated a faster response to the takeover request as compared to Vibration Pattern 1 ($M = 3.33$, $SD = 1.05$) ($p < .01$), pattern 2 ($M = 3.36$, $SD = 1.30$) ($p < .01$), pattern 3 ($p = .03$) ($M = 3.13$, $SD = 1.18$), and pattern 6 ($M = 3.16$, $SD = 1.11$) ($p = .02$). The main effect of vibration patterns on other objective measures (crash rate, minimum TTC and maximum lateral acceleration and longitudinal deceleration) was not observed.

The main effect of task was significant on response time ($F(5,174) = 3.234$, $p = .008$) and minimum TTC ($F(5,174) = 3.301$, $p = .007$). HSD post-hoc test showed that response time under the vehicle monitoring task ($M = 2.60$, $SD = 1.14$) was significantly shorter than under the reading task ($M = 3.40$, $SD = 1.21$)($p < .01$), typing task ($M = 3.14$, $SD = 1.10$) ($p = .03$), video watching task ($M = 3.45$, $SD = 1.35$) ($p < .01$), and nap-taking task ($M = 3.11$, $SD = 1.03$) ($p = .04$). Additionally, driver response after playing games ($M = 2.92$, $SD = .89$) was significantly shorter compared to video watching ($p = .03$) (see Figure 4). As well, minimum TTC under the vehicle monitoring task ($M = 1.81$, $SD = 1.05$) was significantly greater than reading ($M = 1.19$, $SD = .64$) ($p < .01$), typing ($M = 1.42$, $SD = .64$) ($p = .04$), video watching ($M = 1.35$, $SD = .72$) ($p = .01$), and nap-taking ($M = 1.17$, $SD = .71$) ($p = .04$). Also, minimum TTC after playing games ($M = 1.54$, $SD = .92$) was significantly greater compared with taking a nap ($p < .01$) (see Figure 5). The main effect of non-driving related task on other objective measures (crash rate and maximum lateral acceleration and longitudinal deceleration) was not observed.

No significant interaction effect between vibration patterns and non-driving tasks was observed on any objective measures. Covariates were found to influence driver takeover behavior. Specifically, the effects of gender ($F(1,174) = 10.416$, $p = .001$)

and annual mileage ($F(1,174) = 7.808$, $p = .006$) were both significant on minimum TTC. Driving experience had a significant effect on the maximum lateral acceleration ($F(1,174) = 4.530$, $p = .035$).

Non-driving tasks exhibited a significant main effect on participants' non-driving tasks engagement ($F(5,175) = 29.429$, $p < .001$) (see Figure 6). HSD post-hoc test showed that engagement in the reading task ($M = .67$, $SD = .20$) was significantly lower than typing ($M = .86$, $SD = .13$), video watching ($M = .82$, $SD = .15$), and playing game task ($M = .81$, $SD = .19$). Participants' engagement in nap-taking ($M = .56$, $SD = .24$) was significantly lower than any other non-driving tasks. In addition, driver engagement in monitoring ($M = 1.00$, $SD = .24$) was significantly higher than in any other non-driving tasks. Finally, drivers' sleepiness levels before taking naps were compared with their sleepiness levels right before the warning occurred using a Paired t-test. The results showed that the null hypothesis was rejected ($t(35) = -6.778$, $p < .001$), suggesting that drivers were engaged in this task.

The main effect of vibration pattern was not observed on participants' engagement in the non-driving tasks.

3.2. Subjective measures

Neither vibration nor non-driving tasks had a significant effect on subjective measures (see Figure 7, 8, 9, and 10). No significant interaction effect between vibration patterns of take-over requests and non-driving tasks was found on any subjective measures. Significant effects of covariates were observed as follows. The effects of driving experience were significant on perceived intensity of vibration ($F(1,174) = 9.292$, $p = .003$), workload of takeover ($F(1,174) = 10.358$, $p = .002$), trust ($F(1,174) = 17.242$, $p = < .001$), and acceptance ($F(1,174) = 17.617$, $p = < .001$). Similarly, annual mileage had a significant influence on the driver's perceived intensity of vibration ($F(1,174) = 17.838$, $p = < .001$), trust ($F(1,174) = 97.533$, $p = < .001$), and acceptance ($F(1,174) = 30.320$, $p = < .001$). The participant's initial alertness level significantly influenced his/her perceived vibration intensity ($F(1,174) = 8.203$, $p = .005$). In addition, the effects of order on trust (F
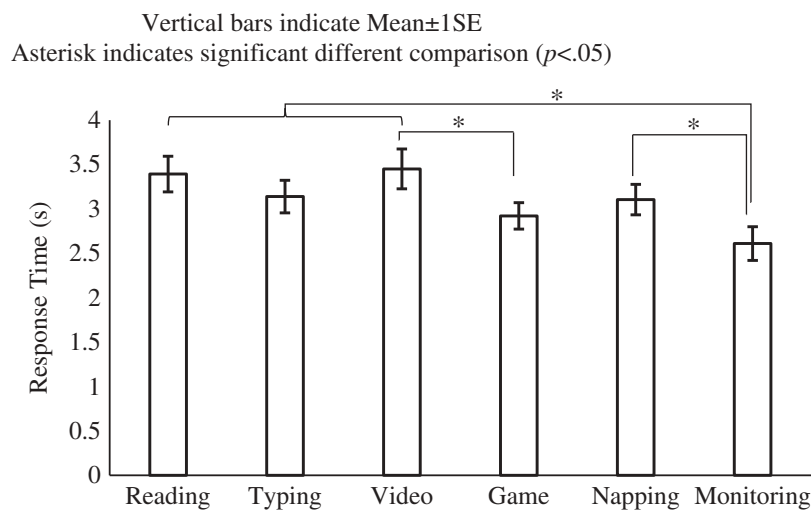

