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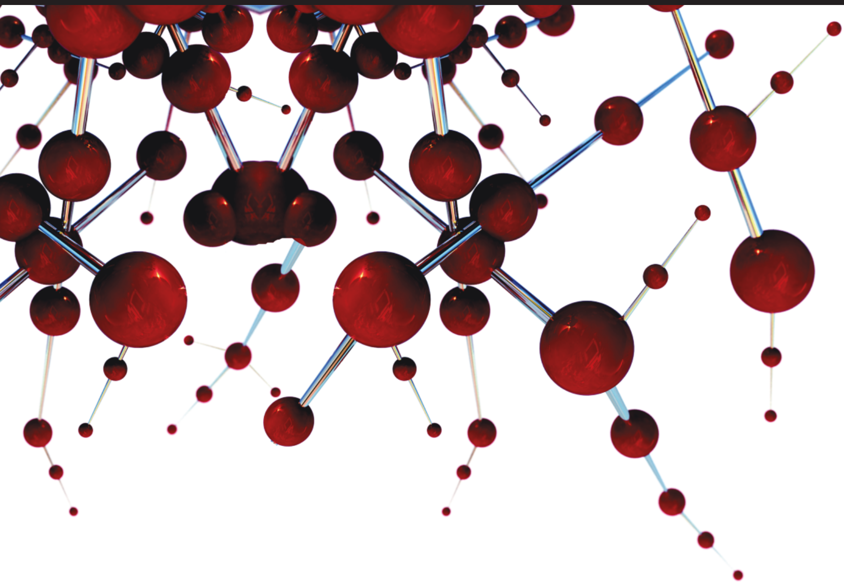

Toni Pakkanen

Supporting Eyes-Free Human-Computer Interaction with Vibrotactile Haptification

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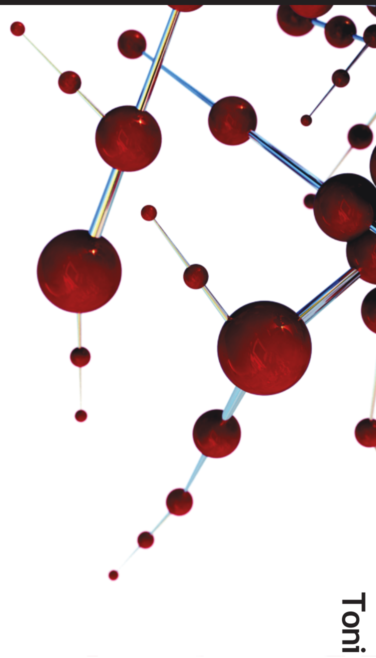
The sense of touch is a crucial sense when using our hands in complex tasks. Touch is a sense that is underutilized in interactions with technology and could provide new ways of interaction to support users. While people are using information technology in certain situations, they cannot visually and mentally focus completely during the interaction. This dissertation investigates how modern touchscreen devices could utilize tactile interaction by using internal actuators more comprehensively. The goal was to find out how to support users with interaction in situations where their sight cannot be used.

Benefits of tactile interaction were evaluated through laboratory experiments during simulated driving tasks. Findings indicated that utilizing tactile interaction in such a way where interaction specific information and UI elements are presented with vibrotactile haptifications, users were able to drive safer during the tasks. These results support the idea to utilize touch more in user interfaces for the users while their main focus is on elsewhere than using the device.



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ACADEMIC DISSERTATION
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Dissertations in Interactive Technology, Number 32
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ACADEMIC DISSERTATION IN INTERACTIVE TECHNOLOGY

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Abstract

The sense of touch is a crucial sense when using our hands in complex tasks. Some tasks we learn to do even without sight by just using the sense of touch in our fingers and hands. Modern touchscreen devices, however, have lost some of that tactile feeling while removing physical controls from the interaction. Touch is also a sense that is underutilized in interactions with technology and could provide new ways of interaction to support users. While users are using information technology in certain situations, they cannot visually and mentally focus completely during the interaction.

Humans can utilize their sense of touch more comprehensively in interactions and learn to understand tactile information while interacting with information technology. This thesis introduces a set of experiments that evaluate human capabilities to understand and notice tactile information provided by current actuator technology and further introduces a couple of examples of haptic user interfaces (HUIs) to use under eyes-free use scenarios. These experiments evaluate the benefits of such interfaces for users and concludes with some guidelines and methods for how to create this kind of user interfaces.

The experiments in this thesis can be divided into three groups. In the first group, with the first two experiments, the detection of vibrotactile stimuli and interpretation of the abstract meaning of vibrotactile feedback was evaluated. Experiments in the second group evaluated how to design rhythmic vibrotactile tactons to be basic vibrotactile primitives for HUIs. The last group of two experiments evaluated how these HUIs benefit the users in the distracted and eyes-free interaction scenarios.

The primary aim for this series of experiments was to evaluate if utilizing the current level of actuation technology could be used more comprehensively than in current-day solutions with simple haptic alerts and notifications. Thus, to find out if the comprehensive use of vibrotactile feedback in interactions would provide additional benefits for the users, compared to the current level of haptic interaction methods and nonhaptic interaction methods.

The main finding of this research is that while using more comprehensive HUIs in eyes-free distracted-use scenarios, such as while driving a car, the user's main task, driving, is performed better. Furthermore, users liked the comprehensively haptified user interfaces.

Acknowledgments

First, I would like to thank Professor Roope Raisamo. As my supervisor, he has been supportive and provided valuable guidance throughout the process of getting this dissertation finished. His guidance and knowledge have helped me to mature as a researcher and guided my thinking toward being more disciplined, but still free thinking, and helped me to find out new ways to see things. I also would like to thank Professor Veikko Surakka, who provided valuable comments and guided me to see the problems of the complex experiments and, by his guidance, helped me to learn the importance of controlled experiments and, through that insight, create experiments, which are more controlled, but closer to real-life situations than pure basic research controlled experiments.

I also would like to thank all my project coworkers and coauthors in the publications in this thesis for all the valuable comments and enlightening discussions throughout the years. All these moments helped to get to this point, where I am writing this thesis. Especially, I would like to thank Katri Salminen for teaching me to use SPSS for statistical analysis, as well as Jani Lylykangas, Jukka Raisamo, Jussi Rantala, and Katri Salminen for all the discussions about haptics, lending your hands for testing different tactons and discussing the experiments and prototype designs and details.

I would like to thank Tampere Unit for Computer-Human Interaction, Tauchi, and all its leaders throughout the years. Working in this environment has been inspiring and has grown me professionally to the person I am today. The research group has provided excellent facilities and support to carry out research and finally getting this thesis done. I also would like to thank Business Finland (formerly the Finnish Funding Agency for Innovation Tekes), which funded all the projects involving the experiments. In addition, I am grateful for the doctoral program of User-Centred Information Technology, UCIT and the funding to finalize the last publications and for the excellent framework for learning in the form of seminars and other courses they have organized throughout the years.

Finally, I would like to thank my family members for all the support and patience they have given to me throughout my studies and work and how they helped me to endure all of the stress and gave me a reason to pursue advancement in my career. In addition, I would like to thank all my friends for all the relaxing moments, helping get mind out of the work. Those moments were valuable and needed, helping to gain fresh energy to continue with all the work required for this thesis.

Contents

List of publications

This thesis consists of a summary and the following six original publications, reproduced here by permission.

I. Pakkanen, T. and Raisamo, R. (2005). Perception Strategies in Modal-Redistributed Interaction. In *Proceedings of World Haptics Conference (WHC 2005),* Pisa, Italy, 18–20 March 2005. IEEE Computer Society, 641–644.

II. Pakkanen, T., Lylykangas, J., Raisamo, J., Raisamo, R., Salminen, K., Rantala, J., and Surakka, V. (2008). Perception of Low-Amplitude Haptic Stimuli When Biking. In *Proceedings of the 10th International Conference on Multimodal Interfaces (ICMI '08)*, Chania, Crete, Greece, October 20–22, 2008. New York, NY: ACM, 281–284.

III. Pakkanen, T., Raisamo, R., Raisamo, J., Salminen, K., and Surakka, V. (2010). Comparison of Three Designs for Haptic Button Edges on Touchscreens. In *Proceedings of the Haptics Symposium 2010,* Waltham, MA, USA, March 25–26, 2010. IEEE, 219–225.

IV. Pakkanen, T., Raisamo, R., Salminen, K., and Surakka, V. (2010). Haptic Numbers: Three Haptic Representation Models for Numbers on a Touchscreen Phone. In *International Conference on Multimodal Interfaces and the Workshop on Machine Learning for Multimodal Interaction (ICMI-MLMI '10),* ACM, New York, NY, USA, Article 35, 1–4

V. Pakkanen, T., Raisamo, R., Surakka, V. (2012). Comparison of Extensive vs. Confirmation Haptic Interfaces with Two Levels of Disruptive Tasks. In *Haptics: Perception, Devices, Mobility, and Communication: International Conference, EuroHaptics 2012*, Tampere, Finland, June 13–15, 2012. Proceedings, Part I. Heidelberg: Springer, 383–394.

VI. Pakkanen T., Raisamo R., Surakka V. (2014). Audio-Haptic Car Navigation Interface with Rhythmic Tactons. In *Haptics: Neuroscience, Devices, Modeling, and Applications: International Conference, EuroHaptics 2014*, Versailles, France, June 24–26, 2014. Proceedings, Part I. Heidelberg: Springer, 208–215.

The Author's Contribution to the Publications

Publications in this thesis were coauthored, while all the research was carried out in the collaborative projects. For all the experiments and publications, the author was responsible for planning and executing the experiments and was the main author. The coauthors were involved in the role of writing individual sections, commenting, helping fine-tune details in the experiments, and reviewing the publication.

In Paper I, the initial idea of representing visual information with haptics and audio came from Dr. Grigori Evreinov, who administrated the project where the work was carried out. Otherwise, the author carried out the work and publication by himself, and coauthor Prof. Roope Raisamo helped by revising the publication throughout the writing process.

In Paper II, the initial idea for the experiment was a result of collaborative work in the project meetings. Planning, execution, and analysis of the experiment was done by the author. The publication was mainly written by the author, and coauthors commented and helped with improving the manuscript.

In Papers III and IV, the initial idea came from the author, and planning and executing the experiment was done by the author. Writing the publication was mainly carried out by the author. The coauthors helped with improving the manuscript by revising it and improving the experiment setups by commenting on the details in the planning phase. Katri Salminen advised with using SPSS for statistical analysis and reporting the results in the correct format.

In Papers V and VI, all the work was mainly done by the author with initial ideas from his plans. The coauthors helped with commenting on experiment plans and with commenting on and helping to improve the manuscript for publication.

1 Introduction

We use our sense of touch, together with our other senses, in everyday tasks. Touch provides us with stimulation cues to support task performance. While our attention is focused on something, we can still perform familiar tasks quite well by touch, supported just by glimpses or auditive feedback (such as operating buttons, turning the radio volume up, etc. while driving).

However, regarding modern touchscreen-based devices, the sense of touch does not support task performance. Simple pulses, used in modern devices for confirmation, do not have recognizable shapes and the individual feel of touch. This kind of recognizable feeling of the objects helps us to use real-world objects even without looking them. These touchscreen-based interactions are replacing traditional physical interfaces around us, and we are losing the help of touch in our interactions. This is particularly problematic, as it is known that interactions with mobile devices in the mobile context is usually split into small fragments, while users must pay attention to the environment (Oulasvirta et al., 2005). When operating a device while driving, walking, and so forth, the device requires greater visual attention to be operated, but the attention would be needed for the main task—driving, walking, or whatever the main task is—while operating the device.

There are specific task-based prototypes, and even products, for some specific tasks in professional and special purposes—such as performing a surgery, operating military devices, remote controlling robots, having a physical touch feeling on digital knobs, and so forth. However, these devices are expensive special devices each built for one purpose. Instead, modern touchscreen devices commonly have simple vibrational actuators—which are cheap, power-efficient, and easily integrated with any systems. The question remains can these simple vibrotactile actuators be used to replace the missing touch from the interaction? And if they can, what kind of vibrational feedbacks would be the most beneficial and preferred by the users?

1.1 Objective

The main objective of this thesis was to find a way to utilize low-cost vibrotactile actuators, which can be found in almost every device, to support users' tasks while they cannot concentrate on interactions with the device. Approach for this was to create *haptic user interfaces* (HUIs) which are user interfaces providing a fully tactile feel for the user interface during interaction by composing rhythmic intuitive tactons for the task-specific user interface elements, primitives, actions, and information. This thesis describes how to design these kind of *haptic user interfaces* (HUIs), what the benefits for the users are, and the general idea of HUIs based on user interface primitives created by tactons (Brewster & Brown, 2004a; 2004b; Brown et al., 2006) generated with rhythmic vibrotactile feedbacks (Hoggan & Brewster, 2007a; 2007b).

This thesis consists of three parts. The first research question is about the limitations in perception of haptics. Do users detect low level haptic feedback while moving or do they understand visual meaning of modal redistributed information through haptics? Two experiments evaluated how people perceive vibrotactile haptics while not seeing the information it is representing and the perception of low-level vibrotactile stimuli while moving. The knowledge gained in these experiments lead to an idea about representing user interface primitives with haptics. Using these basic haptic primitives as building blocks, a HUI can be created by combining these basic haptic primitives with a complete user interface for the selected task.

The second research question is about designing the vibrotactile haptic primitives for the HUI. What kind of haptic representations for user interface elements would be the most preferred and familiar for the users? Another two experiments evaluated design approaches for such haptic primitives.

After that, the third research question is how users would benefit from such HUI compared to nonhaptic or simpler haptic interface—where haptics is just simple pulses for confirmation or alert, as in current user interfaces. Also, to investigate how distracted-use scenarios, where additional levels of distraction are added to the task, will impact these benefits. The last two experiments evaluated these benefits; increasing levels of distraction were used while participants executed the tasks.

1.2 CONTEXT

This research builds on earlier knowledge about how haptic information representation can be used to support the user under a heavy load (Van Veen & van Erp, 2001), how tactons (Brewster & Brown, 2004a; 2004b; Brown et al., 2006) can be used to represent graphical components (Hall et al., 2007) and information (Yatani & Truong, 2009; Rantala et al., 2009), and how user interface interactions can be supported by haptics (Poupyrev et al., 2002; Poupyrev & Maruyama, 2003; Nashel & Razzaque, 2003; Brewster & King, 2005), combining this knowledge to the HUIs based on rhythmic tactons.

Interactions with information systems has moved more and more toward nomadic users; users are connected wherever and whenever. This has raised a new problem for interaction design: how to support interaction while the user is moving, either walking or driving. Research done for this dissertation aimed for supportive HUIs on the devices users are using everywhere. Potentially, this would be the most beneficial for mobile users, when their interactions are fragmented with attention changes between the device and the environment (Oulasvirta et al., 2005).

Also, in a car environment, it is known that using mobile devices has a negative impact on driving safety (Caird & Willness, 2008; Lamble et al., 1999), and while people are aware of this risk (Walsh et al., 2008), they still use mobile devices while driving (White et al., 2010). While safety should be the most important in a car environment and multimodal feedback could help drivers to minimize visual attention to secondary tasks, haptic interactions could be used to provide eyes-free interactions (Burnett & Porter, 2001). This makes the driving situation one of the most optimal everyday context for experimentation with hapticly-enhanced user interfaces within this thesis. Safety issues limited these experimentations to be done with simulated driving in the laboratory environment.

1.3 METHODS

General approach for conducting research in HCI field follows an iterative development method, where new interactions and user interfaces are created through iterative process built around initial requirements. A similar approach was used throughout research conducted in this thesis, constructing several approaches based on the requirements, iterating them and evaluating the most prominent approaches with end users. Finally, the best tactile methods were used in the following experiments where new approaches were constructed on top of the earlier designs. This follows common approach used also in haptic research and development by other professionals in the field (Schneider et al., 2017).

Research done within this thesis was both constructive and empirical. First, prototype software and, in some cases, hardware, were designed and built with the iterative development method following common practice in the field of HCI. After this, these prototype systems were studied with voluntary participants in the laboratory environment by using controlled experimental setups.

Both quantitative and qualitative data were collected in the experiments and analyzed with statistical methods. In the first two experiments, data were collected on the perception of the given haptic feedback. In the following two experiments, data about comprehension and preferences were collected. In the last two experiments, data on performance and preferences were collected. In all of the experiments, data were analyzed with appropriate statistical methods.

In the first two experiments, the participants had a simple task: to detect when they were stimulated or what they were perceiving. In the following two experiments, looking after appropriate tactons for haptic primitives and a design model for the tactons, the participants' task was to rate the given tactile feedbacks and, while comparing number models, enter the given numbers correctly. The experiments covered in this thesis can be found in Figure 1.

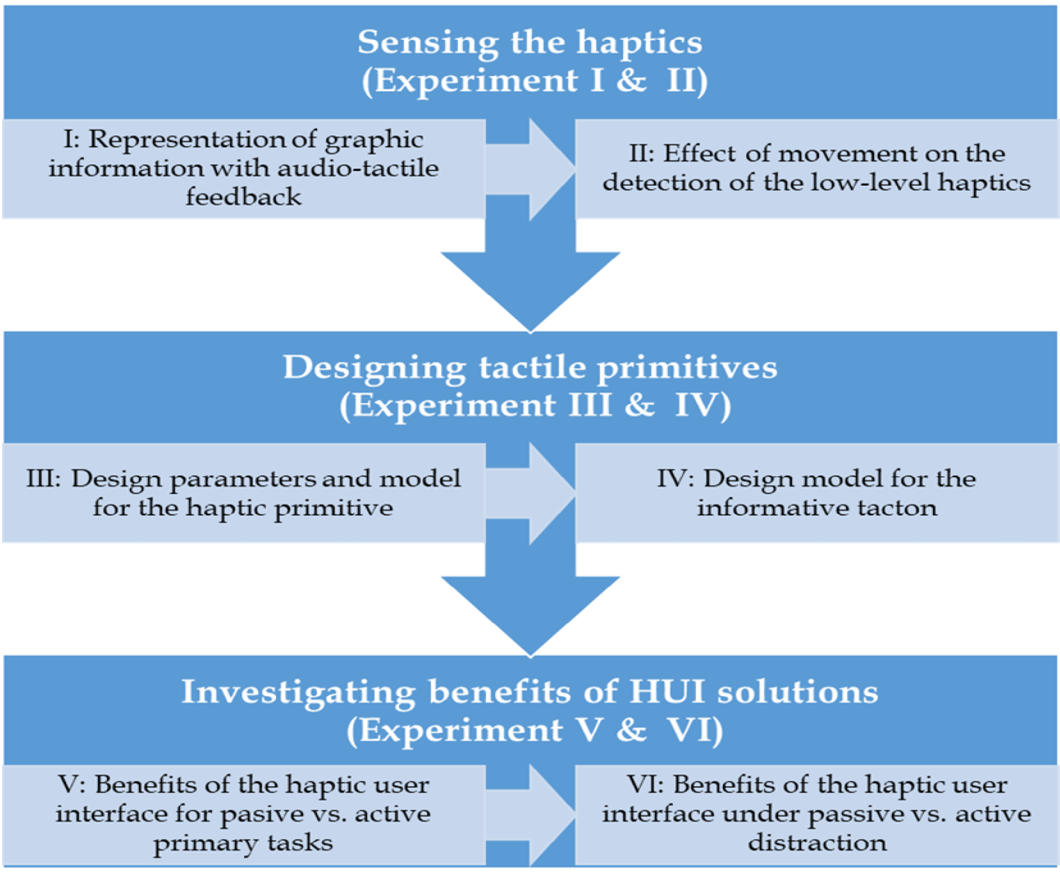

Figure 1: Experiments covered in dissertation.

The last two experiments compared fully built HUIs to nonhaptic and simpler haptic interfaces, where the haptic used was a simple pulse for confirmation or alert. The modality conditions in these experiments were bimodal, where one of these user interfaces was a visual haptic and another an audio haptic. These last two experiments were done while driving in a simulated driving environment.

All of the experiments were done with a controlled, counterbalanced experimental setup in a distraction-free and sound-attenuated laboratory environment.

1.4 STRUCTURE OF THE THESIS

This thesis includes a summary of research and six conference articles published in peer-reviewed international scientific conferences in the fields of haptics and multimodal interaction.

This thesis builds from the first two experiments focusing on how people perceive haptics, to the following two experiments focusing on what kind of tactons are best for the HUI and how to design them, and finally, to the last two experiments focusing on benefits of HUIs under distractive usage scenarios. Figure 2 illustrates a schema of how the experiments built up toward more detailed information about HUIs by adding elements to the experiments.

Chapter one contains introduction to the objectives, the context, and methods of these articles and, briefly, a background context of where this line of studies was built. Chapter two provides a background of tactile sensing, stimulation technologies, and tactile stimulation parameters. Chapter three has information about tactile user interfaces and the role of tactile interaction in an eyes-free and distracted-usage context and more detailed information about tactile primitives and the HUI idea, used as a base for the experiments within this thesis. Chapter four contains a summary of six publications included in this thesis and includes new analysis based on Experiment VI's data. Chapter five is a discussion of the results of all the included publications and what was learned about designing HUIs within these experiments. And finally, chapter six provides conclusions and lessons learned for future work in the HUI field.

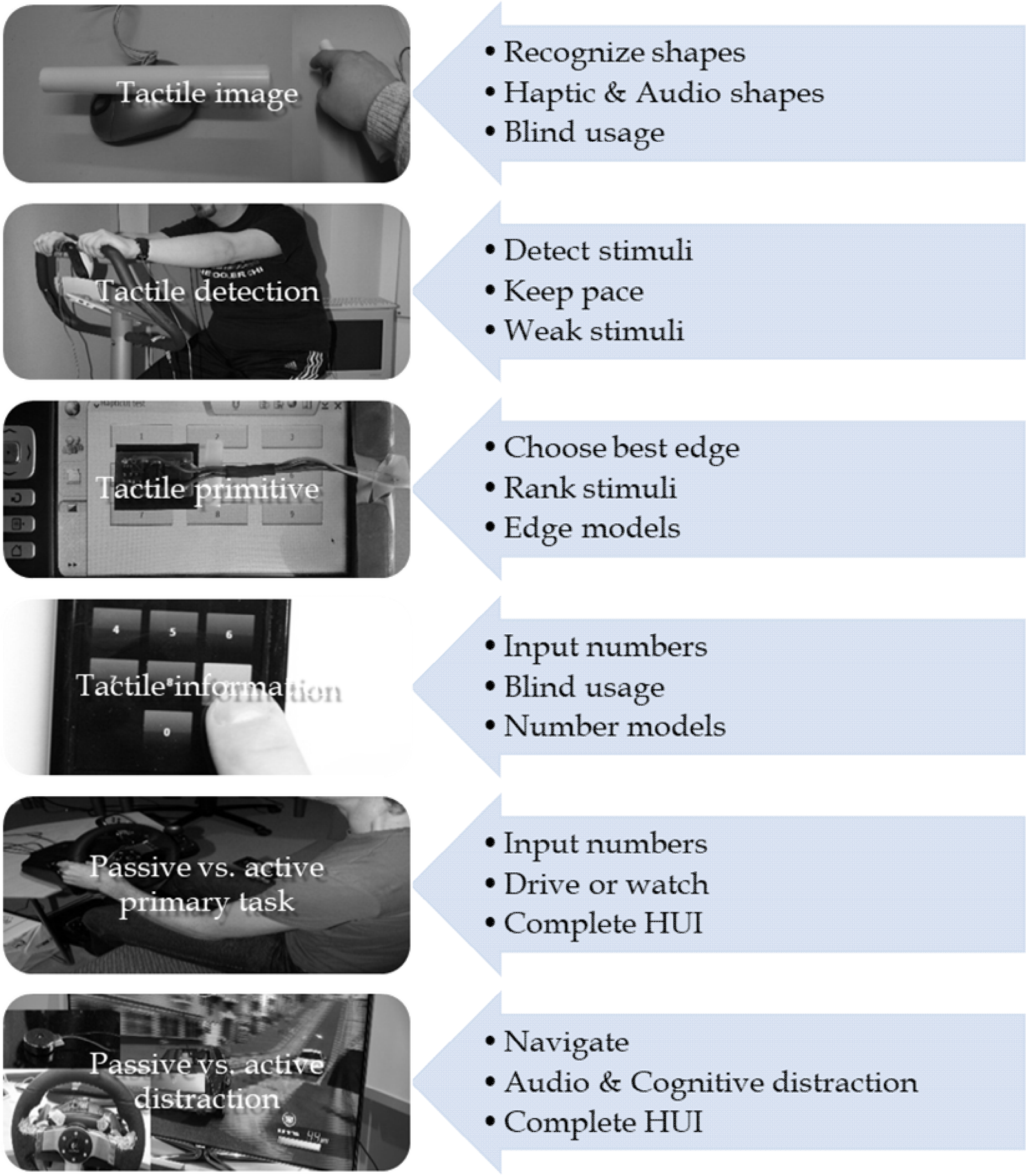

Figure 2: Schematic describing added elements to the experiments.

2 Tactile Sensing

2.1 Sense of Touch

We use the sense of touch to perceive detailed information about our surroundings. This information helps us to perform manual tasks, sometimes solely relying on the touch. The neural network handling these touch signals is the human somatosensory system. The somatosensory system can be divided in three main types of senses of touch: the cutaneous senses, proprioception, and kinesthesis. Cutaneous senses are touch senses felt with receptors in the skin—such as pressure, vibration, temperature, and pain. Proprioception is the sense of the position of the body and limbs. And kinesthesis is the sense of movement (Goldstein, 1999).

Haptics, as a term, covers all varieties of the sense of touch—including proprioception and kinesthesis, as with force feedback devices, and tactile sensing, which refers to stimulation of the skin (through vibration and temperature) (ISO, 2009). While haptics covers the entire somatosensory system, tactile sensing is the subpart of haptics that focuses on cutaneous senses only (Lederman, 1997). Further, Goldstein (1999) divided cutaneous stimulation into three modalities: tactile feedback, temperature, and pain.

In this dissertation, the focus is on cutaneous senses. While utilizing temperature and pain are quite limited (Geldard, 1960) as useful versatile feedback, the research covered in this dissertation focuses on utilizing tactile feedback, more precisely vibrotactile feedback. A focus on vibration was selected because that gave an opportunity to investigate benefits—which can be achieved with simple and cheap haptic devices, such as mobile phones. Haptics provided with vibration is widely used in current devices, but it is still underused. And there is the potential to better utilize touch in complex and distracted-usage environments.

Tactile perception from stimulation on our skin is felt with mechanoreceptors in the skin. They are located both in the epidermis and dermis, which are the two topmost layers of the skin. There are six types of cutaneous receptors: the Merkel complex, Meissner corpuscle, Pacinian corpuscle, Ruffini corpuscle, hair follicle, and free nerve endings (Tsuchitani, 1997). According to Goldstein (1999), most tactile perceptions are done by four of the receptors: the Merkel complex, Meissner corpuscle, Ruffini corpuscle, and Pacinian corpuscle. These mechanoreceptors differ in their structure and mechanics of how they react to stimulation.

