SUPPORTING VISUAL ATTENTION OF DRIVERS INTERACTING WITH IN-VEHICLE TOUCHSCREENS

A Dissertation

by

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ABSTRACT

Touchscreens are widely used in interface designs, with the benefits of ease of use and flexibility in interaction design. However, visual attention is essential to touchscreen interaction, which results in frequent reorientation of attention in multitask contexts and thus leads to task interferences. This visually-demanding nature of touchscreens can expose operators to safety risks in certain domains, such as in driving. In this regard, earlier studies have attempted to address visual distraction potential related to in-vehicle touchscreens. Nevertheless, road traffic statistics show that in-vehicle touchscreens are still contributing to a considerable number of crashes each year.

This dissertation aims to investigate and design means to offload visual demands of touchscreen interaction in complex, data-rich environments, focusing on driving as the application domain. The research tested the configurations of an in-vehicle touchscreen, concerning feedback modality and control size. Vertical locations of this secondary interface were also examined in terms of distraction effects. Preliminary design efforts evaluated the practicality of a symbolic encoding method using vibrotactile beats.

A novel interface design, Nonvisual Aids for Touchscreen Experience (NATE), primarily employs distributed tactile cues that are proximal to operators but physically separated from a touchscreen device. This method involves presenting vibratory cues to the back of operators, and each cue is spatially mapped to each touchscreen control. NATE allows operators to bind those multiple stimuli to perform touchscreen interaction via nonvisual channels. An evaluation study was conducted in a simulated environment, comparing measures in driving performance, glance behavior, and perceived workload between an ordinary touchscreen and NATE-based touchscreen applications. The driving scenarios were based on the Lane Change Test procedure established by the ISO standard.

The findings indicate that the application of NATE to in-vehicle touchscreen designs significantly reduced visual distraction and improved performance in vehicle operation. However, performance measures on a touchscreen task suggest limitations. This body of research provides inputs to the design community of in-vehicle touchscreens, focusing on offloading visual demands of drivers. Theoretical contributions include a deeper understanding of glance behavior, which can inform models of human behavior in multitask contexts.

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Contributors

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The work in Chapter II was performed in collaboration with Texas A&M Transportation Institute (TTI) through the Advancing Transportation Leadership and Safety (ATLAS) program. TTI aided the data collection as well as participant requirement. Jeffery Miles of TTI contributed to the final design of experiment. In addition, Ko-Ching "Katrina" Wu contributed to the development of a touchscreen application. Regarding Chapter III, Christian Bruccoleri and Patrick Loftus of Lynntech, Inc., contributed to equipment acquisition and software development for the data collection.

All other work conducted for the dissertation was independently completed by the student.

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INTRODUCTION

Touchscreens are increasingly popular for interface design, presenting both display and control in a limited enclosure (Orphanides, & Nam, 2017). The use of touchscreens has been covering not only single-task operations with smartphones or tablets but also multitask operations where visual monitoring is critical, such as driving, aviation, and process control. In those multitasking situations with touchscreens, operators need to address competing visual requirements. In high attentional demands, they need to reorient visual attention frequently between a primary task display (or the scene in the real-world) and a touchscreen, while being prepared for unexpected events at urgency, often without proper technological aids. As a result, those operators have to manage interruptions due to multiple visual tasks. The essence of problem is that the interface of touchscreen experience is mostly (if not always) designed to rely on the visual modality which is already overloaded. With a visual monitoring task requiring focal attention, the introduction of a touchscreen task leads operators to draw focal attention away from the monitoring task and increases the likelihood of *task interferences* (Wickens, 2008).

Driving is one of the multitasking environments that touchscreens are popularly used (Kern & Schmidt, 2009) and that could suffer task interferences due to touchscreen interaction. Touchscreens used for vehicle interior design (referred to as *in-vehicle touchscreens*), as shown in Figure I-1, can increase the crash risk by three times when looking at them while driving (NHTSA, 2013). Such risk has been realized as actual damages; the estimated number of crashes involving distractions associated with in-vehicle touchscreens was reported to be about 20,000 occasions per year (NHTSA, 2013). The authority has been attempting to persuade rather than to enforce, which is not necessarily effective. The recent effort by NHTSA (2013) to tackle the distraction effects of in-vehicle touchscreens was to publish *Driver Distraction Guideline for In-Vehicle Electronic Devices*. The guideline recommends drivers limit the time to glance at in-vehicle touchscreens to two seconds or less (NHTSA, 2013), although drivers have hardly been amenable to government guidelines. The portion of distraction-related crashes has been nearly constant at 17% (NHTSA, 2016) since the administration merged all types of driver distraction into "distracted-related" in 2011. That is, at least some drivers would be willing to risk safety and drive in a distracted state anyway if deemed to be "necessary" (White, Hyde, Walsh, & Watson, 2010), which justifies why the distraction potential of in-vehicle touchscreens should be preemptively identified and addressed by design.

Figure I-1. Recent in-vehicle touchscreens

The popularity of touchscreens in vehicle interior design may be related to user satisfaction based on the ease of use. Touchscreens allow users to make direct inputs onto the screen and bolsters the linkage in eye-hand coordination (Dul & Weerdmeester, 2008).

Touchscreen interaction thus involves a natural pointing gesture (Greenstein, 1997) that can be considered to be intuitive and thus easy for novice users (Rydstrom et al., 2005). This can increase user satisfaction and initial acceptance (Rogers, Fisk, McLaughlin, & Pak, 2005). Another advantage of touchscreens is based on the flexibility of design. Touchscreens support a wide range of functions within a smaller spatial footprint than would be required with physical controls, allowing flexibility to support context-specificity and user preferences (Irwin et al., 2011; Park & Han, 2010; Plaisant & Sears, 1992; Sesto, Irwin, Chen, Chourasia, & Wiegmann, 2012). Touchscreens present both display and control elements in a single enclosure, accommodating increasing numbers of nondriving functions with the limited spatial resource.

Hence, physical controls, such as buttons or knobs shown in Figure I-2, once had been widely used for the center console interface, are being replaced with in-vehicle touchscreens. In fact, touchscreens are cheaper in general than physical controls, which justifies the interface transition to the touchscreens.

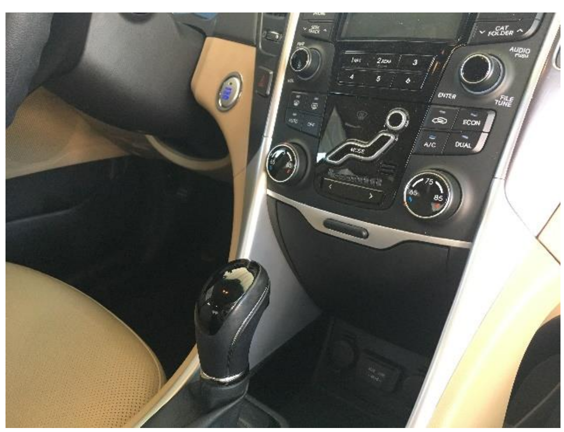

Figure I-2. Physical buttons and knobs in the center console interface

This interface transition also led the size of touchscreens to be larger (e.g., Braun, 2014; Brignall, 2016; Hyunh, 2016); some manufacturers have been featuring a 17-inch touchscreen on the center console with no physical controls (see the two on the top of Figure I-1). However, underestimated are concerns of driving safety pertaining to in-vehicle touchscreens, as any new technologies introduced to driving and supposed to be beneficial can actually become a source of driver distraction (Petzoldt, Brüggemann, & Krems, 2014). The focus of this dissertation is on investigating and designing means to offload visual demands of in-vehicle touchscreens, in order to better support visual attention management of drivers.

Safety concerns with in-vehicle touchscreens

The interface transition from physical to touchscreen-based controls alters user experience in the context of driving. For example, drivers feel resistance force or hear the click of activation when pressing physical buttons, and these nonvisual cues allow interaction to be confirmed even when the eyes of drivers are on the road. In contrast, such naturalistic cues are not available with touchscreens; touchscreen interaction requires visual attention throughout the entire process of user interaction. In this regard, in-vehicle touchscreens could expose drivers to visual distraction to a greater extent than physical controls.

Freitag and colleagues (2012) proposed the model of temporal workflow in user interaction. Depicted in Figure I-3, the model is helpful as a framework to better understand the nature of touchscreen interaction.

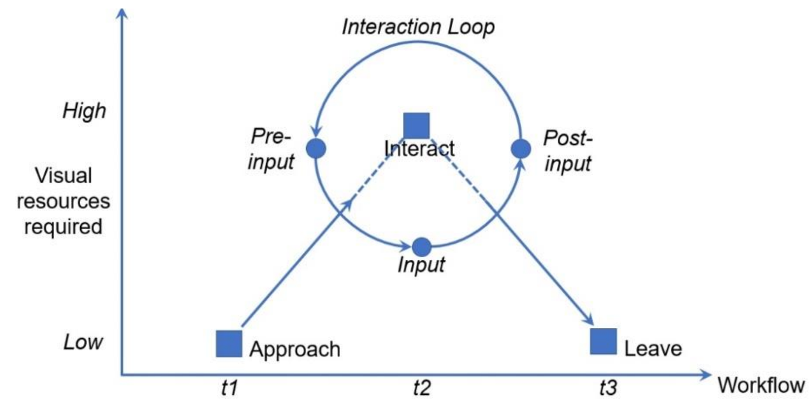

Figure I-3. A workflow diagram for interaction (Freitag, Tränkner, & Wacker, "Enhanced feed-forward for a user aware multi-touch device", In Proceedings of the 7th Nordic Conference on Human-Computer Interaction: Making Sense Through Design, 578-586, © 2012 ACM, Inc. Reprinted by permission http://doi.acm.org/10.1145/2399016.2399104)

The model indicates that interaction starts with operators *approaching* a device. Some will choose to *leave* without any explicit user interaction, but the rest will choose otherwise; they will engage in touchscreen interaction, and required visual resources increase. At this point, operators gather information that are needed to make an input through the interface, which is considered to be a *pre-input* activity. Operators then activate the interface by registering an input with fingers as an *input* activity, perceive the outcome in the *post-input* stage, and get ready for the next input. This *interaction loop* ends when operators decide to physically leave the area of interaction. While operating in the interaction loop, touchscreens do not provide any nonvisual feedback by nature. *Pre-input* activities in touchscreen interaction are possible only when visual attention is allocated properly, as interactive elements are intangible and displayed in a flat screen, as opposed to physical controls that have shapes and textures that are perceivable with the sense of touch. As registering an input requires finger-tapping on an interactive element, activities in the *input* stage needs precision, which demands visual attention to ensure the accuracy of gross and fine movements. *Post-input* activities should be facilitated by feedback, and synthetic presentation (e.g., the color of interactive elements changes upon touch) should be developed deliberately. Otherwise, operators could not confirm the action performed at the *input* stage. Therefore, touchscreen interaction constantly requires vision as long as operators are engaging in the interaction loop.

The problem arises when touchscreen interaction needs to share time with driving; touchscreen interaction requires visual attention, so does driving. Wickens (2002) proposed the Multiple Resource Theory that allows a deeper understanding on attentional demands in multitasking situations. The premise of the theory is that attentional resources are limited and exist in multiple dimensions, as shown in Figure I-4. One of the dimensions is *modality* primarily consisting of focal and ambient vision, audition, and the sense of touch. The Multiple Resource Theory implies that the successful operation in multitasking situations relies on the appropriate allocation of attentional resources. That is, if the primary task relies on one modality, then the extent to which the secondary task relies on the same modality can determine multitask performance (Sarter, 2007).

In this regard, the theory predicts that an interference would occur when operators perform concurrent tasks but attentional demands are not properly allocated across multiple dimensions. This prediction can be meaningful to drivers who interact with in-vehicle touchscreens; focally attending to the road and in-vehicle touchscreens at the same time would interfere with each other. They would experience a competition for the limited resources of focal vision, and either or both tasks would suffer degradation of performance.

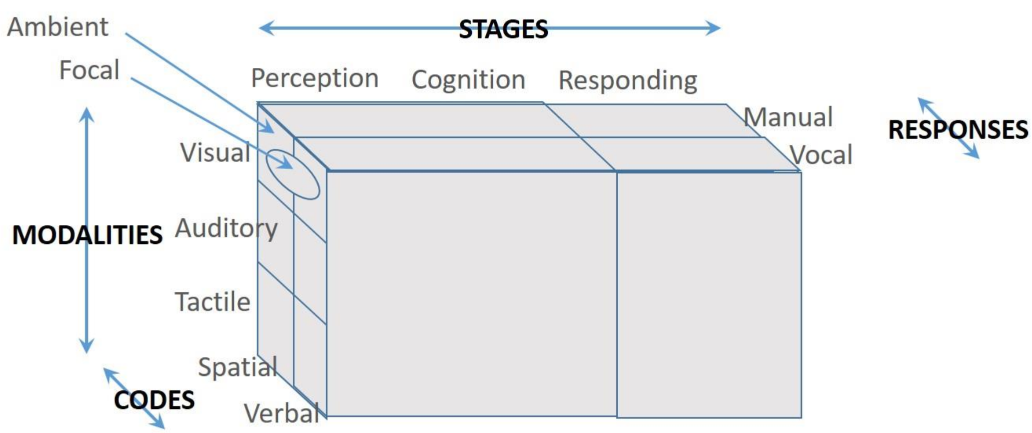

Figure I-4. The multiple resource model (Wickens, "Multiple Resources and Mental Workload", Human Factors, 50(3), pp. 449-455, copyright © 2008 by SAGE, reprinted by permission of SAGE Publications, Inc.)

Another safety disadvantage of in-vehicle touchscreens is associated with the fact that they are being located below the windshield, or the driver's line of sight (LOS). As the field of view of human eyes is horizontally wide and vertically narrow, visual perception can be more vulnerable with diversions in the vertical dimension (Irune & Burnett, 2007; Wittmann et al., 2006). With the center console located beneath the windshield, drivers have to look down to attend to in-vehicle touchscreens, and focal vision is diverted away from the road. Figure I-5 illustrates the visual experience of driver when attending to an in-vehicle touchscreen, depending on its location. When drivers are focally attending to the touchscreen, the location of an in-vehicle touchscreen can determine whether that the road dynamics would be processed through the peripheral view (see the top-left of Figure I-5) or hardly captured (see the top-right of Figure I-5). The size of touchscreen would matter in the same regard. With vehicle manufacturers increasing the touchscreen size (e.g., Braun, 2014; Brignall, 2016; Hyunh, 2016), interactive elements can be lowered away from the dashboard (compared the bottom-left to the bottom-right of Figure I-5). In the worst-case scenario with a large in-vehicle touchscreen, such as the aforementioned 17-inch, the road would not be monitored both focally and peripherally while interacting with the touchscreen. This illustration implies that the driver's ability in processing information through the ambient visual modality is contingent upon the location of interactive elements. Such an ability is actually significant in vehicle operation.

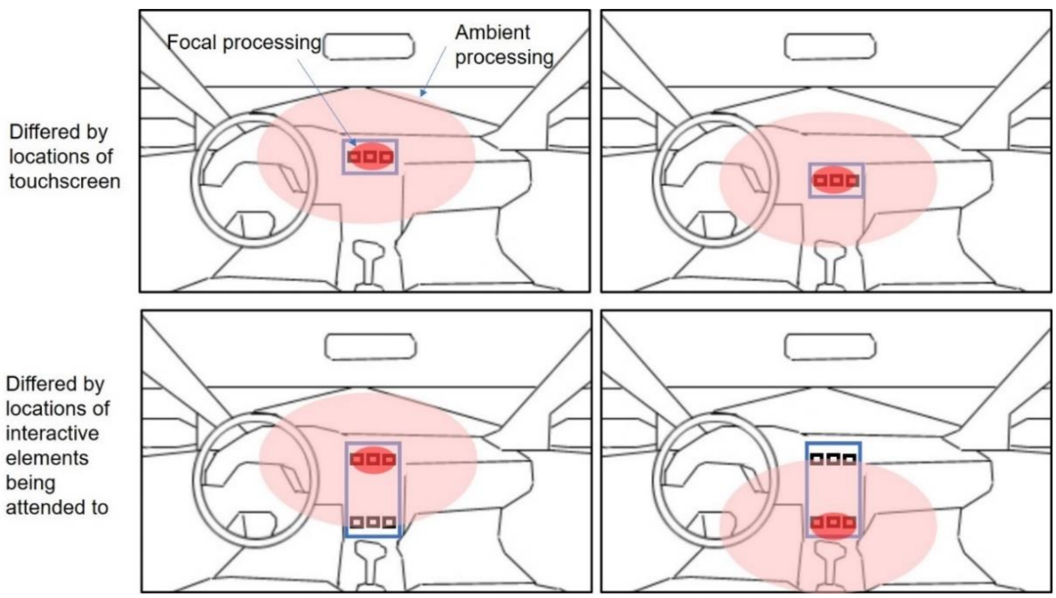

Figure I-5. Effects of in-vehicle touchscreen locations (adapted from Horrey & Wickens, 2004)

Crundall, Underwood, and Chapman (1999, 2002) investigated that the relationship between driving experience and the field of view that drivers can attend to. They demonstrated that drivers with an adequate level of driving experience have more extensive field of view than novice drivers. Horrey and Wickens (2002, 2004) further developed a theory for the significance of ambient vision in driving, proposing that drivers can process information through the ambient channel to support the spatial orientation of vehicles. With drivers practicing visual search in the peripheral visual field, the fact that in-vehicle touchscreens should be placed below the LOS should be a part of design consideration.

Understanding the behavior of multitasking drivers

It is important to understand the relevant driver behavior that is attributable to 1) visual scanning strategy, 2) the distinction from handheld touchscreens, and 3) touchscreen task characteristics. First, when it comes to visual scanning, the interface of an in-vehicle touchscreen is used in situations where drivers have to attend to multiple tasks at the same time, introducing a requirement for time-share. This is likely to affect the strategy to gather information visually. A comparison between in-vehicle touchscreens on the center console and other handheld touchscreens is also important. The distinction between the two can not only highlight the unique characteristics of in-vehicle touchscreen interaction but also provide fundamental ideas for design improvement. Lastly, task characteristics associated with in-vehicle touchscreens should be investigated. This can reveal the demands that need to be supported by design, which contributes to building a valid solution that better support in-vehicle-touchscreen-related tasks.

Visual scanning behavior of multitasking drivers

Understanding visual scanning behavior is imperative for driving safety, as drivers can build the awareness of surroundings through visual perception firstly (Horswill &

McKanna, 2004; Ma & Kaber, 2007; Walker & Stanton, 2008). The findings from neuroscience research indicate that humans practice gaze shifts and fixations in order to inform hand movements (Land, 1992; Land & Lee, 1994; Land & Horwood, 1995). In other words, visual attention is required in eye-hand coordination in order to inform manual interaction of where to go and what to get. Given vision is just one of sensory channels, it may be possible for manual interaction to be successful with no vision, as long as necessary information is acquired properly. This implies a possibility to improve driving safety by offloading the requirements for visual resources in visual-manual interaction while driving (Wickens, 2002).

Kujala and Salvucci (2015) provided an insight into the understanding of drivers' visual scanning strategy while interacting with nondriving in-vehicle interfaces. As depicted in Figure I-6, the model shows how drivers manage a visual sampling strategy with in-vehicle touchscreens; drivers constantly practice frequent reorientation of attention to cope with the time-share requirement due to the fact that they need to attend to two things simultaneously. The model also comprises aspects of multitasking by proposing that drivers monitor the passage of time while engaging in a visual-manual interaction. That is, drivers consider a time limit and adjust their glance durations at the touchscreen, switching back to the driving task once they realized that the time limit is over (e.g., Kim, Kwon, Heo, Lee, & Chung, 2014). This is corroborated by Wierwille (1993); the earlier study found out that drivers tend to limit glances that are away from driving under 1.6 seconds in most real-world driving environments. In this regard, NHTSA (2013) has suggested the so-called "two-second rule" for in-vehicle display designs, meaning a single sequence of visual-manual interaction while driving should be designed to be completed within two seconds. The model equates supporting visual requirements of in-vehicle touchscreens with supporting the timesharing requirement in the context of multitasking, corroborating why practical safety guidelines on in-vehicle touchscreen design are based on limiting the time that drivers can spend on the touchscreens (NHTSA, 2013).

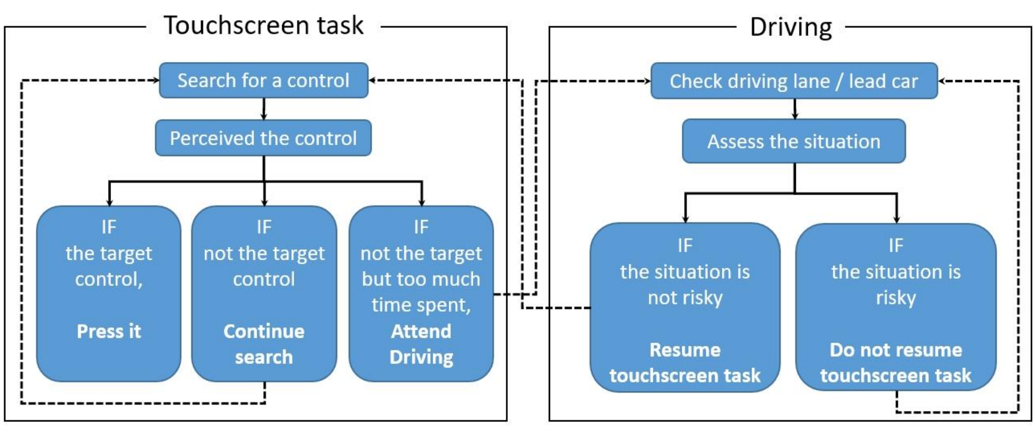

Figure I-6. A model of visual scanning behavior (adapted from Kujala & Salvucci, 2015)

However, the model did not take into account ambient visual contributions on driving. Given the goal to drive safely, the model assumes that drivers attempt to manage focal attention at the road and the nondriving interface. Actually, this explicit management of attention can also be supported by unconscious engagement in the peripheral visual world processed through the ambient channel (Horrey & Wickens, 2004). In fact, the importance of ambient vision may not have been fully appreciated, in association with distraction effects of in-vehicle touchscreens. Previous studies concerning visual scanning behavior of drivers tasked with in-vehicle touchscreens focused on the glance behavior that is driven by the management of focal vision (e.g., Kim et al., 2014; Kujala & Salvucci, 2015; Kujala & Saariluoma, 2011b). Although shifting gazes properly is critical in attention reorientation, drivers are able to attend to the roadway even when gazing at somewhere else other than the roadway (e.g., Summala, Niemeinen, & Punto, 1996; Horrey & Wickens, 2002, 2004; Crundall, Underwood, & Chapman, 1999, 2002). This is understandable in a sense that resources available to process stimuli through the focal channel are different from the resources that ambient vision engages in (Leibowtiz & Post, 1982). Summala and colleagues (1996) demonstrated that the performance in driving tasks, such as lane keeping, can be susceptible to the availability of ambient vision. They employed a forced-peripheral driving technique, whereby drivers performed lane keeping tasks while exclusively relying on ambient vision. Experimenters instructed drivers to fixate a gaze at locations in a vehicle below the windshield and to avoid visual scanning upward to the roadway. The results indicated that drivers were able to maintain vehicle control in lateral positions without fixating directly on the roadway. Crundall and colleagues (1999, 2002) proposed that experienced drivers can have "a wider field of peripheral vision" than novice drivers, allowing to respond to objects on the roadway more effectively even while focal vision is distracted.

The use of ambient vision can also be beneficial to manual performance. Johansson and colleagues (2001) reported that guiding hand movement while visual-manual interaction can benefit from ambient vision, depending on the location of objects. That is, when operators need to simultaneously attend to two or more things that are in distance, it would be significantly helpful if the objects are placed in a single field of view.

Manual interaction characteristics compared to handheld touchscreens

In-vehicle touchscreens are commonly mounted in the center console, like a mounted interface, whereas other touchscreen devices that can be used while driving tend to be handheld. Table I-1 describes the differences between handheld and mounted in-vehicle touchscreens in three categories including fingers-to-be-involved, screen size, and movement amplitude.

Table I-1. Comparison between handheld and mounted in-vehicle touchscreens

Category	Hand-held	Mounted	Design implications
Line of sight	Variant	Lower than windshield	Mounted touchscreens should not be too much separated in location from windshield.
Fingers-to-be-involved	Thumb	Five fingers	More gestures can be possible with mounted, such as pinch/spread, multi-finger touch.
Screen size	Small	Large	Large screens may lead to the location effects.
Movement amplitude	Small	Large	Movement amplitude may affect the required level of dexterity.

First, drivers can determine the location of touchscreens if they are handheld. The location can be in parallel with the LOS on the roadway or at least be as close as the LOS if held properly. In contrast, many in-vehicle touchscreens are fixed in a position on the center console to be lower than the windshield. Drivers always have to look down to glance at the touchscreen, which makes peripheral search harder, compared to handheld touchscreen devices that can be held close to the LOS toward the roadway.