Vertical bars indicate Mean±1SE
Asterisk indicates significant different comparison ($p<.05$)

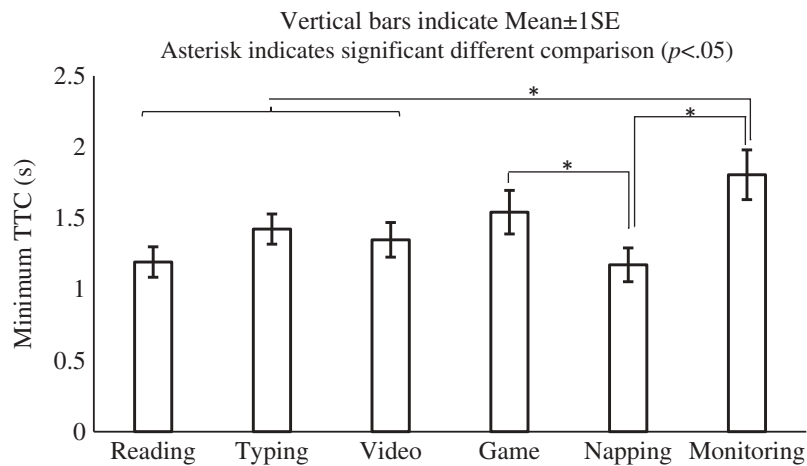**Figure 4.** Main effect of non-driving tasks on response time.

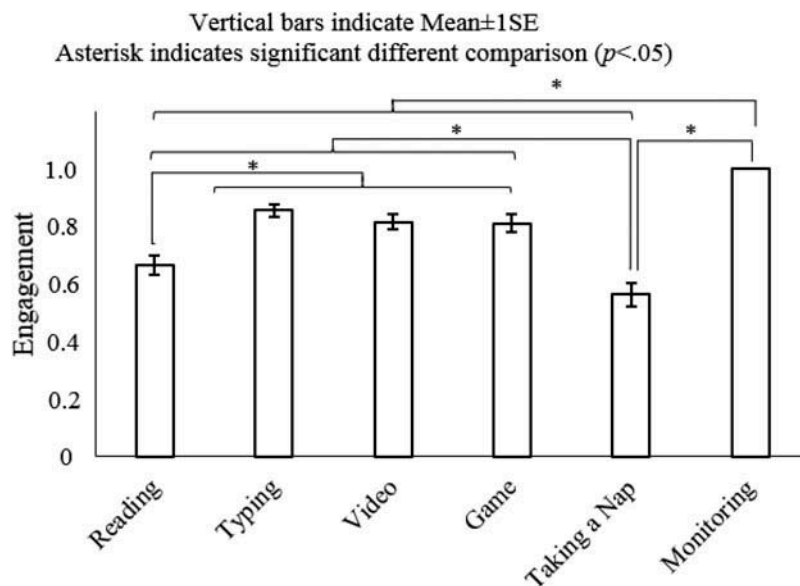**Figure 5.** Main effect of non-driving tasks on minimum TTC.

Figure 6. Main effect of non-driving tasks on driver engagement in non-driving tasks.

$(1,174) = 4.811$, $p = .030$) and acceptance ($F(1,174) = 7.013$, $p = .009$) were significant.

4. Discussion

This study investigated the effects of vibration patterns of both tactile vehicle takeover requests and non-driving tasks on driver takeover behavior and on subjective opinion of the study's automated vehicle system. The fastest response time was observed with Vibration Pattern 5 (back–back–seat–seat) across all non-driving tasks. The shortest response time and largest minimum TTC were each observed when the driver took over vehicle control after monitoring the driving scenario. No interaction effects between vibration patterns and non-driving tasks were observed.