The Merkel complex and Meissner corpuscle are located close to the surface under the epidermis. They react to tactile stimuli differently. The Merkel corpuscle reacts continuously to stimuli, while the Meissner corpuscle reacts only to the beginning and ending of the vibrotactile stimuli. With the Merkel corpuscle, we detect fine details, while with the Meissner corpuscle, we react to the stimuli fast (Goldstein, 1999). Figure 3 shows the structure of these receptors and how they react to the stimuli.

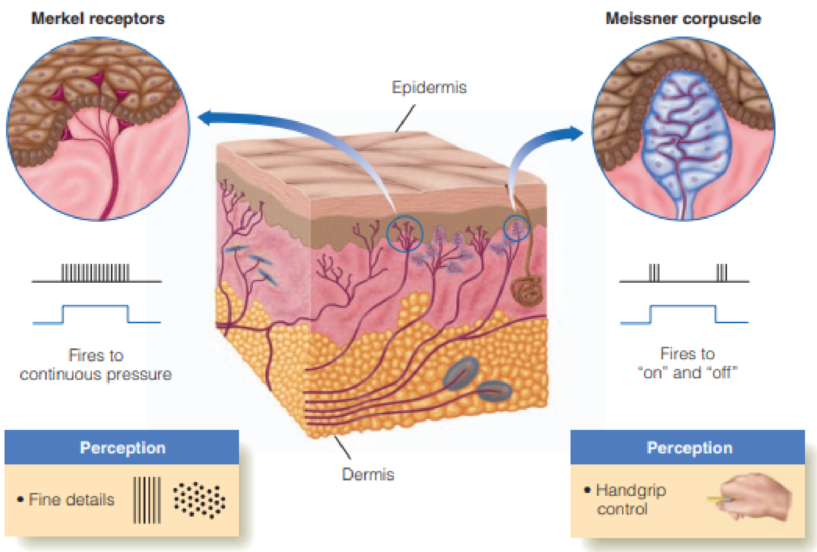

Figure 3: A cross-section of glabrous (without hairs or projections) skin showing the layers of the skin and the structure, firing properties, and perceptions associated with the Merkel receptor and Meissner corpuscle—two mechanoreceptors that are near the surface of the skin (Goldstein, 1999), Figure 14.1 © 2010, 2007 Wadsworth, Cengage Learning. Republished with permission of Wadsworth, Cengage Learning, from (Goldstein, 1999). Permission conveyed through Copyright Clearance Center, Inc.

The Merkel complex consists of the Merkel cell and an afferent terminal ending, the Merkel disk (Figure 4). Protrusions of the Merkel cell connect it tightly to the skin. The Merkel cell is a specialized epithelial cell that contains synaptic vesicles that release neuropeptides, modulating the activity of the afferent terminal. Stimuli distort the Merkel cell, which cause the release of a neuropeptide from synaptic vesicles connected with the Merkel disk. The Merkel cell remains distorted as long as it is stimulated because of its tight connection to the skin. This makes the Merkel complex react to small forces in small areas providing slowly adapting continuous signals. The Merkel cells are receptors that detect fine tactile localized cues and perceive the edges, shapes and/or forms of objects (Tsuchitani, 1997).

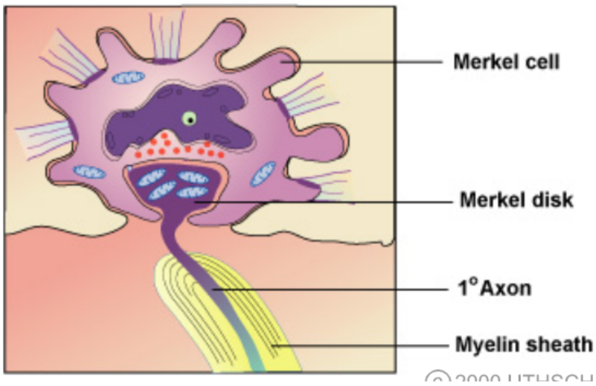

Figure 4: The Merkel complex consists of a specialized Merkel cell, which contains synaptic vesicles and the Merkel disk ending of a 1° afferent terminal fiber. A single 1° afferent axon often innervates only a few Merkel cells within a discrete patch of skin (Tsuchitani, 1997), Figure 2.20 © 2000 The University of Texas Health Science Center at Houston.

The Meissner corpuscle consists of an elongated, encapsulated stack of flattened epithelial (laminar) cells, with afferent terminal fibers interdigitated between the cells (Figure 5). While stimulated, the laminar cells slide, distorting the membranes of the axon terminals located between these cells. The Meissner corpuscle detects the low-frequency (30–50 Hz) vibration stimuli and localized movement on the skin (Tsuchitani, 1997).

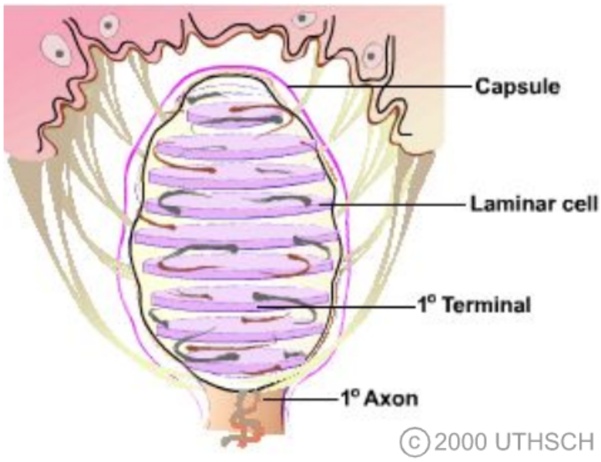

Figure 5: The Meissner corpuscle consists of an encapsulated stack of flattened epithelial (laminar) cells with 1° afferent terminals interdigitated between these cells. The Meissner corpuscle is located within the dermal papilla, near the surface of the skin, with its long axis perpendicular to the skin surface (Tsuchitani, 1997) , Figure 2.12 © 2000 The University of Texas Health Science Center at Houston.

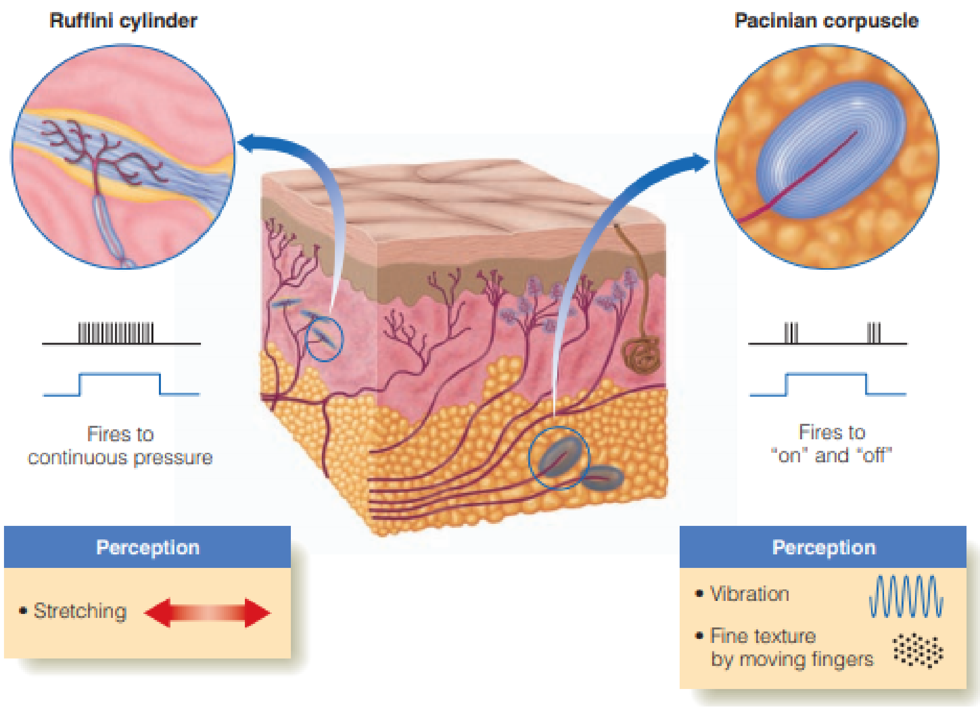

Figure 6: A cross-section of glabrous skin showing the structure, firing properties, and perceptions associated with the Ruffini cylinder and the Pacinian corpuscle—two mechanoreceptors that are deeper in the skin (Goldstein, 1999), Figure 14.2 © 2010, 2007 Wadsworth, Cengage Learning. Republished with permission of Wadsworth, Cengage Learning, from (Goldstein, 1999). Permission conveyed through Copyright Clearance Center, Inc.

The Ruffini cylinder and Pacinian corpuscle are located in the dermis, deeper in the skin (Figure 6). Also, these receptors react to stimuli similarly: the Pacinian corpuscle continuously when stimuli are provided and the Ruffini cylinder when stimuli start and end. With the Pacinian corpuscle, we can react fast to stimuli, and these receptors react to vibrations and subtle touches, such as tickles. The Ruffini cylinder is the receptor that reacts when the skin is stretched (Goldstein, 1999).

The Ruffini corpuscle contains longitudinal strands of collagenous fibers. These fibers connect continuously with the surrounding skin. Inside the Ruffini corpuscle, the afferent fiber branches repeatedly, intertwining with the encapsulated collagenous fibers (Figure 7). The Ruffini corpuscles are parallel with the skin and, thus, sensitive to the skin stretch. Stretching causes the collagen fibers to stretch inside the Ruffini corpuscle, and this compresses the axon terminals. The Ruffini corpuscle is a slowly adapting receptor that gives a sustained signal as long as it is stimulated (Tsuchitani, 1997).

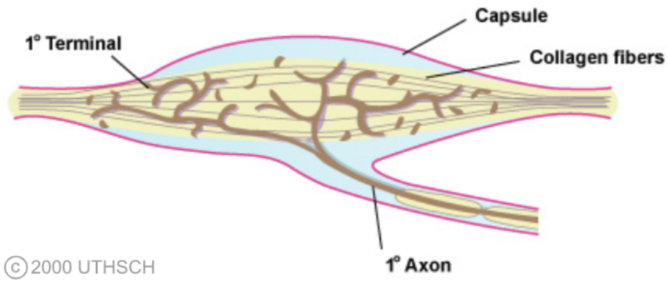

Figure 7: The Ruffini corpuscle consists of 1° afferent terminal fibers that are intertwined with collagenous fibers and, together with the collagenous fibers, encapsulated in a fibrous sheath. The Ruffini corpuscles are oriented parallel to the skin surface and situated deep within the dermis (Tsuchitani, 1997), Figure 2.16 © 2000 The University of Texas Health Science Center at Houston.

The Pacinian corpuscle contains concentrically layered epithelial cells, with a single afferent terminal fiber in the center (Figure 8). The outer layers of the laminar cells contain fluid, which is displaced when stimulated. Stimuli first displace the laminar cells, which distorts the axon terminal membrane. With continuous stimuli, the fluids in the outer layers of the laminar cells start to displace, and this reverses the distortion of the axon terminal membrane. This makes the Pacinian corpuscle detect changing forces, such as vibrating stimuli, but makes it insensitive to steady pressure. The Pacinian corpuscle is the most sensitive to vibrating stimuli between 100 and 300 Hz (Tsuchitani, 1997).

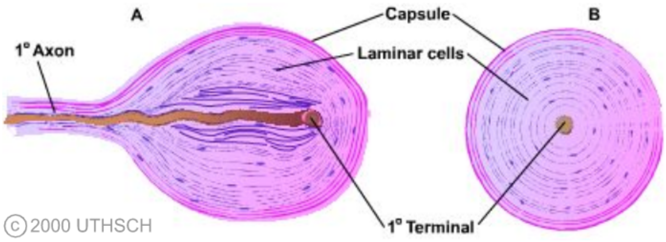

Figure 8: The Pacinian corpuscle consists of a single centrally placed 1° afferent terminal that is surrounded by concentrically layered epithelial (laminar) cells that are all encapsulated within a sheath. In the skin, the Pacinian corpuscle is located deep in the subcutaneous adipose tissue (Tsuchitani, 1997), Figure 2.14 © 2000 The University of Texas Health Science Center at Houston.

The other two types of receptors that do not play a major role in detecting tactile stimuli are hair follicles and free nerve endings. The role of these receptors in cutaneous touch sensing are for hair follicles to react to the movement of the touch and for the free nerve endings to react to temperature and pain (Tsuchitani, 1997).

The hair follicle receptor is a receptor with afferent terminal axons spiraling the hair follicle base or running parallel to the hair shaft (Figure 9). The hair follicle is a fast-reacting receptor that reacts to the movement of the hair it is connected to. The hair follicle detects movement on the skin and the direction and velocity of that movement (Tsuchitani, 1997).

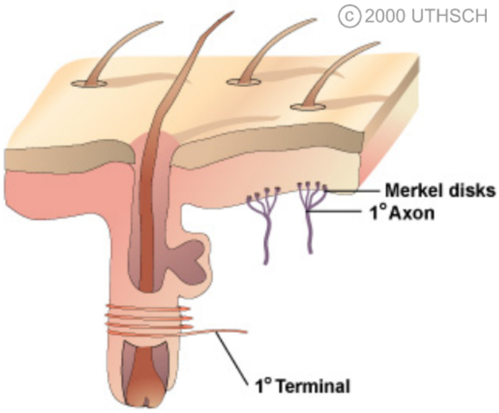

Figure 9: The hair follicle 1° afferent terminal fibers enter the follicle to encircle or to form a lattice pattern around the hair shaft (Tsuchitani, 1997), Figure 2.18 © 2000 The University of Texas Health Science Center at Houston.

Free nerve endings are found everywhere on the skin. Free nerve endings in the skin are stimulated by tissue-damaging stimuli and provide the sensation of pain or temperature. There are different types of free nerve endings for different types of sensations: for example, pain, cold, warmth, or touch (Tsuchitani, 1997).

Signals from the receptors in the skin travel through peripheral nerves to the spinal cord through the dorsal root. In the spinal cord, the signals move through two major pathways: the medial lemniscal pathway and the spinothalamic pathway. In the cutaneous nerve system, these have different perceptual functions. The lemniscal pathway, with larger nerve threads, transmits signals related to proprioception, the position of the limbs, and touch. While the spinothalamic pathway, with smaller nerve threads, transmits temperature and pain signals. Most of these nerve threads are connected to the ventrolateral nucleus in the thalamus, which is responsible for the coordination and planning of movement. Some of these nerve threads also connect to other thalamic nuclei (Goldstein, 1999).

Table 1 shows these six cutaneous receptors and their roles in sensing cutaneous touch signals.

Table 1: Cutaneous receptors (Tsuchitani, 1997; Goldstein, 1999).

Receptor	Sensation	Signals	Frequency Range	Adaptation
Meissner corpuscle	Flutter, Movement	Frequency/Velocity & Direction	30–50 Hz	Rapid
Pacinian corpuscle	Vibration	Frequency	100–300 Hz	Rapid
Ruffini corpuscle	Skin Stretch	Direction, Force	15–400 Hz	Slow
Hair follicle	Movement	Direction, Velocity	—	Rapid
Merkel complex	Touch, Pressure, Form	Location, Magnitude	0.3–3 Hz	Slow
Free nerve ending	Pain, Touch, Temperature	Tissue damage, Contact, Temperature change	-	Depends on information carried

2.2 TACTILE STIMULATION TECHNOLOGIES

Oakley et al. (2000) categorized haptic feedback as follows: haptic (sense of touch), proprioceptive (state of the body), vestibular (perception of head position and movement), kinesthetic (feeling of motion), cutaneous (skin sensations [pressure, temperature, and pain]), Tactile (skin sensations, focusing on pressure), and force feedback (mechanical production of kinesthetic feedback).

While experiments covered in this dissertation focused on using vibration to provide tactile sensations, we focus, in this chapter, on actuator technologies providing tactile stimuli. First, the division between these technologies is the method with which stimulation is provided, stimulation with skin contact or without.

The most common types of haptic devices used in everyday products are mostly technologies based on actuators providing tactile feedback through contact with the skin. The most common types of these are vibrotactile actuators—which stimulate the skin through static pressure, skin stretch, or friction (Choi & Kuchenbecker, 2013). Figure 10 presents a selection of different types of vibrotactile actuators.

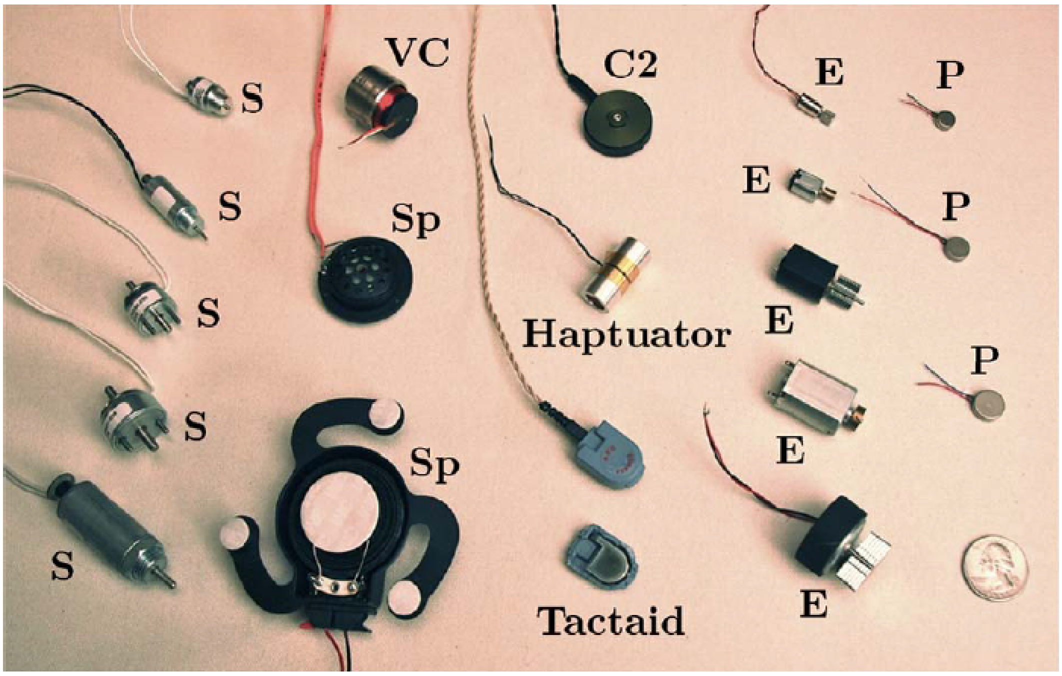

Figure 10: S: Five solenoids of varying sizes. VC: A commercial voice coil without bearings. Sp: Two audio speakers. C2: A C2 tactor from EAI. Haptuator: A Haptuator from Tactile Labs Inc. Tactaid: One complete Tactaid from AEC and one opened to show the suspension inside. E: Five shafted/cylindrical eccentric rotating mass motors. P: Three shaftless/pancake eccentric rotating massmotors. A U.S. quarter appears at the bottom-right for scale (Choi & Kuchenbecker, 2013), Figure 1 © 2013 IEEE. Reprinted, with permission of IEEE, from (Choi & Kuchenbecker, 2013).

The most affordable vibrotactile actuators are eccentric rotating mass actuators (ERMs) and they were the most commonly used in mobile phones for a long period. These actuators provide tactile vibration through rotating an eccentric mass inside a casing. This type of actuators can be found in the most of the consumer devices providing haptic feedbacks due to their inexpensiveness, reliability, and simplicity. These devices are inexpensive and easy to drive, but on the downside, they have control limitations: signal delay and limited frequency and amplitude control (Choi & Kuchenbecker, 2013). Most of the experiments done in this research was done utilizing these kinds of ERM actuators embedded in mobile devices.

Another type of vibrotactile actuators are linear resonant actuators (LRAs), which are also known as voice coil actuators. LRAs are based on a coil that moves a plate up and down. This kind of actuators can be driven with audio files and are fast reacting to signals. Thus, they can be used for more accurate haptic feedback than ERMs. This type of actuator has its optimal resonation frequency unique for each actuator. Typically, this frequency range is 200–300 Hz, but there are LRAs optimized for as low as 100 Hz signals. This means this type of actuators provide accurately modified tactile feedback but is limited to a narrow frequency band (Choi & Kuchenbecker, 2013). One of the experiments in this dissertation was done with C2 actuators, which is an LRA. This type of actuator has become the most common in the modern smartphones, because LRAs can provide a sharper and more controllable tactile stimuli for the users.

The latest common type of actuator is the piezoelectric actuators. These actuators are based on thin layers of piezoelectric material shrink or expand based on signal polarity. This causes element having several layers of these materials to bend and, when attached under the screen, provides localized haptic feedback on the screen (Poupyrev & Maruyama, 2003). The benefits of piezoelectric actuators are highly localized haptic feedback on the screen, sharp and clear tactile feedback, and precise control of stimulus parameters (Tikka & Laitinen, 2006). The challenges of piezoelectric actuators include they typically require high voltages, which raises challenges regarding the system integration band (Choi & Kuchenbecker, 2013). One of the experiments covered in this dissertation was done using a prototype device with piezoelectric actuators under the screen of the device.

There are several contactless actuator technologies created for providing haptic feedback without touch. These types of technologies are however, at the moment, mostly used in research environments, rather than in commercial consumer products, predominantly because they are still quite expensive and require relatively big device setups.

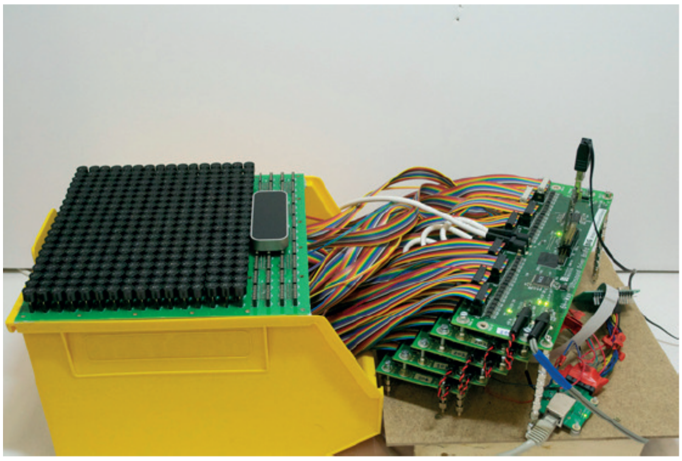

Figure 11: UltraHaptics system (Carter et al., 2013), Figure 1 @ 2013 ACM. Republished with permission of ACM. from (Carter et al., 2013). Permission conveyed through Copyright Clearance Center, Inc.

Probably the most mature methods for providing tactile stimulation without contact to the skin is providing stimulation to the skin with ultrasonic tactile displays (Carter et al., 2013) or by using air-directed air pressure (Suzuki & Kobayashi, 2005). These technologies can be used to remotely provide the sensation of touch. In Figure 11 are arrays of ultrasonic transducers, and in Figure 12 is a system based on air jet nozzles. Ultrasonic displays work with the principle of acoustic radiation force, while air jet haptic feedback is based on moving directed compressed air to the targeted skin area. The benefits of air pressures systems are easier implementation and longer actuation distances over ultrasound systems, but ultrasound systems can be built smaller and have better spatial accuracy (Arafsha et al., 2015).

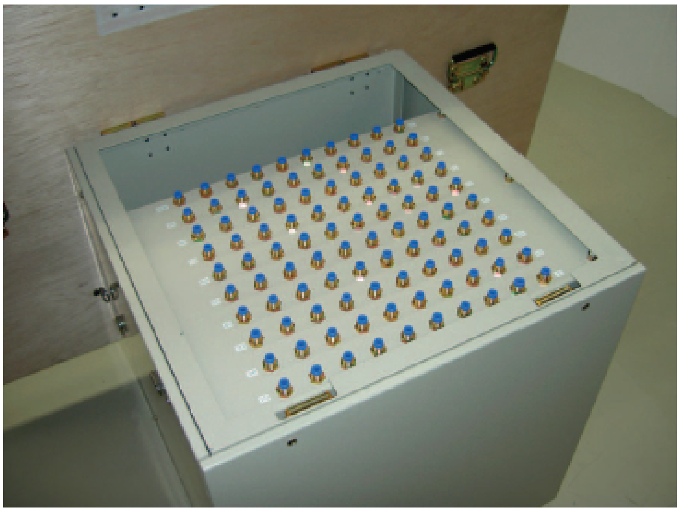

Figure 12: Air jet–driven haptic feedback device (Suzuki & Kobayashi, 2005), Figure 4 @ 2005 IEEE. Reprinted, with permission of IEEE, from (Suzuki & Kobayashi, 2005).

Also, some more exotic contactless haptic feedback devices have been experimented on by researchers, such as utilizing thermoelastic effects by using lasers (Lee et al., 2016) or using a magnetic field controlling small magnetic discs attached to the hand (Zhang et al., 2016). The limitation of everyday haptic usage scenarios with these contactless haptic devices is these devices are not small enough to be integrated with everyday electronic devices and they are expensive and require a high level of skill to use. When these technologies mature and move toward mass production, they could provide some new interesting approaches for using haptic feedback in future UI solutions.

There are some new emerging actuation technologies which show promise for creating a natural tactile feeling for the touchscreens. These technologies are focused on creating a tactile feeling on the surface of the device. Actuation technologies for creating surface haptics can be divided in two main categories: Force modulation in normal direction and Force modulation in tangential plane (Basdogan et al., 2020). The research covered in this thesis is focusing on the first one of these, utilizing normal vibration, which practically creates haptic signals covering the entire device, but which are felt on the surface while using the touchscreen. The latter one includes new promising actuation technologies, such as friction modulation with electrostatic feedback and ultrasonic waves, lateral vibration and net tangential forces with driving force and asymmetric friction (Basdogan et al., 2020). Actuation technologies for creating more accurate and localized haptic signals researched in the community currently includes for example technologies utilizing electro-active polymers (Citérin and Kheddar, 2008), new materials for mediating haptic signals, like soft materials, nanomaterials, organic materials and composite materials (Biswas and Visell, 2019).

Some of the most relevant emerging technologies, which show promise for the future devices, relevant to the theme of this work, are actuation technologies focusing the force to the display surface. These are technologies utilizing liquid materials on the actuation surface for mediating haptic signals to the surface area (Farooq et al., 2015; Miruchna et al., 2015; Jansen et al., 2010), electrostatic feedback created on the surface (Bau et al., 2010) and utilizing accurate piezo electric actuators to friction sense of friction on the surface (Levesque et al., 2011; Winfield et al., 2007).

2.3 TACTILE STIMULATION PARAMETERS

There are several parameters for controlling tactile stimulation. Earlier research investigated which parameters would be optimal for creating recognizable varying tactile stimulations. In this chapter, the most common of these parameters and information about the optimal use of these parameters for tactile stimuli are presented. As the focus of this dissertation is to investigate tactile user interfaces with recognizable and intuitive tactile stimuli for task-specific information, this chapter is focused on those parameters used in the experiments of this dissertation. Earlier research found that for the recognition of tactile stimuli, the best parameters are rhythm, spatial location (Hoggan & Brewster, 2007a), and waveform modulation (Luk et al., 2006; Hoggan & Brewster, 2007b), while the less optimal parameters would be the speed of the moving stimulus (Luk et al., 2006), amplitude (Luk et al., 2006; Hoggan & Brewster, 2007b), duration (Luk et al., 2006), and frequency (Hoggan & Brewster, 2007b). However, for describing the size of an UI-element, amplitude has been found to be the best parameter (Douglas & Willson, 2007).