Second, while using the handhelds, drivers tend to use thumbs, as the other hand should hold the steering wheel. When the touchscreen is mounted on the center console, drivers can use whichever finger in the one hand while manually attending to the steering wheel. This allows multi-finger gesture interaction such as tapping with multiple fingers or pinching/spreading. Previous studies exploited this feature by attempting to introduce complex gestures to in-vehicle touchscreens, although performance deterioration can occur in many ways including but not limited to interaction accuracy and efficiency (e.g., Bragdon, Nelson, Li, & Hinckley, 2011; tsimhoni, Smith, & Green, 2004), fatigue and difficulty in input differentiation (e.g., Yee, 2009), and high workload (e.g., Kim and Song, 2014).

In terms of screen size, in-vehicle touchscreens vary from 7 to 17-inch whereas handheld touchscreens are relatively smaller so they be held with one hand. Large in-vehicle touchscreens can increase perceived user satisfaction (Ma, Li, Gong, & Yu, 2017), although safety risks could be associated with the increasing size of in-vehicle touchscreens; the extent of visual diversion from roadway awareness may increase as the touchscreen location goes lower.

Handheld touchscreens tend to be used with a thumb (or thumbs, if it is two-hand operation), and the distance between the finger and the target would be much smaller compared to interactions with mounted touchscreens initiated by taking a hand off the steering wheel. Such distance can be translated to movement amplitude that can determine reaction time in a single task condition (Fitts, 1954). Although the linear relationship may not be applicable to multitasking situations (Kim et al., 2014), the increase in distance from hand/finger to a control will still lead to increase the index of difficulty regardless of task situation. The increased difficulty would extend the duration that visual attention should be diverted from the primary task (Kujala, 2013). This can be impactful, considering that touchscreen interaction requires accuracy when making direct inputs.

Task characteristics and requirements associated with in-vehicle touchscreens.

Harvey and colleagues (2011) classified touchscreen tasks into three; *discrete selection*, *alphanumeric entry*, and *level adjustment,* graphically illustrated in Figure I-7.

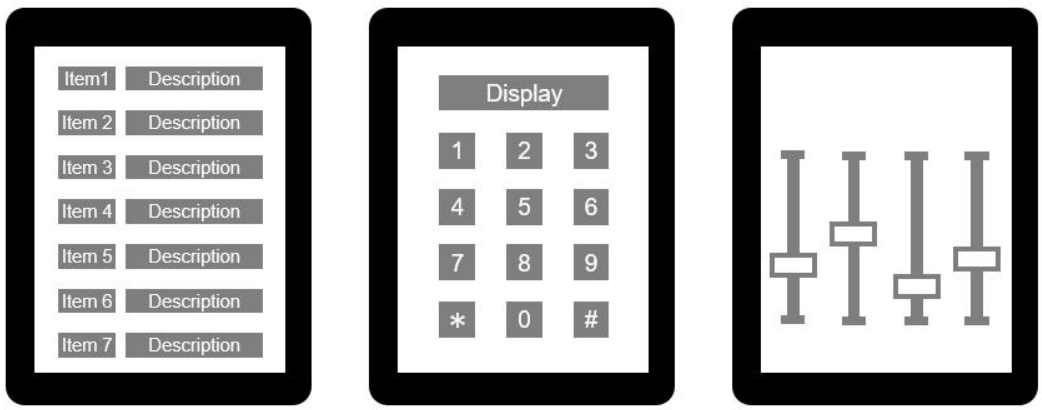

Figure I-7. Illustrations of touchscreen task interfaces. The above interfaces depict tasks for discrete selection (left), alphanumeric entry (middle), and level adjustment (right)

Operators tasked with *discrete selection* would touch an item on the screen with an index finger, in order to open another menu or to activate a function. Several factors are known to be influential to the performance of this task, including the number of alternative menu items displayed at one time (Hick, 1952; Hyman, 1953), the size of the target as well as the amplitude of hand movement (Fitts, 1954), the visibility of information displayed on the target (Stevens, Quimby, Board, Kersloot, & Burns, 2002). *Alphanumeric entry* is a special example of *discrete operation*, involving information encoded symbolically and most likely requiring more inputs than typical types of *discrete* *operation*. The fact that many inputs are required indicate the importance of reducing selection time in inputting for better performance, suggesting that the layout of items can be critical. In addition, the task difficulty would be greater than discrete operation, as the targets would be smaller and more in quantity. Audio volume control or climate adjustment can be examples of *level adjustment*. With physical controls, dials and sliders have been effective for this task, as they can increase or decrease values in a cognitively compatible way. Another example is pressing a button repeatedly for adjustment, which needs constant visual attention to confirm where the adjustment reached the target level.

Design of in-vehicle touchscreen interfaces are required to be task-dependent, considering the aforementioned types. This is because task type can determine the characteristics of manual interaction, such as hand gesture. For example, manual data entry, selecting particular targets among many alternatives, is better supported with tapping than with swiping/sliding (Reyal, Zhai, & Kristensson, 2015). However, tapping an arrow icon may not be ideal for searching pages, as swiping or sliding requires visual attention to a less extent (Kujala & Saariluoma, 2011a).

Manual data entry is one of common forms that earlier studies employed as a secondary nondriving task (e.g., Pitts, Burnett, et al., 2012; Reimer, Mehler, Lammers, Wang, & Coughlin, 2009; Young, Rudin-Brown, Patten, Ceci, & Lenné, 2014). This can be considered as a variation of *alphanumeric entry*, as the task would require many inputs in one sequence but the information to be inputted is not presented with the symbolic code. Primarily, this should be considered as *discrete operation*, a type of visual-manual interaction that draws out visual attention from the roadway for the entire task duration (NHTSA, 2013).

Specifying visual demands relating to in-vehicle touchscreens

NHTSA (2013) has introduced three types of distraction incurred by nondriving tasks; 1) visual distraction when looking away from the road, 2) manual distraction due to interacting with in-vehicle devices by hand, and 3) cognitive distraction incurred when engaging in mental resources. Distraction effects due to in-vehicle touchscreens often accompany all of the three; interacting with in-vehicle touchscreens needs 1) looking at the touchscreen, 2) deciding what to manipulate, and 3) executing the corresponding motor behavior. The most safety-critical effect is related to visual distraction, as safety of operators in outside can be first jeopardized by the failures in visual perception of surroundings (e.g., Hyman, Boss, Wise, McKenzie, & Caggiano, 2010; Nasar & Troyer, 2013; Newcomb, 2012), which is the fundamental level of awareness and all other types of processing/awareness builds on this foundational awareness (Endsley, 1995).

Findings in neuroscience offer evidence for the effects of some of these visual demands. Land, Mennie, and Rusted (1999) suggested four phases of the gaze behavior during visual-manual interaction; 1) locating a target, 2) directing a movement to the target, 3) guiding a contact with the target, and 4) checking the status of task-relevant information. Considering the recent model of visual scanning behavior (Kujala & Salvucci, 2015), Land and colleagues proposed that there would be an additional visual requirement to confirm inputs beyond “press target item”. Although the study was established in a single task operation, evidence indicates that such requirement can be impactful even in the context of multitasking (Suh & Ferris, 2016).

In general, it has been reported that visual demands for secondary tasks while driving deteriorate lateral position maintenance and that cognitive demands can increase *gaze concentration* on the road (Engström, Johansson, & Östlund, 2005), leading to hamper situational awareness and lengthen reaction time (Harbluk & Noy, 2002). Manual demands can increase visual demands. Touchscreens allow direct inputs, which is easy to learn but requires accuracy in motor behavior. As Land and his colleagues (1999) indicated, hand movement should be guided to a correct location, to which visual attention is mostly allocated for the task duration. That is, the more difficult the manual task is (e.g., smaller size of targets to tap), the longer the duration of visual distraction can be. This justifies why some previous studies have put an emphasis on reducing the difficulty of touchscreen task (e.g., Kim et al., 2014; Kujala & Saariluoma, 2011a; Kujala, 2013).

Earlier studies on in-vehicle touchscreen interaction

Earlier studies were concerned with safety risks of in-vehicle touchscreens, and some of them specifically investigated the interface characteristics of in-vehicle touchscreens with regard to driver distraction. Table I-2 summarizes the findings of previous studies concerning perceptual modalities of in-vehicle touchscreen interaction. Table I-2 involves that adding the nonvisual feedback to touchscreen interaction 1) improved the subjective ratings of interaction confidence (Pitts, Burnett, Williams, & Wellings, 2010), 2) decreased response time to safety-critical situations (Lee & Spence, 2008), and 3) reduced the time and duration of glancing at the touchscreen (Pitts, Skrypchuk, et al., 2012). However, such an addition did not improve driving performance. One of the limitations of those studies is that they tested the effects of sensory feedback in simulated environments where perception experience would only be approximated.

Table I-2. Previous studies on modalities of in-vehicle touchscreens

Authors	Main topic	Findings	Notes
Pitts et al. (2010)	Multisensory feedback during touchscreen interaction	Touchscreen nonvisual feedback can improve the confidence of interaction	No indication on attention management. The environment was simulated.
Lee & Spence (2008)		Touchscreen nonvisual feedback can reduce response time to safety-critical events	The safety-critical events were predictable. The environment was simulated.
Pitts et al. (2012)		Touchscreen nonvisual feedback can support the glance behavior in time and frequency	May not necessarily indicate safety. The environment was simulated.
Reimer et al. (2009) Young et al. (2014)	Comparison of handheld devices	Touchscreen is worse than physical keypad in lane keeping and input performance	The test platform was handheld.

These studies employed a proprietary touchscreen producing "haptic" feedback upon a key touch; actuators moved the surface of the touchscreen laterally a small amount, creating a transient perceived as a motion perpendicular to the touchscreen. General forms of feedback such as vibration would have been easier for replication of the study.

Some previous studies employed handheld devices (e.g., Reimer et al., 2009; Young et al., 2014), focusing on the difference between touchscreens and physical keys. In general, they asked participants to perform texting tasks while driving in simulated conditions. Used devices included touchscreen-based smartphones and cellular phones with physical keypads. The findings suggested that the physical keypad phones led to less variability in lane keeping and greater accuracy in texting. These studies pointed out the benefit of naturalistic interaction cues from physical keypads, although the tested devices were handheld and the aspects of manual interaction might have been different if in-vehicle touchscreens in the center console were used.

Table I-3 shows another set of earlier studies, showing that the difficulty of touchscreen task can drive visual loads.

Table I-3. Previous studies on manual interaction with in-vehicle touchscreens

Authors	Main topic	Findings	Notes
Kim et al. (2014)	Touchscreen key size	Increased difficulty of touchscreen task due to key size can produce significant distraction.	The amplitude of hand movement was not explicitly manipulated.
Kujala (2013)	Information search method	Swiping is better in visual attention than target pointing or scrolling.	The required level of dexterity may be critical.
Kujala & Salvucci (2015)	Spatial configuration of menu	Grid is better than List menu in target search and attracts less glance.	The vertical search is not desirable for touchscreen.

Kim and colleagues (2014) examined effects of touchscreen key size on drivers. They found that the width of square-shaped keys smaller than 17.5 mm can lead drivers to glance at the touchscreen longer and more frequently, proposing that more focused attention would have been needed to interact with the smaller ones and thus that the extent of visual distraction was greater. Interestingly, enlarging the 17.5-mm keys did not make a significant difference in glance behavior while the largest width tested was 25 mm.

Kujala (2013) employed several manual techniques for information search with in-vehicle touchscreens. He compared three types of techniques for changing lists of items; 1) *swiping* (swiping a fingertip anywhere on the touchscreen to change lists), 2) *arrows* (touching arrow keys to change lists), and 3) *scrolling* (scrolling a single list containing all the target items). The findings indicated that the smallest glance duration and frequency were observed in *swiping*. They claimed that using *arrows* would have required accuracy for motor function to a greater extent and need more visual attention to guide the input gesture. Particularly, *scrolling* led to increase perceived visual load and workload and to deteriorate performance in lane keeping tasks. It is interesting that participants preferred to use *arrows* for information search instead of swiping, illustrating that user preference does not necessarily match safe suggestions.

Kujala and Salvucci (2015) evaluated layouts of menu items by comparing list styles to grid styles. They also manipulated the number of items from two to twelve. They found that the grid styles with six or nine items led to the smallest duration and frequency of glance. In addition, they proposed that the grid styles were more robust to variations in the number of items.

The aforementioned earlier studies are limited in that they did not address interaction activities beyond activating target items, which is only a part of the *interaction loop* in Figure I-3 and incompletely covers the visual scanning behavior in Figure I-6. Hence, offloading visual loads due to in-vehicle touchscreens has been difficult to achieve, as the rest of visual requirements such as *pre-input* activities were not properly dealt with. As long as the touchscreens are presenting data via the visual channel, the timesharing requirement that can interfere with driving (Wickens, 2002) would continue to exist.

Other studies that have attempted to offload visual demands throughout the interaction loop employed complex gestures or speech recognition, so as to provide drivers with nonvisual methods search for target items on in-vehicle touchscreens. However, these attempts resulted in increasing the difficulty of touchscreen tasks; the results showed low accuracy (Bragdon, Nelson, Li, & Hinckley, 2011; Tsimhoni et al., 2004), fatigue and difficulty in input differentiation (Yee, 2009), and high workload (Kim & Song, 2014).

Selection of methods for assessing driver distraction

Driving studies concerning driver distraction have been employing secondary tasks in experimental settings, expecting the effects of distraction would be incurred by secondary tasks. Measuring such distraction effects is important, and a single measure would not be sufficient to explain the full spectrum of distraction effects. A variety of driving performance measures have been employed in previous driving studies including but not limited to vehicle operation, event detection, response time, and perceived workload.

Measures for assessing performance in vehicle control mainly comprise of aspects in longitudinal and lateral control. First, longitudinal control involves the management of vehicle speed or the following distance to the lead vehicle. Speed-related measures are to collect the central tendency or variability of vehicle speed, and earlier studies have reported that these can be sensitive to distraction effects (Burns et al., 2002; Reed & Green, 1999). The effects of driver distraction can increase the variability of vehicle speed. The distraction effects can also decrease the magnitude of vehicle speed (Burns et al., 2002; Haigney, Taylor, & Westerman, 2000), which can be a form of risk management strategy. However, interpreting performance in longitudinal control with the absolute magnitude can be problematic. For example, distraction effects can make the distance to the leading vehicle shorter (Regan, Lee, & Young, 2008) or longer (Greenberg et al., 2003; Hjälmdahl,

& Varhelyi, 2004). These contradictory results are understandable in that the former was attributable to drivers losing the track of speed due to cognitive loads of distraction and that the latter was attributable to the choice of risk management strategy to secure safe distance to the leading vehicle given distracting environments. Hence, understanding performance in vehicle operation may be clearer by investigating variability or at least deviation from means rather than just focusing on mean values.

Measures for performance in lateral positions of vehicles generally concern lane keeping. Lane keeping refers to the management of vehicle's position in relation to the center of the driving lane, and variously known as lateral position variability, lateral maintenance, and driving lane maintenance. Commonly-used metrics are mean lane deviation (MLD), standard deviation of lateral positions (SDLP), and number of lane exceedances (LANEX) (Regan et al., 2008). Previous studies indicated that visually-demanding secondary tasks generally deteriorate performance in lateral maintenance, leading to increase the variability in lateral vehicle positions (Green et al., 1993; Reed & Green, 1999). Examples of such secondary tasks include dialing or talking on a phone (e.g., Strayer, & Drew, 2004), manual data entry (Reimer et al., 2009), checking with visual navigation instruction (Donmez, Boyle, & Lee, 2007), or manipulating in-vehicle information system (IVIS) (Jancke, Musial, Vogt, & Kalveram, 1994; Wikman, Nieminen, & Summala, 1998).

Performance measures pertaining to event detection and reaction time have been widely used in driver distraction studies, as the relationship between those measures and crash risks is straightforward. A variety of the corresponding measures were studied, such as detection rate, incorrect response rate, response time, and response distance indicating the distance from events when detected. Interacting with in-vehicle devices while driving has been reported to be detrimental in detecting and responding to safety-critical events or objects (e.g., Srinivasan, & Jovanis, 1997; Lee, Caven, Haake, & Brown, 2001; Engström, Johansson, & Östlund, 2005)

Perceived workload is a subjective measure for participants to rate their level of workload immediately followed by the completion of tasks. Previous studies have shown over two decades that subjective ratings of workload can be a sensitive measure in understanding distraction effects (Hart, 2006). Usually facilitated by questionnaire, several simple techniques have been developed and widely used. One of the well-known techniques for subjective workload assessment is the NASA-Task Load Index (NASA-TLX) procedure that is a multidimensional scaling method concerning six dimensions of perceived workload, such as mental/physical/temporal demand, performance, effort, and frustration (Hart & Staveland, 1988). Ratings from each dimension are averaged with equal weightings, or experimenters can decide that participants assign weights to each. However, subjective assessment of workload suffers some drawbacks; participants may forget their performance in experimental trials and have difficulties in setting up a reference of performance.

The current research goals

Although earlier studies mentioned in this chapter have been attempted to address visual demands of in-vehicle touchscreens, those attempts have been limited in that the frequent reorientation of driver attention was inevitable during in-vehicle touchscreen interaction (Kujala & Salvucci, 2015). This would have been resulted in a degree of visual diversion away from the road, which is a concern of safety. Therefore, it is necessary to design the interface of an in-vehicle touchscreen to be accessible with nonvisual modalities, so the reliance on visual resources for touchscreen interaction can be minimized.

This dissertation describes research efforts to develop and evaluate **Nonvisual Aids for Touchscreen Experience (NATE)** that was designed to minimize task interruptions in distracted driving scenarios with in-vehicle touchscreens and to ultimately better support visual attention management. It also aims to provide insights into the data-rich domains in which operators perform visually-demanding tasks with a control interface primarily relying on a visual modality. This work is novel in that it investigates the potential for a new direction in touchscreen design to integrate multisensory signals from distinct spots into a single sensory experience. Such interface design complements earlier work on touchscreen design with nonvisual cues, and has the potential to improve driving safety when drivers are engaging in secondary touchscreen tasks while monitoring the roadway.

Chapter I (the current chapter) describes the background and objective of this research. Chapter II describes research activities that needed to first answer theoretical and practical questions about supporting visual attention of drivers tasked with in-vehicle touchscreens. Chapter III describes a preliminary design and investigation of performance with touchscreen-based communication to be visually processed with a nonvisual modality. This is the initial attempt to provide touchscreens with nonvisual aids; a symbolic encoding method was tested. The findings from these studies served as inputs to the final design. Chapter IV describes theoretical and practical considerations for designing NATE, the nonvisual aids to offload visual demands of an in-vehicle touchscreen. Chapter V discusses the evaluation study conducted with the proposed designs. As Conclusion, Chapter VI summarizes the findings, discuss limitations of this dissertation study, presents directions for future studies in line with the topic of this dissertation.

The theoretical and practical contribution of this line of research is that it provides greater insights into the behavior of drivers (or operators) struggling to cope with timesharing requirements due to the limitation of attentional resources. In particular, this work demonstrates how visual demands of in-vehicle touchscreens can be specified in stages and investigates how such visual demands can affect visual attention management of drivers. Finally, concerning every step of the *interaction loop*, this work further proposes design efforts to offload the visual demands associated with in-vehicle touchscreens, in order to offer drivers an alternative method for touchscreen interaction that diverting visual attention away from driving is not essential.

CHAPTER II

THE ROLES OF INTERFACE CHARACTERISTICS OF IN-VEHICLE TOUCHSCREENS IN ATTENTION MANAGEMENT*

In-vehicle touchscreens demand visual attention, and various interface characteristics can be associated with the orientation of visual attention in different ways. A better understanding of how these characteristics affect driver attention management will be helpful in design efforts to offload visual demands of drivers, leading to safer driving environments.

The first study of this chapter describes a study which investigates the association between driver attention management and the sensory channels engaged during interactions with the center console. Wickens (2002) proposed that task interferences that impact performance can occur when separate tasks compete for the same pool of limited attentional resources to the extent that resources are sharable. That is, the less extent the center console interface requires visual attention, the less likely visual attention of drivers would be diverted away from driving. The first study revealed the effects of nonvisual modalities of the center console interface on driver attention management. The findings show that different combinations of nonvisual cues to in-vehicle touchscreen interaction can lead to significant effects on drivers' performance in both visual detection and manual

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data entry. These findings provide practical design guidelines when utilizing nonvisual cues for a new interface design of in-vehicle touchscreens.

The second study of this chapter describes an experiment to investigate location effects associated with in-vehicle touchscreens. Previous studies demonstrated that visual processing can include engagement of separable resources; focal and ambient channels (Horrey & Wickens, 2004; Horrey, Wickens, & Consalus, 2006; Leibowitz, Shupert, & Post, 1984). That is, drivers who are focally attending to a secondary task interface can simultaneously attend to the roadway via ambient visual channels (Crundall, Underwood, & Chapman, 1999). This parallel processing would rely on the location of task interface, as the field of view should contain the task interface and the roadway at the same time. In this regard, the design trends toward enlargement of the size of in-vehicle touchscreens may need reflection, as the increased size can mean a greater spatial separation from the drivers' line of sight. The findings show that the vertical location of in-vehicle touchscreens can affect the abilities of visual attention management of drivers, leading to impacts on driver performance and safety. The findings also indicate a significant design constraint in terms of driving safety, related to in-vehicle touchscreens.

The effects of perceptual modality on center console interaction

Interface transitions from physical controls (such as buttons and knobs) to touchscreens gain the advantage of more expression in visual qualities of interactive elements. However, the haptic (touch) and auditory cues associated with interaction also changes dramatically in nature. Such multisensory cues are inherent to well-designed physical controls; users can feel buttons pressed and knobs turned and hear the click of activation, and this richness of feedback can provide a clear confirmation on the status of interaction even when the availability of visual attentional resources is minimal. However, touchscreens, which present virtual controls within flat surfaces, would not possess the naturalistic richness of interaction cues and make users rely on vision to a greater extent. The nature of touchscreen interaction would thus require more visual resources as compensation for the insufficiency in haptic/auditory feedback. This can be a problem to some multitasking operators for whom visual attention is critical, such as drivers; compared to physical controls, interacting with touchscreens while driving may result in a greater degree of visual distraction. This may deteriorate performance in event detection and response promptness, ultimately leading to more serious concerns for driving safety.

Effects of perceptual modality on driver performance can be best evaluated in *realistic driving environments* that drivers are allowed to have naturalistic sensory experiences. However, most if not all previous studies concerned with in-vehicle touchscreens have conducted experiments in *simulated* environments (e.g., Lee & Spence, 2008; Pitts et al., 2010; Pitts et al., 2012). Driving simulators allow researchers to observe negative implications of driver distraction in safety-related contexts like car crashes, without posing physical risks to participants (e.g., Medeiros-Ward, Cooper, & Strayer, 2014). On the other hand, operating a real vehicle in an experiment provides participants with "an adequate level of realism" that would be insufficient with driving simulators (National Highway Traffic Safety Administration (NHTSA), 2013). For example of such realism that deserves consideration, force feedback from the steering wheel can substantially affect natural hand motion and control input, and feedback should parallel pedal input in the task of managing vehicle speed. In addition, imperfections in the roadway and engine vibrations can introduce low- and high-frequency vibrations that represent natural noise in the driving environment, and can make secondary interaction tasks more difficult. Depending on the road and driving conditions, any interaction with hands/fingers could be perturbed; this should be considered in design of in-vehicle interfaces. Hence, conclusions about the effects of multisensory feedback can be more representative when testing in a real vehicle with naturalistic multisensory cues, compared to simulation, which primarily loads the visual resources.

One way to determine the effects on roadway awareness comes from the literature on situation awareness (SA). Endsley (1988, 1995) proposed a conceptualization of SA, defining three SA levels: 1) perception of stimuli (Level 1 SA), 2) overall comprehension of the current state (Level 2 SA), and 3) projection of the state to the future (Level 3 SA). Although the field of aviation studies employed the conceptualization at first, studies regarding ground vehicles have used it extensively (e.g., Horswill, & McKenna, 2004; Kass, Cole, & Stanny, 2007; Ma & Kaber, 2007; Salmon, Lenné, Young, & Walker, 2013; Young, Salmon, & Cornelissen, 2013). Measurement of SA while driving usually benefits from a simulator, as the measurement involves "pausing" a simulated world and administering a questionnaire about the current context in the simulated world (Ma & Kaber, 2007). In a real vehicle, it is difficult to measure any of the three levels of SA as the real world cannot as easily be "paused". Nonetheless, the conceptualization of SA is a useful way to assess driver safety, with several sources of evidence linking a failure in developing Level 1 SA directly to increased risk of safety issues (e.g., Newcomb, 2012). Previous studies have been primarily interested in measuring Level 1 SA (Hyman et al., 2010; Nasar, Hecht, & Wener, 2007; Nasar & Troyer, 2013) by using time and accuracy measures in detecting inserted probes. As it has been found to be sensitive to secondary tasks and other manipulations common to driving (Jones & Endsley, 2004; Walker et al., 2008), probe detection method can be a viable option for measuring SA in a real vehicle.