As previously stated, drivers in automated vehicles are free at any time to engage in non-driving related tasks, as well as to switch among different non-driving tasks. Visual and/or auditory takeover requests may not always be effective, especially under emergent conditions. The potential for tactile display in automated vehicles to circumvent this challenge has yet to be fully reached. Bodily movement occurring simultaneously with the vibration of the suspension system may suppress driver perception of tactile stimuli. Because of this, vibration of the tactile stimuli should be readily distinguishable from the vehicle vibration. However, because very few studies had examined vibration patterns of tactile warning prompts in automated vehicles (Telpaz et al., 2015), the interaction effects between vibration pattern and non-driving related tasks went largely unexamined. Under real driving conditions, the probability of the system boundary of automated vehicles should be very low. Normal traffic events and non-warning messages, were therefore designed to minimize learn effect and prevent any immediate response to the delivery of a verbal message, which could help generate more realistic driver responses.

Pattern 1: seat left-seat right-back left-back right
Pattern 2: back left-back right- seat left-seat right
Pattern 3: seat-back-seat-back
Pattern 4: back-seat-back-seat
Pattern 5: back-back-seat-seat
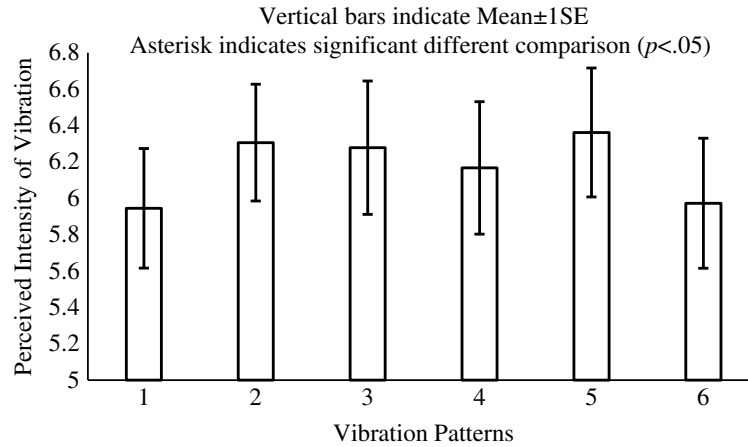Pattern 6: seat-seat-back-back

Figure 7. Main effect of vibration patterns on drivers' perceived intensity of vibration.

Pattern 1: seat left-seat right-back left-back right
Pattern 2: back left-back right- seat left-seat right
Pattern 3: seat-back-seat-back
Pattern 4: back-seat-back-seat
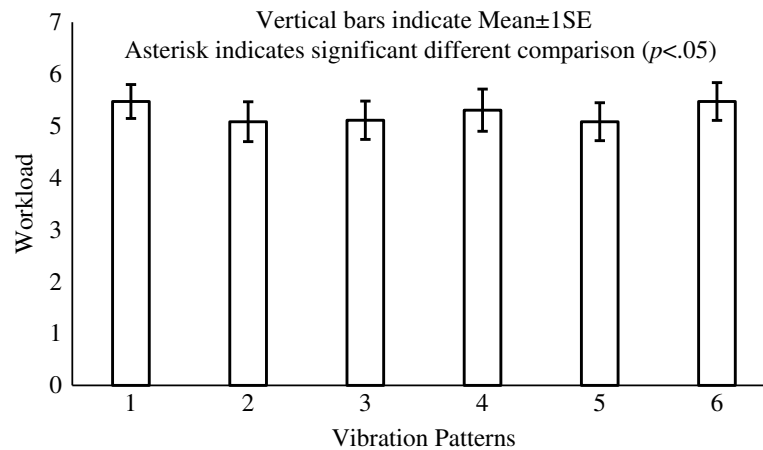Pattern 5: back-back-seat-seat
Pattern 6: seat-seat-back-back

Figure 8. Main effect of vibration patterns on drivers' workload.