According to Jones and Sarter (2008), frequencies from 150 to 300 Hz are optimal for sensing vibration at any location of the body. Although, humans can sense vibrations between 0.4 and 1000 Hz, the higher and lower frequencies require a larger amplitude of the signal to be detected.

Also, sensitivity to the vibrating signals varies widely at different locations of the body. The most sensitive location is the fingertips, which can detect vibrations with a displacement of 0.07 µm at 200 Hz, while the less sensitive abdominal and gluteal regions detect vibrational signals at 4–14 µm at 200 Hz (Wilska, 1954). The sensitivity levels of the different locations of the body for a varying range of tactile signals can be found in Figure 13. In experiments covered in this dissertation, actuators utilizing optimal frequencies were used for minimizing the detection issues.

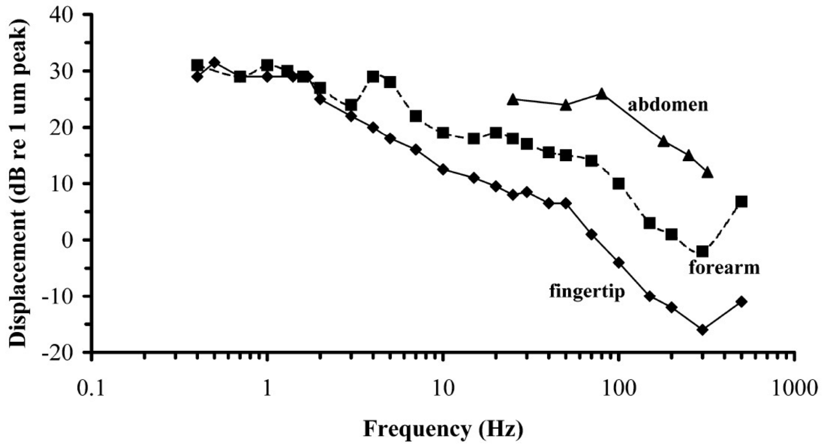

Figure 13: Threshold frequency characteristics measured on the fingertip (diamonds), on the forearm (squares), and on the abdomen (triangles) (Jones & Sarter, 2008), Figure 1 @ 2008 SAGE Publications. Reprinted with permission of SAGE Publications, from (Jones & Sarter, 2008).

As rhythm, spatial location (Hoggan & Brewster, 2007a), and waveform modulation (Luk et al., 2006; Hoggan & Brewster, 2007b) are the best parameters to use for recognizable tactile stimuli and these were the parameters used in the experiments covered in this dissertation, more detailed information about the optimal usage of these parameters is covered next.

For the parameters to use with the tactile stimuli in the vibrotactile displays, van Erp's guidelines for the vibrotactile displays (van Erp, 2002) suggest using long-lasting 200-250 Hz vibrations on glabrous skin with fixed surroundings around the vibrating element for the best stimulus detection. For the information coding, the guidelines suggest using the maximum amplitude of four levels and the maximum frequency of nine different levels. These parameters could be used for encoding simple information with a limited number of options, which users can learn to recognize. For more varying information, haptic icons, *tactons*, (Brewster & Brown, 2004a; 2004b; Brown et al., 2006) are needed by combining basic parameters of tactile stimuli (frequency, amplitude, and duration) and using pauses and several different pulses for creating distinguishable tactons. About coding information with temporal patterns to create rhythms, van Erp's guidelines (van Erp, 2002) suggest using at least 10ms pulses and pauses between pulses. These guidelines should be followed with both single actuator setups and multiactuator displays also utilizing spatial location.

With spatial location, according van Erp (2002), spatial acuity varies within locations of the body and can be as low as 4 cm, which limits the resolution applicable for multiactuator displays used in, for example, the torso. However, spatial acuity is much higher, from 2.5 mm in the finger and lowering toward the torso for the abovementioned 4 cm (van Erp, 2005). The localization of the stimuli can be enhanced by using spatiotemporal patterns (van Erp, 2005)—that is, with optimal burst durations and stimulus onset asynchrony parameters.

Waveform modulation can be used to change the smooth sine signal of the actuator to more rough feeling stimuli. This is done by combining different sine waveforms with a single stimulus. With these modulated stimuli a recognition rate of 80% can be achieved with tactons (Brown et al., 2005). Figure 14 shows an example of modulated stimuli with a 250 Hz sine wave modulated with a 30 Hz sine wave. By changing the modulating wave, different levels of roughness in the sensation can be created for the stimuli. However, as with amplitude and frequency, the number of different recognizable stimuli is limited.

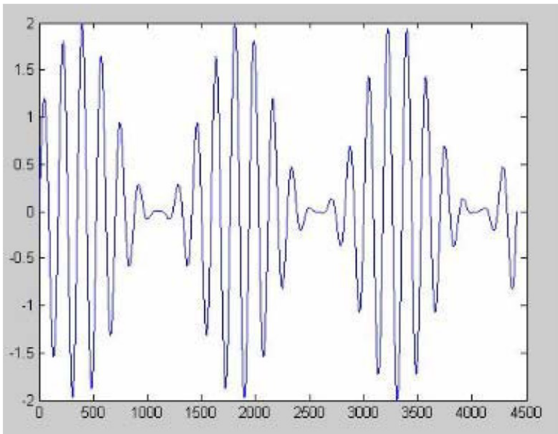

Figure 14: A 250 Hz sine wave modulated by a 30Hz sine wave (Brown et al., 2005), Figure 7 @ 2005 IEEE. Reprinted, with permission of IEEE, from (Brown et al., 2005).

With rhythm (Hoggan & Brewster, 2007a; Brown et al., 2006), using temporal patterns are created by combining several tactile stimuli with pauses to a single new stimulus. As van Erp's guidelines (van Erp, 2002) suggest, the minimum pause and pulse length should be 10 ms. By varying pause and pulse lengths, different rhythmic stimuli can be created. With rhythmic stimuli, a 90% recognition level can be achieved (Brown et al., 2005). The number of possible different stimuli is larger than with other parameters. However, with purely rhythmic stimuli, the number of variables is still lower than needed on more complex haptic representations in the user interfaces.

By combining other parameters with rhythmic stimuli, a large number of distinguishable and recognizable tactons can be created (Hoggan & Brewster, 2007a). This can be combined with other parameters—such as wave form modulation, frequencies, durations, and amplitudes of individual pulses in the rhythmic stimuli. This method provides a wide range of possible distinguishable and recognizable tactons (Hoggan & Brewster, 2007b; Brown et al., 2006). For example, Enriquez and MacLean (2008) created 84 different tactons by combining rhythm, frequency, and amplitude and found out that users can learn an abstract meaning for several tactons. Also, their earlier studies with a smaller set of waveforms modulating tactile stimuli suggested users can easily learn and recognize abstract meanings for the haptic stimuli (Enriquez et al., 2006).

Seifi and MacLean (2017) analyzed a large number of haptic stimuli with point of view of the haptic facets. They collected information about adjectives related to different haptic parameters and stimuli and categorized them to different human centered dimensions for the approach to find out different parameters to achieve the intended outcome from a users' point of view. They found four perceptual constructs: a vibration urgency, liveliness, roughness, and novelty. Their work is still ongoing but shows promising possibilities to find out a higher level of information in tactile stimuli parameter — user experience dimension for selecting appropriate stimuli for certain type of use in the user interfaces.

2.4 SUMMARY

In this chapter the human system for sensing touch was briefly introduced, along with technologies to provide touch, specifically tactile feedback for the sensory system. Also, parameters to modify tactile feedback for representing more versatile information through touch were briefly introduced.

For tactile sensing, there are two cutaneous receptors that are the most important for the human sensory system: Meissner corpuscles and Pacinian corpuscles. Meissner corpuscles are better for detecting lower-level frequencies, while Pacinian corpuscles detect higher-level frequencies. Both of them react to stimuli fast and create sensory signals from the changes in the force, rather than from steady pressure.

There are several technologies to create tactile stimulation, almost all of which are based on the principle of creating fast uneven motion in force-mediating matter. The common way to do this is to use a small mass that is either moved unevenly or rotated using unsymmetrical mass. This uneven motion in the mediating matter causes the vibrating force, which can be detected by the Meissner and Pacinian corpuscles in the skin. Technologies vary in the method of creating the force and in the mediating matter with which they transform the force to vibrations. The most common and cheapest technology currently in the devices is based on the rotating motor, which rotates eccentric mass (ERMs). Vibrations in ERMs are created by uneven rotation inside a shell material. This type of actuators typically has a device-specific optimal frequency. Because these are the common devices and are available in everyday electronics, experiments in this dissertation mostly focused on utilizing this type of actuator. As ERMs are the most robust and simple, techniques used with this type of actuator should also be applicable for more expensive and versatile tactile technologies. Also, creating usable techniques for commonly used devices would make a more practical impact on the industry and create possibilities to utilize results with the existing level of actuator technologies.

3 From Tactile Actuation to Tactile User Interfaces

In this chapter, I describe the steps of creating the HUI—which provide a fully tactile feel for the user interface, where all the task-specific user interface elements, primitives, actions, and information have tactile feeling created by composing rhythmic intuitive tactons. The first part covers knowledge about what parts of the user interface and interaction could be supported by tactile feedback. The second part collects the knowledge, how this kind of user interfaces could help the user and in what kind of usage scenarios. Thus, in this case, eyes-free and distracted-usage scenarios are covered in more detail.

3.1 Tactile User Interface Enhancement

There have been several approaches to create tactile feedbacks for *graphical user interfaces* (GUIs), thus enhancing GUIs with haptic interaction. In this dissertation, GUIs focused on utilizing vibrotactile feedback to enhance GUI interfaces will be briefly introduced—especially GUIs focusing on mobile user interfaces, which were the focus in the experiments covered in this thesis.

Experimental tactile GUI enhancements with mobile devices

Several researchers have worked with enhancing GUI elements using tactile feedback. The basic principle in these approaches has been to create a feel for some of the most common GUI elements and for interactions with them. The knowledge gained from these experiments has led to modern touchscreen devices utilizing haptic feedback as confirmation feedback, letting users know something has been done, or alert enhancements to draw the attention of the user.

One example of alerting haptic feedback is haptic progress bars that keep the user aware of the progress of a task (Poupyrev et al., 2002; Poupyrev & Maruyama, 2003; Brewster & King, 2005). In these interfaces, the intensity of the haptic pulses is used to indicate progress (Poupyrev et al., 2002; Poupyrev & Maruyama, 2003) or different tactons used for marking the start position and end of the progress (Brewster & King, 2005).

With a similar approach as the progress bar, Poupyrev et al. (2002) experimented with the haptic indication of scrolling progress in an interaction method, where users scrolled by tilting the device, and haptic ticks kept users aware of progress in the scrolling task. Further, Poupyrev et al. (2003) enhanced the entire GUI task with different simple tactile pulses, with several GUI elements enhanced: pushing an GUI element, holding an GUI element, dragging an GUI element, and finally, releasing the touch from a GUI element (Figure 15). In this approach, singular tasks in interaction with a GUI have been recognized and amplified with tactile feedback by creating an appropriate tactile feedback for each subtask in the interaction task. A similar approach was used for creating tactile feedback for the UIs in the experiments covered within this dissertation by recognizing subtasks of the interaction task and creating intuitive tactons for each subtask of the interaction to provide a tactile sense of the task.

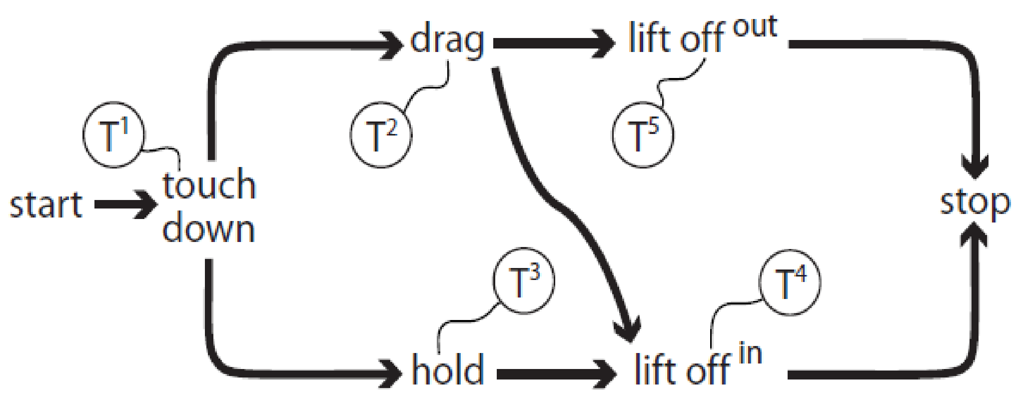

Figure 15: The approach for providing tactile stimuli for touch-based interaction (Poypyrev et al., 2003), Figure 4 @ 2003 ACM. Republished with permission of ACM, from (Poypyrev et al., 2003). Permission conveyed through Copyright Clearance Center, Inc.

Hall et al. (2007) used a similar approach to combine varying tactile stimuli for creating a touchable GUI element for browsing data, called T-Bar (Figure 16). This GUI element had a round pipe-like feeling, with both visual and tactile feedback. The tactile feedback was achieved by having a higher amplitude toward the center of the pipe. A more intense tactile feedback in the center of the element helped users to follow the element and stay in line with interactions. The researchers experimented with two kinds of interaction scheme with the T-Bar: a left–right gesture for selecting items with a linear method and a "Twist 'n' Touch" approach for rotating for the data selections. This approach has been taken into account in the experiments covered in this thesis by designing descriptive tactons for the elements of the user interface used in the experiments.

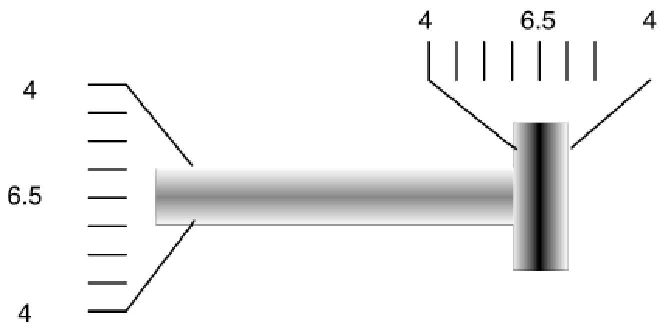

Figure 16: T-Bar's visual look, with information about tactile feedback intensity (Hall et al., 2007), Figure 1 @ 2007 ACM. Republished with permission of ACM, from (Hall et al., 2007). Permission conveyed through Copyright Clearance Center, Inc.

Related to tactile button emulation, there is some new research that is focused on creation of an accurate button feeling. Approaches for achieving this have been, for example, to utilize Force-Displacement-Vibration-Velocity (FDVV) models built on measuring haptic signals during physical button presses (Liao et al., 2020). This kind of models provide possibilities to create a tactile feeling for virtual buttons which accurately represents the intended type of button feeling for emulation of physical feeling of using buttons on the touchscreen.

Through similar approach Sunjun and Geehyuk (2013) evaluated parameters for button click with piezoelectric actuators by modifying force-displacement curves in the way that tactile signal was similar as the measured physical keyboard button press. They divided button press feedback to three phases: Slope, jump and bottom-out sections. By evaluating these three parts of tactile feeling, they created a tactile button press for touchscreen interaction composed with a similar approach as used for tactons designed in this thesis.

Chen et al. (2011) evaluated parameters for identifiable button clicks utilizing piezoelectric actuators. In a set of experiments they evaluated different parameters to create tactile signals and their effect for the capability of participants to identify unique button clicks. They concluded that amplitude and the number of cycles contribute to perceived intensity of keyclicks and frequency to perceived feeling of sharpness. They also found that shorter signals are more difficult to identify, especially for inexperienced users. Finally, they concluded that for gaining identifiable stimuli maximum of one or two levels for each parameter used for creating tactile stimuli should be used. This supports the approach to use just selected few parameters to construct tactons that are identifiable and use a slower stimuli speed for inexperienced users.

Park et al. (2011) evaluated 72 tactile stimuli for tactile confirmation feedback for button clicks. They compared LRA and ERM actuators, with two amplitudes, three durations, two carrier signals and three envelope modulations combining all combinations of these stimuli parameters. Their results showed that shorter stimuli and faster rise times of stimuli are the most effective parameters for a realistic feeling of button clicks. They suggested using with both LRA and ERM actuators with the input voltage for amplitude creation at 5V, stimuli durations between 10 to 15ms, or at maximum 20 ms, or decaying or exponentially decaying out-of-phase envelope signal for realistic button click stimuli. Thus, fast, sharp and strong initial signal, which fades out would be best option based on their results.

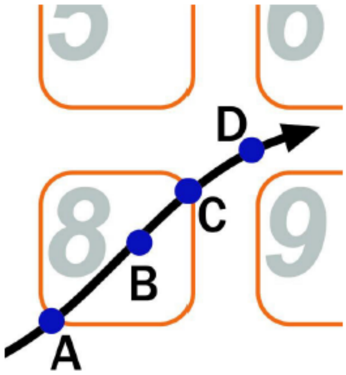

Figure 17: Tactile feedback for buttons (Nashel & Rzzaque, 2003): a) pop for entering the button, b) low-amplitude vibration for texture, c) pulse for leaving the button, and d) no feedback between the buttons. Figure 2 @ 2003 ACM. Republished with permission of ACM, from (Nashel & Rzzaque, 2003). Permission conveyed through Copyright Clearance Center, Inc.

For the approach to create tactile primitives corresponding with GUI drawing primitives of the components, Nashel & Razzaque (2003) created touchscreen buttons that had tactile primitives for the edges, feeling different while entering the button area and leaving it, and for the texture of the buttons (Figure 17). The buttons had tactile feedback described as a “Pop” when entering the button, a low-amplitude vibration for the texture on the button, and a pulse when leaving the button. This approach provides touchable touchscreen GUI elements—which have a recognizable and intuitive feeling, helping the user to interact with the GUI, when also touch can be used as a part of the interaction. This approach has been also adapted to the experiment series covered in this thesis by creating not only subtask tactons but also a layer of haptic primitives for the GUI elements used in the experiments.

While previous UIs have utilized touch with a finger on the screen and provided tactile feedback from the device to the finger, Kyung & Lee (2008) had an approach of tactile GUI feedback with pen-based tasks. In their prototype, the actuator for providing tactile feedback was embedded in the pen that users used with a tablet. With this prototype pen, the researchers experimented by adding tactile feedback (Figure 18) for the button clicking (falling-down and rising-up effects), menu selection (short vibration pulse when a menu is changed), object selection and movement (clicking-like stimulation for selection and tactile vibration while moving an object), scrolling and window resizing (tactile vibration when moving), and closing, minimizing and maximizing the window (short pulse). This approach showed that even with a comprehensive haptification of the GUI, where several tasks and functions provide tactile feedback, the user interface was still approachable and usable by the users. In the experiments covered in this dissertation, this approach has been adapted by creating an HUI for entire user interfaces of the tasks experimented.

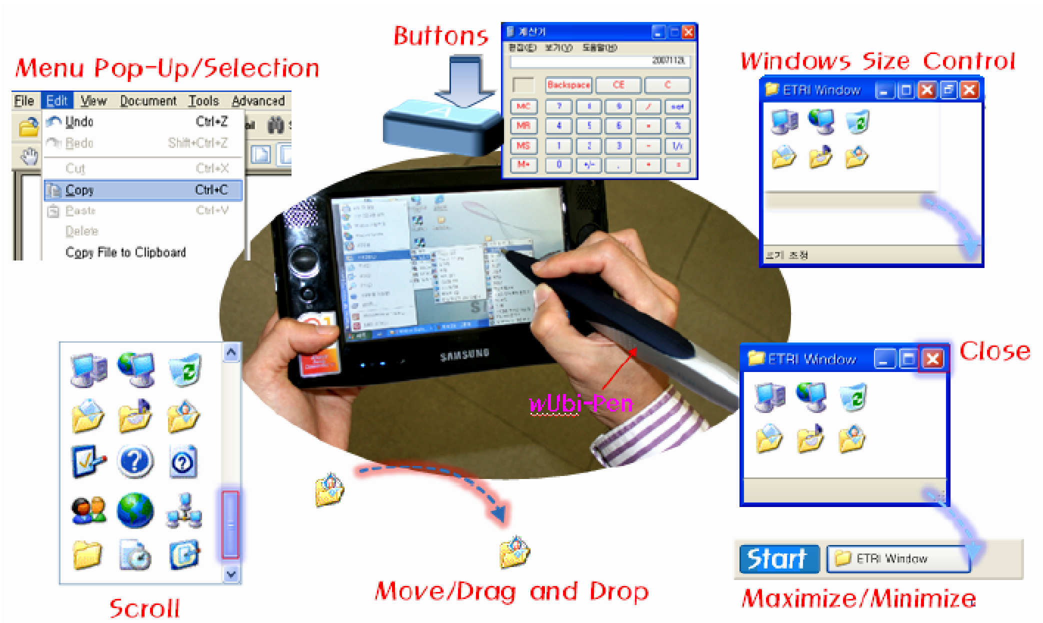

Figure 18: Windows' GUI elements hapticly enhanced (Kyung & Lee, 2008). Figure 5 @ 2008 ACM. Republished with permission of ACM, from (Kyung & Lee, 2008). Permission conveyed through Copyright Clearance Center, Inc.

Gordon and Zhai (2019) approached tactile feedback parameters from the point of task specific tactile signals utilized in mobile context by creating tactile stimuli for tapping, drag & drop and trail following on the screen, which could be utilized for example in sliding or scrolling actions. They evaluated performance of tactually enhanced actions against non-haptic actions while sitting or walking. Their results showed performance improvements in situations where visual feedback was obstructed by the task. Subjectively, the participants appreciated tactile feedback support on the tasks. This suggests that there may not be direct performance gains from tactile enhancement of more complex user interface tasks, but people tend to like the feeling of touch. Similar results were achieved within research covered in this thesis, where direct user interaction performance was not affected, but subjective evaluations were more positive when tacilte feedback was used. As research covered in this thesis shows, performance related gains are more complex. They can be found in other ways than in direct interaction with the device, for example, when visual feedback is obstructed.

For the last part of the HUI, after these previous elements provided the approach for the haptic enhancement of the basic component primitives and the subtasks of the interaction tasks, the semantic information about the task with tactile feedbacks was provided. Yatani and Truong (2009) had an approach to encode individually number keypads' button locations with tactile feedback provided with a five-actuator setup (Figure 19). This approach provided users with the knowledge about which number button their finger was on, instead of only that their finger is on the button. This approach demonstrated the possibility to also encode abstract information from the user interface with tactile feedback, and this way supports the user in eyes-free usage scenarios. This was adopted in the experiments covered by this thesis: one of the used data was numbers on the number keypad, and one of the encoding designs evaluated was location-based encoding, compared to more abstract tacton encodings.

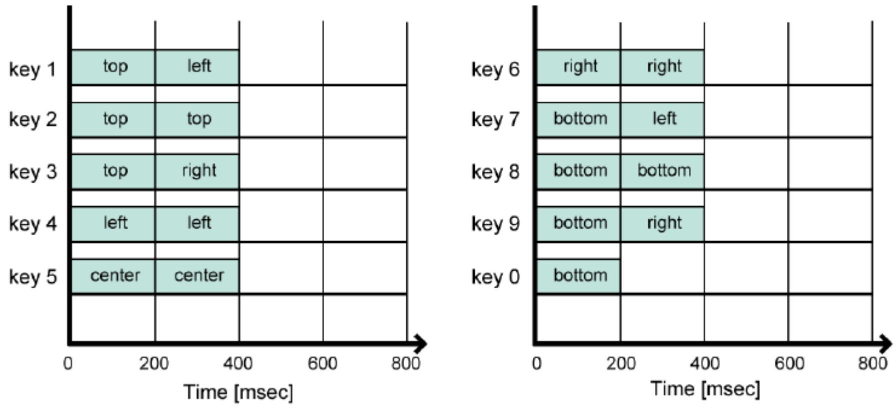

Figure 19: Haptic actuator feedback patterns used by Yatani and Truong (2009). Figure 10 @ 2009 ACM. Republished with permission of ACM, from (Yatani & Truong, 2009). Permission conveyed through Copyright Clearance Center, Inc.

For the abstract rhythm-based tacton encoding of abstract information adopted for the experiments in this dissertation, Rantala et al. (2009) created a rhythm-based representation of Braille characters for blind readers, utilizing a single actuator setup and temporal encoding with a rhythm (Figure 20). This approach demonstrates the possibilities of simple existing technologies (single actuator devices) to utilize more comprehensive tacton-based information for interactions. Even abstract meanings can be presented while designing tactons in a meaningful way, which is intuitive and descriptive for the users by utilizing their existing skills and knowledge. With Rantala et.al.'s (2009) approach, even entire alphabets could be presented for the users who have Braille reading skills. A similar approach was taken while designing number tactons and directional instruction tactons for the experiments covered in this thesis. The basic principle with this approach is to select user interface information that needs to be represented with tactons to support the interaction, discover an appropriate mental model, already known by users, for this encoding and create tactons with this mental model.

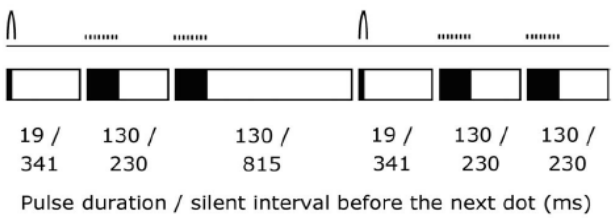

Figure 20: An example of a rhythm-based tacton for a Braille character by Rantala et al. (2009). Figure 8 @ 2009 IEEE. Reprinted, with permission of IEEE, from (Rantala et al., 2009).

Benefits of tactile user interfaces

User studies done with the previously introduced user interfaces and several others have shown some benefits for the users. Generally, using a tactile interface has improved some measurable parameters in interactions, and most importantly, users' subjective evaluations of user interfaces have supported the approach to enhance the user interfaces with a haptic layer. With the user preferences, all user interfaces and evaluations collected here report users generally preferred HUIs over nonhaptic interfaces. This alone would be a motivator to design more comprehensive and better HUIs for touchscreen devices.

But also, with the performance values, there has been reported improvements. For example, with a menu selection task by a tilting gesture (Poupyrev et al., 2002), haptics improved task completion times. Similar results with faster task completion times and faster response times were found in scrolling tasks and progress bar tasks (Leung et al., 2007). Kyung and Lee (2008) reported faster task performance and lower error rates on button-based interactions with a pen interface, where the task was to make calculations with a software calculator. Also, Hoggan et al. (2008) and Brewster et al. (2007) reported improvement in the virtual keyboard writing tasks. Haptics in the touchscreen keyboard enabled a higher writing speed and lower writing error number than the keyboard without haptics. Forlines and Balakrishnan (2008) reported, related to selection times, users gain most likely faster selection times with hapticly enhanced user interfaces in tasks where several selections are done, such as typing, because haptics provides a confirmation of success and help users to move forward to the next selection faster. These reports about performance improvements also confirmed the approach to go further with HUIs and evaluate possible benefits for comprehensively haptified user interfaces.