The assumption tested in the present study is that the richness of feedback in a secondary task interface would affect awareness of the road, based on measurements in time and accuracy when responding to visual probes. It was expected that the best multitask performance would be observed when the task interface consisted of physical controls. Differences would also be found in performance of the secondary task and perceived workload. Previous studies showed how interface characteristics of *handheld* devices can affect performance in texting-while-driving situations (Crandall & Chapparro, 2012; Reimer et al., 2014; Young et al., 2014). The current study was built on these earlier works, comparing touchscreens to a physical interface in terms of performance with different types of interaction feedback. By collecting measures of driver performance and safety, this study assessed perceptual modalities of secondary task interface in views of how they can affect performance measures including awareness of the roadway.

Methods

Twenty-nine drivers (12 males and 17 females, mean age=27, range: 21 – 36) participated in the study. The licensed driving experience was about 11.2 years (*SD*=5.8); participants had an adequate level of experience to practice a peripheral search on the roadside (Crundall et al., 1999; 2002). All of the participants demonstrated normal or corrected-to-normal visual acuity of at least 20/50. Two participants had vehicles employing in-car touchscreens, and five had used in-car touchscreens in the past. Participants received $40 for participation.

A real-world driving experiment was conducted to examine the effects of interface characteristics on drivers interacting with the center console interface. As shown in Figure II-1, participants drove a fleet vehicle along the prescribed course. Participants drove a 2006 Toyota Highlander on the prescribed route in a closed-course track at the Texas A&M University – Riverside Campus, which was a repurposed airport runway. The course was a straight and two-lane road outlined on both sides with rows of 44 traffic delineation barrels (TDBs). Spacing between TDBs was set to be 60 feet. Data were collected for the time duration that participants completed driving a "lap," which included driving the length of the course, then turning around and head back along the same roadway. The total length for one lap was at least 5,200 feet, as the experiment was designed to require participants to change lanes frequently.

Figure II-1. A view of the experiment environment

Figure II-2 shows interior of the vehicle and the course, recorded by a Logitech WebCam C920 HD Pro hung on the ceiling. The frame rate was set to be 30 per second. The camera also recorded the audio so as to confirm verbal responses of participants.

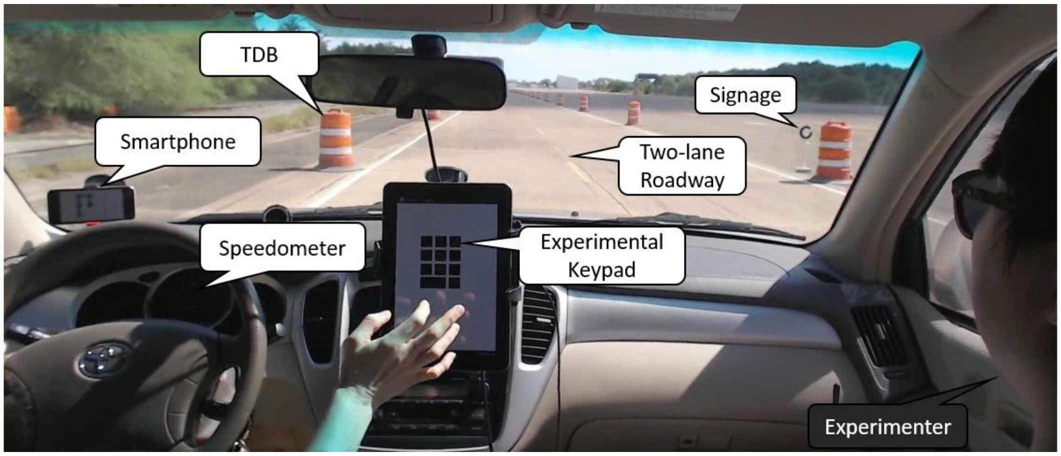

Figure II-2. The experimental setting in the instructed vehicle (Suh & Ferris, "The Impacts of touchscreen and Physical Control Interface Characteristics on Driver Distraction and Attention Management", Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 60, No. 1), p. 1519, copyright © 2016 by SAGE, reprinted with permission of SAGE Publications, Inc.)

Participants performed two primary concurrent tasks of equivalent consisting of 1) an *input task* using keypads configured with various interface characteristics and 2) a *detection task* to detect and promptly respond to signs obscured by the barrels along the roadside. Participants were also asked to maintain the vehicle speed at 25 MPH.

The input task required entering predefined input sequences with keypads configured as illustrated in Figure II-3: 1) a physical keypad (referred to "Physical"), 2) a touchscreen with small keys ("TouchSmall") that were arranged in the same size and spacing as Physical, and 3) a touchscreen with enlarged keys that are proportionately spaced ("TouchLarge").

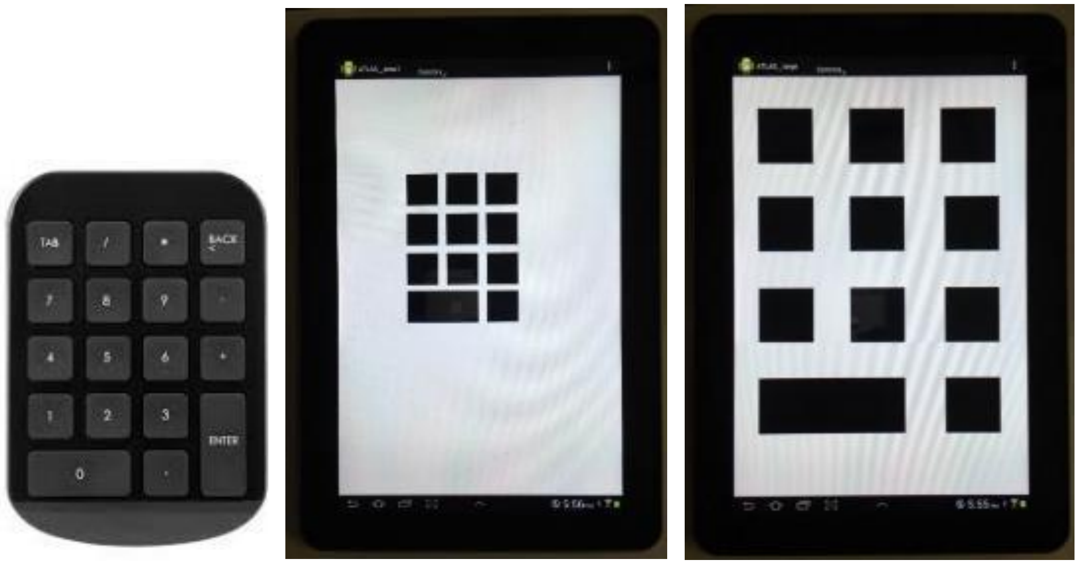

Figure II-3. The three keypads used in the experiment (left: Physical, middle: TouchSmall, and right: TouchLarge). For Physical, unnecessary keys were taped.

The physical keypad was a wireless keypad, Targus AKP11US, affixed to a hardboard in a location that mapped to the spatial arrangement of TouchSmall. Participants were instructed to disregard the numeric characters of Physical and to instead consider it as a 3×3 array of input keys with *enter* (the long key in the bottom) and *clear* (the one next to *enter*) keys in the bottom row. TouchSmall and TouchLarge were implemented in a touchscreen tablet, Samsung GT-P7510, and the keys performed the same functions as in Physical. The brightness of the screen was set to be maximum. As shown in Figure II-3, black keys are displayed in the white background in order to ensure the visibility of keys, although glare was not explicitly controlled.

Table II-1 describes six types of interface characteristics, which was the within-subject independent variable. Synthetic feedback were applied to the five touchscreen conditions. The nature of synthetic feedback involved 1) Visual (V, the color of keys blinks from black to yellow when touched), 2) Auditory (A, the keystroke sound of the tablet's default setting is played), and 3) vibroTactile (T, the tablet vibrates for 0.5 seconds. During testing and training procedures, participants did not report any problems with regard to perceiving all types of synthetic. The keys of Physical looked, sounded, and felt like an ordinary computer keyboard. The intensity of auditory and vibrotactile feedback was set to be the tablet's maximum levels. The touchscreen condition with large keys involved only one feedback condition, as this study was not interested in interaction effects between feedback modality and key size.).

Table II-1. Types of interface characteristics

Type	Description
TouchSmall-V	TouchSmall with visual feedback only
TouchSmall-VA	TouchSmall with visual and auditory feedback
TouchSmall-VT	TouchSmall with visual and vibrotactile feedback
TouchSmall-VAT	TouchSmall with visual, auditory, and vibrotactile feedback
TouchLarge-VAT	TouchLarge with visual, auditory, and vibrotactile feedback
Physical	The keypad with physical keys

Table II-2 presents the size specification of keys. Sizes of TouchSmall were determined to match those of Physical, and TouchLarge represented a sort of optimal key size and spacing for touchscreen interaction (Colle & Hiszem, 2004)

Table II-2. The size specification of experimental task interfaces (mm)

Keypad type	Input and clear keys		Enter keys		Margin between keys
	Width	**Height**	**Width**	**Height**	
Physical and TouchSmall	15	15	34	15	4.5
TouchLarge	25	25	67	25	17

Instructions for the input task were visually presented on the screen of an Apple iPhone® 4S that was mounted right above the instrument cluster, as shown in Figure II-4.

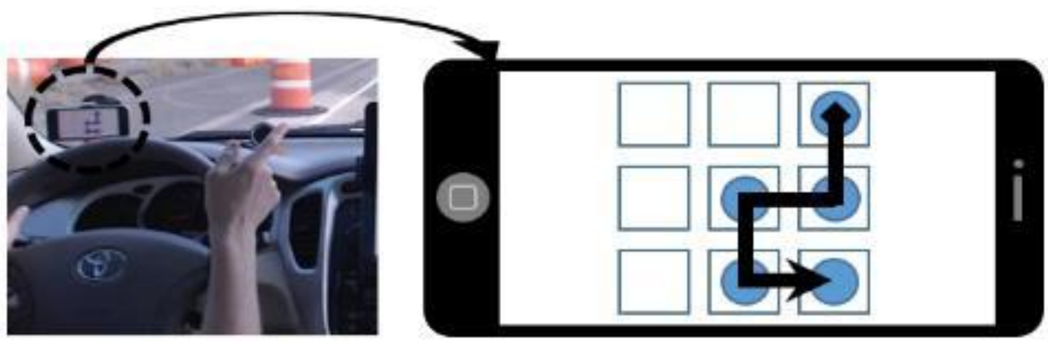

Figure II-4. An illustration of graphical instructions for the input task

Each instruction depicted a 5-key input sequence that included vertically- or horizontally-adjacent keys (with no repetition). Figure II-4 shows that keys to press were marked with circles and that each input sequence began at a diamond shape and ended at an arrow. Pressing *enter* confirmed the corresponding input sequence and entered it for data collection. When noticing an errant entry, participants were instructed to press *clear* to restart the corresponding sequence. Upon completing any 5-key input sequence, participants then touched the smartphone screen to advance to the next instruction.

Participants continued to renew the sequences and to enter them until they completed one lap of the driving course, and were encouraged to enter as many correct sequences as possible during this time. With the smartphone located on the left side of the windshield, participants had to frequently reorient visual attention between the smartphone screen and the keypads on the center console.

Figure II-5 shows some input sequences that were designed for the input task. In total, 90 input sequences were designed. As participants were instructed to drive six laps of the prescribed course in total, 15 out of the 90 sequences were given to one lap. Each distinct set of 15 sequences was repeatedly presented until the corresponding lap was finished.

Figure II-5. Examples of input sequences used in the study

The detection task required verbally acknowledging signs placed between the barrels, and then to perform a lane change depending on the orientation of the sign. As shown in Figure II-6, the signs could be configured to show one of two orientations: “C” and “U”. The “C” orientation signified a need to change lanes (“lane should be Changed”), whereas the “U” did not (“lane should be Unchanged”). Participants were instructed to first verbally respond when signs were identified, and then to change or not to change lanes. They were allowed to use their own words for the verbal response but encouraged to simply say “C”/“Change” or “U”/“Unchanged”.

Figure II-6. The experimental signage (left: “C” and right: “U”)

Figure II-6 also shows that the signs consisted of incomplete circles printed on transparent plastic boards rotatable about a pivot point affixed to traffic delineation posts. The posts were adjusted in height to be as tall as the TDBs; the posts and the affixed signs were visually obscured by the TDBs in distance. The signs were made in two sizes: 6- and 10-inch diameter. Eight signs on each roadside included four pairs of each size, alternating the small and large sizes. Each sign was placed five feet away from the nearest barrel and at a consistent offset, so that the sign would be visually “unveiled” in approximately the same way, and to allow participants a fairly consistent amount of time to detect the sign.

Figure II-7 shows screenshots from the recorded video, illustrating how a sign could be visually *unveiled* from behind an obscuring TDB. Sight lines were controlled for signs to be only visible when approaching the TDB. Experimenters in a separate, trailing vehicle pseudo-randomly reconfigured the orientation and location of signs before starting each lap.

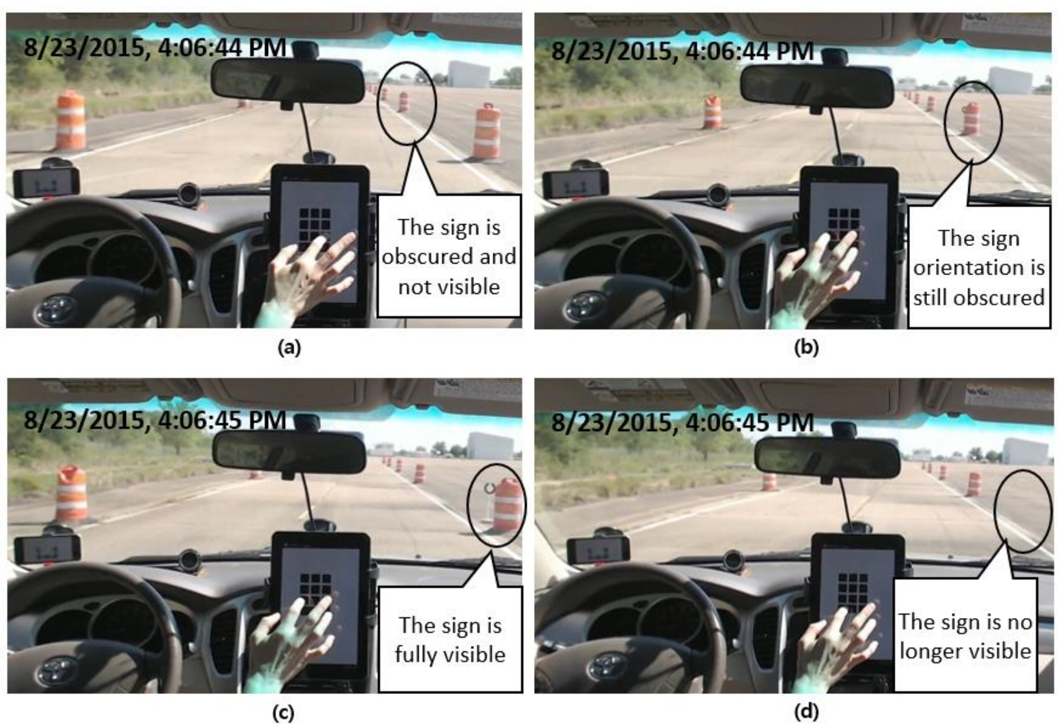

Figure II-7. An illustration of the detection task

Participants were allowed to adjust the driver seat as what was comfortable to them to make sure the touchscreen can be within the reach envelope. As training, participants drove three laps while trying to maintain the vehicle speed at 25 MPH. During the first training lap, they conducted the input task in the first length and the detection task in the second length. During the second and third training laps, participants conducted both tasks, experiencing and familiarizing themselves with each type of the interface characteristic as specified in Table II-1. In the main experiment, participants performed both the input and detection tasks concurrently during each of six laps. As specified in Table II-1, each lap involved a different interface configuration. The order in which the six interfaces were used was partially counterbalanced in order for each condition to appear once in each position of the order, like a standard Latin Square Design.

For the input task, only correctly-entered sequences were collected. Cleared inputs (pressing “clear” to start over the entry before pressing “enter”) were not included. *Input efficiency* (count) was defined as the number of input sequences entered correctly. *Input accuracy* (%) was the percentage of input sequences entered correctly. *Input time* (seconds) was the mean duration measured from the first input key until the enter key.

For the detection task, the video and audio recordings were observed; both verbal and manual responses needed to be correct to be registered as “correct response”. *Detection rate* (%) was the percentage of the correct responses over all the signs. With regard to time-based measures, assessing performance was problematic. Firstly, the recorded video did not display elapsed time. Moreover, the time at which a sign became visible to participants varied; the sight lines to the sign could differ depending on the lane in which the vehicle was travelling at the moment. Hence, a unique measure was needed to assess time-based performance that was independent of driving lane positions.

Response promptness (%) indicates the time at which a participant correctly and verbally acknowledged a given sign, evidenced by the view available to the ceiling-mounted video camera (see Figure II-7). Figure II-8 depicts the concept of response promptness; "**A**" represents the time elapsed between the emergence of a given sign and the initiation of the verbal response, while "**B**" represents the time measured from the verbal response initiation until the acknowledged sign disappeared from the recorded view. The measure of time was assessed as a count of video frames. *Response promptness* therefore was defined as the percentage ratio of video frames corresponding to **B** and the sum of **A** and **B** (see Figure II-8). For example, a response promptness score of 40% means that 20 video frames elapsed between verbal acknowledgement of a particular sign and the final frame of sign visibility, while the total duration of sign visibility was 50 frames. For missing or incorrect responses, the measure was coded as zero frames. To be registered as "correct", both verbal and manual responses needed to be proper; the correctness was adjudicated by the recorded video.

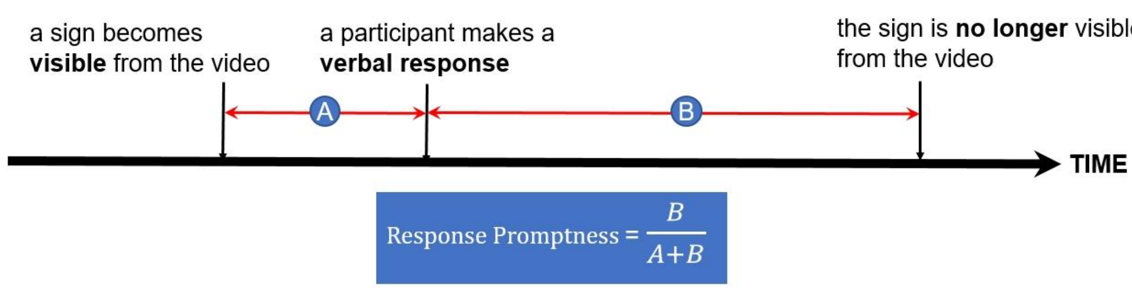

Figure II-8. The concept of response promptness

Perceived workload was the mean of unweighted ratings for the six dimensions of subjective workload included in the NASA-TLX procedure (Hart & Staveland, 1988). The six ratings involved mental, physical, and temporal demand, performance, effort, and frustration, each was evaluated in a 9-point scale; the five was named as *moderate*. Participants completed surveys to record the ratings every time after finishing each of the six interface conditions.

Results

With the interface characteristics as the within-subject independent variable, one-way ANOVA models for the performance measures were developed. When a significance was found, the Bonferroni's multiple comparison was conducted. A significance level of alpha=0.05 was used.

Figure II-9 shows performance of detection rate and response promptness. Error bars represent the standard errors, and letters on the mean values are used to label significantly-different groups. For example, the group labeled with A is significantly different from the one with B, and AB, a group with two letters, is statistically equal to either of A or B. Due to a technical problem in recording, some of the data were lost. The finalized data involved 27 participants for the model of detection rate and 25 for that of response promptness.

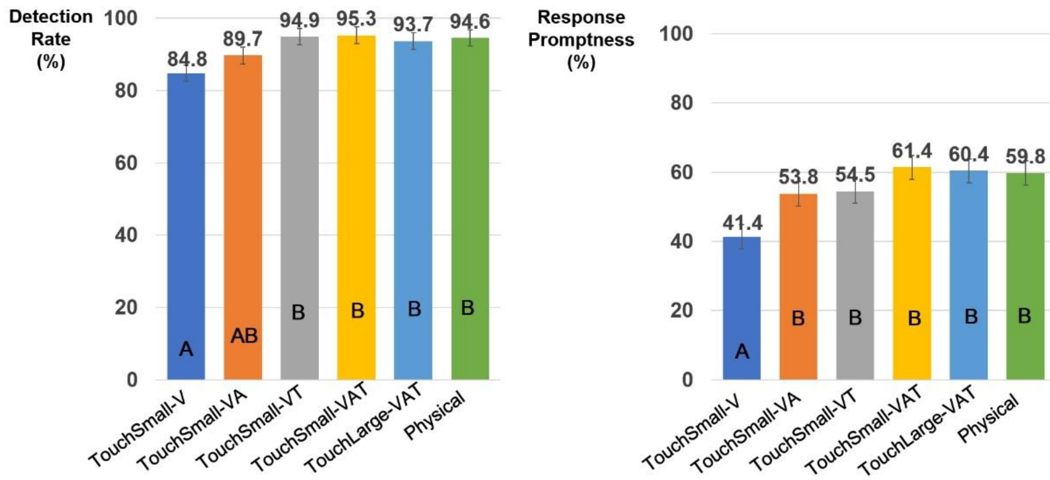

Figure II-9. Performance of detection rate and response promptness

The interface characteristics affected detection rate, F (5, 156) = 6.696, $p < 0.001$, and detection rate in TouchSmall-V (M=84.8%) was lower than that in TouchSmall-VT (94.9%; $p < 0.001$; cohen's d = 1.131), TouchSmall-VAT (95.3%; $p < 0.001$; 1.211), TouchLarge-VAT (93.7%; $p = 0.002$; 0.912), and Physical (94.6%; $p < 0.001$; 1.140). For response promptness, a similar tendency was observed; a significance was found, F (5, 144) = 6.327, $p < 0.001$, and three significant differences were identified when comparing TouchSmall-V (41.4%) to TouchSmall-VA (53.8%; $p = 0.032$; Cohen's d = 1.068), TouchSmall-VT (54.5%; $p = 0.035$; 1.055), TouchSmall-VAT (61.4%; $p < 0.001$; 1.860), to TouchLarge-VAT (60.4%; $p < 0.001$; 1.578), and to Physical (59.8%; $p < 0.001$; 1.597).

Figure II-10 shows performance of input accuracy and input efficiency. Error bars represent the standard errors, and alphabets in the bars represent significantly-different groups.

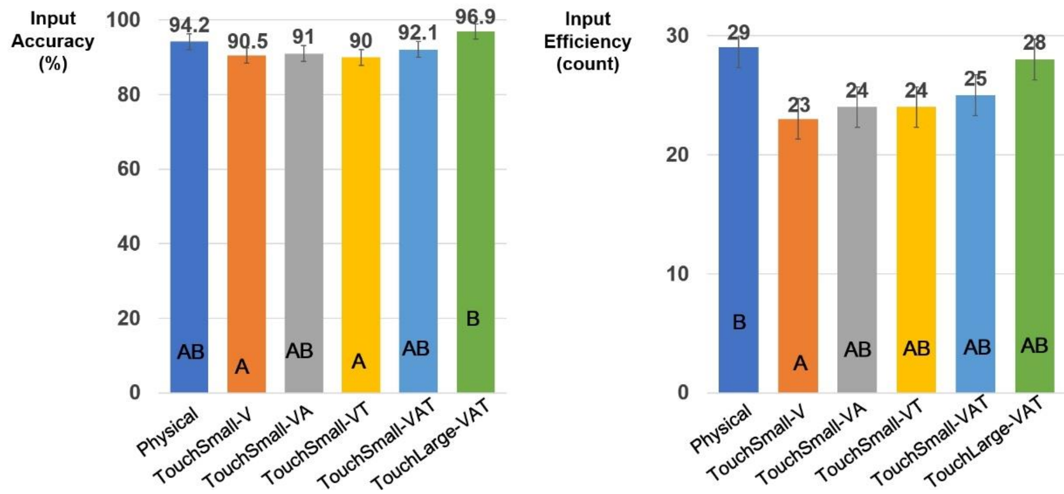

Figure II-10. Performance of input accuracy and input efficiency

The interface characteristics affected input accuracy, F (5, 168) = 3.129, p = 0.010. The post-hoc test revealed that the accuracy measures in TouchSmall-V (M = 90%, p = 0.037; Cohen's d = 0.810) and TouchSmall-VT (90%, p = 0.018; 0.901) was lower than that in TouchLarge-VAT (97%). The significant effect was also found in input efficiency, F (5, 168) = 3.511, p = 0.005, and one significant difference between TouchSmall-V (M = 23 times) and Physical (28 times, p = 0.017; Cohen's d = 0.790).

Indicating no significant effect, Figure II-11 shows performance of input time in addition to perceived workload. Error bars represent standard errors.