The fastest response time was observed with Vibration Pattern 5 (back–back–seat–seat) across all non-driving tasks. The faster response generated by Pattern 5 than Pattern 6 (seat–seat–back–back) suggests that initializing vibration activation from the seat back could generate faster driver response to takeover requests than initializing vibration activation from the seat. The reason may be due to higher levels of sensitivity to vibration stimuli in the human back as compared to the human hip. In addition, during non-driving tasks, the participant may cross/stretch/move his/her legs

which would also influence the vibration perception on his/her legs. Pattern 5 also generated faster responses than Pattern 3 (back–seat–back–seat) and Pattern 4 (seat–back–seat–back), which may suggest an effect of pulse repetition rate on vibration perception on the same location of the body part (Jones & Sarter, 2008). That is, pulse repetition on the same body location may enhance vibration perception. Additionally Pattern 5 generated faster driver responses than Pattern 1 (seat left–seat right–back left–back right) and Pattern 2 (back left–back right–seat left–seat right), which may suggest
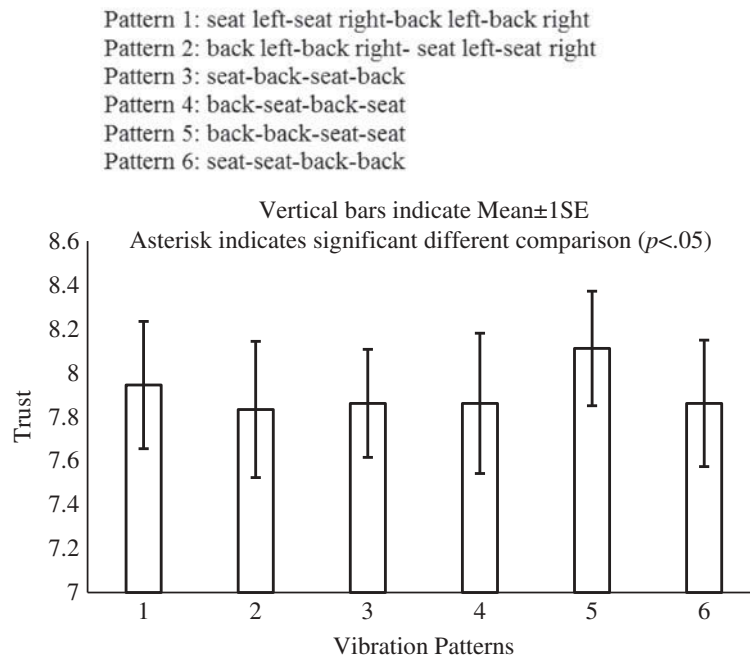
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Pattern 5: back-back-seat-seat
Pattern 6: seat-seat-back-back

Vertical bars indicate Mean±1SE
Asterisk indicates significant different comparison ($p<.05$)

Figure 9. Main effect of vibration patterns on drivers' trust to the automated driving system.

Pattern 1: seat left-seat right-back left-back right
Pattern 2: back left-back right- seat left-seat right
Pattern 3: seat-back-seat-back
Pattern 4: back-seat-back-seat
Pattern 5: back-back-seat-seat
Pattern 6: seat-seat-back-back

Vertical bars indicate Mean±1SE
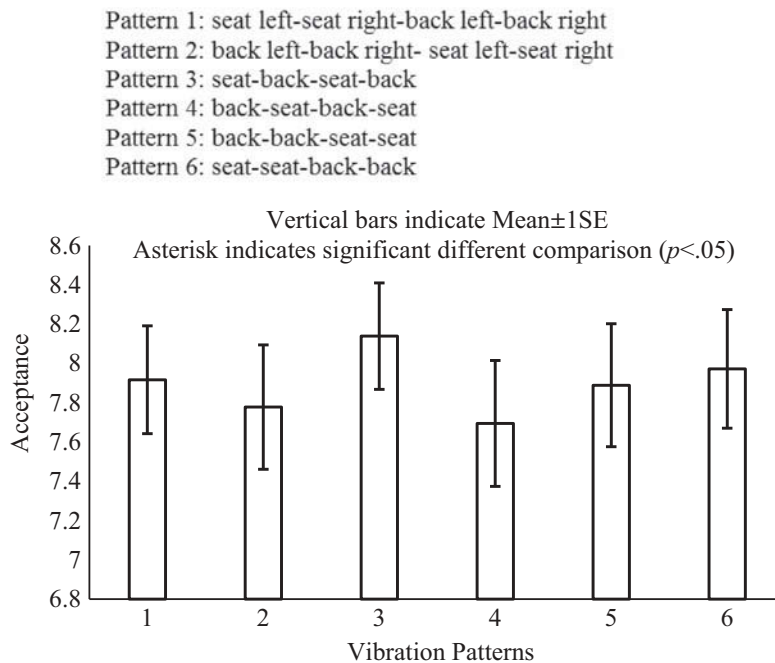Asterisk indicates significant different comparison ($p<.05$)

Figure 10. Main effect of vibration patterns on drivers' acceptance of the automated driving system.

that the directional signal (left vs. right) does not have a significant effect on the driver's perception of vibration as compared with repeated vibration on both left and right sides of the seat.