On the other hand, Yatani and Truong (2009) reported that while using more comprehensive haptic layouts with individual haptic feedbacks for each number button in the keypad, there was better number input accuracy than with simple haptic feedback where buttons could not be recognized by touch. However, with this user interface, the input speed was lower than with a simpler haptic layout. Thus, the expectation for the experiments covered in this thesis was there might be improved error rates but possibly at the cost of reduced task speed.

3.2 Tactile Interaction In an Eyes-Free Context

There are several usage scenarios where eyes-free interaction is needed. While some studies have concentrated on creating user interfaces for visually impaired users, others have focused on ordinary users in situations where users cannot utilize their sight completely for device interaction or how to make user interfaces better suitable for use with short glimpses of the screen. While interactions with modern touchscreen devices mostly rely on visual attention, there is some knowledge on how this could be improved by using audio or vibrotactile feedbacks for supporting the interactions.

An obvious need for the nonvisual interaction is among visually impaired users. Solutions created for their use also provide knowledge on how to utilize other senses, such as audio and haptics in mobile-usage scenarios (Pascoe et al., 2000), for sighted users in usage scenarios where visual interaction is limited. This approach gives the opportunity to create user interfaces, which require minimal attention from the user (Pascoe et al., 2000).

While creating these kinds of interfaces for eyes-free interaction, few basic rules with information mapping were found by Challis (2000). User interfaces and feedback, auditory or tactile, should be consistent. Tactile representation should present static information. And the height of the sound is one appropriate parameter for dynamic information. However, an empty space without any feedback might be a source of confusion for users.

One approach to create this kind of eyes-free user interface is to create interactions completely relying on an audio and haptic interface (Amar et al., 2003). As Amar et al. (2003) evaluated this kind of interface with both visually impaired and sighted users, the researchers could provide some initial information that these kinds of interfaces are suitable for all the users when they have positive impressions of this kind of interface.

For example, with audio interfaces, it is possible to create an abstract audio interface for the visually impaired users by using spatial audio together with different audio cues representing different things. This allows visually impaired users to interact with digital systems and, for example, play a game of Battleship (Hoppe et al., 2003). With similar methods, using sonification gives an opportunity to create an audio image of other specific graphical data—for example, statistical data (Ramloll et al., 2000). And a similar approach for creating a nonvisual image of statistical data can be combined with touch (Ramloll & Brewster, 2002). This approach moves toward tactile interfaces—utilizing similar parameters for information presentation, as these, with abstract audio interfaces, utilize sonification.

Further, Wall and Brewster (2006) used a tactile display, together with an audio system, to represent graphical data. Users had a positive attitude toward this kind of interface—compared to, for example, screen readers. For designing these kinds of audio-haptic interfaces representing graphical data, few basic principles were learned in their experimentation. Tactile elements, such as graphical bars, should rather be filled than just outlines. Users, even visually impaired users with nonvisual interaction experience, had difficulties with spatial location awareness. Thus, user interfaces should support location awareness in eyes-free interaction schemes.

Also, other abstract information has been successfully represented by combining audio and HUIs for eyes-free interaction, such as utilizing audio and tactile feedback for representing geographical information (Jeong, 2001) and music notation (Challis & Edwards, 2000). Pielot et al. (2010, 2011) created a navigation interface with a mobile device, which provides point-to-point navigation aids through tactile feedback. Also, this system was piloted successfully and provided proof that nonvisual eyes-free interaction utilizing tactile feedback can successfully be used in a mobile-usage scenario, where users are moving in the real world.

These prototype systems, among others, have pointed out a direction, where interaction with abstract information in a task-specific context can be used by nonvisual methods utilizing audio and/or tactile feedback. These also raise up the necessity to approach the design with careful consideration about the mapping of the information, supporting the knowledge of location in the user interface and avoiding clutter (i.e., keeping the feedback and user interface consistent and not providing anything unnecessary that would cause confusion).

For the benefits of the audio and tactile interfaces, there is knowledge that these modalities can be used to support visual interfaces without adding a mental load for users (Vitense et al., 2002) and, while used correctly for supporting the task, they will enhance user performance in eyes-free interaction scenarios (Sribunruangrit et al., 2003).

3.3 TACTILE INTERACTION WHILE DISTRACTED

There is some information about which modalities are the best for distracted-use scenarios. Visual feedback used together with audio is better for single tasks under normal workload conditions, while tactile feedback used together with visual feedback is best for multitasking and in high workload conditions (Burke et al., 2006). As in mobile-usage scenarios the user's attention is divided, interaction with the devices is actuated in short intervals (Oulasvirta et al., 2005), and users are multitasking with the device and the environment, this leads to the conclusion that in mobile-usage scenarios tactile feedback together with visual feedback would be the most applicable approach. In the experiments covered by this thesis, most of the usage scenarios were mobile multitasking scenarios, and the approach of the HUI was use it together with other modalities for supporting the interaction with the tasks.

Karuei et al. (2011) evaluated detection and reaction times for tactile stimuli provided at different locations of the body. They found out, that location did not affect detection rate, but affects reaction times. They also found out, that workload does not affect detection. These results support the approach to use tactile feedbacks even with secondary tasks while mental workload is on the other task and at appropriate location based on the task. They conclude to design guidelines based on their results: Location (wrist and spine) are best, if fast response is wished, Stronger vibrations are reacted faster, Movement should be taken account by providing stronger stimuli for faster detection speed, Visual workload slows down user, and that user react slower to unexpected stimuli. Thus, users do detect tactile stimuli regardless of conditions, but speed of recognition is affected and should be taken account in tactile design.

There are earlier results with visual-tactile user interfaces which support utilizing this approach with users being distracted and in multitasking situations. Brewster et al. (2007) found out that vibrotactile cues in text-entry tasks under distracted-usage scenarios improve typing performance and reduce error rates and tactile information helped users to notice and correct errors more accurately. Van Veen and van Erp (2001) found that tactile information for airplane pilots can be used to reduce their visual information overload. Also, in their experimentation it was found that reasonable G-load did not affect the perception of the vibrotactile stimuli. Also, in sports, tactile displays have been used to maintain high performance more easily and with less effort (van Erp et al., 2006). These results show using tactile feedback is a beneficial approach under distractive and high-demanding situations. In the experiments covered in this thesis, distraction level was raised step by step while supportive tactile interfaces were used to support the tasks.

About the approach using more complex, but comprehensive, tactile user interfaces—compared to simpler tactile interfaces providing only confirmation haptics, but not informational haptics—Leung et al. (2007) found that under a cognitive load, with scroll bar and progress bar tasks providing more versatile tactile feedback, performance improvements could be found, but button tasks providing simpler confirmation haptics did not yield the same results. This result indicates a more comprehensive haptification of the user interface might be more beneficial than a simpler tactile user interface providing only confirmation feedback, especially under a cognitive load.

The main approach for evaluating HUI benefits in the experiments covered in this thesis was providing HUIs to support secondary tasks in the driving environment. This provides the possibility to evaluate benefits of tactile feedback in the user interfaces under divided attention in a high cognitive load environment, where safety is a priority. In this environment, multimodal feedback could be used to minimize the need of visual attention to the secondary devices. Especially, haptics is an important modality in the driving context for creating eyes-free interaction scenarios (Burnett & Porter, 2001).

This is supported by the knowledge that users prefer multimodal feedback in touchscreen interactions while driving (Pitts et al., 2009) and users feel they drive better with haptic support in the user interface (Pitts et al., 2010), although this subjective feeling of better driving performance was not supported by measured values. Rydström et al. (2009) had similar results, where a simple menu selection task with a hapticly enhanced rotating knob did not improve either task or driving performance. However, in this interface, tactile enhancement was a simple confirmation tactile click. This leaves open the question evaluated in the experiments covered in this thesis: with an appropriate HUI, can improvements in the measured driving performance be achieved and can more complex usage scenarios benefit more from tactile feedback?

This approach, using a more comprehensive HUI for supporting distracted users in divided-usage scenarios, is supported by previous studies that have investigated using several modalities and more versatile feedback in the driving and mobile-usage scenarios. For example, Lee and Spence (2008) compared visual, audiovisual, haptic-visual and audio-haptic-visual feedback in driving situations while using a mobile device. In this experiment, they found out that the tri-modal condition reduced driving errors, while bi-modal conditions did not reach statistical significance and the haptic-visual condition reduced the measured workload with the NASA-TLX questionnaire.

Also, Richter et al. (2010) evaluated a selection task in a touchscreen interface with tactile feedback and found out a trend, even though not statistically significant, due to the small number of participants, where feedback mimicking physical buttons could improve user performance with the user interface and driving safety with more stable driving. This indicates evaluating the approach for mimicking real objects with tactile feedback should be investigated more thoroughly, which is done in the experiments covered in this thesis. An experiment with varying tactile feedback in the windows position task, providing information about window position, showed informative tactile feedback can also improve the accuracy of the task (Holmen & Zadeh, 2010). In the experiment, users, while driving, could adjust a window with more accuracy to a given position while being provided with tactile feedback.

It has also been shown that a tactile display under a cognitive load can help drivers navigate better than when using a traditional navigator interface (Asif & Boll, 2010). Further the cognitive side task was not impacted by the modality in the study (Asif & Boll, 2010).

With multimodal navigation support while driving, Kern et al. (2009) found that with audio-haptic and visual-haptic navigation guidance, standard deviation from the given drive line was reduced. Thus, users drove in a more stable way, with the interface providing informative haptics together with visual feedback. Similar results providing indications for safer driving performance was achieved by Kim et al. (2012) with audiovisual navigation instructions. In their experiment, users had a reduced number of eyes-off-the-road events. And with younger participants, haptic feedback together with audio-visual feedback reduced their cognitive load. However, in their experiment, they did not find improvements in the navigation task performance with audio-haptic feedback, which leaves a question: do the benefits of the more comprehensive information rich multimodal feedback support only the more demanding driving task, rather than more simple navigation task?

Asif and Boll (2010) found, in their experiment investigating effects of the tactile feedback with navigation task under high cognitive load, that a tactile display helps users to navigate better better than a traditional navigator interface. They also found that a cognitive side task was not impacted by the modality of their study. This result indicates the possibility that only the main task would be benefit from tactile feedback. On the other hand, some of the previously mentioned experiments have indicated results suggesting opposite results. Thus, this aspect of the main task versus the secondary task and the effect of the cognitive load requires more research. In the experiments covered in this thesis, aspects of the benefits of the HUI for the primary task or the secondary tasks and the effect of the cognitive load for the benefits of the tactile interfaces were further investigated.

3.4 Proposed Approach for the Haptification of the GUI

The experiment series covered in this dissertation transitions from blind-usage scenarios to moving, distracted eyes-free usage scenarios, where use of sight is highly limited but not prevented. The studies introduced above provide information on how to approach the idea of an HUI, with an idea where an entire user interface's feeling and information is provided by the tactile feedback, together with other modalities (Figure 21). With this approach, all the task-relevant graphical primitives, information, and interaction tasks have intuitive recognizable tactons, which are provided through device actuators during interactions with the device.

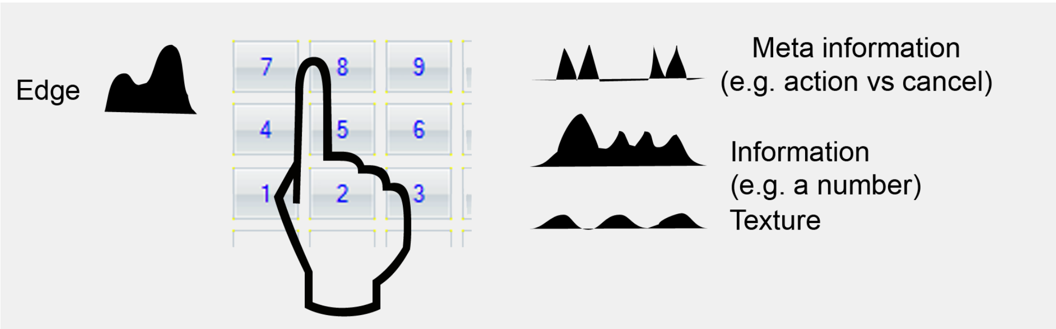

Figure 21: Basic idea of a comprehensively haptified user interface. In this number keypad example: button edges and texture have tactile feeling, as well as the action (button push) and information content (numbers) are represented with tactons.

The earlier studies introduced in this thesis provide information for creating tactile primitives with tactons for the HUI. The studies provide the starting point for the information about how to create informative tactons (Brewster & Brown, 2004a; 2004b; Brown et al., 2006) by using rhythmic tactile feedback (Hoggan & Brewster, 2007a; Brown et al., 2006). Furthermore, earlier studies have shown tactile feedback can be used for supporting the GUI tasks by providing tactile feedback for the actions (Poupyrev et al. 2002, 2003; Kyung & Lee, 2008), graphical primitives (Nashel & Razzaque, 2003), and components of the GUI (Hall et al., 2007). In addition, earlier studies have shown, that abstract information can be presented by tactile information (Rantala et al., 2009; Yatani & Truong, 2009).

The studies presented earlier in this thesis provided a starting point for creating the comprehensively haptified user interfaces experimented on in the latter part of the experiments covered in this thesis (Papers III–VI). Papers III and IV concentrate on the design part of the tactons to be used in the HUI, when the importance of the design problems is known (Van den Hoven et al., 2007), and people tend to value attractive design more than efficiency in the user interfaces (Quinn & Tran, 2010). These two papers evaluated design choices for the tactons to be used in the HUI. One question that arose while creating this kind of comprehensively haptified user interface was what kind of tactons would be intuitive and preferable by the users?

The last part of the comprehensively haptified user interface approach covered here (Papers V and VI) evaluated benefits of the approach. As earlier studies introduced above show varying, and partially contradictory, results of the benefits, the question for these latter experiments was can the HUI benefit the users and how can it? In the approach covered in these experiments, all the user interface primitives and information were presented with tactons, together with other senses, and evaluated under driving scenarios—where the tasks with the devices were secondary tasks, while driving was the main task.

4 Introducing the Experiments

The experiments covered in this dissertation began with an evaluation of the representation of the graphical information with haptics (Paper I) and detection of the haptics during movement, and thus, having a primary task to keep constant pace (Paper II). The second part of the experiments was aimed at evaluating design parameters for the tactons to be used as a part of the HUI (Papers III and IV). These experiments addressed different representation model options for finding out the best approach for the design principles for the tactons used in the HUI. Finally, the last two experiments (Papers V and VI) focused on the benefits of this kind of comprehensively haptified user interface under a demanding primary task—driving—and with increasing levels of distraction (Paper VI) for evaluating whether a measured performance increase would apply in even more demanding conditions (Table 2).

Table 2: Experiments covered in this dissertation.

EXPERIMENT	EVALUATED INFORMATION
I	**Representation of graphic information with audio-tactile feedback**
II	**Effect of movement on the detection of the low-level haptics**
III	**Design parameters and model for the haptic primitive (edge)**
IV	**Design model for the informative tacton (numbers)**
V	**Benefits of the haptic user interface for stationary vs. active primary tasks (video watching vs. driving)**
VI	**Benefits of the haptic user interface under different levels of distraction (passive distraction vs. cognitive distraction) while performing an active task (driving)**

4.1 Experiment 1: Representation of graphic information with audio-tactile feedback

Reference

Pakkanen, T. and Raisamo, R. (2005). Perception Strategies in Modal-Redistributed Interaction. In *Proceedings of World Haptics Conference (WHC 2005),* Pisa, Italy, 18–20 March 2005. IEEE Computer Society, 641–644.

Objectives and methods

The objective of this experiment was to study if users could recognize the graphical shapes with auditory and touch support, rather than visual. The approach was to provide melodic sound and frequency-amplitude varied haptic feedback to describe the shape of the objects when users moved the haptic device across the table and over the virtual shape on the screen.

In this experiment, a prototype haptic device was built to provide haptic representations together with melodic sound for geometrical shapes. The device was a haptic stick, with two rotation motors at each end of the stick. Stereo speakers were used for audio feedback. The device used can be seen in Figure 22.

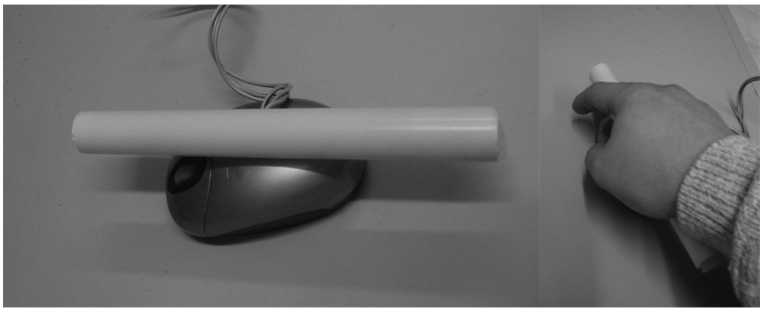

Figure 22: The haptic stick used in the test.

Using audio, left–right stereo separation and the pitch of the tone were used to describe whether the crossing line of the stick was at the top, bottom, left, or right part of the screen. With tactile feedback, amplitude and frequency were used for describing the crossing lines. Figure 23 shows the geometrical shapes that participants were trying to recognize based on their audio-haptic representation.

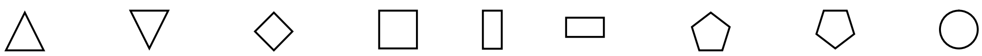

Figure 23: Used shapes and orientations.

The experiment was a simple recognition task where users did not see the screen but saw the mouse with a haptic stick on top of it. They could move the stick with the mouse on the table and swipe over the shape on the screen to get audio and haptic representations of the shape. They had two minutes of time to evaluate each shape and then they were asked to draw a picture of that shape. Users were aware of the shapes being complete geometrical shapes but not of what they were.

Three modality combinations were evaluated: audio only, haptics only and audio and haptics together. At the end of the evaluations, users were asked to evaluate the shapes with all the senses together, visual, touch and audio, for comparison. Movement of the device and the orientation of the stick were recorded during the experiment and these scan paths were evaluated in the analysis, together with the shape drawings made by the participants.

Results and discussion

The results show recognition rates were extremely low (6.2%–12.4% of the total number of the shapes). Thus, untrained users without previous knowledge had difficulties mapping the visual shape to the other modalities. On evaluating how closely the drawn shapes resembled the provided shape, it was found that the participants did have some kind of idea of the shape, even though it was not complete.

While evaluating the recorded scan paths of the mouse, it was found that there were differences in the scan strategies used by the participants within different modalities. With haptics only, users scanned all over the area, while with audio and audio-haptics, more closely across the shape, and with the comparison task with vision, very close to the shape. The scan path strategies were more inclined toward swiping the shape with more modalities—that is, from random scanning with haptics to a more organized scanning with audio and finally, with audio-haptic scanning, as a goal-oriented task over the shape with all the senses in use.

These results support the idea that in a blind usage scenario, using both audio and haptics together helps the users more than unimodal feedbacks, though they fail to successfully compete with the use of vision. Also, the observation during the experiment showed that in the audio-haptic condition, participants easily moved toward the lines of the shapes and followed the lines better than during unimodal conditions.

These results, combined with knowledge from the earlier research where trained users succeeded better, supports the idea that user interfaces in blind usage scenarios could utilize audio-haptic guides, but for recognizable shapes, earlier training would be required. Thus, previously learned audio-haptic cues should be used when recognition of the object is needed, but dynamic unlearned guide paths are feasible to use even without vision.

4.2 Experiment 2: Effect of movement on the detection of the low-level haptics

Reference

Pakkanen, T., Lylykangas, J., Raisamo, J., Raisamo, R., Salminen, K., Rantala, J., and Surakka, V. (2008). Perception of Low-Amplitude Haptic Stimuli When Biking. In *Proceedings of the 10th International Conference on Multimodal Interfaces (ICMI '08),* Chania, Crete, Greece, October 20–22, 2008. New York, NY: ACM, 281–284.

Objectives and methods

The objective of this experiment was to evaluate how physical movement affects the detection of the haptic stimuli. The experiment was a comparison experiment where several conditions were compared for differences in the detection levels of the provided haptic stimuli. In the experiment, two levels of haptic feedback were provided to the participants in four locations of the body while they were either pedaling an exercise bike or sitting still on that same bike. Their task was to push a button of the mouse attached to the handle of the bike when they felt the haptic stimuli.

Figure 24: Experimental setup.

Engineering Acoustics Inc.'s C-2 actuators[1] were used to provide the haptic stimuli. The haptic stimuli were given to nondominant parts of the body—the wrist, leg, chest, and back. In Figure 24, the experimental setup and actuator attachments in the limbs are shown. The haptic stimuli in the experiment were 250 Hz with the 44.1 kHz sample frequency sine waves with durations of 1000 ms and 2000 ms. Amplitudes of the haptic stimuli were, based on pilot testing, fixed for each actuator location to be generally barely detectable while staying still. Measured values of the amplitudes for each location are provided in Figure 25.

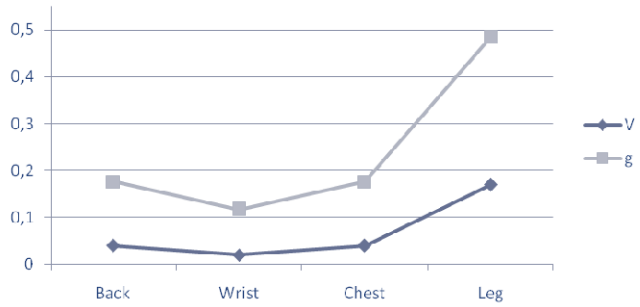

Figure 25: Measured stimuli amplitudes in volts and g-values.

Results and discussion

The results show movement significantly lowered the detection rate of the haptic stimuli, with the stimuli levels that were set to be barely noticeable in the wrist, leg, and back. Also, the haptic feedback with longer stimuli time was detected better on the chest. On reaction times, the results showed that with respect to the stimuli given to the wrist, leg and chest, participants reacted faster to longer stimuli while not moving and faster to shorter stimuli while moving.

In this experiment, it was found out that a 0.12 g stimulus was the lowest usable level, which was barely perceived. The chest and back required 50% higher levels—0.18g—and the leg, 300% higher stimulus level (0.48 g). These values were found to be the lowest limit for vibrotactile stimuli with actuators attached to the skin. Exceeding these values should be enough to create vibrotactile cues for moving users with actuators attached to the skin.

While stimulus length did not have a significant effect on detection rates, elsewhere than at the chest, for most cases, the use of 1000 ms stimuli should be long enough for the users; except where stimuli are provided to the chest, like attaching actuators to a heart rate belt, in which case longer stimuli would be recommended.

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[1] https://www.eaiinfo.com/product/c2/

4.3 Experiment 3: Design parameters and model for the HUI primitive (edge)

Reference

Pakkanen, T., Raisamo, R., Raisamo, J., Salminen, K., and Surakka, V. (2010). Comparison of Three Designs for Haptic Button Edges on Touchscreens. In *Proceedings of the Haptics Symposium 2010,* Waltham, MA, USA, March 25–26, 2010. IEEE, 219–225.

Objectives and methods

The objective of this experiment was to evaluate haptic tacton models for the edges of the graphical elements in the UI. The experiment was a comparison experiment with a ranking task. A prototype device using a piezoelectric actuator embedded under the touchscreen was used in this experiment. The device was based on the Nokia 770 internet tablet (Figure 26). While this experiment was evaluating design models for the tactons describing button edges, the approach was a ranking task by the users. Participants were asked to compare stimuli in different blocks and rank them in an order based on how they felt—whichever describes the button edges the best. The same stimuli were repeated for the participants every time they moved their finger over an edge of a button on the screen and they were allowed to explore feedbacks as long as they felt necessary, to rank them. First, they were asked to rank stimuli within each design, thereafter, to rank three designs, and, lastly, to choose three best button edges. They were asked to reason their choices to avoid first impression selections based on solely pleasantness.

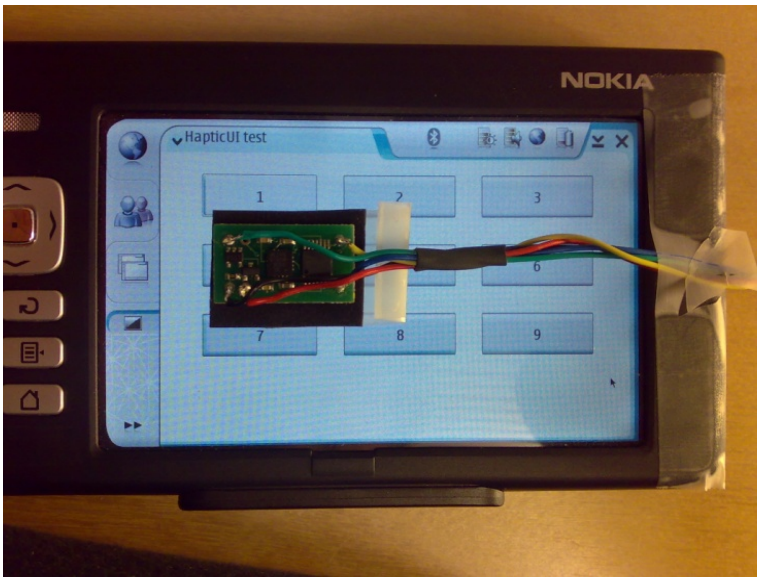

Figure 26: Experiment device and software, with an accelerometer, used to measure amplitudes of the stimuli.

There were three design models with three different stimuli for the tactons describing the edges: *The simple design* with a single burst moving toward or away from the button, and the amplitude was varied. *The GUI transformation design* with tactons composed from several bursts with a 6 ms interval between them. In this model, the idea was to mimic the 3D-shape of the button edge by raising amplitude when moving toward and lowering it when moving off the button. The number of bursts was varied within this model (2, 3 and 4). *The designed model* with manually designed tactons to remind of the natural feeling of the bump of the edge when sliding a finger over the edge of a physical button. The designed tacton combined the stronger and lower bursts while moving on, which felt a bit rough and broken, and the interval was varied with 3, 6 and 11 ms. The tacton for the sliding off of a button was a single moderate pulse, which felt like a slipping. Measured vibration amplitude shapes of the stimuli used can be found in Figure 27.

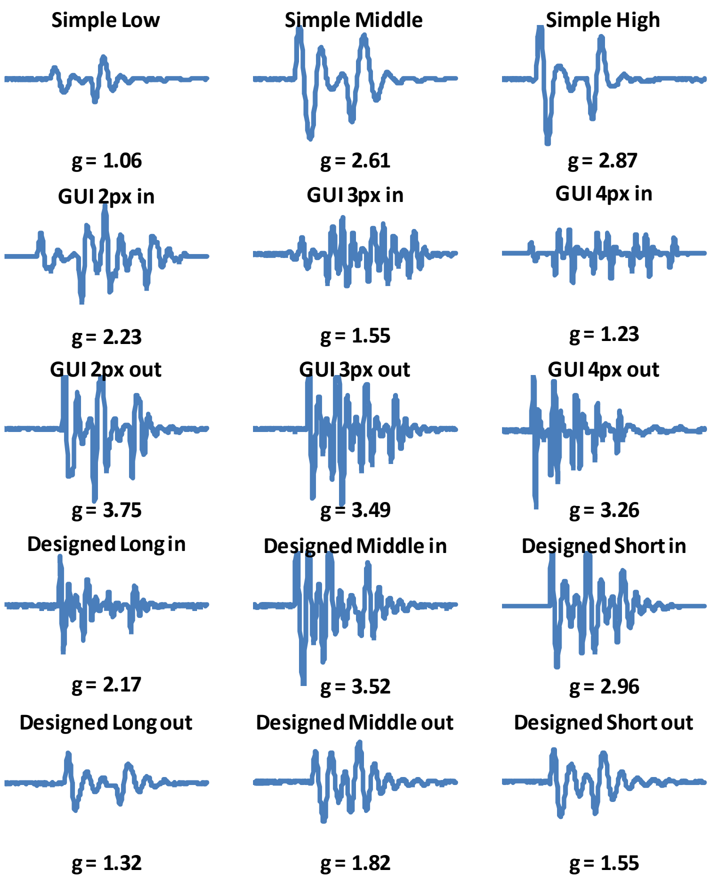

Figure 27: Vibration amplitude shapes and peek-to-peek g-values.