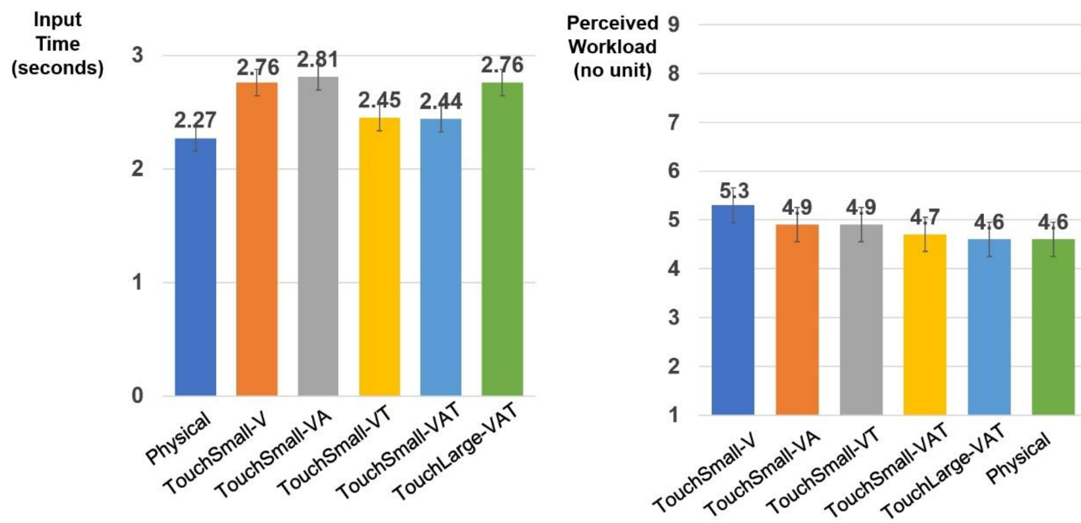

Figure II-11. Performance of input time in addition to perceived workload

Discussion

Earlier studies show that secondary in-vehicle tasks can cause driver distraction to deteriorate driving safety (e.g., Crandall & Chapparro, 2012; Kass et al., 2007; Iqbal, Ju, & Horvitz, 2010; Kutila et al., 2007; Sethumadhavan, 2011). The current findings support those studies and further demonstrate that the characteristics of secondary task interface, including interface type, key feedback and key size, can significantly affect performance of drivers. In the current study, participants drove an instrumented vehicle on the road and conducted a visual probe detection task, while distracted by an input task involving visual-manual interaction. As the detection task persistently demanded visual attention on the roadway, the input task would have competed for the same attentional resources (Wickens, 2008).

The findings highlight that the absence of nonvisual feedback can actually disturb visual perception and response to safety-critical events on the real roadway. The worst performance in *detection rate* and *response promptness* was consistently observed with the touchscreen condition without the aids of nonvisual cues (TouchSmall-V). This is corroborated by an earlier simulated study in which drivers paid longer and more frequent glances at in-vehicle touchscreens when the touchscreen interaction was not supported by “haptic” feedback (Pitts et al., 2012). The current finding creates an addition that how such change in glance behavior can actually undermine performance on the real roadway with regard to visual search.

In the same regard, the findings indicate that nonvisual key feedback of in-vehicle touchscreen can support performance of visual search while driving. Performance in the detection task would have been dependent upon the extent to which visual attention can be allocated to the road (Wickens, 2008), and providing touchscreen interaction with nonvisual synthetic feedback made a significant difference in visual awareness of drivers. Compared to the unimodal visual cue, richer key feedback (e.g., TouchSmall-VA/VT/VAT, TouchLarge-VAT, and Physical) better supported performance. Compared to the physical keypad which provided arguably the richest forms of feedback, performance did not get worse when the touchscreen involved all of the three modalities.

Regarding input accuracy, the performance in the arguably-worst condition (TouchSmall-V) exceeded 90%; the relatively simple and self-paced task supported fairly accurate input. Nevertheless, a room to significantly improve performance was identified when given were both large keys and richer feedback (vs TouchLarge-VAT). Interestingly, the size effect was not significant when the touchscreen keypad was provided the full set of synthetic feedback (TouchSmall-VAT vs TouchLarge-VAT). In contrast, an earlier finding shows that size effects of touchscreen key were significant on a similar input task

(Kim et al., 2014). However, their experiment conditions did not involve the multimodal feedback that this study employed. This led to a speculation that the richness of synthetic feedback may be able to alleviate the task difficulty incurred by key size, indicating a possibility for the interaction effect between key size and feedback configuration.

In input efficiency, the physical keypad was significantly better than the worst touchscreen condition (TouchSmall-V). However, when any type of nonvisual synthetic feedback was given to the touchscreen, no significance was found. Similarly, the physical keypad also showed the best performance in input time although the main effect did not reach significance ($p = 0.07$).

Despite the initial assumption that the interface characteristics would affect perceived workload, no supporting evidence was found. On the contrary, Lee and Spence (2008) reported that the feedback configuration was significant in the subjective ratings of perceived workload based on the same NASA-TLX procedure; the ratings were significantly higher in the touchscreen condition with unimodal visual feedback. Examining this discrepancy is difficult, as task situations are different. Whereas the current study was conducted with a real vehicle but did not impose crash risks on participants, Lee and Spence (2008) explicitly realized such risks in a simulated environment with a car avoidance task. Hence, the sign of danger would have been more conspicuous and more effective in stressing out participants than just showing “safety-critical” signs on the roadside. Investigating distraction effects with regard to perceived workload may need considering situational factors such as crash risks or traffic situation.

This study expanded on previous findings concerning visual demands of in-vehicle touchscreens, supporting that visual attention management of drivers can be contingent upon the richness of synthetic feedback. This finding could be useful to improve design guidelines for in-vehicle touchscreens. For example, NHTSA (2013) published a guideline specifying safety concerns in driver distraction due to in-vehicle electronic devices including touchscreens. Calling for vehicle manufacturers to limit the amount of time associated with in-vehicle touchscreen interaction, the guideline did not involve the benefit of nonvisual modalities with regard to mitigation strategies for visual distraction. The current study indicates an addition, emphasizing that providing in-vehicle touchscreen interaction with nonvisual cues can significantly support multitasking performance of drivers.

Considering the recent trends of in-vehicle design to popularly use touchscreens, a need for reflection is signaled by the current findings regarding how such interface transition from physical elements can impact on drivers. Designers would benefit from being well-informed about how visual demands of touchscreens can negatively impact driving safety, because any features that were first introduced to support drivers may increase safety risks by becoming a source of distraction (Petzoldt et al., 2014).

The location effects of in-vehicle touchscreen on driving safety

In addition to feedback and size characteristics, another major dimension of interest is touchscreen locations relative to the line of sight to the roadway. When attending to an in-vehicle touchscreen, drivers would engage in focal attention to process precise recognition control elements. Concurrently, drivers can also process other stimuli that is in the functional field of view; processing visual information in parallel can be done via focal and ambient channels (Wickens, 2008). Earlier studies suggest that focal vision is for pattern recognition, detecting physical characteristics of environmental objects (Schmidt & Lee, 2005; Sekuler & Sekuler, 2000). On the contrary, ambient vision is rather related to detecting spatial characteristics of surroundings such as orientation and movement (Horrey & Wickens, 2004). While driving, the parallel processing of visual resources can occur in a way that hazard detection is processed focally while ambient visual resources are engaged to process changes of lateral positions (Horrey & Wickens, 2004). Drivers would likely benefit from these dichotomous resources in driving performance and safety.

However, drivers may lose the benefit of ambient visual resources when focally attending to secondary task interfaces in vehicles (Irune & Burnett, 2007). Chapter I outlined the distraction potential linked to location changes of the secondary interfaces; visual awareness of the roadway while focally attending to an in-vehicle touchscreen may be prone to the physical distance between the roadway and the touchscreen. If the touchscreen location was too separated from the line of sight to the roadway, drivers would not be able to practice the skills in parallel processing that otherwise can better support performance in visual perception in the peripheral field of view (Crandall & Chapparro, 2012).

Hence, the location of in-vehicle touchscreens should be regarded as an important design factor in driving safety. This is especially important, considering that touchscreens rely on visual attention to a greater extent than physical controls, as the findings of Chapter II suggested. This location effect would also be in line with the size of touchscreens; if vehicle manufactures enlarges the size of touchscreens in the vertical dimension, drivers would have to look down farther, and the entire field of view would not be able to contain the roadway in the peripheral area. This might be true in reality, with one of vehicle manufacturers currently offering 17-inch in-vehicle touchscreens (see Figure I-1).

This study conducted a simulated driving environment in which participants performed the Lane Change Test (LCT) while interacting with touchscreen tablets. The LCT is an established procedure to assess driver distraction in simulated conditions (Harbluk, Bruns, Lochner, & Trbovich, 2007; ISO/DIS 26022, 2010; Mattes & Hallén, 2009; Young, Lenné, & Williamson, 2011). The test involves drivers' abilities in management of driving lanes based on a visual probe reaction task, concerning performance in both vehicle operation and visual perception. In actual trials, participants were simultaneously dual-tasked with a nondriving task as distraction. This study manipulated the vertical location of touchscreens, which varied in five different levels. No touchscreen condition was also included to highlight distraction effects.

Methods

Twenty-one participants (15 males and 6 females, mean age: 28, range: 21 – 42) were recruited in the study. All of the participants reported that they have normal or corrected-to-normal visual acuity of at least 20/50. No one had any known conditions that may affect performance of the experimental tasks. Three of them reported less than three years of driving experience but all the participants had at least one year of the experience. No compensation was given for 1.5 hours of participation.

This study employed the STISIM Drive® simulator equipped with the Logitech G27 racing wheel, throttle and brake pedals, which provided participants with force feedback of manual interaction, but no kinetic sensation for vehicle speed was involved.

Figure II-12 shows a standard vehicle cockpit view that the simulator presented, with an analog speedometer centered at the bottom of the screen. Based on the standard guidelines from ISO (ISO/DIS 26022, 2010), scenarios for the LCT were designed. Each scenario was built on a straight three-lane roadway which was 10,000 feet in length or approximately a 3-minute drive. Lane change instructions were presented with signs on both roadsides, and each pair consisted of identical signs, as shown in Figure II-12. The signs depicted three symbols including two "X" marks and one arrow, with the position of the arrow represented which of the three driving lanes needs to be taken. For instance, Figure II-12 shows that the arrow is on the left, which signifies that participants should maneuver to the left lane. No other vehicles or obstacles were presented on the simulated roadway.

Figure II-12. A view of the simulator screen

Participants were asked to change lanes as soon as recognizing instructions, as signs were not visible until reaching a distance of 130 feet from the vehicle. The sign-to-sign distance was randomly chosen from a range between 400 and 700 feet. In approximation, these two rules in spacing indicated that participants were allowed for 2 seconds to respond to a sign and that the temporal interval from sign to sign varied from 8 to 12 seconds, given the speed of 40 MPH. Six types of lane change instructions were included (from the left to the middle or the right, and so on), and each was presented three times per experiment condition; one condition included 18 lane change instructions. The order in which instructions were given was pseudo-randomized.

To analyze performance in lane keeping, a normative path was developed for each condition, as illustrated in Figure II-13. These paths were designed to calculate lateral deviations of the simulated vehicle from the normative path. This approach covers 1) visual perception of signs (late perception or missing a sign), 2) quality of the maneuver (slow response results in larger deviation), and 3) lane keeping quality (the simulated vehicle is supposed to operate in the middle of lanes) (Mattes, & Hallén, 2009). The design of the normative paths were based on three assumptions; 1) no curved lines would be shown in the path, 2) 40 feet would need to be advanced to initiate a response to any of the signs, considering the reaction time of 0.5 seconds, and 3) 150 feet would need to be advanced to complete any type of lane changes.

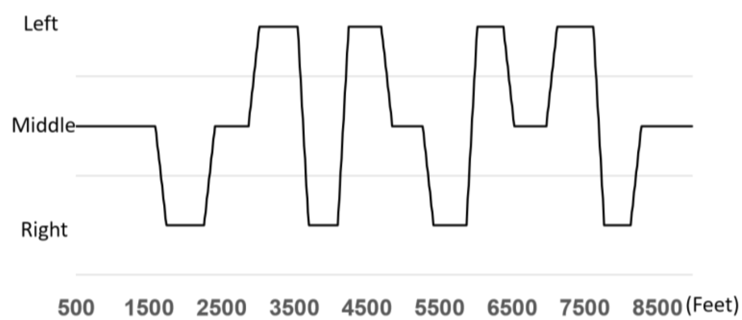

Figure II-13. A normative path designed for the study

Figure II-14 shows the touchscreen tablet that was mounted by a floor stand on the right side of the simulator screen. Fixed in a certain location, the stand was adjusted only in the vertical dimension. The highest condition, Level 5, was defined in a way for the upper end of key layout to be aligned with the upper end of the steering wheel. In others conditions from Level 4 to Level 1, the touchscreen was lowered by 7 cm or approximately 2.76 inches. As a result, the distance between the upper end of Level 5 and the lower end Level 1 was 36cm, which was about 14 inches. This 14-inch length was intended to match the height of the touchscreen of Tesla Model S, which is arguably the largest one in the market in 2017.

Figure II-14. The manipulation of touchscreen locations

Table II-3 defines center locations of touchscreen for each experiment condition, in relation to center locations of the steering wheel and the simulator screen. The calculation for angles was based on the mean of eye locations collected over all the participants, the center of the simulator screen, and the center of the keypad.

Table II-3. Specifications of the touchscreen keypad locations

Level of touchscreen location	Distance (mm) from the center of		Angle (degree) from
	steering wheel	simulator screen	the horizontal center of the simulated roadway
5	476	639	16
4	466	661	22
3	467	689	29
2	478	723	36
1	499	763	41

Participants were instructed to perform concurrent tasks with 1) the *lane change task* mentioned earlier in the LCT procedure, 2) a *speed management task* to maintain the vehicle speed at 40 MPH, and 3) an *input task,* of which the task procedure was very similar to the input task of Chapter II, though the task interface was slightly different.

Figure II-15 shows that the layout of input keys. *Enter* (the long key on the right) and *clear* (the one below *enter*) keys in the far-right column, in order to minimize the likelihood that the vertical location effects of these two differ by the manipulation. All the keys except *enter* were 20mm in both width and height. The spacing between keys was 10mm.

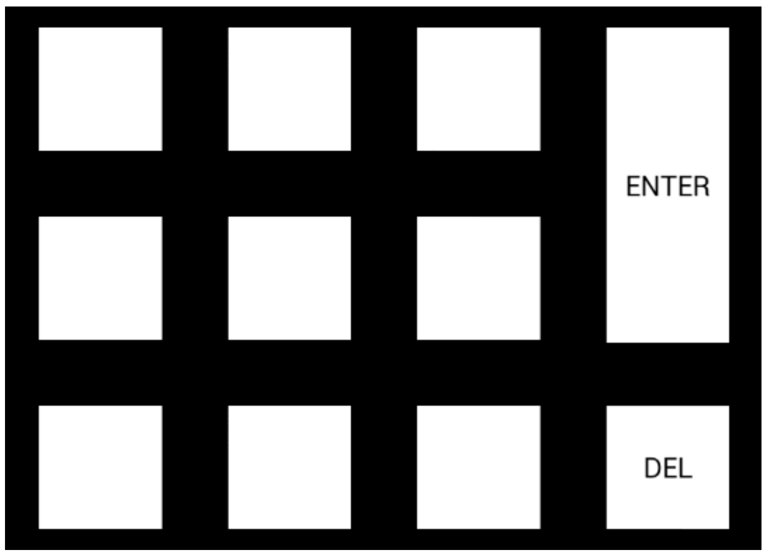

Figure II-15. The spatial configuration of touchscreen keys

In order to facilitate the touchscreen interaction, inputting any key was immediately followed by synthetic multisensory feedback including 1) visual cue: the color of keys blinked from block to yellow, 2) auditory cue: a keystroke sound was played, 3) vibrotactile cue: the tablet vibrated for 300ms. All the participants reported that they were able to perceive the multisensory feedback.

The input instructions were identical to the ones used in Chapter II and presented by an Apple iPhone 5S®. The smartphone screen was mounted on the left side of the simulator screen, and the very bottoms of both screens were aligned. The devices were apart by 10 cm. As opposed to that participants of Chapter II renewed input sequences by themselves manually, participants of this study made verbal requests for the renewal. They were instructed to verbalize the request when they are ready for the next sequence. Upon the verbal requests such as "next", the experimenter renewed the sequences remotely with a Bluetooth keyboard, so the manual attentional resources of participants can be exclusively allocated to driving and the touchscreen interaction.

Participants were first introduced to the purpose and procedure of the study. They were then given consent forms and signed if they wish to participate. After that, participants were briefed about how to interact with the driving simulator and the touchscreen. They were allowed to adjust the driver seat as what was comfortable to them to make sure the manipulation of touchscreen location can be done within the reach envelope.

A training session was prepared for participants to be familiar with the experimental tasks; they performed an LCT scenario while entering input sequences with the touchscreen. They were encouraged to try their best but no instruction for task prioritization was given. They drove three different courses for training for Level 5, 3 and 1, and the order of Levels were pseudo-randomized. Participants were instructed to try their best to maintain the vehicle position to be the middle of any lanes.

Upon the completion of training, they always started a trial with no touchscreen. Then, they conducted trials for each of the five touchscreen conditions in a partiallybalanced order based on a standard Latin Square Design. In each of the five conditions, they firstly speeded up the vehicle to reach 40 MPH, which was the target of speed management task. With regard to this acceleration, no sign appeared for the first 1,000 feet. The last trial was always conducted with no touchscreen once again, and the mean values of performance measures in the first and the last trial were collected as the baseline, considering the general procedure of the Lane Change Test (ISO/DIS 260222, 2010). Following the completion of each trial, the NASA-TLX survey was given.

The sampling rate, the designated rate of data collection, was one foot. However, the collected data showed that the rate actually varied up to three feet. This was because the frame rate of simulation (30 fps) was subject to the performance of graphic processing unit and did not match every foot of distance in the simulation. As a result, the discrepancy between the designated and actual sampling rate led the collected data to slightly overestimate the timing of response by up to 0.05 seconds, give the 40 MPH; the actual sampling rate varied up to 3 feet.

Lane deviation (ft.) was defined as the mean value of differences between the lateral coordinates of normative path and vehicle position over all the collected records. S*peed deviation* (MPH) was defined as the mean value of differences between 40 MPH and the vehicle's speed over all the collected records. The definitions of *input efficiency*, *input accuracy*, *input time*, and *perceived workload* were identical to the ones in Chapter II (see Appendix for more details).

Results

With the vertical locations of touchscreen as the within-subject independent variable, ANOVA models were developed for each performance measure. When a significance was found, the Bonferroni comparison was conducted. A significance level of alpha=0.05 was used. Eye heights of participants were also measured to be included in the statistical models as a covariate, but significance was not found.

Figure II-16 shows performance of lane deviation and speed deviation. Error bars represent standard errors. Alphabets on the bars represent significantly-different groups. The baseline condition was not involved in the statistical testing, as the focus of analysis was to evaluate if touchscreen location had any significant effect, provided with the touchscreen task; the baseline had no touchscreen task. Nevertheless, Figure II-16 shows numeric differences in the mean values when comparing the baseline to the other conditions, indicating that the distraction effects of touchscreen task itself are noticeable.

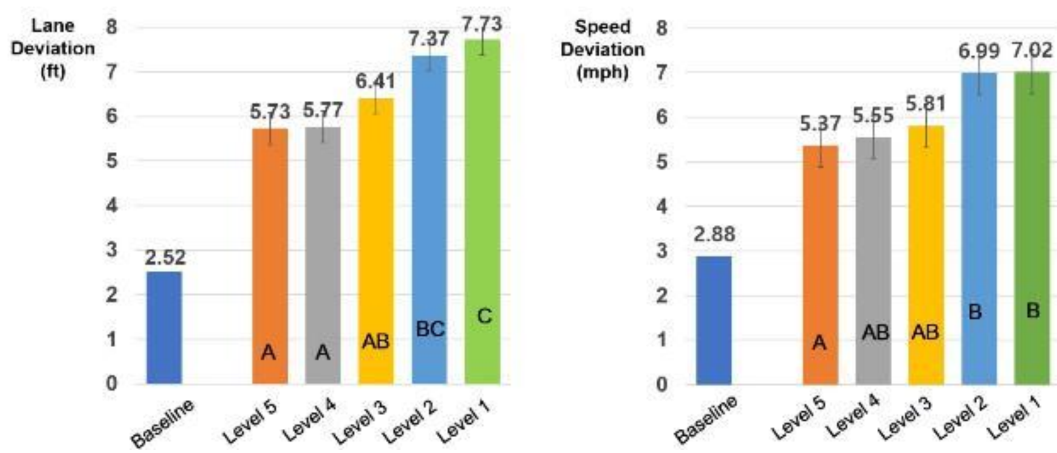

Figure II-16. Performance of lane deviation and speed deviation

The vertical location affected the lane deviation, F (4, 100) = 11.525, p <0.001. The post-hoc test suggested that *the lane deviation in Level* 1 (M = 7.73), the lowest condition, was numerically larger than any other conditions and significantly different from that of Level 3 (6.41, p = 0.014), Level 4 (5.77, p <0.001), and Level 5 (5.73, p <0.001). The results indicate that performance in the lane deviation can have a negative relationship with the vertical location; the deviation significantly increased as the location went lower.

The tendency in the speed deviation was similar; the vertical location showed a significant effect, F (4, 100) = 4.604, p = 0.002. The speed deviation observed in Level 5 (5.37), the highest location, was significantly worse as the touchscreen was lowered to Level 2 (6.99, p = 0.027) and Level 1 (7.02, p = 0.023). Comparing Level 4, the second highest location, to Level 2 and Level 1 did not reach significance, p = 0.072 and 0.062, respectively.

Figure II-17 shows performance of the touchscreen task, and no significant effect was found. The baseline with no touchscreen task was obviously not included. This figure also shows perceived workload, and the baseline condition was not involved in the statistical testing. A questionnaire form in the Level 5 condition was missing, which resulted in 104 records instead of 105 which should have been the total. The vertical location affected the perceived workload, F (4, 99) = 3.031, p = 0.021. The significant difference was found between Level 5 (4.6) and Level 1 (5.5), p = 0.028.

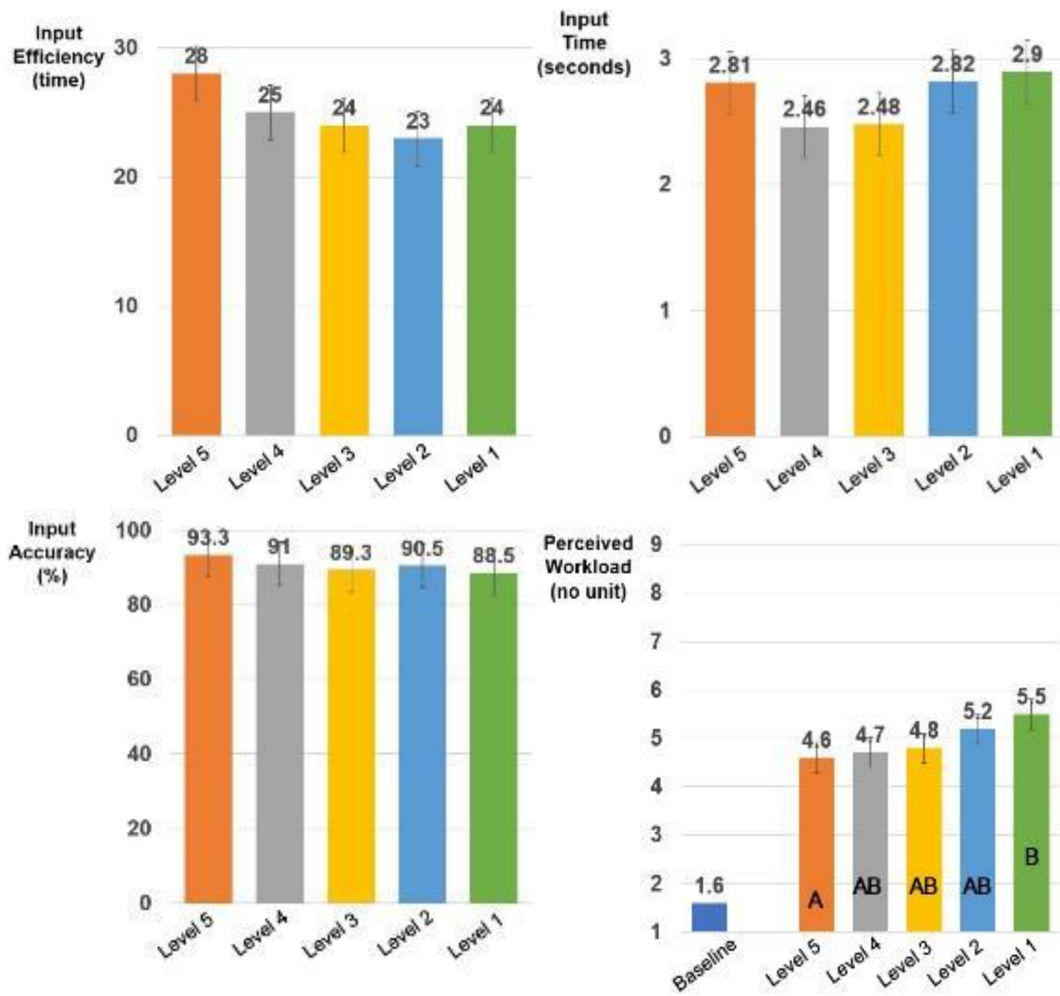

Figure II-17. Performance of the touchscreen task and perceived workload

Discussion

The findings from this study suggest that the vertical location of an in-vehicle touchscreen can affect performance in lateral and longitudinal vehicle control as well as perceived workload, which leads to concerns of driving safety. Participants, distracted by the input task involving visual-manual interaction, operated a simulated vehicle while conducting the Lane Change Test involving visual probe reaction. As the input task required drivers to keep reorienting focal attention, there was a tradeoff in attending to the simulated roadway for vehicle operation as well as the visual search for lane-change signs.