Besides vibration patterns, the effects of non-driving tasks were also analyzed. The shortest response time and largest minimum TTC were observed when the driver took over vehicle control after monitoring the driving scenario. The longest response time was observed when the driver happened to play games or take a nap before responding to the vehicle takeover request. Taking a nap also generated the lowest minimum TTC. Such findings were consistent with Wan & Wu (Under Review)'s work, in that if the driver was engaged in cognitively and physically demanding non-driving tasks, or his/her vigilance was very low, vehicle takeover behavior in terms of response time and engagement would be weaker. Contrary Wan & Wu (Under Review)'s findings, significantly longer response times associated with monitoring the driving scenario were not observed in this study, which was due to the researchers choosing not to include

auditory driver warnings. Even though the auditory channel was occupied, driver perception of tactile warnings was not affected. No interaction effect between vibration patterns and non-driving tasks was observed. This suggests that different gestures across commonly observed passenger non-driving tasks do not influence the effectiveness of tactile stimuli (Gamberini et al., 2013; Guo et al., 2015; Lyons et al., 2004; Sivak & Schoettle, 2015). Thus, the optimal vibration pattern identified in this study is applicable at almost any time in an automated vehicle setting (Sivak & Schoettle, 2015).

Limitations associated with this study had mainly to do with lack of availability of certain technologies. First, due to the high cost of a motion system for the driving simulator, the use of ambient vibration in the study was not possible. Similar settings have been used in previous research with respect to tactile displays in vehicles (Chang, Hwang, & Ji, 2011; Ji et al., 2011). However, even though this experiment was conducted in a simulated driving environment, its findings provide a substantial foundation for the future design of tactile vehicle takeover requests in automated vehicles. Second, just as in Wan and Wu's (2016, under review) study, the absence of warning or false warning messages, and their influence on driver response, were not investigated. In this experiment, the researchers primarily focused on the effects of vibration patterns and non-driving tasks on drivers' vehicle takeover behavior. It was therefore assumed that all takeover requests were necessary for the driver to successfully exhibit vehicle takeover behaviors. The effects of missing warnings and false alarms will be addressed in future work. We expect that the optimal vibration pattern found in this experiment will be complemented by future experiments executed in real driving environments. In addition, other tactile variables, including takeover requests and navigation (e.g., pulse repetition rate and rhythm) and traffic situations (e.g., driving speed and bump) on takeover behavior under automated vehicle conditions require further research.

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References

Baldwin, C. L., Eisert, J. L., Garcia, A., Lewis, B., Pratt, S. M., & Gonzalez, C. (2012). Multimodal urgency coding: Auditory, visual, and tactile parameters and their impact on perceived urgency. *Work*, *41* (Supplement 1), 3586–3591.

Baldwin, C. L., Spence, C., Bliss, J. P., Brill, J. C., Wogalter, M. S., Mayhorn, C. B., & Ferris, T. K. (2012, September). Multimodal cueing: The relative benefits of the auditory, visual, and tactile channels in complex environments. *In Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *56*(1), 1431–1435.

Ballard, J. W., & Hessinger, R. (1954). Human-engineered electromechanical tactual sensory control system. *Electrical Manufacturing*, *54*(4), 118–121.

Bazilinskyy, P., Petermeijer, B., Petrovych, V., Dodou, D., & De Winter, J. C. F. (Submitted). *Take-over requests in highly automated driving: A crowdsourcing multimedia survey on auditory, vibrotactile, and visual displays:* Unpublished..

Brewster, S., & Brown, L. M. (2004, January). Tactons: Structured tactile messages for non-visual information display. In A. Cockburn Ed., *Proceedings of the fifth conference on Australasian user interface* (pp. 15–23). Dunedin, New Zealand: Australian Computer Society, Inc.

Burke, J. L., Prewett, M. S., Gray, A. A., Yang, L., Stilson, F. R., Coovert, M. D., … Redden, E. (2006, November). Comparing the effects of visual-auditory and visual-tactile feedback on user performance: A meta-analysis. In *Proceedings of the 8th international conference on multimodal interfaces* (pp. 108–117). New York, NY: ACM.

Chancey, E. T., Brill, J. C., Sitz, A., Schmuntzsch, U., & Bliss, J. P. (2014, September). Vibrotactile stimuli parameters on detection reaction times. In *Proceedings of the human factors and ergonomics society annual meeting* (Vol. 58,1 pp. 1701–1705). Los Angeles, CA: SAGE Publications.

Chang, W., Hwang, W., & Ji, Y. G. (2011). Haptic seat interfaces for driver information and warning systems. *International Journal of Human-Computer Interaction*, *27*(12), 1119–1132.

Chun, J., Han, S. H., Park, G., Seo, J., & Choi, S. (2012). Evaluation of vibrotactile feedback for forward collision warning on the steering wheel and seatbelt. *International Journal of Industrial Ergonomics*, *42* (5), 443–448.