Results and discussion

The results show shorter tactons with fewer pulses were ranked better, but the amplitude of the pulses did not have significant differences. This indicates that fast and sharp tactons would be preferred for describing the edges of the GUI elements. Also, in free comments, participants commented that longer tactons with more pixels in the GUI transformation method felt too fuzzy. In the comparison of different design methods, both the simple design and the designed model methods were ranked better than the GUI transformation method, which suffered from longer stimuli lengths. Thus, either simple bumps, or by designed fast, but a bit rough edge feeling for the tactons are preferred by the users.

Based on this experiment, the best parameters for the tactons describing edges of the GUI components would be that fast, clear, and sharp tactons should be used and any fuzziness of the tactile feedback should be avoided. Both simple bumps, or asymmetrically designed tactons, would be functional. More research is needed into whether any benefits can be found using asymmetric tactons, which tell users if they are moving toward or off the GUI element. While amplitude did not have a significant effect on the preferences, the best choice would be using adjustable amplitudes, where users can choose the strength of the tacton based on their personal preferences.

4.4 Experiment 4: Design model for the informative tacton (numbers)

Reference

Pakkanen, T., Raisamo, R., Salminen, K., and Surakka, V. (2010). Haptic Numbers: Three Haptic Representation Models for Numbers on a Touchscreen Phone. In *International Conference on Multimodal Interfaces and the Workshop on Machine Learning for Multimodal Interaction (ICMI-MLMI '10)*, Article 35. New York, NY: ACM, 1–4.

Objectives and methods

The objective of this experiment was to evaluate tacton models by describing numbers on the number keypad of a phone. The experiment was a comparison experiment where three different numerical models were compared in a blind usage scenario. The models for the number representation with tactons were Arabic numerals, Roman numerals and the button location-based encoding. Tactons were presented with a Nokia 5800 Express Music phone with custom keypad software (Figure 28), using its integrated rotation motor actuator. The task for the participants was to enter random mobile phone numbers into the phone while their visions were blocked by putting the phone under a box. Task completion times, error rates, and subjective evaluations were collected and analyzed.

Figure 28: The UI of the experimental software

Tactons were created by running short pulses to rotate the actuator's electric motor in the phone. For the numbers, simple pulses were used, for the UI primitives, edge, push down, release button, and texture had their own tactons to help the participants to find and stay on the buttons. The parameters used for each tacton can be found in Table 3. For each number keypad model, there were fast and slow speed versions of the tactons, where the pause between pulses within the number pulses within tacton was 100 or 200 ms. The Arabic numerals were created from identical pulses, with as many pulses as the numbers were, and pulses were grouped into groups of five by using two-times longer pauses between the 5th and 6th pulses. The Roman numerals were created with timings varying amplitude for I, V and X, and the pauses between different numerals were twice longer than between the same numerals. A location encoding amplitude was used to represent the row and the number of pulses for the location of the button in the row.

Table 3: Parameters for the tactons in the experimental software. (P) Proportional power, (rd) rotation direction, and (t) rotation time and pause between pulses.

Roman	P (%)	rd	t (ms)	Pause (ms)	P (%)	rd	t (ms)
I	5	↑	50	-	-	-	-
V	100	↑	100	-	-	-	-
X	100	↑	200	-	-	-	-
Arabic							
1 pulse	100	↑	50	-	-	-	-
Location							
Row 1	25	↑	50	-	-	-	-
Row 2	50	↑	100	-	-	-	-
Row 3	75	↑	150	-	-	-	-
Row 4	100	↑	200	-	-	-	-
Primitives							
Edge in	100	↑	35	10	100	↓	25
Edge out	100	↑	35	-	-	-	-
Texture	5	↑	2	-	-	-	-
Pushdown	100	↑	35	50	100	↓	25
Release	100	↑	50	10	100	↓	25

Results and discussion

The results show there were no significant differences between different models in the measured values—that is, task completion times and error rates. However, measuring user preferences and feelings of ease with regard to subjective evaluations, it was found that participants had feelings of making fewer errors with the Arabic number model than other two, and that they thought the slower representation model and the Arabic model were more pleasant than the location-based encoding. They also felt that both the Roman number model and location-based encoding were more difficult than the Arabic number model. Thus, even if there were no differences found in the performances, user preferences gave some insight into designing tactons for the number representation to be used in eyes-free interactions.

Based on these results, the use of familiar numerals for the users in the encoding numbers to haptic representation is recommended, in this case, Arabic numerals. Also, at least with users not familiar with the system, a slower pace would be recommended.

4.5 Experiment 5: Benefits of the HUI for stationary versus active primary tasks (video watching versus driving)

Reference

Pakkanen, T., Raisamo, R., and Surakka, V. (2012). Comparison of Extensive vs. Confirmation Haptic Interfaces with Two Levels of Disruptive Tasks. In *Haptics: Perception, Devices, Mobility, and Communication: International Conference, EuroHaptics 2012*, Tampere, Finland, June 13–15, 2012. Proceedings, Part I. Heidelberg: Springer, 383–394.

Objectives and methods

The objective of this experiment was to evaluate the benefits of using comprehensively haptified user interfaces versus simple confirmation haptics user interfaces while using a mobile phone for a secondary task. The experiment was a comparison experiment where both subjective and objective data were collected. The task for the participants was to enter 4-digit numbers into the phone while driving in a simulation or watching a video recording of the driving in the same simulation. The user interfaces used were the fully haptified number keypad with the slower Arabic number model used in Experiment IV and a simple confirmation HUI, where entering a digit was confirmed by a single haptic pulse. The experiment setup is shown in Figure 29.

Figure 29: Experiment setup

The data collected were number input task times, error rates, driving error rates collected with video analysis from the recorded driving, and video and subjective questionnaires measuring how well participants felt they managed and about the pleasantness and difficulty of the task. For the comparison of driving errors, data on driving with the same instructions without using the mobile phone was also collected.

While driving, participants were asked to drive with full speed and stay on the guideline for the optimal driving line in the game used. Driving errors were collected by counting deviations from that optimal line and categorized into small, large (more than car width of the line), and crash when the participant lost the control of the car. The phone was held down during the experiment (Figure 29 right) so that participants could not watch the phone otherwise than with short glimpses when entering the numbers. While the task was to watch the video on the screen, participants were instructed to concentrate on watching the video and not to stop watching it while using the phone.

Results and discussion

The results show that regarding driving errors, participants made fewer small errors (unstable driving) and medium errors (like changing lane by accident) with comprehensively haptified user interface than with confirmation HUI. Thus, a comprehensively haptified user interface on a mobile phone while using it helped users to drive safer. In driving conditions, there were no differences in input errors, and participants entered numbers faster with a UI having confirmation haptics only. Thus, comprehensively haptified user interface did not help with the phone usage itself but rather with the main task—driving the car in simulated driving.

Participants reported subjective feelings that the comprehensively haptified user interface was supporting the task better than the confirmation HUI. Participants also felt that using the phone was more difficult while driving than while watching the video, and they felt that they made fewer input errors in the video-watching condition.

However, in the comparison task—driving without using a mobile device—participants made fewer errors than with either user interface. Participants also reported in the subjective evaluations that the task was more demanding while driving. Based on these results, using mobile devices while driving, even with a comprehensively haptified user interface solution, cannot be recommended. But as it is known that users do this, even though they know it is not safe (Piateski & Jones, 2005), using comprehensive haptification in the user interfaces of mobile apps could have an impact on driving safety.

4.6 EXPERIMENT 6: BENEFITS OF THE HUI UNDER DIFFERENT LEVELS OF DISTRACTION (PASSIVE DISTRACTION VERSUS COGNITIVE DISTRACTION) WHILE PERFORMING AN ACTIVE TASK (DRIVING)

Reference

Pakkanen T., Raisamo R., and Surakka V. (2014). Audio-Haptic Car Navigation Interface with Rhythmic Tactons. In *Haptics: Neuroscience, Devices, Modeling, and Applications: International Conference, EuroHaptics 2014*, Versailles, France, June 24–26, 2014. Proceedings, Part I. Heidelberg: Springer, 208–215.

Objectives and methods

The objective of this experiment was to evaluate comprehensively haptified tactons in an audio-haptic condition with a navigation task under heavy distraction. The experiment was a comparison experiment where three haptic levels—audio-only, audio and alerting haptics, and audio and comprehensive haptification with encoded information in the haptics—were compared under two levels of distraction while following navigation instructions in a simulated drive. For haptic feedback, small 3V pancake vibration motors attached to the driving wheel and driven with an Arduino board were used (Figure 30).

Figure 30: The wheel used in the experiment with attached actuators

The task for the participants was to drive in a driving game (Driver: San Francisco), safely obeying traffic lights, traffic signs, and maintaining a speed of 45 mph following the given navigation instructions. Turning instructions were given in three parts—“closing up,” “soon,” and “now.” Modern navigator instructions were provided. During the driving, there were two levels of distraction. The first level was passive, where there was music, audiobook in the “back seat,” playing (simulating passengers’ talking). This level did not require attention from the participants. The higher level of distraction had additional tasks—simulating talking with a passenger in the form of simple plus-minus math tasks given from the right side. The schematics for the setup can be found in Figure 31. Driving errors and navigation errors were collected with video analysis of the recorded driving sessions, and subjective questionnaires measuring subjective feelings of performance, distraction, and pleasantness were collected.

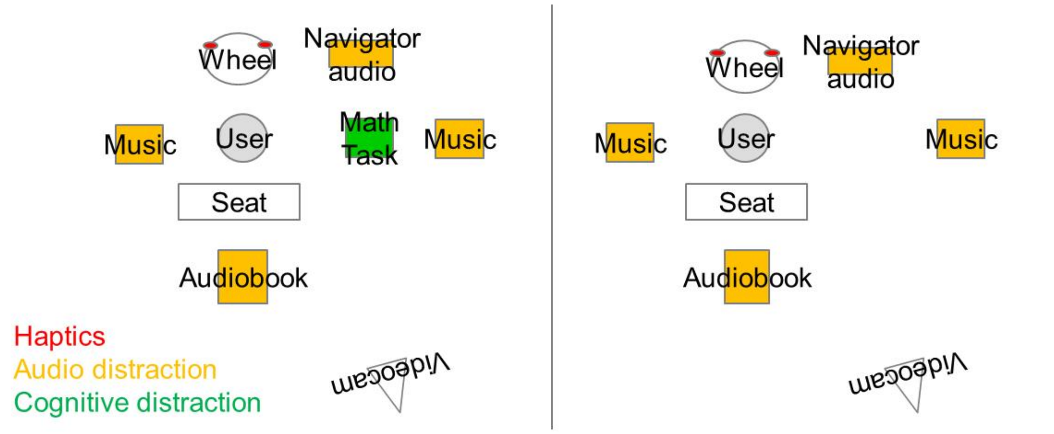

Figure 31: The experiment setup.

Tactons used for the navigation instructions were similar rhythmic tactons composed from the short pulses used in previous experiments. In this experiment, they were given utilizing two actuators. With the comprehensively haptified UI with audio instructions, an informative tacton providing the same information was given through the actuators in the wheel. Actuator location was used to provide a sense of direction by moving a signal from one actuator to another and tacton speed was used to provide information on how close the next turn was. Whereas, with simple haptic UI, an alerting pulse was played just before audio instructions were given. The haptic parameters used can be found in Table 4.

Table 4: Haptic parameters of turning instructions.

	Side	*t (ms)*	*Pause (ms)*	*Side*	*t (ms)*	*Pause (ms)*
Left far	Right	200	150	Left	100	1500
Left near	Right	200	150	Left	150	750
Left now	Right	200	150	Left	200	150
Right far	Left	200	150	Right	100	1500
Right near	Left	200	150	Right	150	750
Right now	Left	200	150	Right	200	150
Simple	Both	200				

Results and discussion

The results published in Paper VI show that in the answers to the subjective questionnaires, participants thought that driving was safer, they could concentrate better and noticed and followed navigation instructions better, and navigation instructions were more pleasant without the cognitive side task than with it. Also, they thought that navigation instructions were more pleasant with comprehensively haptified user interface than with alerting HUI or in audio-only instructions. With regard to navigation performance, earlier results by Kim et al. (2012) were repeated and there was no improvement in the navigation error rates by adding haptics to the audio instructions. Thus, audio-only is enough for navigation instructions, even though users preferred added haptic feelings in the instructions.

Further analysis was done for this thesis based on video analysis of the driving safety. This analysis showed that participants drove more safely with comprehensively haptified user interface than with the alerting haptic interface or in the audio-only condition. There was no significant difference between the alerting haptic condition and the audio-only condition. This was found in all categories of driving errors: Crashes, near accidents (almost hitting another car or driving to the sidewalk), and dangerous driving (instability in driving, measured in seconds). Also, the results showed that participants changed to the correct lane before turning more often with the comprehensively haptified user interface in the distraction level without the cognitive side task than with the cognitive side task. This shows that comprehensive haptification of the user interface could be beneficial for safe driving behavior until the distraction level rises too high but is actually beneficial to driving safety even when the driver starts to make more driving errors due to demanding conditions. The results of the detailed analysis of the significant results on driving safety are presented below.

Additional analysis from the data collected for Paper VI

Means and standard error of the means for the lane-taking before the turning are presented in Figure 32. For not taking the lane before a turn, a two-way ANOVA 2 × 3 (distraction level × haptic feedback level) showed a statistically significant main effect of distraction level $F(1,23) = 12.701$, $p < 0.01$ and haptification level $F(2,46) = 8.062$, $p < 0.01$. There was also a significant interaction of the main effects between distraction level and haptic feedback level $F(2,46) = 3.523$, $p < 0.05$.

The two-way interaction was further analyzed with two separate one-way ANOVAs (i.e., one for each distraction level with haptic level as the independent factor). The results showed that the interaction was due to the fact that a significant effect of the haptic level was found for the distraction level without the cognitive side task $F(2,46) = 9.432$, $p < 0.001$, but not for the distraction level with the cognitive side task. Post hoc pairwise comparisons showed that the participants took the right lane before turning significantly more often in the distraction level without the cognitive side task with comprehensive haptification (MD = 15.4%, $p < 0.01$) than with the audio-only condition (Figure 31). Other pairwise comparisons were not statistically significant.

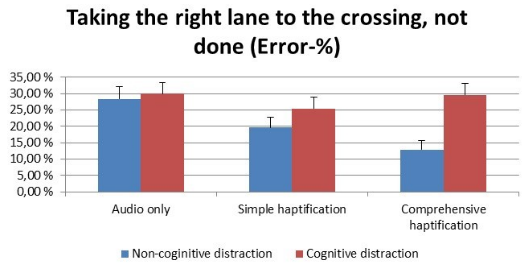

Figure 32: Taking the correct lane in the crossing before turning.

Means and standard error of the means for the driving errors are presented in Figure 33. For the "crashed" error, a two-way ANOVA 2 × 3 (distraction level × haptic feedback level) showed a statistically significant main effect of distraction level $F(1,23) = 7.510$, $p < 0.05$ and haptification level $F(2,46) = 4.018$, $p < 0.05$. The interaction of the main effects was not statistically significant. Post hoc pairwise comparisons showed that the participants crashed significantly less with the comprehensive haptification condition than with the simple haptification condition (MD = 60.4%, $p < 0.05$) and audio-only condition (MD = 50.0%, $p < 0.05$) and significantly less without the cognitive side task than with it (MD = 59.7%, $p < 0.05$). The other post hoc comparisons showed no statistically significant effects.

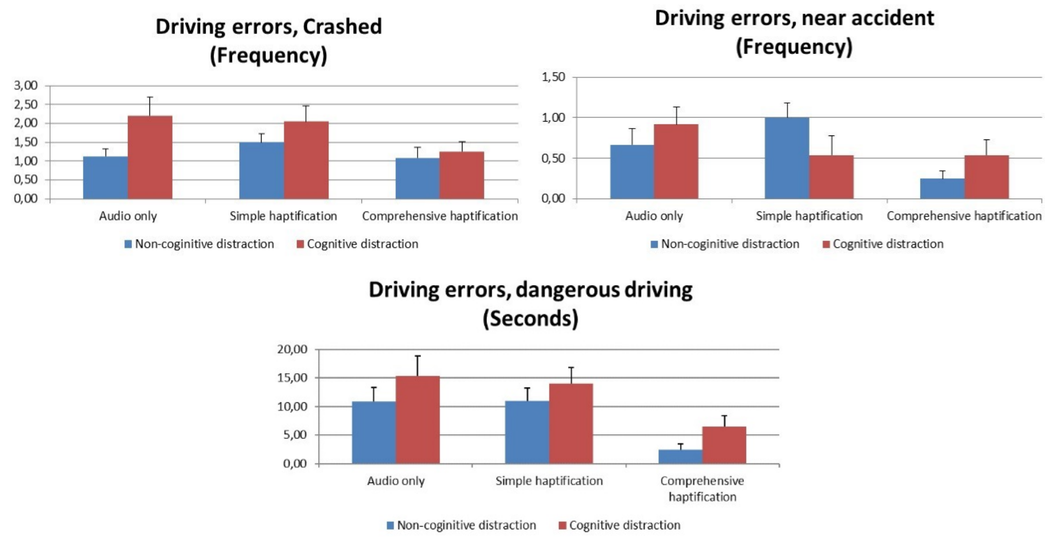

Figure 33: Values of driving errors and reckless driving.

For "near accident," a two-way ANOVA 2 × 3 (distraction level × haptic feedback level) showed a statistically significant main effect of haptification level $F(2,46) = 4.584$, $p < 0.05$. The main effect of the distraction level and the interaction of the main effects were not statistically significant. Post hoc pairwise comparisons showed that the participants had near-crashes significantly less with the comprehensive haptification condition than with the simple haptification condition (MD = 37.5%, $p < 0.05$) and audio-only condition (MD = 39.6%, $p < 0.05$). The other post hoc comparisons showed no statistically significant effects.

For "dangerous driving," a two-way ANOVA 2 × 3 (distraction level × haptic feedback level) showed a statistically significant main effect of haptification level $F(2,46) = 12.323$, $p < 0.001$. The main effect of the distraction level and the interaction of the main effects were not statistically significant. Post hoc pairwise comparisons showed that the participants drove the car out of control significantly less with the comprehensive haptification condition than with the simple haptification condition (MD = 8.104 s, $p < 0.001$) and audio-only condition (MD = 8.688 s, $p < 0.001$). The other post hoc comparisons showed no statistically significant effects.

The results from this experiment repeated the results from the previous experiment (Paper V) where, by using the comprehensively haptified user interface in the secondary task, driving safety was improved. Thus, providing information through haptic modality with secondary tasks in high cognitive load usage scenarios seems to help users perform better on the main task. For example, in this experiment, providing navigation instructions with both audio and haptics helped users to drive safer. Based on these findings, it would be suggestible to provide task-specific comprehensive haptifications for the user interfaces used during driving.

5 Discussion

The experiment series covered in this thesis were divided into three groups. The first two experiments (Papers I and II) focused on the perception of tactile feedback. They were investigating answers to the first research question: *What are limitations of haptic perception for the users within limited context? How do they detect low level haptic feedback while moving or do they understand visual meaning of modal redistributed information through haptics?* Paper I focused on the perception of graphic information through other modalities. Paper II focused on the detection of low-level haptic feedback while moving and focusing on another task.

The second group of experiments focused on the design part of the HUI (Paper III and IV). These experiments evaluated how to design tactons to be used in HUI applications. The goal of these experiments was to find answers to the second research question: *What kind of haptic representations for user interface elements would be the most preferred and familiar for the users?* Paper III investigated the vibrotactile representation of a graphical primitive, button edges. Paper IV then focused on information representation by investigating how to represent numbers with tactons.

The last part of the experiments (Paper V and VI) used a task-specific HUI solution to investigate how these kinds of user interfaces would be beneficial to the users. *These papers evaluated answer to the third research question: How users would benefit from comprehensive HUI compared to nonhaptic or simpler haptic interface?* Paper V focused on active versus passive main task while using HUI application—driving or watching a video, respectively. Paper VI focused on the high level of distraction and how it affects the benefits of HUI with having an active main task (driving) and auditive distraction around the participants compared with an additional cognitive side task.

The work done in this experiment series started with perception, continued with designing HUI elements, and ended with using highly distracting scenarios to evaluate the benefits of the haptics in the user interfaces.

Perception

Research question 1: What are limitations of haptic perception for the users within limited context? How do they detect low level haptic feedback while moving or do they understand visual meaning of modal redistributed information through haptics?

The purpose of Experiments I and II was to evaluate the limitations of haptic perception. Experiment I evaluated the human capability to understand abstract graphical information redistributed to other modalities such as audio, haptic, and audio-haptic sensory channels. Experiment II evaluated the detection of the haptic signal through different locations when the haptic signal was barely noticeable and participants had another task of keeping constant speed movement. These two experiments led to the basic knowledge of the latter experiments.

Experiment I showed that it was difficult for the participants to recognize abstract graphical shapes through other sensory channels, especially the untrained sighted participants who did not have pre-existing skillsets to evaluate shapes without vision. Earlier research utilizing task-specific abstract information representation with haptics or audio (Ramloll et al., 2000; Ramloll & Brewster, 2002; Amar et al., 2003) have shown that users can learn abstract meanings of the audio and haptic feedback when they have a pre-existing understanding of the expected representation. However, this could not be repeated with more abstract shape tasks in Experiment I. Moreover, it was found that haptics and audio helped the participants to stay focused on the target. Thus, these results support the idea that haptics or audio or both together can be used to help users to stay focused.

The earlier experiments suggest that task-specific haptic and audio representations would be more suitable to use with haptic interaction. Also, the results from Experiment I showed that completely abstract nontask-specific representation is not a usable approach for meaningful perception of mental meaning through haptics. This leads to conclusion that upcoming experiments should focus on designing more task-specific haptic approaches, rather than transform graphical user interface directly to haptic or auditory representations of the user interfaces and the information on them. Also, the finding that participants could follow the haptic lines and focus on the objects with the help of the haptics and audio led to the first idea of investigating the haptic representation of graphical primitives with haptics, rather than creating haptic components, which would require more abstract recognition from the users.

Experiment II evaluated how moving, focusing on another task, and keeping a steady speed impact the detection of weak haptic signals. As van Erp (2001) showed, the detection rate was not impacted by movement when it did not close up the tolerance limits of the participants. Also, with the two stimulus lengths evaluated, it was found that the shorter stimulus length did not have a significant impact on the detection rates. Thus, for upcoming experiments considering the HUI idea, these results suggest that haptic stimuli do not need to be amplified, taking into account external movement conditions, as long as these would not approach human capability limits. Also, these results suggest that short tactons can be utilized for the HUI approaches haptic primitives representing graphical or informational primitives. With this approach, it was possible to create haptic layers for the GUI, which did not slow down the usage of the interface to the unacceptable levels.

These first two experiments, evaluating how people perceive haptic representation of graphical information and detect haptic signals while moving and partially concentrating on another task, provided the first key elements for the HUI approach. First, the required representations for the graphical information need to be intuitive and simple. Second, haptic feedbacks used in these representations can be fast and their amplitude level does not need to take the surroundings into account, unless if it is extreme.

Designing haptic user interface primitives

Research question 2: What kind of haptic representations for user interface elements would be the most preferred and familiar for the users?

The purpose of Experiments III and IV was to evaluate different haptic design models and the haptic parameters for these models to create haptic representations for graphical primitives and information for the user interface. These experiments used different design approaches to create tactons for the HUI approach and compared these design approaches to find out the most intuitive and pleasant tactons to use in a HUI prototype.

Experiment III evaluated the creation of tactons for the edges of the components. In the experiment, the example of a component to create edges for was a button in the GUI. There were three different models: one for direct GUI transformation, where 3D shape of button edge was presented with haptic pixels; another for simple approach, where just a simple bump was used; and the third one—a designed model—where through iterative design, rhythmic tactons were created to mimic the physical feeling of a physical button edge. The parameters, number of pulses, length of the stimuli, timings, and amplitudes of the parts of the stimuli were varied.

As earlier experiments with tactile component enhancements (Poupyrev et al., 2002; Poupyrev & Maruyama, 2003; Brewster & King, 2005; Poupyrev et al., 2003; Hall et al., 2007; Nashel & Razzaque, 2003) has shown, simple haptic primitives and varying haptic feedback and tactons can be used to create the feeling of the components. Experiment III was targeted at finding out more information about how these tactons should be designed. This study aimed to identify a way to create intuitive tactile counterparts for the GUI primitives and to confirm if the type of tactons used for that purpose matters. Results of Experiment III showed that participants preferred shorter tactons that felt sharper rather than fuzzy. Also, both the simple and the designed methods were preferred by the users. Thus, in the last two experiments, where the benefits of the HUI approach were evaluated, both of these models were compared. The parameters used in Experiment III were directly adapted to Experiment V to evaluate visual HUI, as well as the best model for the numbers, which was evaluated in Experiment IV.

Experiment IV evaluated different tactile representation models for the numbers to be used in the HUI approach. Tactons used in the experiment were based on three design models—button location-based encoding, Roman numerals, and Arabic numerals. There were two speed levels for the tactons evaluated. Yatani & Truong (2009) used a similar approach to encode number buttons based on the location of the button. While they used a multiarray tactile display, in Experiment IV, a rhythmic tacton encoding this information was used with a single internal actuator of the device used. A similar approach with rhythmic tactons encoding the information was used by Rantala et al. (2009) in their method for presenting Braille characters for visually impaired users.

In Experiment IV, measured performance values were also recorded and analyzed over the subjective ratings. It was possible to look after the most efficient but intuitive and pleasant approach for the tacton design for the numbers. Initially, high expectations were with Roman numeral representation because their tactons were faster with larger numbers and the users were familiar with the numerals, even though they do not use them every day. However, there were no statistically significant differences in the measured performance between the models; thus, any tactile representation would be usable in the merits of the performance. Thus, making tactons as fast as they can be does not seem to improve the performance values of the users based on these results. However, while analyzing subjective evaluations for the number models, it was found that the familiar Arabic numerals were preferred, and the participants had an internal feeling of performing better, even though this was not supported by the measured values. Thus, for the abstract information, the most common model for information encoding through tactons should be used, rather than the fastest tacton models. This does not have an impact on the performance level but has a positive impact on user satisfaction and feeling of control.