The location effects of in-vehicle touchscreen on driving performance were found. The largest lane deviation was observed when the touchscreen location was lowest; the lowest location was designed for the peripheral view of participants not to capture roadway situations, which otherwise would have been helpful for lane keeping (Horrey & Wickens, 2004; Horrey, Wickens, & Consalus, 2006). As the location was heightened to a certain level, the lane deviation decreased. This finding implies a possibility for the causality between the touchscreen location and lateral position maintenance. Horrey and Wickens (2004) agrees with these results in that the manipulation of an in-car display location can affect performance of lane keeping. However, their findings were not informative in determining the range of touchscreen location to the extent that ambient visual processing of the roadway is allowed or at least less affected. The current findings suggest a quantitative recommendation for the vertical location of in-vehicle touchscreens.

Regarding *speed deviation*, the effect was significant; Level 1 and 2 showed significantly larger speed deviation, compared to the highest location. With no kinetic sensation to experience vehicle speed (Chan et al., 2010), in this study, the management of vehicle speed was exclusively relying on checking the speedometer and the longitudinal changes on the roadway, which would have been aided by the ambient visual perception (Kappé, van Erp, & Korteling, 1999; Summala, Nieminen, & Punto, 1996; Wickens & Horrey, 2004). This finding indicates that the vertical location of in-vehicle touchscreens can be also manifested as performance in the longitudinal control of vehicle.

The Department of Defense (DOD) Design Criteria Standard (MIL-STD-1472G, 2012) for optimal display locations can support the above findings. The standard states that the optimum visual zone should not exceed 35 degrees from the normal line of sight (LOS) in the vertical dimension. When applying this standard to support drivers who are meant to maintain focal attention on the roadway, a secondary in-vehicle display should be within the vertical range of 35 degrees from the LOS to the roadway. Concurrent with MIL-STD-1472G (2012), the current findings show the extent and range of LOS deviance. In fact, Level 2 (36 degrees) and Level 1 (41 degrees) where and the degradation of lane/speed deviation reach significance from are representative of current in-vehicle touchscreens like the ones manufactured by Tesla Motors.

The touchscreen location also affected the perceived workload. The subjective ratings numerically increased when lowering the vertical location, and it reached significance at the lowest location. Examining the individual ratings on six dimensions enlightened this in that only *frustration* was increasing. This indicates that the location of in-vehicle touchscreen can be also associated with user satisfaction (Schmutz, Heinz, Métrailler, & Opwis, 2009). In this sense, one may argue that the lowered location increased visual demands of attention reorientation and made participants “annoyed”. It is noteworthy that all of the locations were within the reach envelopes of all the participants; ensuring the manual access to the touchscreen would not be enough depending on its vertical location.

Regarding the touchscreen task, no evidence suggested a significant effect. This finding is deviated from the initial assumption that the location would affect the task. One should take caution to explain data based on insignificance. A speculation is that participants might have put a higher priority on the touchscreen task at the expense of driving performance. Simulated driving environments, such as the one in this study, can allow such prioritization as no physical risk is imposed on participants (Fischer, Kubitzki, Guter, & Frey, 2007; Medeiros-Ward, Cooper, & Strayer, 2014). This is clearly different from the task environment of the first study of Chapter II; participants were driving in a real environment where frequent reorientation of attention was necessary between tasks, and significant effects were found for performance of touchscreen interaction.

The overall findings of this study show that the location of in-vehicle touchscreens can have significant effects on drivers. Assuming that such location can determine the availability of ambient visual resources, the findings put an emphasis on the importance of parallel processing of visual resources while driving, especially concerning timesharing requirements in multitasking situations.

The limitation of this study is that, as mentioned above, increasing levels of visual distraction was attempted in a simulated environment in which participants were not exposed to physical risks and thus implicitly allowed to put a priority on the touchscreen task over driving. This might have led to an overestimation of the main effect on driving performance. Moreover, the two studies included in this chapter were again limited in that touchscreen interaction was still based on frequent reorientation of attention that the visual diversion away from the road inevitable. With regard to the goal of dissertation, the following chapters describe efforts to design touchscreen interaction to be accessible through nonvisual cues without visual reliance.

CHAPTER III

A PRELIMINARY INVESTIGATION ON NONVISUAL TOUCHSCREEN INTERACTION*

This dissertation primarily explores potentials of vibrotactile cues for developing a design method to support visual attention management of drivers while interacting with touchscreens. Considering that they can *perceive* and *differentiate* physical control elements via nonvisual channels (e.g., shape, texture, and force feedback), touchscreen interaction could be designed similarly. That is, synthetically-recreated tactile cues, such as vibration, could be embedded into touchscreen interaction so as to offload visual demands of touchscreen interaction. Earlier studies (e.g., Ferris & Sarter, 2011; Roady & Ferris, 2012; Suh & Ferris, 2016) have demonstrated that operators can nonvisually interact with a system under high demands through vibrotactile cues.

It is then important to determine how to encode information with vibrotactile cues. While complex information can be effectively encoded with letter, shape, size, or color, these general types of *symbolic* representation require visual resources and thus would be challenging with vibration, given an equivalent degree of signal complexity. In this regard, the "beats" phenomenon is noteworthy. When two vibratory signals at dissonant frequencies are combined, the resultant signals have repetitive rising-and-falling amplitudes, referred to vibrotactile *beats* (Lim, Kyung, & Kwon, 2012). What makes this

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* Part of this chapter is reprinted with permission from "Examining Change Sensitivity to Vibrotactile Beats in a Hand-Held Touchscreen Device" by Y. Suh & T. Ferris, 2017, *Proceedings of the Human Factors and Ergonomics Society Annual Meeting,* Vol. 61, No. 1, p. 1569. Copyright 2017 by HFES.

phenomenon interesting is the fact that it is possible to manipulate the *frequency of beats* by adjusting the difference between the combined frequencies (Lim et al., 2012). In fact, it has been known that human perception is able to differentiate at least two distinct beat frequencies (Yang, Tippey, & Ferris, 2014). However, no further studies have been done with regard to the resolution of change sensitivity to vibrotactile beats, which would be fundamental for developing applications with vibrotactile beats.

This chapter describes a preliminary design effort for developing nonvisual touchscreen interaction, by investigating the potential of vibrotactile beats as a method of symbolic nonvisual communication. The present study examined change sensitivity to vibrotactile beats in association with touchscreen interaction. The findings indicate the perceptual ability in differentiating beat frequencies propagated through a touchscreen tablet. Regarding its practicality, the limitations of vibrotactile beats are also described. The implications still suggest a need to overcome the visual reliance of touchscreen interaction to which the first two studies were limited, leading to the next chapter describing efforts on exploiting *spatial* resources for the final design.

Testing the perceptual ability to differentiate vibrotactile beats

Beat frequency (ΔHz), the difference between the two combined frequencies generating vibrotactile beats, determines the intensity of vibrotactile beats. That is, low beat frequencies produce relatively *smooth* (or *slow*) representation of vibrotactile beats, whereas high beat frequencies relatively lead to *rough* (or *fast*) representation. Yang and colleagues (2014) demonstrated a practical design mapping beat frequencies to a range of vehicle speed, and the benefit of this design in attention management was shown in driving.

This earlier study suggest a possibility for vibrotactile beats to be used in nonvisual communication. In fact, the hardware structure to produce vibrotactile beats does not need to be complex; it is even possible to produce various beat frequencies with a single actuator if that actuator can synthesize two dissonant vibratory signals.

The development of user applications with vibrotactile beats would benefit from the knowledge on their psychophysical characteristics in communication. Especially, it is important to understand the perceptual ability to differentiate vibrotactile beats at distinct beat frequencies. This ability can be quantified with the just noticeable difference (JND). The JND of pure vibrotactile signals at *single frequencies* has been tested (e.g., Pongrac, 2008). As mentioned earlier, however, it has been unknown what the perception resolution is when differentiating the *combined frequencies*. The ability to notice changes in vibrotactile beats will determine how complex an encoding method with vibrotactile beats can be, as signal complexity in data-rich environment is a function of perception resolution.

The method of adjustment, one of the classical psychophysical methods, can be useful to determine such perception resolution by allowing participants to be in charge of adjusting changes in stimuli (Stevens, 1958; Wier, Jesteadt, & Green, 1976). The common procedure starts with giving participants a stimulus at a particular strength either far above or below the perception threshold. Then, they are asked to adjust the strength in either an ascending or a descending series until noticing a change. In order to avoid errors in psychophysical methods (e.g., errors of habituation and expectation), it is important to randomize the starting point of stimulus intensity (Gescheider, Thorpe, Goodarz, & Bolanowski, 1997). The increasing and decreasing series of stimuli should be counterbalanced in number so as to eliminate, or at least minimize, constant errors related to the temporal order of stimuli.

Testing perception of vibrotactile beats should be associated with the platform in which the signals are implemented. The testing platform can determine the way in which signals would be propagated and also the way in which user interaction progresses. The present study is novel in that vibrotactile beats were implemented through a touchscreen tablet, and this needs some consideration. First, the point of physical contact with vibrotactile beats would be crucial. Recently, many touchscreen devices are designed to be hand-held, with the increased use of smartphones and tablets. If vibrotactile beats are activated in a hand-held device, the signals would be propagated through hands that are holding the device. On the other hand, if a touchscreen is mounted (e.g., in-vehicle touchscreens and kiosks), users would perceive the signals through a finger. If this is the case, the area of physical contact would be much smaller, compared to the aforementioned handheld situations. Another concern is that touchscreen users could maneuver their fingers in any directions or at any speed in reality. Hence, kinetics in finger movement may affect perceptual ability in differentiation of vibrotactile beats. Lastly, the context of use should be also considered, as touchscreen tablets can be used in mobile conditions. For example, walking users would naturally experience a sort of up-and-down vibration, which could be realized as a masking effect on fine perception of vibrotactile beats.

The present study aimed to examine the perceptual ability of vibrotactile beats propagated through a touchscreen tablet. The focus of study was on design specifications for vibrotactile beats when applying them to touchscreen interaction.

Method

A psychophysical test was conducted to examine the ability to differentiate beat frequencies increasing from 1- to 20-ΔHz or decreasing from 20- to 1.0-ΔHz at the interval of 0.1-ΔHz. Participants put fingertips on the touchscreen and maneuvered them in vertical directions to perceive various beat frequencies through the tablet body.

Fifteen participants were recruited (male: 9, mean age: 27). However, only 11 of them (male: 7) completed all of the experiment conditions; the four of them did not participate in particular conditions with a mounted touchscreen. All the participants were given $20 for compensation upon the completion of the study.

An 8-inch touchscreen tablet, Samsung Galaxy Tab A® (1920 × 1200 pixels), was used to develop an experimental task interface. This interface was programmed to extract the vertical coordinates of finger positions when in contact with the screen. With a finger maneuvering on the screen, the tablet wirelessly transmitted the corresponding vertical coordinates to a laptop computer. Receiving the coordinate, the computer then translated them to beat frequencies and operated a vibrotactile display, EAI C2 Tactor® (www.eaiinfo.com), via Bluetooth. The range of beat frequencies was between 1- and 20-ΔHz at the interval of 0.1-ΔHz. Therefore, participants perceived this range of beat frequencies according to the vertical position of a finger in contact with the touchscreen. This range was chosen based on inputs from a pilot test; beat frequencies below 1.0-ΔHz or beyond 20.0-ΔHz were difficult to be distinguished in perception.

The left of Figure III-1 illustrates the touchscreen interface consisting of three areas, 1) *top area*, 2) *bottom area*, and 3) *gradated area.* These areas were not visible to participants; the right of Figure III-1 shows the actual view of the touchscreen tablet used in the experiment. The top area was near to the power button, which was mapped to the one end of the beat frequency range. The bottom area was mapped to the other end. The gradated area was in the middle between the top and bottom areas and allowed participants to experience gradual changes within the aforementioned range of beat frequencies excluding the two ends (between 1.1- and 19.9-ΔHz). In order to prevent participants from using postural or proprioceptive cues for perception, the interface automatically and randomly always reset the size of both top and bottom areas after participants completed one trial. The sizes varied between 10 and 30mm. The size of gradated area was then determined to be the rest of the screen.

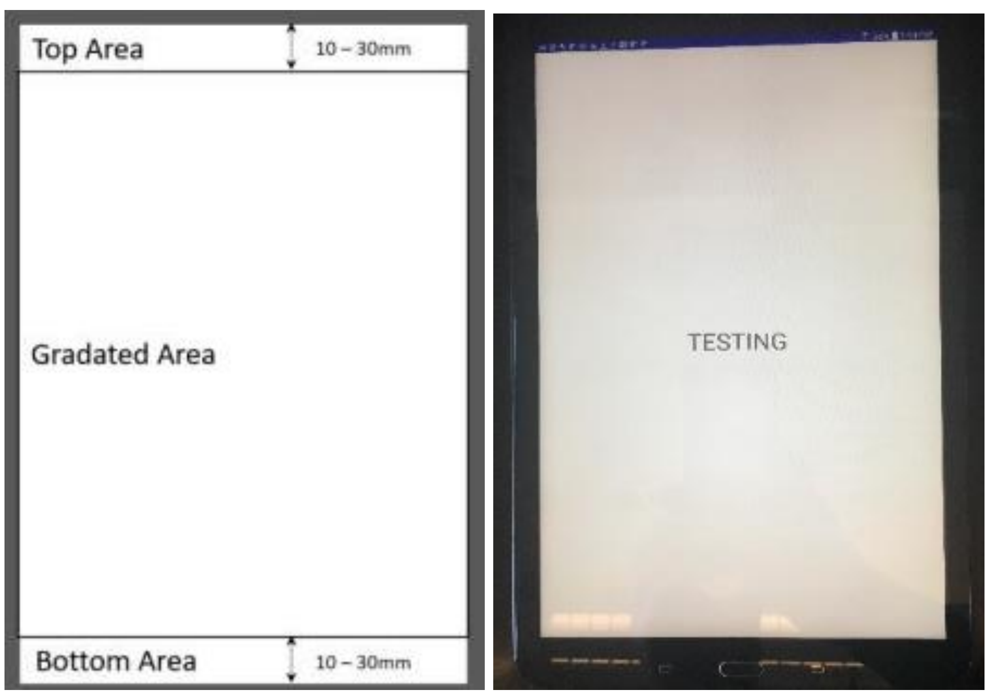

Figure III-1. The experimental interface (left: an illustration, right: the actual view)

The experimental task was to report changes in beat frequencies while maneuvering fingers from the one end in the vertical dimension to the other end; thus, two directions were involved. This led participants to rely on tactile perception of vibrotactile beats changing from *very loose* (at 1.0-ΔHz beat frequency) to *very intense* (at 20.0-ΔHz), or vice versa. They started trials by placing a fingertip on either the top or bottom area and moved all the way to the other end. While maneuvering a finger in the vertical directions, they tapped on the screen with another finger whenever they thought they perceived a change in beat frequency. They continued to make such responses until the finger reached the end of the screen, at which point one trial was registered.

Figure III-2 shows that participants conducted the experiment in three contexts; 1) *sitting*: holding a touchscreen with one hand while sitting at a desk (see the left of Figure III-2), 2) *walking*: holding a touchscreen with one hand while walking along the corridor (see the middle of Figure III-2), and 3) *mounted*: using a mounted touchscreen at a desk while sitting (see the right of Figure III-2). Trials in the walking condition were conducted in a Texas A&M University campus building, and the path was a 200-foot straight course. In the sitting and walking contexts, participants held the tablet with one hand. Thus, they perceived vibrotactile beats through not only fingertips in contact with the screen but also the other hands holding the tablet. In the mounted context, fingertips on the screen were the only point of physical contact at which tactile perception of the beats was possible.

Figure III-3 shows how the vibrotactile actuators were attached to the tablet. Two actuators were attached to magnets taped in the back of the tablet body. Hence, when playing vibratory signals, they were propagated through the entire body. Pilot testing suggested that the propagation of vibration was most uniform when the actuators were placed at the center.

Figure III-2. The context of use (Suh & Ferris, “Examining Change Sensitivity to Vibrotactile Beats in a Hand-Held Touchscreen Device”, Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 61, No. 1), p. 1569, copyright © 2017 by SAGE, reprinted with permission of SAGE Publications, Inc.)

The EAI C2 controller can synthesize two vibration frequencies and produce one integrated signal via a single actuator. Therefore, each actuator shown in Figure III-3 was able to present vibrotactile beats; it was not that vibrotactile beats were produced by putting together two actuators playing dissonant frequencies. The two actuators was intended to make the signals stronger and thus perception easier. In this study, one of the two synthesized frequencies (carrier) were fixed to be 250.0-Hz, and the other (modulator) was changing from 251.0-Hz to 270.0-Hz.

Figure III-3. The affixed vibrotactile actuators

This study involved three independent variables; 1) *context*, 2) *beats change*, and 3) *finger movement,* as described in Table III-1. The total number of experiment conditions were twelve, as one variable had three levels while the other two variables had two levels. As a result, each context had four conditions based on the combinations of beats change and finger movement. Participants first completed each set of four conditions in the sitting and the walking context. They completed the four conditions in the mounted context in a later day, as this was conducted as a follow-up experiment. Four participants did not show up in the latter experiment.

Table III-1. Independent variables for vibrotactile beats perception

Variables	Levels	Description
Context	Sitting	Participants were sitting at a desk in an office room.
	Walking	Participants were walking on a straight corridor.
	Mounted	Participants were using a mounted touchscreen on a desk.
Beats Change	Increasing	The beat frequency was in an increasing sequence from 1- to 20-ΔHz by 0.1-Hz.
	Decreasing	The beat frequency was in a decreasing sequence from 20- to 1.0-ΔHz by 0.1-Hz.
Finger Movement	Downward	Movement of the fingertip was going from the top area to the bottom area.
	Upward	Movement of the fingertip was going from the bottom area to the top area.

Procedure

Participants were given a consent form to review and signed if they wish to participate. After consenting to participate and receiving instructions, participants were briefed about the hardware and characteristics of vibrotactile beats. They were then allowed some time to freely explore the touchscreen with fingers to experience the perception of vibrotactile beats.

Prior to the initiation of trials in each condition, the experimenter adjusted the setting of beats change and told participants the direction in which their fingers should move. In each trial, participants moved their fingers one the touchscreen in one of the two vertical directions, according to experimenter’s instructions. While conducting the task, participants wore earphones continuously playing white noise. The white noise was expected to mask the sound from vibrotactile beats so as to prevent participants from taking advantage of auditory sensation when differentiating beat frequencies. Each condition involved at least five trials, though a few participants finished more than five when they lost the track of counting trials. Upon the completion of each trial, the experimenter reset the sizes of top, bottom, and gradated areas as mentioned earlier. Additionally, in the walking condition, the experimenter walked together with participants to prevent anything that could be an interference from disturbing them.

Performance measures

Two measures were defined. First, *perceived difference* (ΔHz) was the mean value of differences in beat frequency between one response and the very next response, including the difference between the initial beat frequency and the beat frequency at the first response. Therefore, smaller values of perceived difference mean higher change sensitivity to the vibrotactile beats. Second, *response time* (seconds) was the mean duration for participants to register a response, measured from the moment at which a given beat frequency was activated until the response to that beat frequency was registered. Hence, this measure indicates the time elapsed for participants to determine whether the change in beat frequency was noticeable. The timer restarted when participants moved fingers and activated another beat frequency at the interval of 0.1-ΔHz.

Results and discussion

The collected data included 1,033 trials in total. Figure III-4 shows mean values of perceived difference. Error bars represent standard errors. Levels of finger movement were distinctively colored with dark gray and light gray. Significant effects of beats change were labeled on the bars, if any.

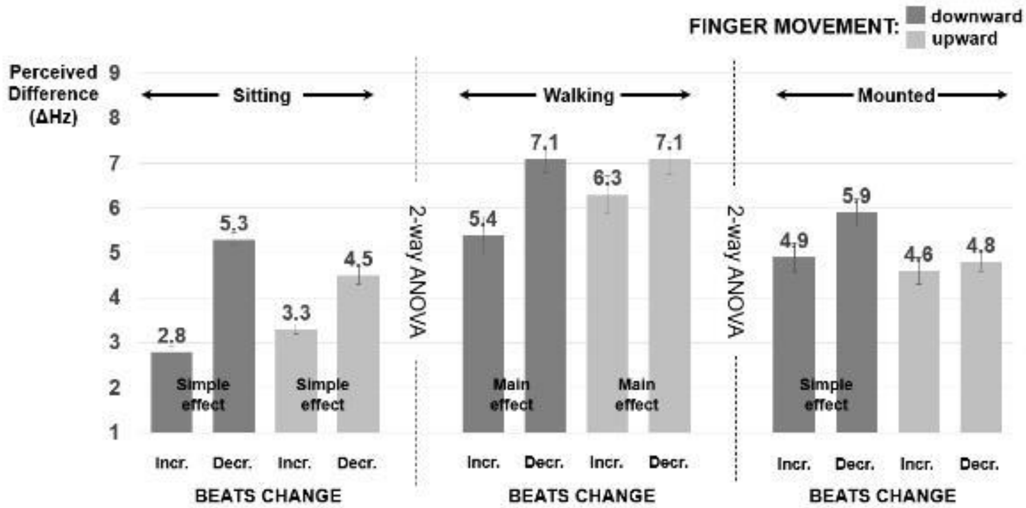

Figure III-4. Perceived difference in beat frequencies

The vertical dash lines delineate each level of context and indicate that two-way ANOVA models were developed exclusively. This was because the full factorial model was not deemed to be valid due to violation of the variance homogeneity. Not to mention that the Levene test indicated the heterogeneity, F (11, 1021) = 15.187, p <0.001, group variances varied considerably by context; one group variance in the walking condition was 16 times greater than that in the sitting condition. Hence, with beats change and finger movement as independent variables, the two-way ANOVA model was developed for each level of context.

In the *sitting* context, the model indicated the two-way interaction between beats change and finger movement was significant, F (1, 374) = 13.645, p <0.001. The *simple effect* of beats change was significant regardless of whether the direction of finger movement was downward or upward (F (1, 188) = 211.554, p <0.001, and F (1, 188) = 27.188, p <0.001, respectively).

In the *walking* context, only the *main effect* of beats change was significant, F (1, 370) = 12.251, p <0.001.

In the *mounted* context, the two-way interaction was significant, F (1, 277) = 31.536, p <0.001. The *simple effect* of beats change was significant only when fingers were moving downward, F (1, 144) = 74.268, p <0.001.

Generally, perceived difference was smaller when sitting participants were experiencing beat frequencies in the increasing sequence. The smallest perceived difference (2.8-ΔHz), or the highest sensitivity, was found in the sitting condition with beat frequencies increasing from 1- to 20-ΔHz while participants were moving fingers downward. Conversely, the largest perceived difference (7.1-ΔHz) was found in the walking context with beats change was decreasing from 20- to 1.0-ΔHz; finger movement did not make a difference in that condition.

Although the aforementioned results involve the effects of beats change and finger movement, the effects of context was unclear. In this regard, a statistical analysis with blocks was involved to assess context effects. Each combination of beats change and finger movement was involved as a block, and thus four blocks were used. Considering the variance heterogeneity among levels of context, a non-parametric Kruskal-Wallis test was conducted. When an effect was significant, the Bonferroni pairwise comparison was followed. Figure III-5 visualizes the corresponding results. In general, the sitting conditions led to the better performance, as opposed to the other conditions. The walking conditions were generally worst in performance.

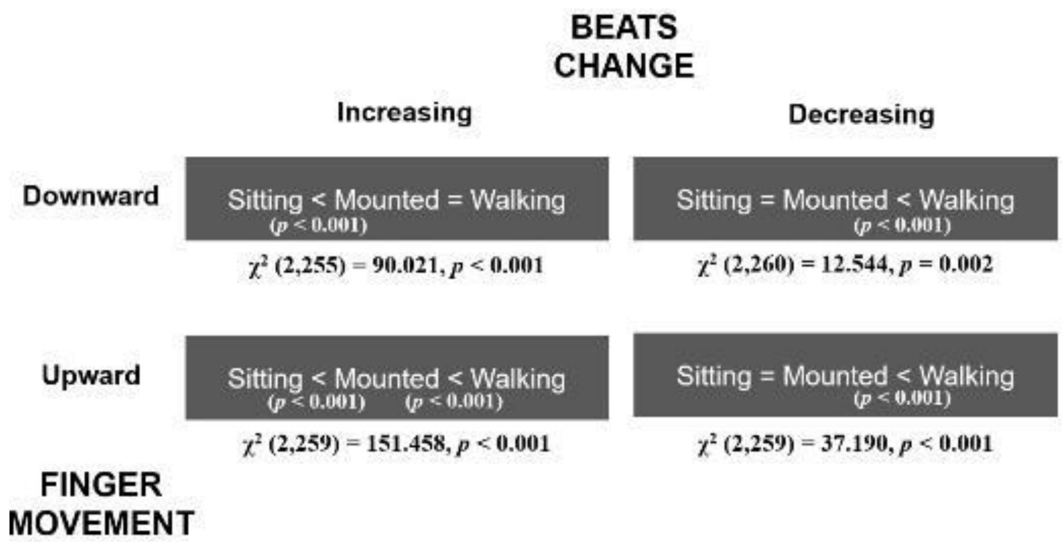

Figure III-5. The results of the blocked analysis

Figure III-6 shows mean values of response time for each treatment group. Error bars represent standard errors. Levels of finger movement were distinctively colored with dark gray and light gray. Significant effects of beats change were labeled on the bars, if any. The full factorial model was developed for response time, indicating that the 3-way interaction was significant, F (11, 1033) = 5.189, p = 0.006. Hence, further analysis was categorized based on each context.