Chun, J., Lee, I., Park, G., Seo, J., Choi, S., & Han, S. H. (2013). Efficacy of haptic blind spot warnings applied through a steering wheel or a seatbelt. *Transportation Research Part F: Traffic Psychology and Behaviour*, *21*, 231–241.

De Rosario, H., Louredo, M., Díaz, I., Soler, A., Gil, J. J., Solaz, J. S., & Jornet, J. (2010). Efficacy and feeling of a vibrotactile Frontal Collision warning implemented in a haptic pedal. *Transportation Research Part F: Traffic Psychology and Behaviour*, *13*(2), 80–91.

Drew, D. A., & Hayes, C. C. (2012). An exploration of decision support for drivers, inside and outside the vehicle. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *22*(5), 420–436.

Ferris, T. K., & Sarter, N. (2011). Continuously informing vibrotactile displays in support of attention management and multitasking in anesthesiology. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *53*(6), 600–611.

Ferris, T. K., & Sarter, N. B. (2008). Cross-modal links among vision, audition, and touch in complex environments. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *50*(1), 17–26.

Fitch, G. M., Hankey, J. M., Kleiner, B. M., & Dingus, T. A. (2011). Driver comprehension of multiple haptic seat alerts intended for use in an integrated collision avoidance system. *Transportation Research Part F: Traffic Psychology and Behaviour*, *14*(4), 278–290.

Gamberini, L., Spagnolli, A., Miotto, A., Ferrari, E., Corradi, N., & Furlan, S. (2013). Passengers' activities during short trips on the London underground. *Transportation*, *40*(2), 251–268.

Gescheider, G., Bolanowski, S., & Verrillo, R. (1974). Temporal relations in cutaneous stimulation. In F. A. Geldard (Ed.), *Cutaneous communication systems and devices* (pp. 33–37). Austin, TX: The Psychonomic Society.

Gescheider, G. A., Bolanowski, S. J., Pope, J. V., & Verrillo, R. T. (2002). A four-channel analysis of the tactile sensitivity of the fingertip: Frequency selectivity, spatial summation, and temporal summation. *Somatosensory & Motor Research*, *19*(2), 114–124.

Gescheider, G. A., Bolanowski, S. J., & Verrillo, R. T. (2004). Some characteristics of tactile channels. *Behavioural Brain Research*, *148* (1), 35–40.

Gray, R. (2011). Looming auditory collision warnings for driving. *Human Factors: the Journal of the Human Factors and Ergonomics Society*, *53*(1), 63–74.

Gunther, E. (2001). *Skinscape: A tool for composition in the tactile modality* (Doctoral dissertation), Cambridge, MA: Massachusetts Institute of Technology.

Gunther, E., & O'Modhrain, S. (2003). Cutaneous grooves: Composing for the sense of touch. *Journal of New Music Research*, 32(4), 369–381.

Guo, Z., Derian, A., & Zhao, J. (2015). Smart devices and travel time use by bus passengers in vancouver, Canada. *International Journal of Sustainable Transportation*, 9(5), 335–347.

Haas, E. C., & Van Erp, J. B. (2014). Multimodal warnings to enhance risk communication and safety. *Safety Science*, 61, 29–35.

Ho, C., Reed, N., & Spence, C. (2007). Multisensory in-car warning signals for collision avoidance. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 49(6), 1107–1114.

Ho, C., Spence, C., & Gray, R. (2013, December). Looming auditory and vibrotactile collision warnings for safe driving. In *Proceedings of the 7th international driving symposium on human factors in driver assessment, training, and vehicle design* (pp. 551–557). Bolton Landing, NY: University of Iowa.

Ho, C., Spence, C., & Tan, H. Z. (2005). *Warning signals go multisensory*. Paper presented at the Proceedings of HCI International, Las Vegas, NV.

Ho, C., Tan, H. Z., & Spence, C. (2005). Using spatial vibrotactile cues to direct visual attention in driving scenes. *Transportation Research Part F: Traffic Psychology and Behaviour*, 8(6), 397–412.

Ho, C., Tan, H. Z., & Spence, C. (2006). The differential effect of vibrotactile and auditory cues on visual spatial attention. *Ergonomics*, 49(7), 724–738.

Hoddes, E., Zarcone, V., & Dement, W. (1972). Development and use of Stanford Sleepiness scale (SSS). *Psychophysiology*, 9(1), 150.

Ji, Y. G., Lee, K., & Hwang, W. (2011). Haptic perceptions in the vehicle seat. *Human Factors and Ergonomics in Manufacturing & Service Industries*, 21(3), 305–325.

Jones, L. A., & Sarter, N. B. (2008). Tactile displays: Guidance for their design and application. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 50(1), 90–111.