Experiments III and IV evaluated the parameters and design models for the tactons to be used in HUI prototypes. Results from these experiments suggest that using tactons, which feels sharper rather than fuzzy, and familiar mental models for creating these kinds of tactons is recommended for future HUI solutions. Also, these experiments showed that there was probably no performance differences between different tactons, which supports the approach that any tactile feedback is sufficient for the performance improvement, as shown, for example, by Hoggan et al. (2008) and Brewster et al. (2007) with a virtual keyboard writing task.

These results impacted on Experiments V and VI in two ways. First, the best parameters and models were directly adopted to Experiment V and the other tactons used in the HUI number keypad solution by using similar parameters from these two experiments to design tactons for the Experiment V. Also, a similar approach was used to design navigation instruction tactons for Experiment VI using an audio-haptic interface. Second, based on the experiments so far, it seemed that no performance improvements might be found by using a more comprehensive HUI solution than just simple haptic enhancement providing confirmation or alerting haptic feedback. Thus, Experiments V and VI focused on using haptic interface as a secondary task interface and added distraction to the use scenarios. This approach was chosen to find out if the HUI approach would gain any measurable improvements, or if the only impact of more comprehensive use of haptics would be just user satisfaction.

Evaluating the benefits of the HUI approach

Research question 3: How users would benefit from comprehensive HUI compared to nonhaptic or simpler haptic interface?

The goal for Experiments V and VI was to find out the benefits of using a comprehensively haptified user interface in HUI approach to the users. Experiment IV suggests that there might not be additional performance improvements from these kinds of comprehensively haptified user interface solutions, as this kind of performance improvement has already been found in simpler HUIs evaluated in earlier research (Poupyrev et al., 2002; Hoggan et al., 2008; Brewster et al., 2007; Leung et al., 2007; Kyung & Lee, 2008). Due to this, in Experiments V and VI, the approach was to use HUI prototypes in a secondary task, while there was another main task (i.e., driving in a simulated environment). Also, more distraction was added to Experiment VI to find out if the limit of the benefits of the HUI solution can be found.

In Experiment V, the task was to enter numbers into a mobile phone while driving in an oval track or watching the driving from a recorded video.

The participants were guided to use mainly their touch, and the phone to be used was held outside of their field of vision. Three conditions were compared—nonhaptic, confirmation haptic, and full HUI solution—where all the UI elements had tactons as well as the numbers in the keypad.

As a secondary task, results of the improvement in the entry task showed that participants actually entered numbers faster with simpler confirmation haptic interface, similar to the findings of Hoggan et al. (2008) and Brewster et al. (2007). Thus, a simpler level of haptification alone would be a better choice if the target is to improve the user interface task. Although the interesting finding was the impact on the selected main task—driving.

While driving errors from the video recording were categorized into three categories with video analysis methods—small error, when the car swayed from the given driving line less than the width of the car (i.e., unstable driving); lane change error, when the car slid from the given line more than the car width; and the crashes, when control of the car was lost—there were impact from the haptification level of the secondary UI. Participants made fewer lane change errors and the extent of unstable driving was lesser with a comprehensively haptified user interface interface than with a simpler confirmation haptic interface or an interface without haptics. Thus, the main benefit of the HUI solution was when the UI task was a secondary task and using the HUI approach in that task enabled people to perform the main task (i.e., driving) in a better and safer way.

This result is important because it is known that people tend to use mobile devices while driving, even though they are aware that it is dangerous (Piateski & Jones, 2005). This result is also different from the results of previous studies (Pitts et al., 2010; Rydström et al., 2009; Lee & Spence, 2008), where using simpler haptic interfaces did not have significant impact on driving safety, supporting the finding that task-specific haptics, together with visual and audio feedback, help drivers to be more stable (Kern et al., 2009). Based on these results, it would be recommended to have a HUI approach in the interfaces that users use in the car while driving.

Experiment VI evaluated HUI approach with an audio-haptic interface using a navigation interface where instructions were provided with audio only, audio together with a haptic alert that instructions were coming, and the HUI approach where turning instructions were provided with both channels, audio, and haptic. In the experiment, haptic feedback was provided by actuators embedded in the wheel. Two levels of distraction were also added to the task to evaluate the limits of the benefits of the HUI approach. The experiment aimed to determine if the more demanding environment would benefit from the HUI approach even more, or if the distraction level had an overload limit for the users, where even the HUI approach would not be able to provide additional help for the user. These distraction levels were passive and active. In the first one, there was only an audio distraction that did not require the participants' concentration. In the second one, there was an additional cognitive side task, where the participants had to respond verbally to simple math tasks.

As regards the secondary task, the earlier results of navigation (Kim et al., 2012) were repeated, and there was no impact on the navigation performance from the haptic added to the interface. Thus, similar to Experiment V, the user interface task did not improve from the added haptic level. However, as in all the earlier experiments, users did prefer haptic solutions, especially the HUI approach, where all the information was provided through the haptic channel. This supports the approach that the HUI solution is beneficial by providing users with an interface they like more, which is basically a key component for successful user interfaces in the market (Quinn & Tran, 2010).

In the aspect of driving safety, analysis made for this thesis about driving performance based on a similar categorization of driving errors in Experiment V showed similar results. While in this experiment, there were other AI-driven traffic, categories recorded for the analysis were unstable driving (car swaying), near-crashes (where the car almost hit another car or sidewalk), and crashes (where the car crashed into an obstacle). In all these categories, there were fewer errors while using HUI solution than while using an alerting haptic interface or audio interface only. The interesting result on driving safety was a category where the number of correct lanes taken before turning at the crossing was counted (lining up). In these, it was found that in the lower level of distraction (without cognitive side task), participants took the correct lane more often with HUI solution than with the audio interface, but there was no significant difference with the cognitive side task. Thus, the limits of the benefits of the HUI was found on the driving behavior.

While cognitive load was raised to a level where participants had to follow navigation instructions, the audio channel was overburdened by auditory distraction. When there was a cognitive discussion while driving, HUI did not help drivers to choose a safer way to drive (i.e., lining up in time), while without cognitive distraction, it did. However, this limit was not still reached on the stability of driving, and HUI solution, even in this extreme condition, supported participants to drive more stably.

Both experiments support the approach to use comprehensively haptified user interface solutions in the tasks that drivers undertake while driving. Also, for those user interfaces drivers are not supposed to use, such as mobile phone, while it is known that drivers do use those anyway (White et al., 2010; Walsh et al., 2008). Based on these results, the benefits of driving safety would be measurable.

Limitations and future work

While the last two experiments were done as driving tasks, the results are directly applicable to the user interfaces used in the car. However, these experiments were done with a simulated driving situation in the laboratory. Thus, more research evaluating real-world scenarios in real traffic would be required to confirm that these findings apply to real traffic driving. However, this is challenging because of the ethical reasons—you cannot push the driver to the limits where the risk for real traffic accidents could occur. Thus, the way to investigate this kind of interface would be end-user products and analysis of the traffic accidents to find out if there is less of those with cars using HUI solutions in their interfaces. This, naturally, would have ethical implications.

Also, in these experiments, only a few haptic primitives were used—edge, texture, push down button, release button, numbers, and navigation instructions. More research in the future would be needed to create a more versatile set of haptic primitives to be used in the HUI solutions. Also, these primitives used in the experiments in this thesis were direct haptification of GUI primitives with tactons. It could be assumed that while creating a larger set of tactons for the HUI, basic haptic primitives could be found, which can be combined to represent GUI primitives. Thus, future work could create a set of basic haptic building blocks and their parameters to create more complex tactons for representing UI building blocks, such as the haptic feelings used in the tactons used in the experiments here—a bump, a broken bump, a slippery feeling, and so on.

Concerning actuators, the ones used in these experiments were mostly ERMs, while in two of the experiments, a voice coil actuator was used in one and a piezoelectric actuator in another. Differences between the actuators, the sensory feelings, and the parameters to run them limit the generalization of the parameters used in the experiments in this thesis. Although edge effects evaluated with the piezoelectric actuator successfully transformed to ERM actuator in Experiment V, the transformation of the parameters from actuator type to another would require additional future work.

Last, while these experiments focused on the secondary task user interfaces used while driving, a generalization of the results would be that main task performance can be improved by using HUI solution in the secondary task. Confirming this to be the general outcome of the HUI solution would require more experiments with various primary-secondary task combinations to confirm that similar results can also be found in another context other than driving in a simulated environment.

6 Conclusions

In this thesis, an approach was developed to build the HUI solution for the secondary task interfaces. First, initial evaluations were made about the perception of the haptics. Second, design parameters and models for creating haptic primitives corresponding to graphical primitives were evaluated. And last, fully built HUI solutions for the secondary tasks and their benefits for the driving task in a simulated driving environment were evaluated, with an added level of distraction and its' impact on the benefits of the HUI solutions.

These HUI solutions haptic feedbacks were designed by creating rhythmic tactons for information representation. The research was done in six individual studies, where the first two evaluated haptic perception, the next two evaluated the designing of rhythmic tactons for the HUI solution, and the last two evaluated the benefits of HUI solutions compared to the nonhaptic and simple haptic with alerting or confirmation haptic interfaces. The following conclusions can be made from these studies:

- Haptics can be used to represent simple and familiar, known, graphical, or abstract information, but it cannot be used for creating a mental image of a graphical image that people do not have a mental model for.
- Haptics can be detected without amplification regardless of the movement and while focusing on another task, as long as physical limits are not approached.

- People tend to prefer sharper and faster, rather than fuzzier and slower tactons representing GUI or information haptic primitives.

- People tend to prefer the most familiar pre-existing mental models for the tactons representing information.

- Fully haptified comprehensive HUI solutions presented in this thesis helped people to perform better with the main task (driving) when these interfaces were used in the secondary task, compared to simpler haptic interfaces with confirmation or alerting haptics and the interfaces without haptics.

- When distraction under tasks grows to the extreme levels, users' strategy for the main task (driving) will start to break up, even with the HUI solution, but there is still a beneficial impact on the main task (driving) from the use of the HUI solution.

The limitations of these results are that the main task in the experiments have been simulated driving, and there is only one example of the experiments with the visual-haptic and one with the audio-haptic interfaces. More work is required to confirm the wider generalization of these results.

These conclusions suggest that HUI solutions introduced in this thesis should be used in the user interfaces used while driving. This could have a significant impact on driving safety with the modern driving environment where users use touchscreen devices embedded in their car and mobile devices while driving. Also, these results provide the haptic community and industry with an approach to develop fully haptified rhythmic tacton based HUI interfaces for the touchscreen applications.

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Paper I

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Perception Strategies in Modal-Redistributed Interaction

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Abstract

Computer interfaces provide information to users mostly graphically. This method of presentation is not suitable for the visually impaired or for users in situations where interaction is limited, like in mobile context. One possibility to present information to these kinds of users would be using melodic sounds and haptic feedback to replace graphical information. We describe a new method to redistribute graphical information to melodic sounds and haptic cues with a stick interface. We discuss the impact of this redistribution to user behavior in simple shape recognition tasks. Appropriateness of redistribution is evaluated and design recommendations given based on user behavior in modal-redistributed interaction.

1. Introduction

Traditionally information is presented graphically to users, which does not serve users in visually limited interaction situations. These kinds of situations are, for example, interfaces for visually impaired users and mobile users, who cannot concentrate on looking at the device used. Visual user interfaces do not provide good methods for presenting data to visually impaired users or in blind manipulation situations, like mobile interaction where minimal attention is a requirement that can be achieved by using audio and tactile feedback [6].

Especially blind users need other modalities if they are using mobile computing systems [1]. Often when using devices in mobile situations users have to watch presented data throughout all interaction, even if more applicable would be using interface blindly and check the results at the end of an interactive task. Even better would be, if information could be presented without visual feedback by using other modalities. Presenting graphical information without vision is a novel way to utilize haptic and auditory feedback. In this study we are suggesting an approach to present simple graphical objects using melodically varying sound and tactile feedback with a stick-manipulation interface to provide location cues in the user interface.

Spatial sound has been used in prototype systems for blind users to allow them collaborative entertainment [4] or methods for working with specific graphical data, like statistical data [7, 8]. Also haptic and auditory feedback together have been used in the same way, for building prototype systems for blind users [5] and designing non-visual systems for all users [3]. Still, there is a need for basic research: how to visualize without vision?

It has been proven that audio and tactile feedback can be used as additional modalities to visual information without adding mental load for users [10]. It is still not clear how visual feedback can be replaced with other modalities. When designing blind manipulation user interfaces, feedbacks should be consistent, the height of the sound could be used, and tactile feedback should be bound to static information [2]. It has also been shown that tactile and auditory feedback used correctly to support tasks will enhance user performance in blind manipulation [9].

In this paper we will introduce a new kind of interaction method using melodic sounds and tactile feedback with a two-dimensional stick for replacing visual modality. Simple recognition tasks were tested and the results provided information about non-visual interaction strategies in blind manipulation.

2. Interaction method and modality redistribution

Our approach to problem of blind interaction is to use melodic sounds to represent simple graphical objects and haptic feedback to help users to navigate in the information and feel the objects. A physical stick representing a line on the screen was used.

Interaction on the screen was provided so that the maximum number of simultaneous interaction points on the stick was limited to two. These interaction points were not fixed points on the stick, but points moved freely on the stick and dynamic feedback provided information about where the interaction points were located in the stick and on the screen. This provided a method to outline objects using a wide area of contact surface with a stick, and in this way providing locations of the interaction points.

Auditory feedback was provided using stereo speakers with stereo resolution for left-right spatial information and the pitch of the tone for up-down spatial information. Tactile feedback was provided through a physical stick attached to a small wireless mouse which users moved on an empty table to move the analogous stick on the screen. The users could also rotate the stick 90 degrees in both directions to inspect information from various directions.

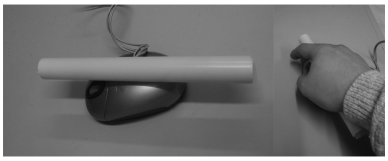

Figure 1: The stick used in the test.

The stick was built from a plastic tube (Figure 1). Two small electrical motors were attached to rubber plugs inside the heads of the tube to provide tactile feedback. Motors were attached with a cable to a Logitech iFeel mouse which was used to provide tactile feedback through Immersion drivers. Speakers were located behind the working area and sound was provided in stereo using left-right resolution. SoundBlaster Live! soundcard with 4 Mb general midi bank was used. The musical instrument to provide sound chosen for the test was violin. From several optional instruments tested it seemed that instruments which naturally have continuous sound scale suited better in this use than those that have discrete sound. I.e., organ, stringed instruments and wind instruments suited better than drums, guitars, piano etc.

Audio feedback was used so that every crossing the stick had with a line drawn on the screen caused a sound. The lower on the screen crossing was the lower the pitch was. Information on two crossings on the screen was provided by playing both tunes at the same time and the farther crossings were from each others, the louder the sound was. This provided a natural mapping between visual and audio by giving information higher pitch is up and lower pitch down.

Tactile feedback was used to provide spatial information so that crossing in the ends of the stick caused weaker vibration and in the centre of the stick stronger vibration. The lower end of the stick caused a lower frequency vibration and the upper end of the stick a higher frequency vibration. This gave users a direction where crossing occurred in the stick. This way the user got information about location on the screen through melodic sound and location on the stick through tactile vibration.

3. Test Setup

User behavior on blind manipulation situation was tested by giving the users various simple objects to be recognized. Users had two minutes of time to examine each object before they were asked to draw a picture of the object. Same tests were run with three conditions: Audio feedback only, tactile feedback only and audio and tactile feedback together. At the end users were asked to scan objects with all senses used; tactile, audio and visual feedback using as much time as they felt necessary in order to get a good visualization from the object with all three senses.

During tests stick movement paths including stick orientation were recorded. These paths were then compared in order to find out differences in user behavior in various conditions. The test assistant observed the users during tests to collect differences in user strategies. Users were also asked to comment freely their experiences while they drew the images.

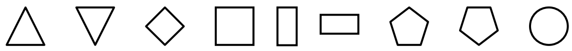

Figure 2: Used shapes and orientations.

The objects used in the test setup were geometrical shapes which included triangle, quadrangle, pentagon and circle in different orientations (Figure 2). The users were told that shapes are complete shapes, i.e., they are not consisting of several separate parts. However, the users were not told what kind of shapes they were, because in the test we wanted to measure how well the users could recognize unknown shapes instead of so called audio or haptic icon recognition. The same shapes and evaluation time were used as Sribunruangrit et al. [9] used in their testing. In our test setup, the users did not have the possibility to train with the recognition of objects and were not told what kind of shapes they are recognizing contrary to Sribunruangrit et al.'s test setup. This way we could see differences in recognition rates and have a hint of how much more difficult it is for the users to recognize unknown shapes than to select a correct one from a limited number of possibilities.

There were nine participants in the tests. All participants were sighted and experienced computer users with experience of computers from 9 to 25 years.

The subjects were mostly novices in blind use of computer systems.

The tests were run randomized in three sessions each of which included nine tasks done with one feedback mode and took less than an hour. In the last session comparison tasks with vision were ran at the end of the session. Randomization was used in task order and session order so that all subjects completed tasks in different order in different sessions and between each other. Also the order of feedbacks within subjects were varied. This eliminated possible learning effects from the results.

4. Results and discussion

The results consist of recognition percentage of shapes, subjects' scan strategy during perception tasks and observations done during the tests.

Contrary to recognition percentages by Sribunruangrit et al. [9], we got much lower recognition percentages shown in Table 1. While Sribunruangrit et al. trained their subjects to be familiar with the recognition tasks and told their subjects what kind of shapes to recognize, we had our subjects untrained and unprepared because we wanted to find out how well the users could recognize shapes without preconception of the shapes.

Table 1: Recognition percentages.

	Tactile	Audio	Audio&Tactile
Correct	6.2 %	12.4 %	7.4 %
Partially	27.2 %	29.6 %	51.9 %
Combined	19.8 %	27.2 %	33.3 %

As it can be seen in Table 1, completely correct answers were rare. Thus blind recognition of unknown objects by untrained users seems to be extremely difficult and user interfaces based on requirement of exact recognition of objects without vision cannot be recommended. However, the subjects recognized objects at least partially correct much more often. With partially we mean here a correct kind of shape which isn't exactly correct, for example an octagon instead of a circle, or a part of the shape, like a part of the correct angles or lines used in the shape. This result suggests that the users had a kind of non-exact image of objects in their mind. We also calculated combined recognition percentages where we gave one point from exactly correct answers and half a point from partially correct answers. The results were following what we expected: pure tactile is the worst alone, auditory feedback is better, and the best is the combination of these two.

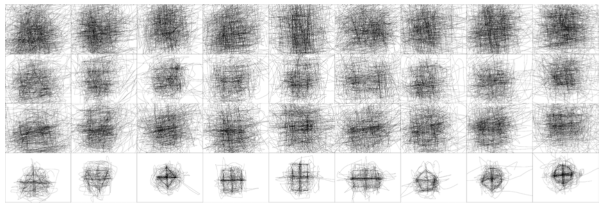

Figure 3: Combined scan paths.

Combined scan paths are presented in Figure 3. From left to right figures used in tasks are in same order as in Figure 2. The uppermost row is with tactile, second with audio, third with audio and lowest comparison task with vision. The subjects' stick movements from every task done in the tests were compared with full screen images and there was a trend in scan strategies. In pure tactile feedback the subjects used "scan the screen" strategy, where they scanned throughout the screen and movements were fumbling. With vision the movements were very determined and goal-oriented. Movements with audio, and tactile and audio together were pretty close to each other, but audio and tactile together were a bit more determined and reminding a bit more of scan paths with vision than those with pure audio feedback. Scan strategy with audio seems to be a little more kind of "scan throughout the object" and with combined audio and tactile "scan determined in certain path and figure out what the object is" like with vision.

So it seems that tactile feedback supports auditory feedback in blind use situation in the way that the users can better follow a determined strategy in recognition than with pure auditory feedback. Tactile feedback alone isn't helpful enough in perception tasks and thus user strategy is a fumbling "scan everything and try to figure out what it is".

Observations done during the test support these conclusions. The subjects got the most lost with pure tactile feedback and the least lost with combined audio and tactile feedback. Also while using audio and tactile feedbacks together the subjects found correct directions to the object faster and easier; i.e., when the stick crossed a line the subjects moved the stick to a correct direction toward the object more often with combined audio and tactile feedback than with the other conditions. The subjects could also pretty well follow the paths of lines that build the objects with auditory and combined conditions. This suggests that blind user interfaces using auditory and auditory-tactile paths to objects might be worth considering.

As the results show, people can easily follow combined haptic-auditory cues and keep their knowledge of location even without visual feedback. However, recognizing unknown shapes is extremely difficult. Earlier research results, however, show that recognizing auditory and haptic icons from a limited collection of possibilities is relatively easy. This leads to the conclusion that the best way to utilize haptic-auditory feedback would be using haptic-auditory guide paths to the information or function which could be recognized from learned auditory or haptic icon.

A possible way to use this information could be designing user interfaces for visually impaired people or for people in mobile or otherwise in non-visual control situation for information technology applications. For example, user interface of a home theater or mobile phone could be controlled with movements and feedback given with haptic and audio.

5. Conclusions

In this paper three conditions of user behavior in blind object recognition tasks were compared. The conditions used were providing information from objects through tactile, audio and combination of these two. The movements of the stick used in the tasks were recorded, and the scan paths and recognition percentages were compared.

The results showed that tactile feedback giving spatial information supported audio feedback that was used to substitute for visual feedback. Using combined auditory and tactile feedback caused users to scan objects in a more determined way and helped them to stay in focus with the objects. Exact recognition of objects seemed to be difficult and thus user interfaces based on requirement of exact recognition of shapes cannot be recommended. The users could follow the paths of lines well while provided with auditory feedback or auditory and tactile feedbacks together. This result suggests that auditory-tactile paths guiding users could be used in non-visual applications.

6. Acknowledgments

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Paper II

Pakkanen, T., Lylykangas, J., Raisamo, J., Raisamo, R., Salminen, K., Rantala, J., and Surakka, V. (2008). Perception of Low-Amplitude Haptic Stimuli When Biking. In *Proceedings of the 10th international Conference on Multimodal interfaces (ICMI '08)*, Chania, Crete, Greece, October 20–22, 2008. New York, NY: ACM, 281–284.

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Perception of Low-Amplitude Haptic Stimuli when Biking

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ABSTRACT

Haptic stimulation in motion has been studied only little earlier. To provide guidance for designing haptic interfaces for mobile use we carried out an initial experiment using C-2 actuators. 16 participants attended in the experiment to find out whether there is a difference in perceiving low-amplitude vibrotactile stimuli when exposed to minimal and moderate physical exertion. A stationary bike was used to control the exertion. Four body locations (wrist, leg, chest and back), two stimulus durations (1000 ms and 2000 ms) and two motion conditions with the stationary bicycle (still and moderate pedaling) were applied. It was found that cycling had significant effect on both the perception accuracy and the reaction times with selected stimuli. Stimulus amplitudes used in this experiment can be used to help haptic design for mobile users.

Categories and Subject Descriptors

H.5.2 [**Information Interfaces and Presentation**]: User Interfaces – *Evaluation/methodology, Haptic I/O.*

General Terms

Performance, design, experimentation, human factors.

Keywords

Tactile feedback, perception, mobile user, biking.

1. INTRODUCTION

Using haptic feedback provides several benefits compared to other modalities for mobile users. First, haptics can provide private information in a nonintrusive way. Second, with haptics it is also possible to provide information in the ways where users do not have to interrupt their actions, while still getting the information they need when moving. Several factors affect the design of haptic feedback in mobile situations. These include, for example, optimal stimulus parameters and low power consumption.

There has been some previous work on using haptic cues to provide information for mobile users. Most of the work on haptics in human-technology interaction (HTI) has focused on prototype studies. In these studies a haptic prototype has been built and tested to answer special needs of a mobile user. Other approaches have studied how haptic components should be designed and how users recognize and distinguish different haptic stimuli.

A number of studies have described which parameters can be used to encode information using single vibrotactile actuators. For example, van Erp [6] studied acuity of perception of vibrotactile stimuli on several locations on the torso. Brewster and his colleagues have done research on how to design and recognize information decoded into tactile icons (i.e., tactons) [1][3]. Often questions about perception of the stimuli are solved simply by providing large enough amplitudes to be perceived, so that research on distinguishing varying stimuli could be carried out. Another way is to create a tactile display by linking two or more actuators together to provide more versatile information for the user. (e.g., Piateski and Jones [4]).

Tactually enhanced user interfaces have also been created and tested with mobile users. Brewster *et al.* [2] proved that users benefit from vibrotactile cues in text entry tasks in distracting use situations. Van Veen and van Erp [8] showed that tactile information can be provided for the airplane pilots to reduce their visual information overload. They also observed that reasonable G-load did not affect the perception of the vibrotactile stimuli but decreased performance was reported close to the individual G-tolerance levels. Thus, based on this, it can be assumed that a similar phenomenon could also be found on the effects of the movement in perception. Tactile displays could be beneficial also in the sports, where haptic information can be used to maintain high performance more easily and with less effort, as van Erp *et al.* [7] proved in their study.

Van Erp's guidelines [5] based on psychophysical studies on vibrotactile perception in the context of HTI suggest that optimal stimuli would be long-lasting 200-250 Hz vibration on glabrous skin with fixed surroundings around the vibrating element. Van Erp concludes that threshold for the sensation of the haptic feedback varies widely between individuals and by age.

Optimal haptic stimulation would be perceived both when moving and when staying still. Furthermore, optimized feedbacks would also be more comfortable for the users willing to avoid unnecessarily high-amplitude feedbacks. Although it would be beneficial to have a rough limit for the lowest amplitudes to use in the field of haptic design, there is little if any research done on perception limits of the haptic feedback for the needs of mobile users in the field of HTI. Probably this is due to the fact that several variables are effective when sensing tactile stimuli. One factor is that it is difficult to measure those actual forces in between the contact point of skin and the actuator. Even skin properties vary individually a lot. For example, the amount of body fat and temperature do affect the sensitivity of tactile receptors. Furthermore, the technology as such can provide within stimulus variation which further creates difficulties for exact threshold measurements. For these reasons our aim was in general to find out whether and how much moderate physical exertion affects the perception of the vibrotactile stimulation.

2. EXPERIMENT

2.1 Participants

16 voluntary participants (3 females and 13 males) participated in the experiment (mean age 32 years, range 20-50 years). All of the participants were right-handed by their own report. One participant was rejected from the analysis due to missing all of the stimuli presented in both experiment conditions. Thus, the results are based on data from 15 participants.

2.2 Apparatus

In the experiment the participants were provided with vibrotactile feedback to four body locations (i.e., wrist, leg, chest, and back). Two motion conditions were used: sitting still on a stationary bicycle (i.e., immobile condition) and keep up a moderate bicycling pace (i.e., mobile condition). A mouse with a button was attached in the middle of the handlebars to provide user input. Data from the perceived stimuli was collected with the reaction times measured from stimulus onset to the response of a button push. The stationary bicycle used in the experiment was a Tunturi E40 ergometer[1].

Figure 1: Experimental setup.

Four actuators were attached in the non-dominant side of the body. Locations of the actuators were wrist (i.e., hairy side of the wrist, in the watch location), leg (i.e., above the knee between knee joint and quadriceps), chest (i.e., in the side of the thorax) and back (i.e., under the shoulder blade). Actuators in the leg and wrist were attached with an elastic Velcro strap and in the chest and the back attached under the partially elastic transmitter belt of the heart rate monitor (see Figure 1 for the actuator attachments). During the experiment participants listened to pink noise via a hearing protector headset to avoid responses based on the sound produced by the haptic actuators.