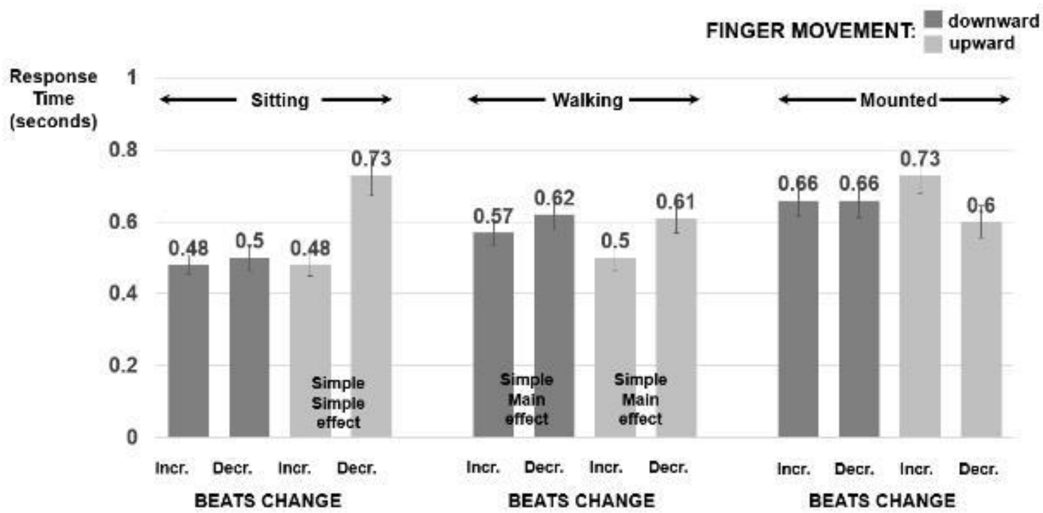

Figure III-6. Response time to perceptual changes in beat frequencies

In the *sitting* context, the two-way ANOVA model indicated the two-way interaction was significant, F (1, 374) = 13.645, p <0.001. The *simple simple effect* of beat frequency was significant only when finger was upward, and F (1, 186) = 23.014, p <0.001. In the *walking* context, only the *simple main effect* of beat frequency was significant, F (1, 370) = 4.564, p = 0.033. In the *mounted* context, no effect was found.

The fastest response (0.48 seconds) was observed in the sitting condition when beats were increasing, as the same condition resulted in the smallest perceived difference. The slowest response (0.73 seconds) was observed in the mounted condition with the increasing sequence of beat frequencies and the upward direction of finger movement.

This study implemented vibrotactile beats through the body of a touchscreen tablet, in order to examine the ability to perceptually differentiate beat frequencies. Based on a psychophysical method of adjustment, participants moved their fingertips on the screen in the instructed vertical directions to experience beat frequencies in the range between 1-

and 20-ΔHz. They reported changes in beat frequencies while 1) *sitting* at a desk while holding the touchscreen with one hand, 2) *walking* along an indoor corridor while holding the touchscreen with one hand, and 3) using a *mounted* touchscreen with a finger. Whereas the first two contexts allowed participants to hold the tablet with a hand, the last one involved the tablet to be mounted on a desk and allowed only fingertips to perceive the beats. These differences in the context of use affected change sensitivity to beat frequencies. The results reveal the perception range of vibrotactile beats propagated through a physical object.

The mean values of perceived difference indicate the tactile sensitivity of participants in differentiating vibrotactile beats propagated through the tablet. The findings firstly suggest that the change sensitivity to various beat frequencies was generally higher when participants were experiencing the *increasing* sequence starting from 1.0-ΔHz. This effect of beats change on perception was significant in every type of the context. Weber's law can corroborate this in that initial stimulus intensity can determine change sensitivity (Stevens, 1957; Wickens, Gordon, Liu, & Lee, 1998). That is, comparing a signal to another one is easier when the reference signal is smaller in intensity. The increasing sequence of beat frequencies presented few beats at first, and it would have been easier for participants to notice changes from the early moment of trials. Also, this might have led participants to have a prediction such as "this condition seems to have many numbers of beat frequency change". In the same regard, the decreasing sequence of beat frequencies could make participants to have an opposite thought from the first.

The effects of context were significant in change sensitivity to vibrotactile beats. The blocked analysis results show that the significance was found in all the combinations of beats change and finger movement. The *sitting* conditions generally led to the lowest perceived difference, or the highest change sensitivity. In those conditions, participants were able to perceive the beats through two points of contact: 1) hands holding the tablet and 2) fingers in contact with the screen. In contrast, the walking conditions led change sensitivity to significantly worse, even though the two points of contact in the sitting conditions were maintained. Moreover, most walking conditions were less sensitive in the differentiation than the mounted conditions where the point of physical of contact was just a fingertip. This suggests that the context of walking can deteriorate the ability in perceptually differentiating beat frequencies, possibly due to instability, manual demands for walking, and arousal for the mobile condition.

The collected data regarding response time indicate that perceiving a change in vibrotactile beats can take more than the previously-reported response time to pure vibration that is about 200 milliseconds (Diederich & Colonius, 2004). This is understandable in that the experimental task required a sort of pattern recognition rather than merely focusing on performance of sensory receptors. However, the longer response time implies that designing applications with vibrotactile beats would need caution if the context of use involves time-critical situations. A similar suggestion could also be applied to situations with high demands where multitasking operators need to perform under heavy workload. Engaging in attentional resources to communicate through vibrotactile beats may intensify the difficulty in attention management, especially if the context of use is already demanding in attention.

The overall findings suggest an addition to an earlier study (Yang et al., 2014), regarding the perceptual ability in differentiating pairs of beat frequencies. The current results involve a quantitative perception range for various beat frequencies in the use of touchscreens (Suh & Ferris, 2017). At most, seven distinct beat frequency can be employed at the interval of 3-ΔHz, given the tested range of beat frequencies. Depending on usage scenarios, the perceptual ability can differentiate at least three distinct beat frequencies at the interval of 7-ΔHz. The mounted conditions were most similar to the aspects of in-vehicle touchscreen interaction, involving four distinct beat frequencies at the interval of 5-ΔHz.

The aforementioned degrees of complexity may not be sufficient to replace the entire aspects of touchscreen interaction with vibrotactile beats. However, the practicality of the beats phenomenon needs to be further tested. In fact, this emergent feature of vibration can still be an effective way to provide continuous tactile feedback, especially in a situation where operators can benefit from nonvisual modality. For example, Yang et al. (2014) developed a driving speedometer with vibrotactile beats. This previous study played vibrotactile beats in the back of participants, and the beats indicated the deviation of vehicle speed compared to the target speed. The results indicated performance of attention management was significantly improved. This suggests that a meticulously-designed use of vibrotactile beats can be beneficial to operators in multitasking situations, where limited visual attentional resources have to be managed effectively.

CHAPTER IV

THE DESIGN OF NONVISUAL AIDS FOR TOUCHSCREEN EXPERIENCE

Regarding in-vehicle touchscreens, interaction cues are *distal* to drivers. Considering the sense of touch needs physical contact, drivers would use fingers for the interaction, and fingertips would be the point of contact. However, the resultant perception from the fingertips would not be that rich in tactile experience; touchscreen interaction is based on intangible elements presented on a flat screen, from which tactile perception hardly benefit. In this regard, Chapter III was attempt to test the practicality of symbolic vibrotactile cues for fingertip interaction with a touchscreen, indicating that a sufficient level of data complexity is hardly achieved. This nature of in-vehicle touchscreens may have been justifying the reliance on visual processing, regarding touchscreen interaction. With respect to in-vehicle touchscreen interaction, such visual reliance while driving can lead to safety risks (Kim et al., 2014; NHTSA, 2013; Pitts et al., 2012).

On the other hand, if cues were *proximal*, that would mean vibrotactile cues can be presented to a larger area, such as a torso, and information can be coded with spatial resources rather than symbolic representation. Earlier studies have shown that a required level of data complexity can be achieved with spatially-coded vibrotactile signals (e.g., Ferris & Sarter, 2011; Gray, Tan, & Young, 2002; Tan, Gray, Young, & Traylor, 2003). If this is the case with in-vehicle touchscreen interaction, it would be possible to replace visual loads of touchscreen interaction with tactile resources, thus better supporting visual attention management of drivers.

This dissertation aims to investigate visual demands of touchscreen interaction and to develop design guidelines for offloading such demands in multitasking situations. Focusing on driving as the application domain, this chapter specifies the development of a method for touchscreen interface design with minimal visual attention: **Nonvisual Aids for Touchscreen Experience (NATE)**. This chapter firstly describes the process of NATE, in relation to visual demands of in-vehicle touchscreens based on the findings of the previous chapters. Next, a development of in-vehicle touchscreen system based on NATE is described. Lastly, theoretical and practical considerations that guided the final design are discussed.

The system concept of NATE

The motivation for NATE was to find effective and replicable methods for the development of nonvisual cues that can be integrated with in-vehicle touchscreens, as this can reduce visual demands of the touchscreens (Wickens, 2008). To this end, NATE places actuators on the back of drivers, so interaction cues can be *proximal* to drivers. These actuators present vibrotactile cues that are uniquely-mapped onto each of touchscreen controls. To allow natural mappings between the controls and vibrotactile cues, NATE arranges each of the vibrotactile actuators to spatially correspond to each of the controls, as illustrated in Figure IV-1. The numbers on the actuators and on the touchscreen keys show the mappings between the two devices, which are maintained wirelessly. These wireless connections are facilitated by a personal computer and a controller of the vibrotactile actuators, though the driver experience with the NATE-based touchscreen system involves no interaction with either the computer or the controller. The premise of NATE is to provide drivers with nonvisual means of orientating attention and guiding hands to spatial target with minimal visual diversion away from the roadway.

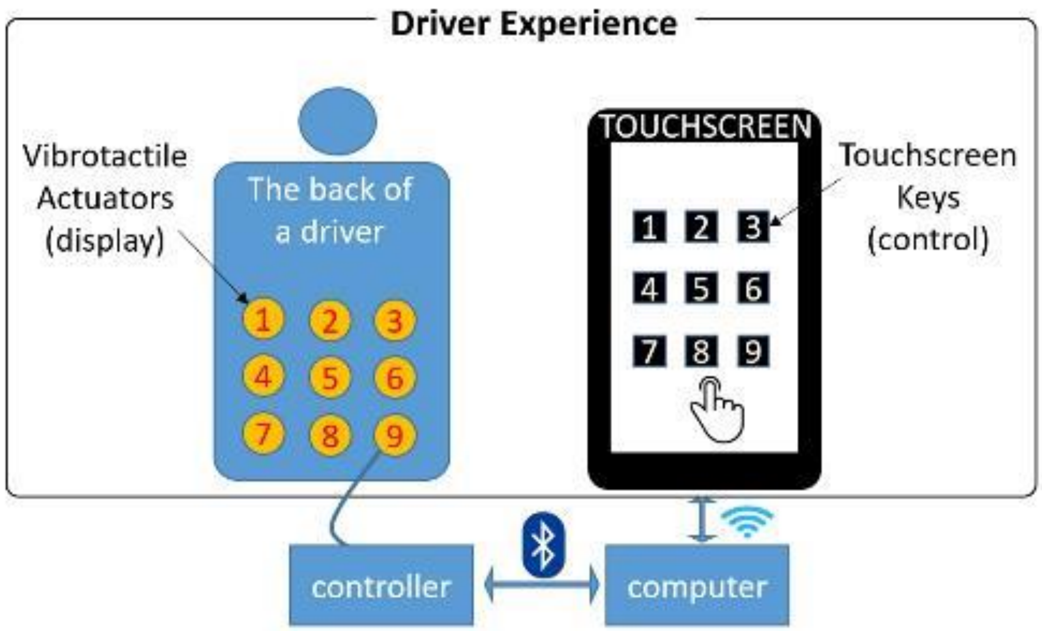

Figure IV-1. An illustration of a NATE-based in-vehicle touchscreen system

Whereas earlier studies on in-vehicle touchscreens have shown benefits for the stages of *input* and *post-input* (e.g., Kim et al., 2014; Kujala, 2013; Kujala & Salvucci, 2015; Lee & Spence, 2008; Pitts et al., 2010; Pitts et al., 2012), visual demands associated with pre-input activities have remained. The proposed design focuses on addressing visual demands of in-vehicle touchscreens, associated with the entire aspects of the interaction loop including consisting of *pre-input*, *input*, and *post-input* stages (Freitag et al., 2012). In regard to this, the current study investigates the practicality of proximal and spatialized cues for touchscreen interaction based on multisensory integration. The process of NATE are further described in detail, with regard to visual demands involved in each of the stages.

NATE in the pre-input stage

In the *pre-input* stage (see Figure I-3) where drivers need to *identify* a particular touchscreen key, the allocation of visual attention is essential for touchscreen interaction (Land, 1992). Such allocation of attentional resources can result in safety concerns in the context of driving (Pitts et al., 2012; Kim et al., 2014). Earlier studies, including Chapter II, suggest that nonvisual modalities can be used to reduce task interferences and lower the demand for visual resources in situations that are demanding for visual attention (e.g., Ferris & Sarter, 2011; Politis, Brewster, & Pollick, 2014; Wickens, 2008).

NATE allows drivers to perceive continuous vibrotactile cues from the back. These *proximal* cues notifies drivers of not only the presence of touchscreen keys but also their locations. With the spatial mappings between the keys and the vibrotactile cues, locating a given key can done by engaging in spatial processing resources. Thus, a visual on the key may be helpful but not necessary. Besides, the proximal cues of NATE imply a physical separation between interaction cues and the touchscreen interface. Hence, the nonvisual perception of touchscreen keys would be independent of touchscreen locations. Chapter II suggests that the location effects of an in-vehicle touchscreen can be significant, with regard to the abilities to process focal and ambient resources in parallel. NATE would be able to minimize or at least reduce such location effects.

Additionally, interaction cues with NATE will not *capture* visual attention of drivers; a diversion of visual attention to the location at which the tactile stimulation occurs will hardly happen. Horrey and colleagues (2006) proposed that the conspicuity of stimuli while driving can capture visual attention of drivers, and such a visual capture would not be the case with the vibrotactile stimuli of NATE.

NATE in the input stage

In the *input* stage (see Figure I-3) where operators *perform actions* to make inputs, dexterity is important. Earlier studies have demonstrated that manipulating factors of manual interaction can affect visual attention of drivers (e.g., Kim et al., 2014; Kujala, 2013). That is, the more difficulty a touchscreen task becomes, the longer duration visual attention stays. This is because ordinary touchscreens take direct inputs with one finger but inevitably require visual attention for accuracy (Whitefield, 1986). A NATE-based touchscreen interface could make inputs with a two-finger gesture; with one finger staying on a touchscreen key, tapping another finger *anywhere* on the screen makes an input of the key. Once they identify a target key with one finger, tapping another finger on anywhere of the screen does not require accuracy. Therefore, this two-finger gesture allows drivers to register inputs with minimal visual attention.

NATE has a similar characteristic when compared to other interfaces with physical keys. Physical keys allow operators to separately perform *pre-input* actions (touch) and *input* actions (press). This makes possible for them to search for a key through physical tactile cues (e.g., shape, texture, material resistance/damping, and etc.) without entering an errant entry. On the contrary, interaction with ordinary touchscreens does not provide nonvisual cues for locating controls. With NATE, the vibrotactile signals would aid drivers to search for a touchscreen key through the sense of touch in the back, instead of visually perceiving the interface.

NATE in the post-input stage

In the *post-input* stage (see Figure I-3) where operators need to *confirm* the action performed in the previous stage, the requirement for visual attention still remains for that confirmation (Land, 1992, 1994). Although such visual demand has been often disregarded in some previous studies concerning in-vehicle touchscreens (e.g., Feng, Liu, & Chen, 2017; Kujala & Salvucci, 2015; Lee, Gibson, & Lee, 2016), nonvisual feedback of touchscreen keys can effectively support performance in visual search while driving, as demonstrated in Chapter II. In this regard, NATE generates a synthetic keystroke sound upon making an input; auditory cues can support attention management in the context of multitasks (e.g., Cellario, 2001; Sigrist, Rauter, Riener, & Wolf, 2013; Spence & Driver, 1997).

Finally, design guidelines for NATE include the followings;

1) *Perceiving touchscreen controls through proximal cues that are nonvisual*
2) *Locating a particular control via spatial resources*
3) *Entering inputs with actions designed for the first two stages of the interaction loop; an action to indicate a target control should be explicitly separated from the other action for activating the control.*
4) *Providing multisensory nonvisual cues for confirmation of the inputs; audition confirms the entry while tactility specifies which control was activated.*

Figure IV-2 shows a vibrotactile actuator (C-2 Tactor developed by Engineering Acoustics, Inc.) that is referred to a “tactor” in this dissertation. Each tactor oscillated a 7.5-mm “skin contactor” in the center at the frequency of 250 Hz; mechanoreceptors of the back are maximally-sensitive to this range (Cholewiak & Collins, 1991). The strength of vibration was set to be at the maximum displacement, approximately 1mm.

Figure IV-2. A vibrotactile actuator employed in this study

Figure IV-3 shows the arrangement of tactors that were fixed to a belt. Attached to the belt with Velcro, nine tactors were used. The two boxes below the belt are the controllers to operate tactors; one controller can operate eight tactors at most, so two controllers were needed to operate nine tactors. As an attempt to minimize the difficulty in discriminating vibrotactile signals from multiple locations, the spacing between tactors was set to be 60 mm. This was considerably larger than 11mm of the two-point discrimination threshold for vibrotactile stimuli on the back (e.g., Eskildsen, Morris, Collins, & Bach-y-Rita, 1969). This physical separation of signals would have made the interval between them distinctive in perception.

Figure IV-3. The spatial configuration of vibrotactile actuators on the belt

Figure IV-4 shows the arrangement of touchscreen keys, implemented in a 9.7-inch touchscreen tablet, Samsung Galaxy Tab A. To match the spatial configuration of the vibrotactile actuators on the back, the same number of touchscreen keys were displayed in the same 3x3 layout.

Figure IV-4. The touchscreen interface of a NATE system

The key size was set to be 30 mm in both width and height. Earlier studies generally suggest that a significant difference would not be observed if the size was larger than 20 mm, concerning both driving (Kim et al., 2014) and other single-task contexts (Colle & Hiszem, 2004; Jin, Plocher, & Kiff, 2007; Martin, 1988; Scott & Conzola, 1997). However, whereas ordinary touchscreens that require visual attention to make direct inputs, NATE was designed to discourage visual access to the touchscreen and to allow a finger to locate a particular touchscreen control with the sense of touch. If a person is blind searching for an object, larger keys would be easier to find, and the 30-mm was chosen to accommodate the screen size.

The spacing between touchscreen keys (the "empty space" where no input is recorded) has not been found to significantly affect input performance for gaps less than 10 mm (Colle & Hiszem, 2004; Martin, 1988; Scott & Conzola, 1997). For NATE, 3 mm were given for spacing between keys, which allowed visual discrimination of keys within the given display size.

Design considerations for the integrated multisensory experience

NATE was intended for drivers to have awareness of touchscreen interaction without requiring them to look at the touchscreen, based on the idea that providing them with the equivalent level of information to facilitate interaction would be possible even when employing different sensory channels (Land & Lee, 1994; Land & Horwood, 1995). To achieve this idea, the design of NATE requires presenting *pre-input* interaction cues from multiple locations and physically separating them from the touchscreen.

Considerations were taken to design the entire interaction with NATE to bind the incoming vibrotactile and proprioceptive stimuli from the distributed sources.

The integration of stimuli from multiple senses into a single perceptual experience is called "binding" (Levitin, MacLean, Mathews, Chu, & Jensen, 2000) and has implications for designing multimodal interfaces when there are practical reasons for multimodal signals and critical information to be distributed (Gray et al., 2002); nonvisual cues that are physically separated from the main display can still effectively reorient attention according to the displayed information (Tan, Gray, & Young, 2003).

In order to integrate sensory information from separate sources, the spatial stimulus-response compatibility among different stimuli should be maintained (Wallace et al., 2004). If stimuli and responses are related with each other in a spatially-corresponding way, no additional levels of decoding efforts other than interpreting the presence of elements would be necessary, which can make responses faster and more accurate (Umiltá, & Nicoletti, 1990). Otherwise, multisensory integration needs additional steps to interpret the relationship between display and controls, which can break perceptual linkages between stimuli (Wallace et al., 2004), disturb information transfer, slow down response, and degrade its accuracy (Liu & Jhuang, 2012). Furthermore, achieving the spatial compatibility can support natural mappings and thus allow tasks to be independent of operators' memory or knowledge (Proctor & Vu, 2006).

To this end, NATE employs vibrotactile actuators in the same number and layout as those of the touchscreen keys; nine touchscreen keys and nine actuators were identically arranged in the 3x3 layout, and each key maps to each vibrotactile actuator located in a spatially-corresponding spot. It is noteworthy that signals from the vibrotactile actuators do not indicate the confirmation of input but the presence of control elements in corresponding locations. It was expected that applying the spatial compatibility to NATE would allow drivers to intuitively locate touchscreen keys through the sense of touch.

Another primary factor for multisensory binding (or integration) has been reported to be associated with temporal aspects. Earlier studies assert that a temporal window of multisensory integration exists, within which stimuli can be bound together as a single event of perception experience (Lewkowicz, 1996; Wallace, Wilkinson, & Stein, 1996; Wallace & Stein, 1997; Diederich & Colonius, 2004). In other words, the presentation of stimuli should occur closely together in time so as to form an integrated perceptual experience based on the stimuli. However, in the previous studies, measuring the temporal window has been done with different tasks, stimulus types, and statistical criteria, and these differences make it difficult to come up with a "universal" temporal window (Stevenson & Wallace, 2013). NATE was designed to present vibration upon a finger-touch on the screen, with no intentional delay. It was also intended to immediately discontinue the vibration when switching the location of a finger to a different key. However, performance of wireless connection could be occasionally unstable, which may generate a time lag between one signal and another. The hardware, C-2 Tactor Controller, also has inherent delays relating to control board processing and actuators' mechanical "ramp up". This issue should be considered for the evaluation study on NATE that Chapter V describes.

When presenting proximal tactile cues to the body, there is potential of confusion in the perception of tactile cues location that are presented to the body. Frontal Plane Hypothesis suggests that "Symbols drawn upon anterior or posterior surfaces of the body are perceived as if they were drawn and viewed by subjects upon one common, transparent two-dimensional surface projected out in front of subjects" (Duke, 1966). The design of NATE presents spatialized cues to the back of operators, as the reproduction of tactile cues can be more congruent in the posterior loci (Allen & Rudi, 1970).

CHAPTER V

THE EVALUATION STUDY OF THE FINAL DESIGN

This chapter describes a set of touchscreen interface designs developed for an evaluation study of the NATE method; an ordinary touchscreen keypad was compared to three NATE-based touchscreen designs. Then, with respect to these designs, research hypotheses are described in terms of performance measures including drivers' glance behavior, various performance measures for both the driving and touchscreen task and workload. Next, the evaluation study to test these hypotheses is specified, followed by the results and discussion based on the findings. Finally, a general discussion on overall findings of this dissertation is described.

NATE-based touchscreen interaction designs

Table V-1 describes four types of touchscreen design tested in the evaluation study. Each represented a keypad with the same size, spacing, and layout of keys.

Table V-1. Touchscreen design alternatives tested in the evaluation study

Design	Descriptions
Ordinary	An *ordinary* touchscreen keypad with multisensory synthetic feedback
NATE	The touchscreen interface system developed by the **NATE** guidelines, described in Chapter IV
NATE-Beat	A system of **NATE** (like the second) with vibrotactile *beats* for vertical differentiation of signals
NATE-Low	A system of **NATE** (like the second) with a touchscreen mounted at a *lower* position

The first, called “ordinary”, represented a virtual keypad implemented on a touchscreen with which users can register direct inputs. With this ordinary touchscreen, touching any key registered an input and simultaneously generated a set of multisensory synthetic feedback involving visual, auditory, and vibrotactile cues; the feedback characteristics were the same as those described in Chapter II.

The second was called “NATE”, which was the implementation of design that Chapter IV describes.