Lee, J., McGehee, D. V., Brown, T., & Nakamoto, J. (2007). Driver sensitivity to brake pulse duration and magnitude. *Ergonomics*, 50(6), 828–836.

Lee, J. D., Hoffman, J. D., & Hayes, E. (2004). *Collision warning design to mitigate driver distraction*. Paper presented at the Proceedings of the SIGCHI Conference on Human factors in Computing Systems, Vienna, Austria.

Lee, J. D., McGehee, D. V., Brown, T. L., & Reyes, M. L. (2002). Collision warning timing, driver distraction, and driver response to imminent rear-end collisions in a high-fidelity driving simulator. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 44(2), 314–334.

P., Oskarsson, P. A., Hedström, J., Andersson, P., Lindahl, B., & Palm, C. (2014, June). Evaluation of tactile drift displays in helicopter. In M. Kurosu Ed., *International conference on human-computer interaction* (pp. 578–588). Crete, Greece: Springer.

Liu, Y.-C., & Jhuang, J.-W. (2012). Effects of in-vehicle warning information displays with or without spatial compatibility on driving behaviors and response performance. *Applied Ergonomics*, 43(4), 679–686.

Lloyd, M., Wilson, G., Nowak, C., Bittner, A. (1999). Brake pulsing as haptic warning for an intersection collision avoidance countermeasure. *Transportation Research Record: Journal of the Transportation Research Board*, 1694, 34–41.

Lopez, J. A. (2012). Kia named Quoris his K9 flagship sedan for export markets. Retrieved from http://thekoreancarblog.com/2012/07/18/kia-named-quoris-k9-flagship-sedan-export-markets-wvideos/

Luft, A. (2013). Feature spotlight: Cadillac's driver assist technology makes driving safer, easier. Retrieved from http://gmauthority.com/blog/2013/03/feature-spotlight-cadillacs-driver-assist-technology/

Lyons, G., Jain, J., Susilo, Y., & Atkins, S. (2004). How do rail travellers use their time. A comparison of national (rail) passenger survey findings between 2004 and 2010. Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-71708

MacLean, K. E., & Hayward, V. (2008). Do it yourself haptics: Part ii [tutorial]. *Robotics & Automation Magazine, IEEE*, 15(1), 104–119.

McGehee, D., & Raby, M. (2002). Snowplow lane awareness system. *Final Report prepared for the 3M Company and the Minnesota Department of Transportation*. St. Paul, MN: Minnesota Department of Transportation.

Meng, F., Ho, C., Gray, R., & Spence, C. (2015a). Dynamic vibrotactile signals for forward collision avoidance warning systems. *Human Factors*, 57, 329–346.

Meng, F., Ho, C., Gray, R., & Spence, C. (2015b). Dynamic vibrotactile signals for forward collision avoidance: Toward the torso vs. toward the head. *Ergonomics*, 58, 411–425.

Meng, F., & Spence, C. (2015). Tactile warning signals for in-vehicle systems. *Accident Analysis & Prevention*, 75, 333–346.

Morley, J. W., & Rowe, M. J. (1990). Perceived pitch of vibrotactile stimuli: Effects of vibration amplitude, and implications for vibration frequency coding. *The Journal of Physiology*, 431(1), 403–416.

Mulder, M., Abbink, D. A., Van Paassen, M. M., & Mulder, M. (2011). Design of a haptic gas pedal for active car-following support. *IEEE Transactions on Intelligent Transportation Systems*, 12(1), 268–279.

Mulder, M., Mulder, M., Van Paassen, M., & Abbink, D. (2008). Haptic gas pedal feedback. *Ergonomics*, 51(11), 1710–1720.

OpenDS. (2016). OpenDS 4.0. Retrieved from https://www.opends.eu/

Oviatt, S. (1997). Multimodal interactive maps: Designing for human performance. *Human-Computer Interaction*, 12(1), 93–129.

Petermeijer, S. M., Abbink, D. A., Mulder, M., & De Winter, J. C. (2015). The effect of haptic support systems on driver performance: A literature survey. *IEEE Transactions on Haptic*, 8(4), 467–479.

Petermeijer, S. M., De Winter, J. C., & Bengler, K. J. (2015). Vibrotactile displays: A survey with a view on highly automated driving. *IEEE Transactions on Intelligent Transportation Systems*, 17(4), 897–907.

Pongrac, H. (2008). Vibrotactile perception: Examining the coding of vibrations and the just noticeable difference under various conditions. *Multimedia Systems*, 13(4), 297–307.

Pratt, S. M., Lewis, B. A., Penaranda, B. N., Roberts, D. M., Gonzalez, C., & Baldwin, C. L. (2012, September). Perceived urgency scaling in tactile alerts. *In Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 56(1), 1303–1306.