Vibrotactile stimuli in the experiment were provided by Engineering Acoustics Inc. C-2 actuators[2] driven through a sound card with WAV audio files. Stimuli were amplified with a StageLine STA 1508 eight-channel amplifier[3] which provides possibilities to accurately modify output amplitudes for separate channels. The stimuli were played and data collected with a C++ software ran on a powerful Windows XP PC. The system clock of the computer was used for timing the stimuli and the collected data. The software collected data from all the responses and reaction times calculated from the stimulus onset to the button down event. If participant pushed the button later than 2000 ms after the stimulus offset, the answer was considered to be late and not taken to the analysis.

2.3 Pilot Testing

The stimuli used in the experiment were selected through extensive pilot testing. The same participants that attended to the pilot tests were not used in the experiment. After the first pilot runs it was found that there is a need to look after appropriate stimuli amplitudes through extensive pilot testing, because exertion appeared not to have any effect on the perception. At first the idea was to use the same amplitudes in all locations and to compare the detection between different locations. However, it was soon found that the stimuli should be designed location-specific due to the differences in perception sensitivity. Because we were interested in whether the exertion affects the perception, we decided to adjust the stimulus amplitudes step by step closer to the perception limits of the participants to see whether the performance decreases or not.

The first pilot tests were carried out with one of the four actuators attached in the palm. However, the location was reported uncomfortable by the participants and the actuator was relocated in the back. The amplitude values for each location were varied from the maximum of the homogenous 250 mV to location-specific values of 20, 170, 40, and 40 mV for wrist, leg, chest, and back, respectively. It was also confirmed during pilot testing that there is variation between and even within the participants; the same participant could one day perceive all the stimuli in one location and another day miss all the same stimuli in the same location under the same clothing and environmental conditions.

2.4 Stimuli

Stimuli used in the experiment were 250 Hz sine wave mono WAV files with 44.1 kHz sample frequency. Stimulus durations used were 1000 ms and 2000 ms. Amplitudes varied based on actuator location and were selected for each location to be barely noticeable for the participants. These amplitudes were selected through extensive pilot testing so that on average the participants could perceive most of the stimuli in an immobile condition but not all of them in a mobile condition. Reason for this was that in pilot testing it seemed that the effect of the movement fades away if the stimuli were more intense than the stimuli close to the average perception limit. Thus, with higher amplitudes participants perceived all the stimuli, both in immobile and mobile conditions.

Amplitudes used in the experiment are shown in Figure 2 and accelerometer values for each location are presented in Table 1. The acceleration data was collected with DimensionEngineering DE-ACCM3D +/- 3g tri-axis analog accelerometer. The g values presented here are peak-to-peak accelerations analyzed from the 24800 samples gathered during 2500 ms intervals (10000

[1] http://www.tunturi.com/

[2] http://www.eaiinfo.com/

[3] http://www.monacor.de/

samples/s). During the measurement the C-2 actuator was placed firmly in a cut slot inside a matchbox filled with Bostik Blue-Tack reusable adhesive to eliminate unwanted resonance. Only the data from the z-axis was gathered for the analysis.

Table 1: Amplitudes of the stimuli.

Amplitudes	Back	Wrist	Chest	Leg
V	0.04	0.02	0.04	0.17
G	0.1760	0.1171	0.1760	0.4838
V/g	0.2273	0.1708	0.2273	0.3514

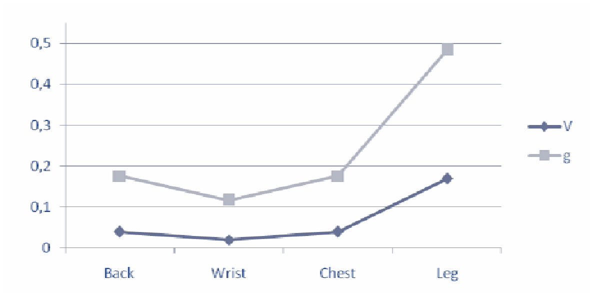

Figure 2: Stimuli amplitudes in volts and g-values measured by accelerometer.

During the experiment the participants were provided with a total of 40 stimuli, ten to each location. For each location a half of the stimuli were 1000 ms long and the other half were 2000 ms long. The stimuli were presented in the blocks to one location at a time. The order of the blocks was randomized between the participants by using Latin square table. Interstimulus interval varied randomly between 5000 ms and 10000 ms. 1000 ms and 2000 ms stimuli were presented randomly within each block.

2.5 Procedure

First, the participants were instructed to what they should do during the experiment and a background questionnaire was collected. The experiment was run in two blocks, each of which took approximately five minutes to complete. At first immobile condition was carried out to ensure that participants were not physically stressed as immobile condition was used as a reference to the exertion condition. In the immobile condition participants were sitting on the stationary bicycle and in the mobile condition they were cycling with a 50 W resistance. Participants were instructed to keep the pedaling rate between 45-55 rpm. They were also told not to interrupt the experiment if they failed to keep up the pace. Eventually, none of the participants failed to keep the requested pedaling rate during the experiment.

Participants were instructed to respond as fast as possible by pushing a button every time they felt a stimulus, even if they noticed it "late", for example, after the stimulus offset. They were asked to use their dominant hand to push the button. Thereafter, actuators were attached in their non-dominant side. The mouse was attached in the middle of the handle bars of the bicycle and in the handle bar there was a mark, over which participant should keep the thumb during the experiment.

After the instructions a block was put under the pedal of the bicycle on the participant's non-dominant side to prevent pedal movement during immobile condition (see Figure 1) and actuators were attached to the participant. Stimuli were introduced before the experiment by providing stimulation to all locations simultaneously for a couple of seconds. This gave participants a reference point for what to expect to feel during the experiment. Then the immobile condition was carried out. During the immobile condition the participant held the pedal towards the wooden block and sat still while receiving stimuli. After the immobile condition the participant was asked to step off the bike and stretch out a bit, while experiment setup was prepared for the mobile condition. After a short break participant was asked to sit on the bike again and mobile condition was carried out.

2.6 Data Analysis

Repeated measures analysis of variance (ANOVA) was used for statistical analysis. Pairwise Bonferroni corrected *t*-tests were used for post hoc tests. Stimulus locations were analyzed separately because the stimulus amplitudes varied through the locations.

3. RESULTS

3.1 Perception Rates

Mean perception rates and standard error of the means (SEMs) are presented in Figure 3. A two-way 2 × 2 (motion condition × stimulus duration) ANOVA showed a statistically significant main effect of the motion condition for the back $F(1, 14) = 8.2$, $p < 0.05$, the wrist $F(1, 14) = 7.0$, $p < 0.05$, and the leg $F(1, 14) = 9.5$, $p < 0.01$. The main effect of the stimulus duration was significant for the chest $F(1, 14) = 13.1$, $p < 0.01$. The interaction of the main effects was not statistically significant for any location. Post hoc pairwise comparisons for all locations individually showed that the participants reacted significantly more accurately in immobile than in mobile motion condition to the stimulation in the back $MD = 21.3$, $p < 0.05$, the wrist $MD = 20.7$, $p < 0.05$, and the leg $MD = 37.3$, $p < 0.01$. To the stimulation in the chest the participants reacted significantly more accurately to 2000 ms than to 1000 ms stimuli $MD = 10.0$, $p < 0.01$.

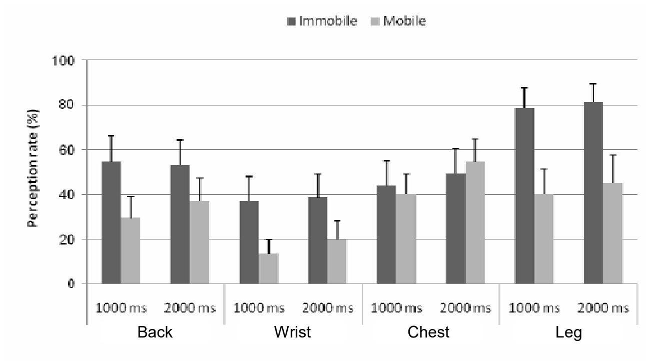

Figure 3: Mean ratings and SEMs for perception rates of the stimuli by motion condition, stimulus duration, and location.

3.2 Reaction Times

Mean reaction times and SEMs are presented in Figure 4. A two-way 2 × 2 (motion condition × stimulus duration) ANOVA showed a statistically significant main effect of the motion condition for the back $F(1, 14) = 21.9$, $p < 0.001$. The main effect of the stimulus duration and the interaction of the main effects were not significant for this location. A statistically significant interaction effect of the motion condition and stimulus duration was found for the wrist $F(1, 14) = 5.5$, $p < 0.05$, the chest $F(1, 14) = 6.6$, $p < 0.05$, and the leg $F(1, 14) = 14.2$, $p < 0.01$. As it can be seen from Figure 4 the interactions were due to the fact that the participants reacted faster to the 2000 ms stimuli than to the 1000 ms stimuli in immobile condition and the other way around in mobile condition. Thus, two separate one-way ANOVAs were performed for wrist, chest and leg locations. These analyses revealed a significant effect of the motion condition for the wrist $F(1, 14) = 18.1$, $p < 0.001$ and the chest $F(1, 14) = 26.1$, $p < 0.001$, but not for the leg. The effect of the stimulus duration was not statistically significant for any of the three locations. Post hoc pairwise comparisons for all locations individually showed that participants reacted significantly faster in immobile than in mobile motion condition for the stimulation in the back $MD = 289.1$, $p < 0.001$, the wrist $MD = 344.9$, $p < 0.001$, and the chest $MD = 553.0$, $p < 0.001$.

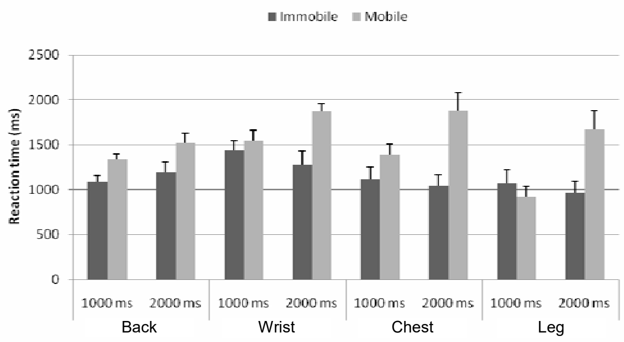

Figure 4: Mean ratings and SEMs for reaction times to the stimuli by motion condition, stimulus duration, and location.

4. DISCUSSION AND SUMMARY

We found that lower amplitudes than the ones commonly used today can be applicable for haptic feedback, and thus, there are possibilities to lower power consumption by optimizing stimuli amplitudes. van Veen and van Erp [8] found that the G-load on the fighter pilot did not have an effect on the recognition of the stimuli until being close to the G-tolerance limits of the participants. It seems that a same kind of phenomenon can be found with physical exertion close to the perception limits of the participants.

Our results showed that movement had statistically significant deteriorating effects on the perception and reaction times of tactile stimulation when stimulus amplitudes were close to the perception limits of the participants. However, in any of the conditions the perception did not totally drop to zero. For reaction times it is noteworthy that in immobile condition the 2000 ms stimuli were reacted faster than 1000 ms stimuli. These results can have different implications for designing haptic stimulation guidelines for mobile and immobile applications. Therefore, when providing clearly noticeable vibrotactile cues, which can be perceived when not moving, the cues should be perceived also when moving with low physical exertion. However, when providing very low-level stimulation, motion condition of the user has to be taken into account and haptic stimulation has to be modified based on the user's level of exertion.

We found that the wrist needed less than 0.12 g vibratory stimuli to be barely perceived, while the chest and the back required 50% (0.18 g) and the leg 300% (0.48 g) higher amplitudes (see Table 1). Exceeding these values with a fair tolerance should be better perceived by both immobile and mobile users when using vibrotactile actuators attached to the skin, like the C-2 actuators used in this experiment.

Stimulus duration did not have a significant effect on the the reaction times or perception rates for other locations than the chest. Thus, it seems that 1000 ms stimuli are long enough to be perceived. Based on our experiment we cannot, however, argue that stimulus duration does not have an effect at all, but more research is required with longer and shorter stimulus durations.

To summarize, the results showed that movement had an effect on the perception rates and reaction times in most locations studied when low level amplitudes were used. Because of this, we suggest using slightly higher amplitudes for mobile users than immobile users when using very low amplitude haptic stimulation.

5. ACKNOWLEDGMENTS

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Paper III

Pakkanen, T., Raisamo, R., Raisamo, J., Salminen, K., and Surakka, V. (2010). Comparison of Three Designs for Haptic Button Edges on Touchscreens. In *Proceedings of the Haptics Symposium 2010 (Waltham, MA, USA, March 25–26, 2010)*. IEEE, 219–225.

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Comparison of Three Designs for Haptic Button Edges on Touchscreens

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ABSTRACT

Systematic research on haptic stimuli is needed to create suitable haptic feeling for user interface elements. In this study we compared three alternative designs for creating haptic edges for buttons. All the designs compared are based on the physical parameters of graphical user interfaces and thus they are applicable for different kinds of user interfaces. A handheld prototype device with haptic feedback created by piezoelectric actuators integrated in the touch screen was used in the experiment. The designs used were minimalistic (*Simple*), direct transformation of visual pixels to haptic pixels (*GUI transformation*) and iterative design (*Designed*). The amplitude, the number of haptic bursts (*haptic pixels*) and the delay between the bursts was varied in this experiment. The results showed that the most promising designs were Simple and Designed. Less haptic bursts and less delay between the bursts were preferred by the users. The preferred level of the amplitude varied and thus should be adjustable.

KEYWORDS: Haptic feedback, User interfaces, Design, Mobile user.

INDEX TERMS: H.5.2 [Information Interfaces and Presentation]: User Interfaces – Evaluation/methodology, Haptic I/O.

1 INTRODUCTION

Human being is by nature a multimodal being. In all interaction with our environment we use touch together with vision while manipulating items in our environment. With haptic cues we can do many tasks by touch after having a glimpse of the task environment, like tying up our shoelaces. This unfortunately is not the reality with modern mobile touch devices, where interaction metaphors are similar to real world interaction. A problem arises here, when it is known that interaction with mobile devices in the mobile contexts is usually split in small fragments, while users have to pay attention to the environment [13]. They use devices by direct touch and manipulate virtual elements, but without the haptic feeling of the elements on the screen. However, many of the modern devices have tactile actuators, which could make it possible to create haptic representation for graphical user interface elements. This approach would make it possible to add haptic information cues for the users of the devices to describe the items they are manipulating.

In the current state of the haptics research, there is a lack of information about how to design haptic cues for the components used in the user interfaces and how to represent GUI primitives as haptic primitives. However, in the research for the haptic user interfaces (HUI) representing graphical user interfaces the design problems should be taken into account [5].

In this study, we compared three designs for creating haptic cues to represent button edges on a touch screen device. For this first study about haptic primitives, the edges were selected, because they are basic primitives for the graphical components and they can also help finding the GUI elements on the screen by utilizing touch. The aim of this study was to compare three different approaches to build haptic description for the edges, to compare the affect of the parameters of haptics involving each design and to find out which design and parameters gives the users the best haptic “image” of an edge.

The approach for this purpose was to use haptics as an additional aid for vision rather than supporting complete blind usage of the device. This approach was selected because it is known that blind usage of complex information systems is rather difficult, even with well built multimodal aids for visually impaired users [9] who are accustomed to use information technology with limited aids. This could make complete blind usage of the devices almost impossible for the sighted users who are not used to act solely relying to the touch.

2 RELATED WORK

There have been several experiments which have proven that haptics improves performance and user experience. For example, in a menu selection task by a tilting gesture, haptics improves performance and it is preferred by the users [2]. Haptics is also preferred while used together with audio. For many users, combined haptics and audio seem to improve subjective feeling about the audio quality [3]. Haptics also improves task times with selection tasks when using the stylus, even though haptic confirmation is received after the task. Thus, using haptics likely makes users more comfortable with tasks and they perform faster in the following tasks [7]. Improvement in performance has also been reported in the scrolling tasks and progress bar tasks [8], though in the latter experiment, the improvement in the button selection tasks could not be confirmed. Difference in the results about button selection task performance can be argued to be depending on the task formulation. While in the first experiment haptics confirmed successful selection, in the second experiment visual confirmation of correct selection (number) was required. Thus, it seems that haptics improves the performance in selection tasks when no cognitive confirmation is required and the task is repeating. Improvement in the virtual keyboard writing tasks [14][17] also supports the interpretation that haptics improves the performance in some selection based tasks. Based on these earlier results, it seems clear that haptic feedback is beneficial and preferred in selection based tasks and also preferred when enhancing audio. It is also known that haptics improves performance most with more difficult drawing-like gestures [11]. Thus, using haptics is beneficial at tasks where a pen or finger movement is required on the screen with accuracy, but also haptic confirmation signals, for example for selections should be provided.

It is known that visual feedback together with audio is more effective in single tasks and under normal workload conditions, while tactilely enhanced visual feedback is the most effective with multitasking and high workload conditions [4]. This supports the approach to use tactile feedback in the mobile context, where attention is divided [13] and user multitasking between the device and the environment in complex usage situations. This leads to the conclusion that primarily in the HUI there should be haptic cues for graphical elements, which are either interacted with or found by pen or finger gestures. Secondarily, the confirmation haptic stimuli are also beneficial.

In the present study this has been taken into account by experimenting with the edges which are basic primitives for the graphical components. With haptic edges users can find the GUI elements on the screen by drawing gestures on the screen. Secondarily, the confirmation haptic stimuli are also beneficial, which is taken into account by representing whether user moves the finger over the edge to or off the component in two designs out of three used. In these two designs, participants could know if they were moving over the edge towards or away from the component. Also knowledge that users can easily learn and recognize abstract meanings for the haptic stimuli [12][16] supported the approach that experiment participants could understand the meaning of towards and away stimuli.

There is some research regarding which parameters to use for creating haptic stimuli describing the graphical elements. In the recognition of tactile stimuli the best parameters were rhythm, spatial location [6] and waveform modulation [1][15] compared to speed of the moving stimulus [1], amplitude [1][15], duration [1] and frequency [15]. Amplitude was the best parameter for describing the size [10]. In this experiment stimuli were created by changing rhythm and waveform in two out of three designs. In the third one, the Simple design, the amplitude was used as the varied parameter.

There have been some user interface prototypes with haptically enhanced components, which have been reported to be approachable and usable by the experimenting users. Different haptic stimuli have been used, for example, for the selection tasks (buttons, menus, etc.) [18][20][22], for the dragging tasks like scrollbars or window resize [18][22], movement on the items like in the menu, the list or drawing on previous lines or items [20][22] or the temporal tasks like progress bar or holding the button at the end of the scrollbar [21][18]. All of these experimental prototypes have shown that haptic components in the GUI are beneficial and preferred by the users. Also some primitives of the components have been built and experimented with promising results. For example, similar to our experiment, the buttons have been haptically enhanced with a "Pop" when entering in the button, with vibration on the button, and with a pulse when leaving the button [19].

Even though several proof of concept prototypes with haptically enhanced graphical user interface elements have been built, there is a lack of research on systematic approach for finding out how to design haptic counterparts for the graphical primitives and how different haptic parameters affect user impression of those haptic primitives.

In the present study we focused on the edge of a button, the basic graphical interaction component. We selected three promising approaches for haptic design and systematically varied parameters to study which designs and stimuli were the most representative for the edges.

3 EXPERIMENT

3.1 Participants

20 voluntary participants (3 females and 17 males) participated in the experiment (mean age 31 years, range 22-41 years). 17 of the participants were right-handed by their own report. None of the participants reported constraints with vision, hearing and sense of touch. One participant was rejected from the analysis due to inability to separate any of the stimuli used. Thus, the results are based on data from 19 participants.

3.2 Apparatus and Software

The haptic device used in the experiment was a prototype device based on Nokia 770 internet tablet. The prototype was equipped with a piezoelectric actuator solution which was embedded under the touch screen of the device. By utilizing this actuator technology we were able to produce tactile feedback on the touch screen with various pulse shapes and displacement amplitudes. The sharpness of the pulses was controlled by the current fed to the piezoelectric actuator and the displacement amplitude by the driving voltage [23]. Using this setup haptic feedback could be triggered by the touch and felt under the finger pressing the touch screen. The device was capable for creating short haptic bursts, like “clicks”, the feeling of which can be adjusted (crispness, sharpness and amplitude) by regulating input voltage, current and load timings. The stimuli used were composed of these short bursts.

The software used in the experiment had nine standard GTK buttons in a 3 × 3 grid (Figure 1). Every button had a different tactile stimulus describing the edges of the button. The stimuli were repeated every time the participant moved a finger across the edge. In the first stimulus design, the stimuli were the same both when moving inside the button and when getting away from the button. In other two designs, there were different stimuli for moving inside the button and getting away from it.

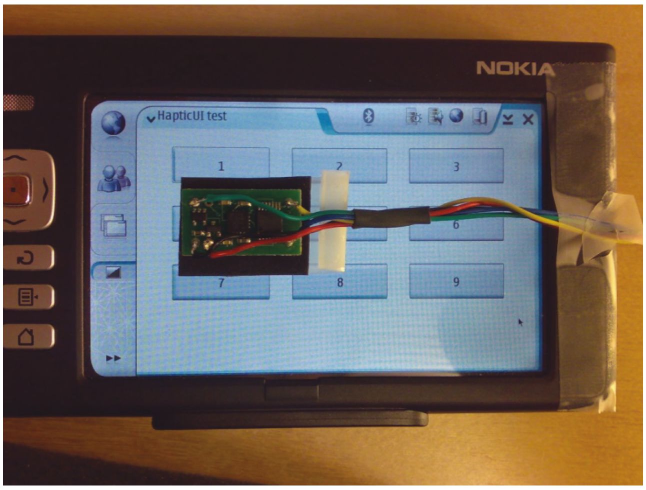

Figure 1: The experimental software with an accelerometer used to measure the amplitude of the stimuli.

3.3 Stimuli

There were nine different stimuli: three categories and three stimuli in each of the categories. The stimuli were organized as a button grid where each row had one category of haptic stimuli, and one parameter was varied between the three buttons in that row. Stimulus categories were based on three different designs to create the haptic stimuli. These designs were Simple, GUI transformation and Designed.

The stimuli in the *Simple* design were single bursts and the same stimulus was used whether moving towards or away from the button. The amplitude of the burst was varied between the buttons. In this design a simple stimulus was given to mark the edge of the button.

In the *GUI transformation* design stimuli were combined from several bursts. When moving over the button edge, burst amplitude was raised burst by burst from the minimum to the maximum when moving towards the button and from the maximum to the minimum when moving away from it. The number of bursts was varied from two to four between the buttons. In this design bursts represented pixels on the screen, and the amplitude was used to represent the height of the pixel in 3-dimensional button edge. The number of bursts represented how many pixels were given as feedback. The interval between the bursts was 6 ms.

In the third design used, *Designed*, stimuli were designed by iterative selection and method for building up the stimuli selected by the designer based on the naturalness and the feeling of the stimuli. Most haptic interaction is created today with a similar method. In this design stimulus, when moving off the button, was a single burst (the same as the middle amplitude from the simple design), which feels like slipping off the button. Stimulus, when getting on the button, was composed from two bursts, where the first burst was more powerful (the maximum amplitude from the simple model) and the second burst was weaker (the minimum amplitude from the simple model). This felt like a crisp edge which a finger collides with. The delay between two bursts was varied as 3, 6 and 11 ms.

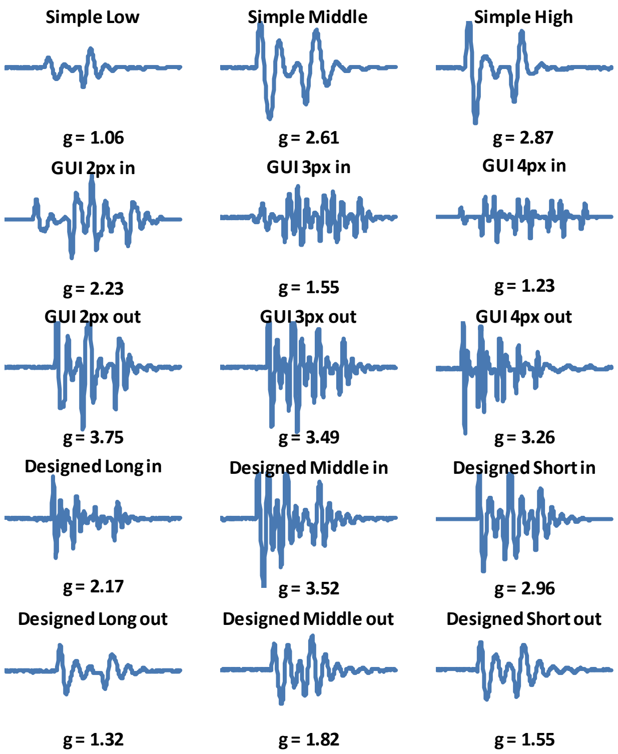

Figure 2: The measured stimuli vibration shapes and peek-to-peek *g* values.

The stimuli were measured with the DimensionEngineering DE-ACCM3D +/- 3g tri-axis analog accelerometer. The *g* values presented here are peak-to-peak accelerations analyzed from the 24800 samples gathered during 2500 ms intervals (10000 samples/s). Only the data from the z-axis was gathered for the analysis. Vibration shapes of the measured stimuli and peek-to-peek *g*-values of the stimuli are shown in Figure 2.

3.4 Procedure

As the aim of this experiment was to find out the effect of design approaches and haptic parameters to the user impression of a haptic edge, subjective data measurement was used as the method. Thus, rather than creating, for example, input tasks and measuring performance, participants were asked to rank the stimuli with the reasoned answers. With this method, some conclusions about parameters affecting user impression of edges could be made.

There were five ranking tasks for the participants. In each task the participants were asked to compare given stimuli and to rank them. There was no time limit and the participants were allowed to compare stimuli as long as they felt was needed. They were asked to give a considered opinion, opposed to making their opinion at first impression. The expected outcome was to find out which stimuli would fit best for real user action.

The participants were asked to give a different rank for each stimulus, if they had any impression, however faint, that there was a difference in the stimuli. They were allowed to give the same ranking for several stimuli only if they were absolutely certain that those stimuli were the same. Based on interviews after the experiment, mostly the participants did distinguish stimuli from each other. In the data analysis rankings were counted so that if two stimuli got the same ranking (for example the first) then the third stimuli got its ranking after the ones the first two had taken (thus the third, when the two first slots were taken). A similar method is used for rankings in the sports results.

The participants were asked to give a reason for their selection for the ranks. This was due to forcing the participants to compare the stimuli with thought, not just by feeling “which is nice”. They were asked to select rankings with the thought that which one feels the most like an edge. Thus, the expected outcome was to find the most descriptive and natural stimuli for describing the edges.

The first three tasks were called *Ranking within the designs*, where the task was to rank stimuli within a design one by one. Thus, the task was to select from three stimuli at time which one is the best, the second and the third from the button grid row by row; first to rank the Simple design in row one, second to rank the GUI Transformation design in row two and third to rank the Designed design in row three. Because at each task the task was to compare stimuli within the row and rank them within each other, not to compare for other designs and rank to them, it was considered that randomizing the order was not needed. Thus, earlier tasks should not have affected comparison of other stimuli.