The third, called “NATE-Beat”, was a modified version of NATE. Some participants in a pilot test with NATE mentioned that it was “difficult” to vertically differentiate vibrotactile signals from the back and that the vertical distinction of vibrotactile signals needs to be clearer. Guided by inputs from Chapter III, the vibrotactile display of NATE-Beat was designed to present vibrotactile beats through the actuators in the middle row at three beat frequencies (ΔHz), as opposed to other actuators that presented pure vibration. This addition of the symbolic cue was expected to incur minimal interference with task-related spatial processing (Wickens, 2008).

The fourth, called “NATE-Low”, was identical to NATE, except that the touchscreen location was lowered in the vertical dimension by 14 inches, compared to other touchscreen conditions that were set in a way that the top of keypad is aligned with the top of the steering wheel. That lowered touchscreen location represented the level that can significantly and negatively affect performance of visual attention management, which was the same as the position of Level 1 demonstrated in Chapter II. This manipulation was also to test the NATE method to see if the design was robust to such location effects. As NATE was designed to minimize the reliance on visual resources for touchscreen interaction, an assumption was made that the touchscreen location would not affect visual attention as long as the touchscreen is within the reach envelope.

Research hypotheses

The following hypotheses, regarding performance and workload, guided the evaluation study. In total, 10 research hypotheses were established.

H1*: Participants will show less lane deviation when equipped with either NATE, NATE-Low, or NATE-Beat than with Ordinary.*

The primary interest of this evaluation study is visual attention management of drivers using in-vehicle touchscreens. The literature suggests that performance in lane keeping is subject to the availability of visual attentional resources (Horrey & Wickens, 2004; Horrey, Wickens, Consalus, 2006). With the nonvisual aids described in Chapter IV, the NATE-based touchscreen designs (NATE, NATE-Low, and NATE-Beat) would be able to decrease the variance of lateral positions in driving.

H2: *Participants will show less speed deviation when equipped with either NATE, NATE-Low, or NATE-Beat than with Ordinary.*

The management of vehicle speed also requires visual attention. Drivers perceive the vehicle speed when visual attention is allocated to the speedometer or to the roadway. With the simulator supporting no kinetic sensation for the speed of movement, the reliance on visual resources for speed management would have been essential in this study. If the NATE-based touchscreen designs were able to minimize the occasions of visual diversion away from driving, a performance improvement in speed management would be observed.

H3: *Participants will glance at the touchscreen less frequently when equipped with either NATE, NATE-Low, or NATE-Beat than with Ordinary.*

The NATE-based touchscreen designs should support touchscreen interaction with minimal demands for visual attention, alleviating the effects of visual distraction on drivers. Consequently, the reorientation of visual attention would occur less frequently when participants were equipped with any of the NATE-based designs, compared to the ordinary touchscreen.

H4: *Participants will spend less time per individual glance at the touchscreen when equipped with either NATE, NATE-Low, or NATE-Beat than with Ordinary.*

With the NATE method, there is no need for the focus of visual attention to be maintained on the touchscreen for the entire duration of interaction. Instead, the vibrotactile signals from the back can nonvisually aid drivers to locate a given touchscreen key through the sense of touch. Visual attention may still need to be diverted from the road to the touchscreen so as to guide a hand to reach the touchscreen, but the two-finger interaction for key entry can be done without vision. Therefore, the mean duration of individual glances at the touchscreen would be shorter with any of the NATE-based designs, compared to the ordinary touchscreen.

H5: *Participants will correctly enter more input sequences when equipped either NATE, NATE-Low, or NATE-Beat than with Ordinary.*

The two-finger gesture introduced in Chapter IV would not lead to visual distraction but may have no positive impact on the efficiency of manual interaction. However, The NATE-based touchscreen designs would offload visual demands that drivers should cope with and thus reduce task interferences that can disturb performance

(Wickens, 2008). Therefore, the NATE method was expected to also lead drivers to better perform touchscreen tasks.

H6: *Participants will enter input sequences faster, on average, when equipped with either NATE, NATE-Low, or NATE-Beat than with Ordinary.*

For similar reasons as those discussed in **H5**, the NATE-based touchscreen designs was expected to reduce task interferences that can occur while driving. Hence, in-vehicle touchscreen tasks would also benefit in terms of reduced interaction time from the NATE-based designs.

H7: *Participants will enter input sequences more accurately when equipped with either NATE, NATE-Low, or NATE-Beat than with Ordinary.*

Registering a given key with the ordinary touchscreen needs participants to touch the exact location of the key. Otherwise, that trial will result in either no or an errant entry. The accuracy of this action is contingent upon whether visual attention is properly allocated to the touchscreen or not (Land, 1992; 1994). As driving requires visual attention in high demands, this allocation of attention to an in-vehicle touchscreen needs to be limited in order to manage safety risks (NHTSA, 2013). On the contrary, The NATE method provides drivers with spatially-mapped vibrotactile cues on the back, and drivers can be aware of where their fingers are located within the space of touchscreen controls without visual interference. Moreover, registering an input with the two-finger gesture reduces the need for accuracy in the initial gross movement.

H8*: Participants will rate perceived workload to be less when equipped with either NATE, NATE-Low, or NATE-Beat than with Ordinary.*

The NATE-based designs were intended to decrease visual loads for touchscreen interaction, and this was expected to improve the subjective ratings of perceived workload.

H9*: When equipped with NATE, the vertical location of the touchscreen will not have an effect on any of the recorded performance measures.*

Chapter II demonstrated that the vertical location of touchscreens can have significant effects on roadway awareness. If the NATE method can minimize the occasions of visual diversion from the road to the touchscreen, changes in the vertical location of touchscreen were not expected to affect performance of drivers, given the touchscreen is within their reach envelopes.

H10*: When equipped with NATE, presenting vibrotactile beats in the middle row of actuators will result in improvements for all the recorded performance measures.*

As mentioned previously, the pilot test indicated that the vertical discrimination of vibrotactile signals could be difficult when all the signals are perceptually identical. A symbolic presentation was introduced to the design by highlighting the signals in the middle row with vibrotactile beats.

Method

The evaluation study employed the same simulated environment as that employed in Chapter II; the driving environment involved the Lane Change Test (LCT) procedure (ISO/DIS 26022, 2010). The touchscreen designs previously specified in Table V-1 were involved in the study to evaluate performance under these touchscreen conditions.

Participants

Twenty-three drivers participated in this study (16 males and 7 females, mean age=28, and range: 22-37). The licensed driving experience was 8.1 years on average. All of the participants demonstrated normal or corrected-to-normal visual acuity of at least 20/50. None had any injuries or conditions diminishing the sensitivity of the back to vibrotactile stimulation. Eleven had experience using in-vehicle touchscreens, and seven reported that their personal vehicles were equipped with in-vehicle touchscreens.

Experimental settings

Regarding the LCT procedure, this study employed the same scenario design model that was used in Chapter II, involving the roadway design, the arrangement of lane-change signs, traffic condition, the spacing of signs, vehicle speed, the method to measure lane deviation and etc. Participants did not encounter any cars or obstacles on the simulated roadway.

This study primarily used the STISIM Drive® desktop driving simulator equipped with the Logitech G27 racing wheel, throttle and brake pedals. These controllers provided participants with force feedback of manual interaction but no kinetic sensation for speed management was involved. The simulator collected several measures of driving performance. As shown in Figure V-1, participants were asked to wear an eye tracker for collecting the data for glance behavior based on eye fixations: the open source "PUPIL" eye tracker, designed by Pupil Labs® (Kassner, Patera, & Bulling, 2014). The software operating this eye tracker employed a dispersion-threshold algorithm to determine eye fixations when glancing at a particular location for more than 100ms.

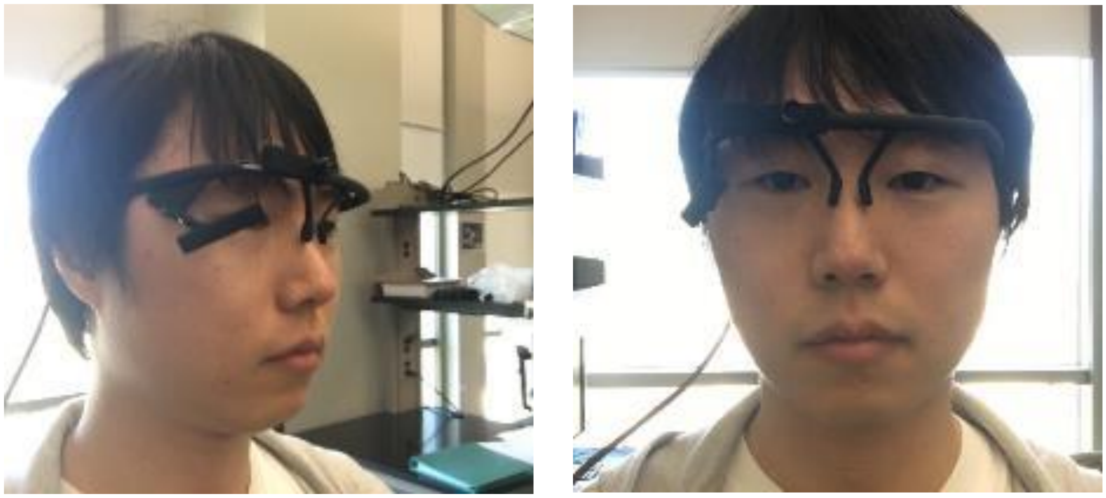

Figure V-1. The head-mounted “PUPIL” eye tracker

Experimental tasks

As described in Chapter II, the same experimental task set was involved; a) a *lane change task* (changing lanes based on visual detection), b) a *touchscreen task* (entering predefined input sequences with one of the touchscreen designs), and c) a sp*eed management task* (maintaining the vehicle speed at 40 MPH).

Procedure

Participants first read through and signed the consent form for the study, then filled out a questionnaire regarding demographic information and past experience with in-vehicle touchscreens. Then, the experimenter introduced them two training sessions.

The first training session involved a set of absolute identification trials to ensure that participants can perceive the vibrotactile signals and can differentiate them. The experimenter explained how to use NATE, and participants wore the belt to which the actuators were affixed. They were asked to take a seat in the driving cockpit and adjust the belt so the actuators can be in contact with the lower back. After that, the experimenter instructed them to think of the 3x3 touchscreen keypad the way each touchscreen key maps to a natural number from one to nine, like numeric keys of a smartphone. The experimenter then spoke one number out of the nine and asked participants to enter the corresponding touchscreen key without looking at it. The experimenter spoke 50 numbers in a pseudo-randomized order in which each of the numbers 1 – 9 were included at least five times. Participants had to achieve 90% accuracy (45 of the 50 number) to “pass” this session. Generally, two to three trial sets were needed for them to pass.

The second training session was conducted for the LCT procedure. Participants performed two LCT scenarios with the touchscreen task: one with the ordinary touchscreen and the other with NATE. They were encouraged to try their best for all the tasks but no instruction for task prioritization was given, as specified in the ISO standard (ISO/DIS 26022, 2010).

Upon the completion of training, participants conducted six main trials in total. The first and last were performed with no touchscreen, and mean values of driving performance from these trials were registered in the “none” condition (no touchscreen task was performed). Between the first and the last trial, participants conducted each of the four touchscreen conditions in a counter-balanced order. In all the trials, participants were instructed to try their best to maintain a vehicle position to be “the middle” on any lanes. After the completion of each touchscreen condition, participants completed the NASA-TLX survey.

Performance Measures

The definitions of *lane deviation*, *speed deviation*, *input efficiency*, *input accuracy*, *input time*, and *perceived workload* were the same as described in Chapter II and B. Two additional measures regarding the glance behavior of drivers were introduced. First, *Glance frequency* was defined as the number of eye fixations (count) on the touchscreen. Second, *Glance time* (seconds) was the mean duration of eye fixations on the touchscreen.

Results and discussion

The within-subject independent was the design configuration described in Table V-. The "none" condition was not involved in the statistical testing. Performance measures were analyzed in repeated measures ANOVAs, formulated in the software package SPSS 21. When a significant effect was found, the post-hoc test with Bonferroni's adjustment was conducted to identify significantly different groups. The significance level of the experiment-wise error was set to be 5%.

The results from statistical analyses are described in terms of 1) vehicle operation, 2) glance behavior, 3) touchscreen interaction, and 4) perceived workload. Discussion with respect to the corresponding research hypotheses follows each set of reported results.

Vehicle operation

Figure V-2 shows the mean values of *lane deviation* and *speed deviation*, in addition to numeric differences when comparing "none" to the other conditions. Error bars represent standard errors while letters on the mean values are used to label significantly-different groups. A significant effect was found for *lane deviation*, F (3, 88) = 7.177, $p <$ 0.001. The Bonferroni method then showed that differences were significant when comparing the ordinary touchscreen (M = 6.21 feet) to NATE (3.25, p = 0.021) and to NATE-Beat (2.74, p < 0.001). This tendency was similar in *speed deviation* which was also significantly affected, F (3, 88) = 4.559, p = 0.005. The post-hoc test identified significant differences between the ordinary (*M* = 5.46 mph) and NATE (2.32, $p = 0.023$), NATE-Low (2.49, $p = 0.047$), and NATE-Beat (1.97, $p = 0.014$).

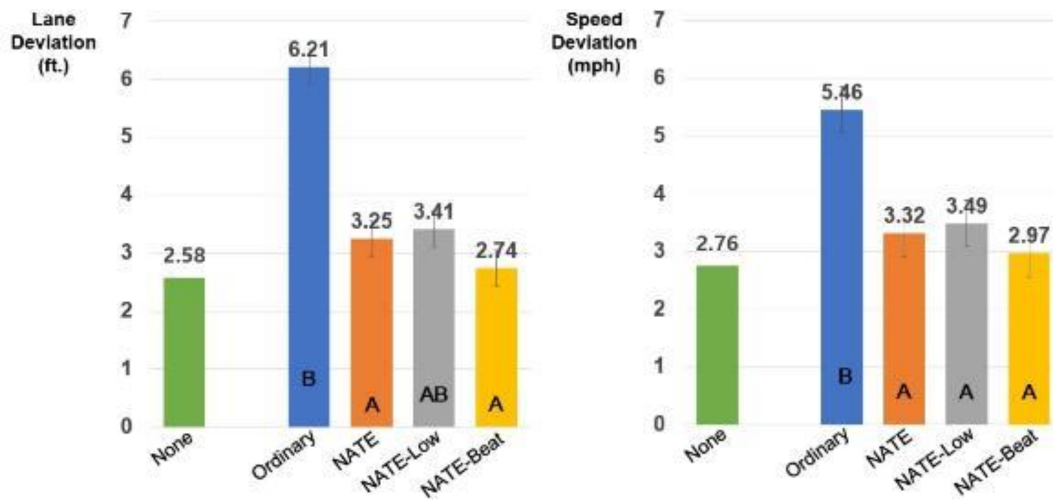

Figure V-2. Performance of driving with significant effects

H1: *Participants will show less lane deviation when equipped with either NATE, NATE-Low, or NATE-Beat than with Ordinary*

The results indicate no evidence to reject **H1**. Compared to the ordinary, performance in lane deviation significantly improved when participants were equipped with the NATE-based touchscreens. Considering the lane change task would have depended on the availability of visual attentional resources for roadway awareness, the lesser lane deviation indicate that visual demands of touchscreen interaction were lower than those of the ordinary touchscreen.

H2: *Participants will show less speed deviation when equipped with either NATE, NATE-Low, or NATE-Beat than with Ordinary.*

The results indicate no evidence to reject **H2**. The speed deviation from the 40 mph was significantly reduced when participants were equipped with the NATE-based touchscreens, compared to Ordinary. This was consistent with the trend of lane deviation. In addition, the difference in speed deviation between the conditions of Ordinary and NATE-Low reached significance; for lane deviation, the difference of the same pair was marginal ($p = 0.083$).

Glance behavior

Figure V-3 shows the mean values of glance frequency and glance time. A significant effect was found for glance frequency, $F(3, 88) = 37.307$; $p < 0.001$. The post-hoc test suggested that participants glanced at the touchscreen more frequently with the ordinary (*M*: 42.7 times) touchscreen than with the conditions of NATE (18.8; $p < 0.001$), NATE-Low (16.5; $p < 0.001$), and NATE-Beat (17.3; $p < 0.001$). The design configuration also affected glance time, $F(3, 88) = 4.442$; $p = 0.006$. The post-hoc test indicated that the mean duration of glances at the touchscreen was longer with the ordinary touchscreen (*M*: 1.7 seconds) than with the conditions of NATE (0.8 s; $p = 0.005$), NATE-Low (0.7 s; $p = 0.003$), and NATE-Beat (0.9 s; $p = 0.006$).

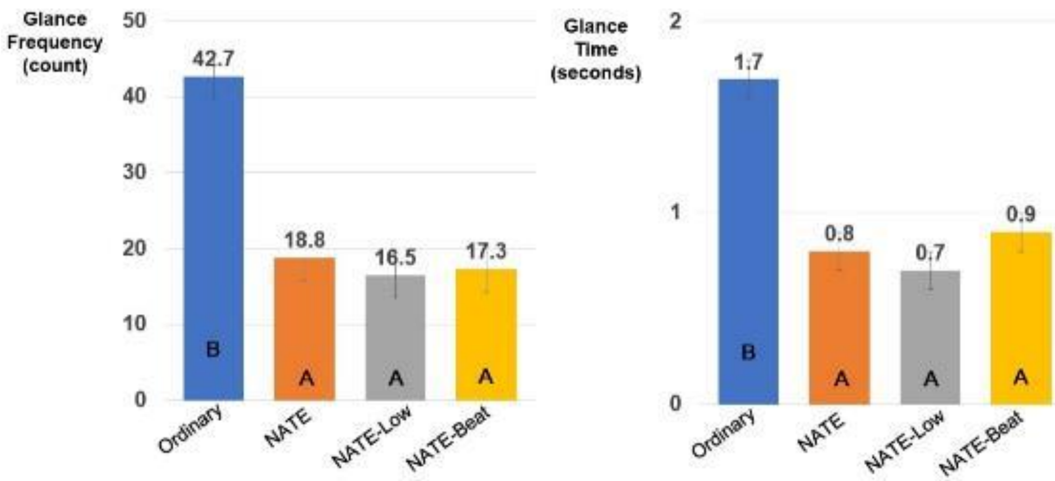

Figure V-3. Glance behavior with significant effects

H3: *Participants will glance at the touchscreen less frequently when equipped with either NATE, NATE-Low, or NATE-Beat than with Ordinary.*

H4: *Participants will spend less time per individual glance at the touchscreen when equipped with either NATE, NATE-Low, or NATE-Beat than with Ordinary.*

The results indicate no evidence to reject both **H3** and **H4**. The glance frequencies of the NATE-based touchscreens were reduced from that of the ordinary condition by more than 70%. The glance time was also reduced by about half. These significant reductions in the both measures of glance behavior can be direct evidence that the NATE systems can offload the visual demands of an in-vehicle touchscreen.

Touchscreen interaction

Figure V-4 shows performance of the touchscreen task. A significant effect was found for input efficiency, F (3, 88) = 4.169; p = 0.008. The post-hoc test indicated that participants entered the largest quantity of input sequences with the ordinary touchscreen (M: 26.96), and the difference was significant when compared to the conditions of NATE

(19.04, $p = 0.012$), NATE-Beat (18.45, $p = 0.006$), and NATE-Beat (20.96, $p = 0.047$). A similar trend was observed in input time, F (3, 88) = 7.489; $p < 0.001$. The mean duration for completing each input sequence was shorter with the ordinary touchscreen (M: 2.26) than with the conditions of NATE (3.89, $p = 0.001$), NATE-Low (3.45, $p = 0.021$), and NATE-Beat (3.71, $p < 0.001$). No significant effect was found in input accuracy.

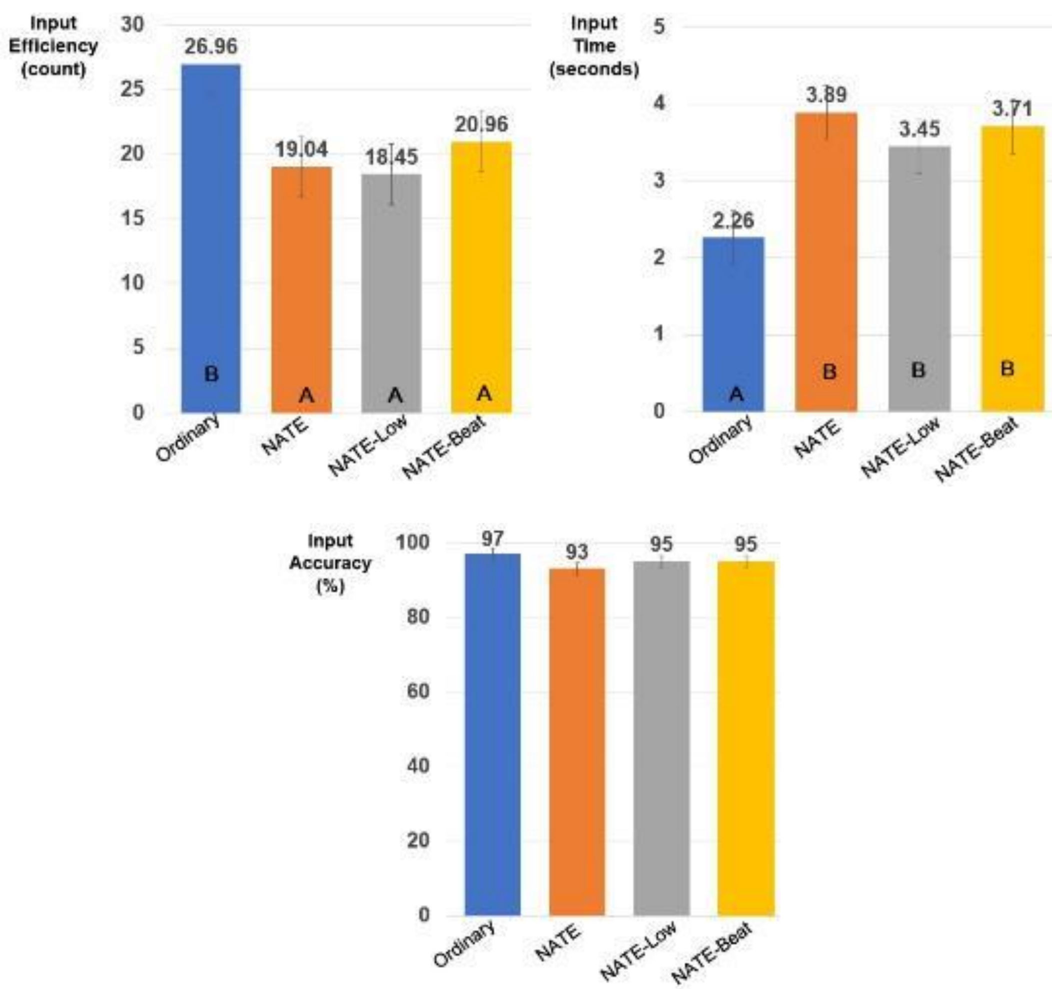

Figure V-4. Performance of the touchscreen task

H5: *Participants will correctly enter more input sequences when equipped either NATE, NATE-Low, or NATE-Beat than with Ordinary.*

H6: *Participants will enter input sequences faster, on average, when equipped with either NATE, NATE-Low, or NATE-Beat than with Ordinary.*

Evidence was found to reject both **H5** and **H6**. Comparing Ordinary to the NATE-based touchscreen systems, performance deteriorated in both *input efficiency* and *input time*. The ordinary touchscreen keypad allowed drivers to directly register inputs with just a single finger-touch. The NATE-based touchscreens, on the contrary, required to manually complete the *pre-input* interaction (holding a target key one finger) before making the *input* action (tapping another finger on the screen). The NATE's interaction method involved an additional step that the ordinary touchscreen did not need and might have increased manual workload to a significant extent. Another speculation could come from the fact that locating touchscreen keys with the NATE method required spatial attentional resources, so did the LCT procedure; this procedure needed drivers to interpret the position of the arrow mark so as to determine which driving lanes to take. In this regard, participants would have experienced task interferences with regard to the limited attentional resources for processing the spatial codes of both experimental tasks (Ferris & Sarter, 2010). If this was the case, the performance deterioration in the touchscreen task would be attributable to such task interferences (Wickens, 2008).

H7: *Participants will enter input sequences more accurately when equipped with either NATE, NATE-Low, or NATE-Beat than with Ordinary.*

The results indicate no evidence to reject **H7**, possibly due to a ceiling effect; the lowest accuracy was 93%, and no significant effect was found. More complicated input sequences or the increase of task difficulty would be needed in order to find a significance in the input accuracy.

Perceived Workload

Figure V-5 shows subjective ratings of *perceived workload*. The touchscreen configuration did not show a significant effect.