Radlmayr, J., Gold, C., Lorenz, L., Farid, M., & Bengler, K. (2014, September). How traffic situations and non-driving related tasks affect the take-over quality in highly automated driving. *In Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 58(1), 2063–2067.

Rees, D. H., & Preece, D. A. (1999). Perfect Graeco-Latin balanced incomplete block designs (pergolas). *Discrete Mathematics*, 197, 691–712.

Rothenberg, M., Verrillo, R. T., Zahorian, S. A., Brachman, M. L., & Bolanowski, Jr, S. J. (1977). Vibrotactile frequency for encoding a speech parameter. *The Journal of the Acoustical Society of America*, 62(4), 1003–1012.

Rotter, J. B. (1967). A new scale for the measurement of interpersonal trust. *Journal of Personality*, 35(4), 651–665.

Sarter, N. B. (2002). Multimodal information presentation in support of human-automation communication and coordination. In E. Salas (Ed.), *Advances in human performance and cognitive engineering research* (pp. 13–36). New York, NY: JAI Press.

Sherrick, C. E. (1985). A scale for rate of tactual vibration. *The Journal of the Acoustical Society of America*, 78(1), 78–83.

Sivak, M., & Schoettle, B. (2015). *Motion sickness in self-driving vehicles*. Retrieved from https://deepblue.lib.umich.edu/handle/2027.42/111747

Spence, C., & Driver, J. (1997). Cross-modal links in attention between audition, vision, and touch: Implications for interface design. *International Journal of Cognitive Ergonomics*, 1(4), 351–373.

Spence, C., & Ho, C. (2008a). Multisensory warning signals for event perception and safe driving. *Theoretical Issues in Ergonomics Science*, 9(6), 523–554.

Spence, C., & Ho, C. (2008b). Tactile and multisensory spatial warning signals for drivers. *IEEE Transactions on Haptics*, 1(2), 121–129.

Spence, C., & Ho, C. (2009). Crossmodal information processing in driving. In C. Castro (Ed.), *Human factors of visual and cognitive performance in driving* (pp. 187–196). Boca Raton, FL: CRC Press.

Spirkovska, L. (2005). *Summary of tactile user interfaces techniques and systems*. Retrieved from https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20050041780.pdf

Štrbac, M., Belić, M., Isaković., M., Kojić, V., Bijelić, G., Popović, I., & Keller, T. (2016). Integrated and flexible multichannel interface for electrotactile stimulation. *Journal of Neural Engineering*, *13*(4), 046014–046032.

Tan, H. Z., Gray, R., Young, J. J., & Traylor, R. (2003). A haptic back display for attentional and directional cueing. *Haptics-E*, *3*(1), 1–20.

Telpaz, A., Rhindress, B., Zelman, I., & Tsimhoni, O. (2015). *Haptic seat for automated driving: Preparing the driver to take control effectively*. Paper presented at the Proceedings of the 7th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, Nottingham, UK.

Tijerina, L., Johnston, S., Parmer, E., Pham, H., & Winterbottom, M. (2000). *Preliminary studies in haptic displays for rear-end collision avoidance system and adaptive cruise control system applications*. Retrieved from https://trid.trb.org/view.aspx?id=680993

Van Erp, J. B. F., & Van Veen, H. A. H. C. (2001, July). Vibro-tactile information presentation in automobiles. In C. Baber (Ed.), *Proceedings of eurohaptics* (Vol. 2001, pp. 99–104). Paris, France: Eurohaptics Society.

Van Erp, J. B. F., & Van Veen, H. A. H. C. (2004). Vibrotactile in-vehicle navigation system. *Transportation Research Part F: Traffic Psychology and Behaviour*, *7*(4), 247–256.

Van Erp, J. B. F., Veltman, J., Van Veen, H. A. H. C., & Oving, A. B. (2003). Tactile torso display as countermeasure to reduce night vision goggles induced drift. *Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures*, *86*, 49–51.

Wan, J., & Wu, C. (Under Review). The effects of lead time of take-over request and non-driving tasks on taking-over control of automated vehicles. *IEEE Transactions on Human-Machine Systems*.

Weinstein, S. (1968, March). *Intensive and extensive aspects of tactile sensitivity as a function of body part, sex and laterality*. Paper presented at the First International symposium on the Skin Senses, Tallahassee, FL.

Wilska, A. (1954). On the vibrational sensitivity in different regions of the body surface. *Acta Physiologica Scandinavica*, *31*(2-3), 285–289.

Zheng, Y., & Morrell, J. B. (2010). *A vibrotactile feedback approach to posture guidance*. Paper presented at the 2010 IEEE Haptics Symposium, Waltham, MA.

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