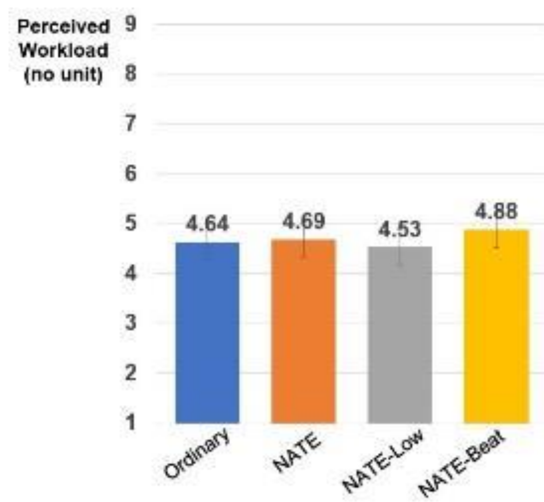

Figure V-5. Perceived workload with no significant effect

H8: *Participants will rate perceived workload to be less when equipped with either NATE, NATE-Low, or NATE-Beat than with Ordinary.*

Evidence was found to reject **H8**, as the main effect of touchscreen configuration did not show a significance in *perceived workload*. Participants rated perceived workload to be nearly “moderate” over all the conditions.

Modifications of NATE

H9*: When equipped with NATE, the vertical location of the touchscreen will not have an effect on any of the recorded performance measures.*

Not enough evidence was found to reject **H9**. The NATE-Low condition did not show a significant difference from the NATE condition in any of the performance measures.

H10*: When equipped with NATE, presenting vibrotactile beats in the middle row of vibrotactile actuators will result in improvements for all the recorded performance measures.*

The results indicate evidence to reject **H10**. The introduction of vibrotactile beats did not lead to a significant improvement in any of the performance measures, given the results with the NATE condition.

General discussion

This chapter describes the evaluation study of some key characteristics of touchscreen interfaces that employ the NATE method. The NATE method was intended to offload visual demands when interacting with advanced manual controls, especially touchscreens, and thus to better support visual attention management of drivers. The evaluation study was conducted in a simulated environment, based on the Lane Change Task, which is a well-practiced ISO-standard procedure that requires participants to perform driving actions under visual-manual distraction. Based on the NATE method, the touchscreen interface systems that were tested in the evaluation study employed the integration of multisensory interaction cues. These systems mainly involved a touchscreen tablet and a set of vibrotactile display presenting *proximal* cues to the back of drivers, so as to take advantage of spatial resources through the sense of touch. The findings from the evaluation study primarily suggest benefits of NATE in the design of an in-vehicle touchscreen, with regard to addressing visual demands of the task interface. Overall, the better objective performance in driving and glance behavior was observed when participants were equipped with the NATE-based touchscreens, compared to the ordinary touchscreen that allowed participants to register direct inputs but required visual attention essentially. However, performance of the touchscreen task turned out to be degraded when using NATE possibly due to the complexity of manual interaction. Nevertheless, NATE did not impose more difficulty in tasks, evidenced by no significant difference in perceived workload. The addition of vibrotactile beats and the change of the vertical location of the touchscreen were investigated to see if further improvement (or costs) would result from those, but no significant difference in either performance measure or workload was found.

Chapter II describes an experiment that demonstrated the effectiveness of nonvisual sensory feedback from touchscreen interaction on supporting reorientation of visual attention. Drivers who were tasked with touchscreen interaction detected visual probes more accurately and responded to them faster. This finding suggests practical benefits of multisensory cues with regard to the interface design of in-vehicle touchscreens. The allocation of attentional resources to multiple dimensions can effectively support parallel processing in data-rich environments (Wickens, 2008). The finding also serves to demonstrate the practicality of synthetic feedback (e.g., presenting vibrotactile cues to a fingertip through a touchscreen), while operating a real vehicle. This realistic context of use involves noise factors, including but not limited to sounds of vehicle operation, engine vibration, and road bumpiness, that could disturb multisensory experiences. However, it is challenging to realize such naturalistic masking effects in simulated environments. Considering earlier studies that tested multisensory cues of in-vehicle touchscreens were primarily conducted in simulated driving environments (e.g., Lee & Spence, 2008; Pitts et al., 2010; Pitts et al., 2012), the current driving study is useful to fill the gap in the literature in that the effects of feedback modalities were evaluated in a real driving environment with naturalistic multisensory background stimuli.

The findings of Chapter II also imply that the effects of task difficulty with touchscreens may depend upon the richness of synthetic feedback. The current study manipulated the task difficulty by employing two distinct sizes of touchscreen keys. The difference in *input accuracy* between the two conditions was significant only when the touchscreen did not include any type of nonvisual feedback. The difference was not significant when the multisensory feedback supported the both conditions. This finding signifies a need to consider a possibility that task difficulty of touchscreen interaction could depend on the quality of interaction feedback. In this regard, the evaluation of performance with in-vehicle touchscreens may not be complete unless an adequate quality of interaction feedback were provided, as this has been often disregarded or in adequately considered in relevant earlier studies (e.g., Kim et al., 2014; Kujala, 2013; Lasch & Kujala, 2012). Furthermore, the effects of key size would have been clarified to a greater extent if the current study involved a condition with large touchscreen keys without the auditory cue and vibration, with only the visual feedback. As the explicit comparison of key sizes was done only with the full set of sensory cues, a significance of the interaction effect between key size and feedback modality has not yet been explored. In addition, the current study is also meaningful in that the interface characteristics of in-vehicle touchscreens were tested *while driving*. This is especially important in a practical sense. As vehicle manufacturers would usually outsource the development of in-vehicle touchscreens, the corresponding vendors often neglect the fact that the interface would likely be used in demanding situations. One senior designer of vehicle interior allowed his quote to be included in this dissertation (January 10, 2018).

"You gotta know that we don't make all the parts. We have contractors who can do things that are secondary, though we give them guidelines and do the verification to see if the integration was ok. But this doesn't mean that all the components were tested in all driving environments. Governments will get us to pay for the crash tests to see if a car is physically solid, but they are not going to fail our design just because it is distracting."

This dissertation also investigated whether the location of in-vehicle touchscreens can be a factor of driver distraction, and Chapter II demonstrates how the vertical location of in-vehicle touchscreens can affect the imposed visual demands and driving performance. The locations were below the line of sight for drivers monitoring the roadway, and glances at in-vehicle touchscreens necessitated the diversion of focal visual attention away from the road. At this point, some visual resources, such as ambient vision, can remain engaged in driving-related processing, as it can support spatial orientation and detect positional deviation while driving (Horrey & Wickens, 2004; Schmidt & Lee, 2005; Sekuler & Sekuler, 2000). However, visually attending to vehicle positions via the ambient channel is possible only when the roadway is contained in the functional field of view. The design of the study assumes that the ability for drivers to attend to the road while concurrently interacting with a touchscreen would be contingent upon the touchscreen location. The findings indicate a vertical range (less than 35 degrees below the line of sight to the roadway) for the location of an in-vehicle touchscreen that would not incur performance decrements in visual search tasks. In the same regard, the findings predict the degradation of performance would be significant if the location is out of the range. This finding is consistent with the guidelines of MIL-STD-1472G (2012), which states that the deviation between multiple displays in the vertical dimension should not exceed 35 degrees.

It is worthwhile to mention that the pairwise comparison between touchscreen locations in the vertical dimension did not show a significant difference in any measures of the touchscreen task. As Chapter II describes, the changes in location introduced differences in the distance from the steering wheel to the touchscreen, which was expected to affect the touchscreen task but performance was not affected. On one hand, the touchscreen task itself may have been difficult to be assessed due to a ceiling effect, For example, input accuracy was considerably high for all conditions (88 to 93%). On the other hand, the lack of significance in any performance measures of the touchscreen task may indicate that participants prioritized the touchscreen task over driving. When more attention is allocated to the touchscreen to ensure the highest level of performance in that task, this is likely at the expense of attentional resources that can be allocated to roadway awareness. This is plausible when considering that the study was conducted in a simulated environment where participants understood that there was no real physical risk to engaging in distracting behaviors. However, performance measures for the touchscreen task were affected in the first study of Chapter II, where participants were operating an instrumented vehicle and implicitly aware of physical risks if visual attention on the roadway was not maintained properly.

The findings from the two studies of Chapter II provided specific requirements for the body of research for this study to better support visual attention of drivers interacting with in-vehicle touchscreens. The first study necessitated the provision of nonvisual channels for drivers to communicate with touchscreens, while the second study demanded the consideration of touchscreen location as one of critical design factors such as key size (Kim et al., 2014), information search methods (Kujala, 2013), and key layout (Kujala & Salvucci, 2015).

Chapter III describes the first attempt to develop a new way of interaction with touchscreens which minimally demands visual attentional resources. This study tested the feasibility of encoding information with nonvisual symbolic codes. The beat phenomenon, which occurs when two dissonant frequencies of vibration are combined (carrier and modulator), was elicited to determine the effectiveness of this encoding for nonvisual reception. The focus of the related human subjects study concerned the ability to perceive and differentiate various beat frequencies in the context of touchscreen use. Earlier findings on vibrotactile beats have focused on whether the phenomenon is replicable (Lim et al., 2012) or whether perceptually-different vibrotactile beats are implementable (Yang et al., 2012), although the sensitivity to changes in vibrotactile beat patterns has not yet been well-described. The findings of Chapter III indicate that only a handful of beat frequencies can be perceptually differentiated in the context of touchscreen use. If encoded with vibrotactile beats, the complexity of this vibrotactile display for touchscreen interaction would not be matched by the capability of visual representation to be complex.

The findings also suggest that the ability to perceive and differentiate vibrotactile beats can be subject to usage scenarios. For example, the change detection of vibrotactile beats through a fingertip on a mounted touchscreen was not as sensitive as that of the condition in which participants perceived the signals through a hand holding the entire touchscreen. It is not fair to condemn vibrotactile beats as a means of supporting nonvisual interaction, although this symbolic method alone would not be able to provide in-vehicle touchscreens with a sufficient level of data resolution.

The aforementioned studies gave useful inputs to the design guidelines of NATE that are primarily based on the benefits of multisensory binding. Humans are able to integrate sensory stimuli from multiple modalities into one single perceptual experience when certain conditions are met (King & Calvert, 2001; Levitin, et al., 2000; Lewkowicz, 1996). Earlier studies propose that those conditions involve spatiotemporal compatibility for the natural mapping in spatial arrangement and coincident activation (Levitin et al., 2000; Wallace & Stein, 1997; Wallace et al., 2004), on which the design of NATE was based. The findings from the evaluation study suggest that the NATE method can support visual attention management, evidenced by the significant improvement in driving performance and in glance behavior. In the context of distracted driving, participants showed better vehicle control in both lateral and longitudinal position maintenance when equipped with the NATE-based touchscreens than with the ordinary touchscreen. This implies that NATE can alleviate the deterioration of driving performance incurred by in-vehicle touchscreen interaction. It is also notable that lowering the location of touchscreens did not affect performance with NATE-based touchscreens. This is attributable to the characteristic of NATE that allows operators to be informed of touchscreen interaction via channels other than focal attention. Hence, NATE can is beneficial regardless of the location of touchscreens. Chapter II demonstrated that changes in the line of sight to the touchscreen can be negatively impactful on drivers, which was not the case with NATE.

The advantage of NATE was also found for the glance behavior, as characterized by glance frequency and time. With the NATE-based touchscreens, participants showed significantly fewer occasions of visual diversion from the road, compared to the ordinary touchscreen condition. This indicates that NATE can actually reduce visual demands required for the interaction with an in-vehicle touchscreen while driving. In this regard, the improvements in vehicle operation performance mentioned earlier could also be attributable to the reduction of such visual demands. It is noteworthy that mean duration of glances to the touchscreen also decreased with the NATE-based touchscreens. Earlier studies suggest that drivers manage safety risks with a nondriving task by adjusting the glance behavior with tradeoffs; they limit the individual duration for visual diversion and instead increase the frequency of the diversion (Kim et al., 2014; Kujala & Salvucci, 2015; Wierwille, 1993). Then, the 1.7 seconds of glance time observed with the ordinary touchscreen can be considered as a model time window for visual sampling of the touchscreen task can be imposed on drivers. In this regard, the significant reduction of glance time, observed in the NATE-based conditions, indicates evidence that the application of NATE to in-vehicle touchscreen designs can be effective in offloading visual demands of drivers.

Given the significance of glance frequency and time measures, it was of interest to investigate the total duration glance at the touchscreen, which is simply calculated by multiplying the two together. When equipped with the ordinary touchscreen, the experimental task set led participants to be visually distracted for at least 72.6 seconds, based on the corresponding glance frequency and time (42.7 glances in 1.7 seconds per each). This duration of visual distraction makes up 40% of the expected total duration of driving in the LCT scenarios, which is approximately 180 seconds if a vehicle speed of 40 mph was maintained. On the other hand, the NATE-based touchscreens yielded the total duration of glance in a range from 11.5 (= 16.5 x 0.7) to 15.6 seconds (17.3 x 0.9). Although this is a rough calculation for estimating visual demands, the total glance duration observed with the ordinary touchscreen was considerably higher than those of the NATE. This result not only highlights the influence of distraction effects incurred by the ordinary touchscreen but also quantifies the visual demands of an in-vehicle touchscreen that can be offloaded via NATE displays. Nevertheless, the glance behavior data indicate that NATE was not able to eliminate the costs of visual distraction imposed by touchscreen interaction while driving; the touchscreen experience with the nonvisual aids was not exclusively nonvisual.

On the downside, drivers equipped with the NATE-based touchscreens suffered a degree of performance degradation in the touchscreen task. The ordinary condition allowed participants to make more input sequences. The completion of input sequence was also faster. This may be because NATE requires drivers to additionally engage in attentional resources for tactile perception on the back. The tactile interpretation of signal locations might have been more effortful than visually locating touchscreen keys. Another reason could be attributable to that NATE separately requires both *pre-input* (putting one finger one a touchscreen key) and *input* (double-tap on the screen with another finger) actions. This unique gesture would have contributed to the decrease of visual demands but might have increased manual demands of the *input* action, as opposed to the ordinary touchscreen allowed direct inputs with a single touch.

Overall, the NATE-based touchscreens better supported visual attention management, evidenced by the glance behavior and driving performance, but suffered performance degradation in the touchscreen task. These results indicate a trade-off issue in the design of in-vehicle touchscreens, which may originate in the nature of driving. Since driving is already demanding in the limited visual, cognitive, and manual resources (Haigney et al., 2000; Harbluk, Noy, Trbovich, & Eizenman, 2007; Jamson, & Merat, 2005; Tivesten, & Dozza, 2014), the introduction of any secondary task would degrade performance of at least one task, regardless of the quality of touchscreen design. Therefore, this dissertation study demands reflection of vehicle interior designers who consider to employ touchscreens. This tradeoff should be addressed by the decision on which task should be prioritized; if the design of touchscreen interaction is aimed for user satisfaction (e.g., Tengler, 2013), the expense of visual distraction would be incurred, and then safety risks will accompany the corresponding design in the context of driving. Recent public sources have been realizing that the current trends of vehicle interior design involve replacing physical control elements with touchscreens and that such trends are linked to a matter of safety (e.g., Glinton, 2017; Laurel, 2017; Shropshire, 2017). The NHTSA statistics (2013) based on actual crash reports corroborate the safety concerns of in-vehicle touchscreens, as mentioned in the first chapter.

The studies that this dissertation describes use a partial counterbalancing technique for the orders of treatment conditions, although the corresponding effects were not explicitly tested. The perfect level of counterbalancing was never achieved in any of individual studies, as the recruitment of participants were not sufficient in quantity. Nevertheless, significant effects that were found in the current studies imply that the effects of treatments were strong enough to overcome the counterbalancing effects. However, this does not necessarily mean that counterbalancing effects never existed. This uncertainty leads to a possibility for the effects that did not reach significance in the current results to show significance if counterbalancing effects existed and were well-controlled. Besides, testing counterbalancing effects could provide knowledge on the influence of learning effects, which will contribute to the validity of the findings.

Finally, perceived workload was not affected. This could be understandable with the performance tradeoff; drivers would have been able to monitor the roadway with less visual distraction although making input sequences with the touchscreen would have been more demanding, which resulted in no significant effects of NATE.

CHAPTER VI

CONCLUSION

Driver interaction with an in-vehicle touchscreen leads to frequent reorientations of visual attention under high demand (NHTSA, 2013). Such reorientations of attention originate in that driving and touchscreen interaction tasks concurrently compete for the limited resources in visual attention (Wickens, 2008). Therefore, the allocation of visual attentional resources needs to be effective and efficient. This is further justified in the sense that touchscreens inherently involve safety concerns associated with visual distraction to a greater extent than traditional interfaces with physical controls, as demonstrated in Chapter II. Road traffic statistics suggest that such safety concerns of in-vehicle touchscreens have been realized as actual crashes (NHTSA, 2013)

Researchers have attempted to address distraction potentials relating to in-vehicle touchscreens, and several contributing factors have been identified, including feedback modality (Lee & Spence, 2008; Pitts et al., 2010; Pitts et al., 2012), key size (Kim et al., 2014), information display style (Kujala, 2013; Kujala & Salvucci, 2015). However, the model of interaction workflow (Freitag et al., 2012) consisting of *pre-input*, *input*, and *post-input stages* indicates that previous attempts would have addressed only a part of the three. In other words, reduced visual demands in one stage would have been compensated by unresolved visual demands in the other stages, leading drivers to still rely on vision for in-vehicle touchscreen interaction.

Although this visual reliance can be relieved by the employment of nonvisual modalities such as the sense of touch (e.g., Ferris & Sarter, 2011), an effective use of tactility for touchscreen interaction needs further consideration. As cues of touchscreen interaction are *distal*, a physical contact for the perception of distal cues would happen at the small area of a fingertip. Then, the tactile perception of those cues occurs at the point on the flat screen where actual controls are *intangible*. Considering these difficulties with touchscreen interaction, it is a challenge to present tactile cues communicating additional information other than the registration of contact, even with synthetically recreated ones such as vibrotactile beats (see Chapter III). Nevertheless, in interface design, nonvisual modalities can be useful for supporting concurrent tasks which are to be processed in parallel under minimal visual requirements (Sarter, 2007; Wickens, 2008).

In order to offload visual demands of touchscreen interaction in multitasking situations, the present research efforts attempted to address all of the three stages involved in the interaction loop (*pre-input*, *input*, and *post-input*). Two empirical studies were conducted to investigate safety aspects of in-vehicle touchscreens. Chapter II describes a study investigating the effects of interface characteristics on drivers' multitasking performance, involving visual search and touchscreen interaction. The findings show that it can be critical to provide drivers with nonvisual channels to confirm inputs of touchscreen interaction so as to reduce visual diversion away from of the road. Chapter II describes a study that examined location effects of an in-vehicle touchscreen in a simulated driving environment. The findings indicate that physical separation between the point of focal attention to the road and that to the touchscreen can affect drivers' ability to maintain lateral and longitudinal positions of a vehicle. Chapter III describes a study tested the practicality of *symbolic* tactile interaction with a touchscreen, based on vibrotactile beats. It was concluded that the perceptual ability to differentiate various beat frequencies may not be able to sufficiently support a required level of complexity for touchscreen interaction. Consequently, the final research efforts adopted a *spatial* encoding method to develop the **Nonvisual Aids for Touchscreen Experience**, referred to as **NATE**. Chapter IV describes the concept of NATE and specified how NATE can support each stage of the interaction loop with *proximal* vibrotactile cues that are spatially mapped onto touchscreen locations. Chapter V describes an evaluation study involving NATE-based touchscreen designs, comparing them to an ordinary touchscreen that can register direct inputs. Presenting spatialized vibrotactile signals on the driver's back and employing the two-finger gesture for touchscreen interaction, the NATE-based designs led to significant improvements in performance with regard to vehicle operation and glance behavior, as compared to the ordinary touchscreen condition. The use of NATE supported smaller lane deviation and speed deviation, and led to fewer glances at the touchscreen for shorter durations. However, performance measures on a touchscreen task suggest some limitations, possibly because of the increase in manual and cognitive demands incurred by the two-finger gesture and the additional engagement to interpret the spatialized tactile cues on the back. Neither lowering the touchscreen location (NATE-Low) nor providing vibrotactile beats for vertical discrimination of signals (NATE-Beat) led to a significant effect on performance or workload. The findings of the evaluation study suggest that the NATE method can offload visual demands of touchscreen interaction while driving. It is expected that the method could be applicable to touchscreen interactions in other complex, data-rich domains such as process control, aviation, or surface transportation. These areas usually involve operators who visually monitor the status of system and concurrently use input interfaces that also impose visual demands.

This body of work makes an impactful contribution to previous understandings of drivers' attention management strategies while interacting with in-vehicle touchscreens. In fact, the current work highlights perceptual and cognitive aspects that have not been or are not often considered in the design of in-vehicle touchscreens. Chapter II employed various types of synthetic interaction feedback and compared them to a physical interface. It showed how performance of visual search while driving can be significantly affected by the configuration of multisensory interaction feedback. It is noteworthy, the perceptual experience of participants was tested with a real vehicle on the road, whereas similar previous studies have been conducted in a simulated environment where such experience would have been approximated (e.g., Medeiros-Ward, Cooper, & Strayer, 2014; NHTSA, 2013).

A specific design recommendation for in-vehicle touchscreens can also be informed by Chapter II. This study demonstrated that the increase of the vertical separation between the line of sight to the road and that to the touchscreen can lead to visual distraction and be manifested as degraded performance of vehicle control. In this regard, the study found a particular range of touchscreen locations from which the increase of visual distraction can reach significance. This finding is especially meaningful in that the tested range of vertical locations represented the height of a 17-inch in-vehicle touchscreen which is being installed in the recent generation of vehicles used by vehicle manufacturers such as Tesla Motors.

Also, the findings help advance theories proposed in earlier studies that focused on cognitive aspects in timeshare strategies of multitasking drivers. These studies asserted that drivers can manage timesharing requirements by *monitoring* and *limiting* the temporal duration of visual distraction (e.g., Kujala & Salvucci, 2015; Wierwille, 1993). To this earlier knowledge, the findings from Chapter II suggests that such timesharing performance can also be contingent upon the location of a touchscreen; if the fixation point on the touchscreen is too separated from the line of sight to the road, the ability to process ambient visual resources, such as is required in lane keeping performance, can be disturbed.

Another practical contribution was also made through a psychophysical approach, described in Chapter III. This study tested the perception range with respect to vibrotactile beats at various beat frequencies. The ability to differentiate vibrotactile signals at *single* frequencies has been previously explored (e.g., Pongrac, 2008), but less is known about the perceptual resolution in in differentiating the *combined* frequencies generating vibrotactile beats. The present study suggests a range of beat frequencies that can be differentiated to differentiate beat frequencies propagated through a touchscreen tablet.

Chapter IV and V described the development and evaluation of NATE which employs distributed multisensory cues that are proximal to operators but separated from the touchscreen. It was an attempt to offload visual demands in relation to each stage of the interaction loop. The design was guided by 1) nonvisual *pre-input* feedback that can be integrated as a part of multisensory experience, 2) the spatial compatibility to maintain connections between controls and the corresponding interaction cues, 3) a unique *input* action requiring minimal visual attention, and 4) nonvisual confirmation supporting the *post-input* stage.

The efforts described in this dissertation suggest possibilities for offloading the corresponding visual demands and thus for reducing visual distraction effects in many complex multitasking domains. However, drivers adapt to risks on the road, whilst being motivated towards faster speeds and objectively more risky behavior (Wilde, 1988), which is why design efforts should accompany more naturalistic research on drivers so as to address masking effects in reality (e.g., vibration induced by a subwoofer from another vehicle may interfere with the perception of vibratory signals of NATE). Through continued efforts, it would be possible to develop more effective design strategies to mitigate the effects of visual distraction incurred by secondary task interfaces in reality.

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APPENDIX

THE DEFINITIONS OF DEPENDENT VARIABLES

Appendix Table. The definitions of dependent variables used in this dissertation

Dependent Variables (unit)	Definition
Input efficiency (count)	The number of correctly-entered input sequences, regarding the input task (see Chapter II) and the touchscreen task (Chapter II and V)
Input accuracy (%)	The percentage of correctly-entered input sequences over all entered input sequences, regarding the input task (see Chapter II) and the touchscreen task (Chapter II and V)
Input time (seconds)	The mean duration for correctly-entering one input sequence, regarding the input task (see Chapter II) and the touchscreen task (Chapter II and V)
Detection rate (%)	The percentage of correctly-acknowledged signs over all the signs, evidenced by both verbal and manual response (see Chapter II)
Response promptness (%)	The percentage of temporal availability after a verbal response to a given sign over the entire duration of sign visibility, measured by video frames (see Chapter II)
Lane deviation (feet)	The mean value of the absolute difference between lateral positions of the normative path and the simulated vehicle, given the sampling rate of one foot (see Chapter II)
Speed deviation (mph)	The mean value of the absolute difference between 40 mph and the speed of the simulated vehicle, given the sampling rate of one foot (see Chapter II)
Perceived difference (Hz)	The mean difference of beat frequencies between responses for noticing changes (see Chapter III)
Response time (seconds)	The mean duration of registering a response to a noticed difference in changes of beat frequencies (see Chapter III)
Glance frequency (count)	The number of glances at the touchscreen (see Chapter V)
Glance duration (seconds)	The mean duration of individual glances at the touchscreen (see Chapter V)
Perceived workload (no unit)	The mean of subjective ratings on six questions designed by the NASA Task Load Index protocol (see Chapter II and IV)