The fourth task was *Ranking of the designs i.e.* to compare button rows generally with each other. Thus, the task was to select which is the order for the designs used to create the stimuli generally. The last task was to select *the three best stimuli* out of all nine. In this task users were asked to compare all the edges and select three stimuli best describing the edge and put them in the order for the 1st, 2nd and 3rd.

The last two tasks were given in this order providing more time and experience for the participants from different stimuli so the stimuli would be more acquainted for them. Thus, in generic ranking of the designs the participants had some idea of all the stimuli to more easily compare them. And for selecting the three best they had most experience of all the stimuli. With this approach the aim was to minimize answers made by first impression and, thus, get the answers which would be more considered and would be more applicable for deciding which kind of stimuli would be better for longer term usage in the applications.

3.5 Data Analysis

Non-parametric Friedman's rank test was used for statistical analysis for data from each task. Non-parametric Wilcoxon signed-ranks test were used for pairwise comparisons of results within each task.

The analysis of the last task, selecting the three best stimuli, was done in two parts: 1. In the same way as for the other tasks and 2. The stimuli were divided to three groups, based on the results of Wilcoxon signed-ranks test pairwise comparisons.

Grouping was done with a method where for the group "Best" were selected the stimuli which were statistically better than all in the group "Worst". *I.e.* for the "Best" and the "Worst" groups were looked after all the stimuli, which had significant differences with each others, but had no significant difference within the group.

For the "Middle" group were put those stimuli, which had not so clear statistical difference to others, *i.e.* stimuli either had no statistical difference to some stimuli from both "Best" and "Worst" groups, or did have statistical difference to at least one of the stimulus in the group, it could otherwise have been put in. Thus, within any of these groups were no statistical differences between the stimuli and they could be considered as equally good. All the stimuli between the "Best" and the "Worst" had a statistical difference.

Groups were formed by combining the data in the way, that each group's data units got the best ranking from the corresponding data units from the stimuli included in that group. Thus, each group got 19 data units, as all the stimuli had. For each participant, the group got one ranking value: 1^{st}, 2^{nd}, 3^{rd} and not selected for the best three stimuli. This value was the same as the best ranking the participant had given for all of the stimuli included in the group.

This grouping had two goals. First, to find out, were the "Best" group significantly better than other groups. Second, find the group of the best stimuli, so there could be found common features in the parameters of the best stimuli and from these features discussed what haptic features makes the best haptic edges.

4 RESULTS

4.1 Rankings within the Designs

Frequencies of the rankings as the first for each design are presented in Figure 3. Friedman's rank test showed a statistically significant main effect of the number of haptic pixels in GUI Transformation design $X^2 = 26.48$, $p < 0.001$. Wilcoxon signed-ranks tests showed that three haptic pixels ($Md = 2{,}00$) was ranked better than four haptic pixels ($Md = 3.00$), $Z = -3.273$, $p < 0.001$, two haptic pixels ($Md = 1.00$) was ranked better than four haptic pixels ($Md = 3.00$), $Z = -3.894$, $p < 0.001$ and three haptic pixels ($Md = 2.00$), $Z = -2.970$,$p < 0.01$. Differences in the Simple and Designed designs were not statistically significant.

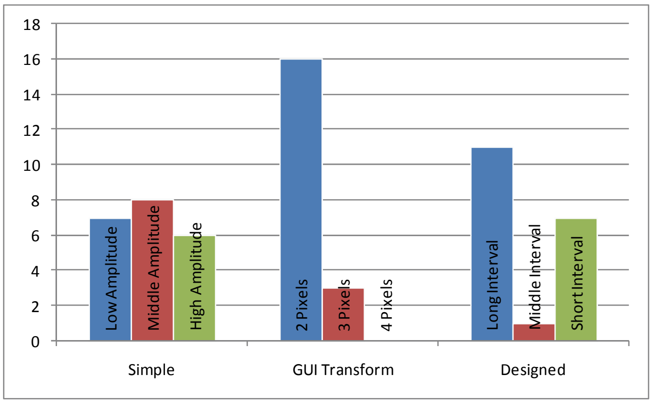

Figure 3: Rankings as first within each design

4.2 Ranking of the Designs

Frequencies of the rankings of designs are presented in Figure 4. Friedman's rank test showed a statistically significant main effect of the design method, $X^2 = 17.158$, $p < 0.001$. Wilcoxon signed-ranks tests showed that Simple design ($Md = 1.00$) was ranked better than GUI Transform design ($Md = 3.00$), $Z = -3.697$, $p < 0.001$ and that Designed design ($Md = 2.00$) was ranked better than GUI Transformation design ($Md = 3.00$), $Z = -3.697$, $p < 0.05$. There was no statistically significant difference between Simple and Designed designs.

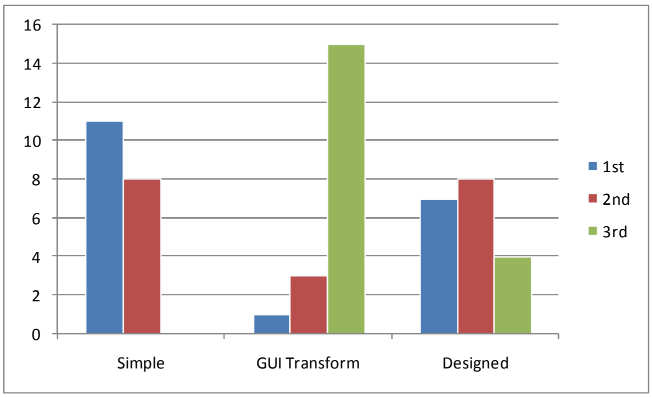

Figure 4: Frequencies of the rankings of designs.

4.3 The Three Best Stimuli

Frequencies of the selection of each stimulus to be one of the best three out of nine stimuli are presented in Figure 6. Friedman's rank test showed a statistically significant main effect of the rankings for stimuli, $X^2 = 35.23$, $p<0.001$. All the significant Z and p values of Wilcoxon signed-ranks tests can be seen in the Figure 5. Significant differences are marked with a highlight colour. Shortly summarized, Low and high amplitude simple, and middle and short interval designed stimuli (Group "Best") were all significantly better than 3- and 4-pixel GUI transformation (Group "Worst"). Middle amplitude simple, 2-pixel GUI transformation and long interval designed (Group "Middle") had significant differences with some of the other stimuli and did not have between some of them. Due to this indefiniteness with group "Middle" stimuli an additional analysis was made with comparison of the stimuli between these groups.

Groups: **Best**, Middle, *Worst*	**Low Amplitude Simple**	Middle Amplitude Simple	**High Amplitude Simple**	2-pixel GUI Transformation	*3-pixel GUI Transformation*	*4-pixel GUI Transformation*	Long Interval Designed	**Middle Interval Designed**	**Short Interval Designed**	
Low Amplitude Simple				Z= -2.192 p=0.028	Z= -2.842 p=0.004	Z= -2.913 p=0.004				p < 0.05
Middle Amplitude Simple					Z= -1.983 p=0.047	Z= -2.232 p=0.026		Z= -2.066 p=0.039		p > 0.05
High Amplitude Simple				Z= -2.360 p=0.018	Z= -2.724 p=0.006	Z= -2.701 p=0.007				
2-pixel GUI Transformation	Z= -2.192 p=0.028		Z= -2.360 p=0.018					Z= -2.221 p=0.026		
3-pixel GUI Transformation	Z= -2.842 p=0.004	Z= -1.983 p=0.047	Z= -2.724 p=0.006					Z= -3.154 p=0.002	Z= -2.835 p=0.005	
4-pixel GUI Transformation	Z= -2.913 p=0.004	Z= -2.232 p=0.026	Z= -2.701 p=0.007				Z= -2.060 p=0.039	Z= -3.228 p=0.001	Z= -2.980 p=0.003	
Long Interval Designed						Z= -2.060 p=0.039				
Middle Interval Designed		Z= -2.066 p=0.039		Z= -2.221 p=0.026	Z= -3.154 p=0.002	Z= -3.228 p=0.001				
Short Interval Designed					Z= -2.835 p=0.005	Z= -2.980 p=0.003				

Figure 5: Pairwise comparisons of stimulus rankings.

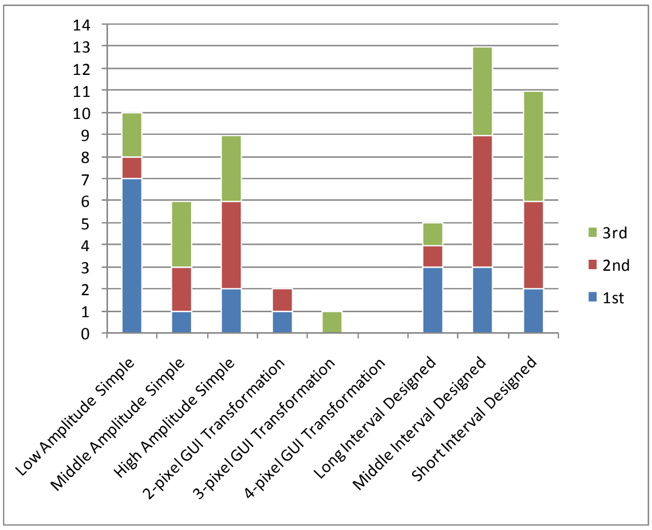

Figure 6: Selections for top-3 of each stimulus.

4.4 Grouped stimuli

In the additional analysis of the differences on the ranking of the best stimuli, above mentioned groups were formed by combining the data in the way, that each group's data units got the best ranking from the corresponding data units from the stimuli included in that group. Thus, each group got 19 data units, as all the stimuli had. For each participant, the group got one ranking value: 1^{st}, 2^{nd}, 3^{rd} and not selected for the best three stimuli. This value was the same as the best ranking the participant had given for all of the stimuli included in the group. Frequencies of these rankings are presented in Figure 7. Friedman's rank test showed a statistically significant main effect of the rankings for the groups, $X^2 = 24.269$, $p < 0.001$. Wilcoxon signed-ranks tests showed that The best stimuli group ($Md = 1.00$) was ranked better than the middle ($Md = 2.00$), $Z = -2.87$, $p < 0.005$ and the worst ($Md = 3.00$), $Z = -3.981$, $p < 0.001$ and that the middle stimuli group ($Md = 2.00$) was ranked better than the worst ($Md = 3.00$), $Z = -2.85$, $p < 0.005$.

Thus, stimuli could be ordered in the groups of the best stimuli to use, the stimuli that are neither the best, nor the worst, and the worst stimuli which should not be used in any situation. Discussion about common features of the haptic parameters that should be taken account for creating good haptic edges can be found in the discussion.

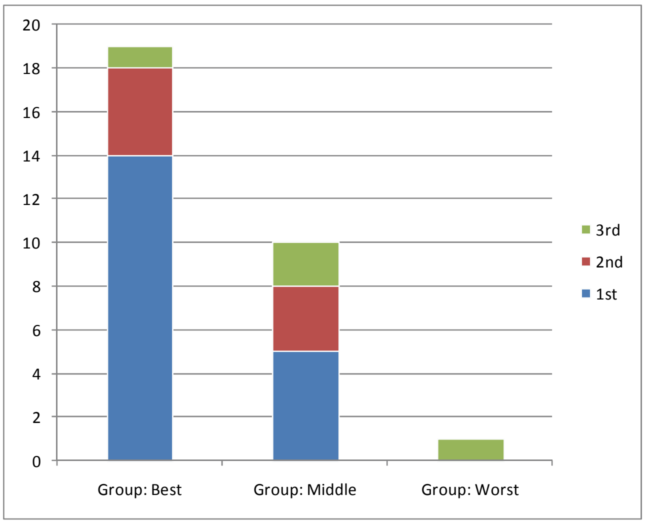

Figure 7: Selections for top-3 of each group of stimuli.

5 DISCUSSION

The aim of the present experiment was to find out how different haptic parameters affect the experience of feeling the edge of the component and which kind of transformation methods from GUI representation to haptic representation would be most applicable for natural and intuitive representation of the edges.

While examining results within the designs, some conclusions can be made from the parameters used. When talking about edges, the number of haptic pixels and length of the stimuli should be as low as possible, as can be seen from the results within GUI Transformation design. This came up also with participant comments during the experiment. Longer stimuli with more haptic pixels were often commented to be too fuzzy. Sharp fast stimuli were more preferred. GUI Transformation method would be interesting to experiment in the future with devices with faster actuators, where stimulus length could be shortened to be as fast as they were in the Simple and Designed designs. With these results it cannot be said, if direct pixel transformation from graphical to haptic could be a functional method for creating haptic representation or not. Based on the comments of the participants, the most debilitating factors for the GUI Transformation design compared to the others were too long and fuzzy stimuli which could be improved by using a device capable for the faster haptic actuation.

While examining results from the Designed design, at first, it seems that the delay between the pulses does not affect experience. Comparison within method did not show any significant differences on the results. However, when studying selections from a larger set of stimuli, the task where the participants selected the three best stimuli, it can be seen that stimuli with shorter delays were more preferred than stimulus with longer delay. Participants' comments about the sharpness and fuzziness of the stimuli support this result.

These results differ a bit from earlier studies, where speed and duration of the stimuli did not have that big impact [1], but this can be dependent on the task and haptically represented information. Thus, requirements for speed and duration of the stimulus should be taken into account depending on information presented.

Amplitude varied in the simple method did not affect results, thus amplitude level can be set based on user preferences: amplitude level should be adjustable for optimal representation. This could be compared to the volume setting on the audio. This result supports earlier studies, with a conclusion that amplitude is not the best choice for parameter used for recognition tasks [1][15], but rather possible for the description for the size [10].

When the participants selected three best stimuli out of all the stimuli, it can be seen that there are three different groups formed by popularity of the stimuli. The most preferred were shorter delay Designed and both low and high amplitude Simple stimuli. Common for these stimuli is a sharp and fast effect which was also preferred in subjective comments during the experiment. Fuzzy and longest GUI transformation stimuli formed the "Worst" group.

The middle group was formed from two remaining stimuli, middle amplitude Simple and the shortest GUI transformation. Even though middle amplitude Simple stimulus did not differ from other two ones in the comparison within the method, it seems that it may be so that users prefer a bit more either high or low amplitude, while selecting stimulus from a larger set of stimuli. A bit better popularity with the Shortest GUI transformation stimulus indicates that the direct GUI transformation method may be usable, if the stimuli could be repeated fast enough to make them clear and sharp.

Thus, the least popular GUI transformation stimuli could be made better by faster stimulus, which would be more clear and sharp. The device used in this experiment could not perform faster without errors, so this could be an interesting experiment to run with more capable device in the future.

Within the most popular groups, there were two kinds of stimuli, symmetric Simple and asymmetric Designed. In this experiment there were no differences in the results between symmetric and asymmetric stimuli. However, in the instruction this difference was not emphasized anyway, because participants did not get any information beforehand about what kind of stimuli were used. This was chosen to be able to get unaffected opinions about the stimuli. An interesting experiment in the future would be to instruct the users beforehand about symmetric parameters of the stimuli, and to guide them to select if symmetric (i.e. user could not separate stimulus while moving on or off the element) or asymmetric (i.e. there is a difference between the stimuli, while moving on or off the element) stimuli would be better for describing the edges of graphical elements on the screen. As the results now indicate, either preference on symmetry is divided, one likes the other one or another likes the other one, or then users do not have any preference on the matter and other parameters affected more for the preferences of the participants. However, a bit crisp, but sharp, faster Designed asymmetric stimuli were two the most popular stimuli, even though they did not differ significantly from the symmetric Simple stimuli. These results support earlier studies about that best parameters would be waveform modulation [1][15] and rhythm [6].

We expect that our results can be generalized for common phones, which are using rotating motor actuators at the present time. The results of earlier technology transfer of Vibrotactile Braille [24] which was developed using the same device as we used were promising. A prototype software has been successfully developed and published for commercial phones[1]. Thus, results gained when using the device used in this experiment are in a certain extent generalizable for consumer devices using rotating motor actuators.

6 CONCLUSIONS

A few conclusions can be made about the parameters of the haptic stimuli describing edges of the graphical elements on the screen. First, the amplitude should be adjustable with similar methods as audio volume. It is a personal preference for each user, how large amplitude is appropriate. Second, fast, clear and sharp stimuli are needed. Any fuzziness in the stimuli makes it feel bad and makes users lose the contact on the edge. Third, a bit crisp but fast asymmetric stimulus is a good choice, as well as a clear simple symmetric stimulus. Which one to select depends more on if there is a need to inform users about if they are moving on or off the element on the screen.

7 ACKNOWLEDGMENTS

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Paper IV

Toni Pakkanen, Roope Raisamo, Katri Salminen, and Veikko Surakka. (2010). Haptic Numbers: Three Haptic Representation Models for Numbers on a Touchscreen Phone. In *International Conference on Multimodal Interfaces and the Workshop on Machine Learning for Multimodal Interaction (ICMI-MLMI '10)*. New York, NY: ACM, Article 35, 1-4.

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Haptic Numbers: Three Haptic Representation Models for Numbers on a Touch Screen Phone

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ABSTRACT

Systematic research on haptic stimuli is needed to create viable haptic feeling for user interface elements. There has been a lot of research with haptic user interface prototypes, but much less with haptic stimulus design. In this study we compared three haptic representation models with two representation rates for the numbers used in the phone number keypad layout. Haptic representations for the numbers were derived from *Arabic* and *Roman* numbers, and from the *Location* of the number button in the layout grid. Using a Nokia 5800 Express Music phone participants entered phone numbers blindly in the phone. The speed, error rate, and subjective experiences were recorded. The results showed that the model had no effect to the measured performance, but subjective experiences were affected. The Arabic numbers with slower speed were preferred most. Thus, subjectively the performance was rated as better, even though objective measures showed no differences.

Categories and Subject Descriptors

H.5.2 [**Information Interfaces and Presentation**]: User Interfaces – *Evaluation/methodology, Haptic I/O.*

General Terms

Performance, Design, Experimentation, Human Factors.

Keywords

Haptic feedback, User interfaces, Design, Mobile user.

1. INTRODUCTION

In the current state of the haptics research, there is a lack of information about how to design haptic cues for the components used in the user interfaces as well as how to represent GUI primitives and information haptically. However, in the research on haptic user interfaces (HUI) corresponding to graphical user interfaces the design problems should be taken into account [11]. With an attractive design people tend to value the usability of the device, even more than with more efficient but less attractive device [9].

In this study, we compared three designs with two representation rates for creating haptic cues to represent numbers on a touch screen device. The aims of this study were to compare three different approaches to define haptic descriptions for the numbers, to compare the effect of the representation models of haptic numbers to user performance and satisfaction, and to find out which representation model would be the best for the users.

Improvement in the virtual keyboard writing tasks [1][5] supports the interpretation that haptics could be applicable for number entry tasks. There is some research regarding which parameters can be used for creating recognizable haptic stimuli. In the recognition of tactile stimuli the best parameters were rhythm, spatial location [3] and waveform modulation [4][6] as compared to speed of the moving stimulus [6], amplitude [4][6], duration [6], and frequency [4]. Amplitude was the best parameter for representing size [2].

Also primitives of the components have been built with promising results. For example, similar to our experiment, the buttons have been haptically enhanced with a "Pop" when entering in the button, with vibration on the button, and with a pulse when leaving the button [7]. Haptic design models for describing the button edges have been studied earlier [8]. Similar approach for representing number keys, as in the current study with location based coding, has been used with a prototype device with several actuators [12]. A successful implementation of Braille characters with similar rhythm based coding [10] supported the approach to represent numbers with rhythm based haptic representation based on existing literal number coding.

Even though several proof of concept prototypes with haptically enhanced graphical user interface elements have been built, and some research for haptic modeling of user interface primitives exists, there is still need for research with systematic approach for finding out how to design haptic counterparts for the graphical primitives and how different haptic parameters affect user impression of those haptic primitives.

The present aim was on haptic number representation. Three promising approaches for haptic design were selected. Their stimulus parameters were systematically varied to to find out which designs was the most applicable for representing numbers.

2. EXPERIMENT

2.1 Participants

24 voluntary participants (7 female and 17 male) participated in the experiment (mean age 31 years, range 20-54 years). 21 of the participants were right-handed by their own report. In the experiment three participants used their non-dominant hand, because they were used to use that with mobile phones.

ICMI-MLMI'10, November 8-10, 2010, Beijing, China.

2.2 Apparatus and Software

The haptic device used was a Nokia 5800 Express Music phone with a resistive touch screen. The phone's rotation motor actuator was used to generate haptic feedback with the QT software built for the experiment. The used software had a standard phone keypad layout, with number keys only (Figure 1). The software was developed using QT for Symbian 4.6.0 with Mobile Extension Preview 2 for the vibrating motor control.

Figure 1: Software

In the software some haptic primitives were provided for making it easier to find and use the touch screen buttons. The haptic stimuli representing graphical primitives of the buttons were the same in all the number representations. Haptic information was provided for participants with a texture while moving the finger on the button to inform, if they were over a button or not. For the edges of the buttons haptic feedback was different while moving over the edge towards the button and while moving out of the button. These edge primitives were adapted from known design paradigms for the haptic edges [8]. When a button was pressed down, a "click" down was repeated and while releasing a button there was haptic representation for the rising button, which also told the participant that a number was selected. Representation for the number attached to the button was provided with 500 ms delay, after the participant's finger had entered the button. Parameters of individual primitives can be found in Table 1.

2.3 Stimuli

There were three representation models for the numbers. These representation models were based on *Arabic* numbers, *Roman* numbers and the *Location* of the number key in the keypad grid. With all the models, number 0 in the keypad was represented with number 10. All the models were experimented with two presentation speeds: *Fast* with 100 ms as basic pause time between the individual pulses and *Slow* with 200 ms basic pause time. Parameters are the proportional power input to the rotation motor actuator in percentage, the direction the motor is driven, the power input time to the motor and the pause between separate haptic pulses provided. Parameters can be found in Table 1.

The stimuli in the Arabic representation were combined from identical haptic pulses, with as many pulses as the number indicated, except for the number zero that had ten pulses. Pulses were grouped so that with larger numbers than five the pause between fifth and sixth pulses was twice as long as within other pulses.

The stimuli in the Roman representation were combined from three different haptic pulses, where the weakest pulse represented I, the strongest X and the middle one V. Numbers were combined from these digits as ordinary roman numbers, except for number zero which was presented with X. The pause was twice longer between different digits; *i.e.* between I and V.

The stimuli in the Location representation were combined from four different haptic pulses. The length and the amplitude of the pulse represented the row number in the keypad grid where the button was located. The weakest pulse marked the topmost row with numbers one to three and the strongest pulse marked the lowest row with the number zero. The amplitude and the length of the pulses grew with even steps from top to down. The number of the pulses was the same as the position of the button in the row from left to right *i.e.* one to three pulses.

Table 1: Haptic parameters. (P) Proportional power, (rd) rotation direction, (t) rotation time and pause between pulses.

Roman	P (%)	rd	t (ms)	Pause (ms)	P (%)	rd	t (ms)
I	5	↑	50	-	-	-	-
V	100	↑	100	-	-	-	-
X	100	↑	200	-	-	-	-
Arabic							
1 pulse	100	↑	50	-	-	-	-
Location							
Row 1	25	↑	50	-	-	-	-
Row 2	50	↑	100	-	-	-	-
Row 3	75	↑	150	-	-	-	-
Row 4	100	↑	200	-	-	-	-
Primitives							
Edge in	100	↑	35	10	100	↓	25
Edge out	100	↑	35	-	-	-	-
Texture	5	↑	2	-	-	-	-
Pushdown	100	↑	35	50	100	↓	25
Release	100	↑	50	10	100	↓	25

2.4 Procedure

The task for the participants was to enter phone numbers with the phone blindly. During number entry the selection times for each individual number and selected number were recorded. After each model the participants rated the model with the following three nine point bi-polar scales: "How well you recognized the numbers?", "How pleasant the representation was?", and "How difficult the numbers were to understand?". In the scale value -4 was did not recognize at all, very unpleasant and very difficult, and value 4 was perfectly, very pleasant and very easy.

Before the experiment each participant was allowed to explore all the representation models with both speeds to learn how numbers were represented. The participants were instructed to perform as accurately as possible, but still as fast as they could. The accuracy was emphasized. In the actual experiment participants' vision was blocked using a box where the entry hand was in it with the phone. Hearing was blocked with pink noise played through a hearing protector headset. The participants used the phone with their thumb.

The presentation order of the numbers was counter-balanced between the conditions and condition order between the participants. There were seven 7-digit phone numbers in the experiment, excluding operator code 050, which was at the beginning of all numbers. This was to initialize participant's finger to middle line of the phone and have everyone's finger in the same position at task start. Thus, in total there were 7*7=49 numbers in each condition which were taken in the analysis. The numbers were balanced so that the phone numbers did not include any number twice and all numbers were presented equally, except 0 which had one occurrence less.

2.5 Data Analysis

Users had difficulties to blindly press the screen with the required amount of pressure for error-free detection for the resistive touch screen. This caused random input, when a participant moved the finger on the screen touching lightly and the phone received the input randomly as touching or not touching. This caused some errors in the data which were recognized and processed manually.

Data was processed manually with following method. Data from each task segment was first split to individual phone numbers. This could be done by recognizing initial strings (050), which were not taken into analysis. Each phone number was processed and accidental double entries and extra numbers on the path from one number to another were taken out. After that, correct number sequences were manually recognized. If there was doubt whether the input was correct or not, it was interpreted as an error. Thus, the effect to the result was raising the error percentage. The missing values (input missing from requested phone numbers) were not calculated to the error percentage. They were analyzed separately to ensure that there was no difference between conditions in missing values, which could have then affected the results and the comparison of the conditions. Selection times were calculated from the time spent between individual number entries.

Within-subjects repeated measures analysis of variance (ANOVA) was used for statistical analysis. If the sphericity assumption of the data was violated, Greenhouse-Geisser corrected degrees of freedom were used to validate the F statistic. Bonferroni corrected pairwise t-tests were used for post hoc tests.

3. RESULTS

Means and standard error of the means (S.E.M.s) for all the results are presented in Figure 2. For the ratings of the subjectively estimated stimulus recognition rate, a 2 × 3 two-way (speed × number presentation style) ANOVA showed a statistically significant main effect of number presentation style ($F(2, 46) = 9.9$, $p < 0.001$). Post hoc pairwise comparisons showed that the participants rated the Arabic number presentation style as more recognizable than the Roman (MD = 1.0, $p < 0.05$) or the Location based (MD = 1.8, $p < 0.001$) number presentation styles.

For the ratings of the pleasantness, a 2 × 3 two-way (speed × number presentation style) ANOVA showed a statistically significant main effect of speed ($F(2, 46) = 4.7$, $p < 0.05$) and number presentation style ($F(2, 46) = 6.7$, $p < 0.01$). Post hoc pairwise comparisons showed that the participants rated numbers presented slowly as statistically significantly more pleasant than numbers presented quickly (MD = 0.6, $p < 0.05$). Post hoc pairwise comparisons also showed that the participants rated the Arabic number presentation style as more pleasant than the Location based (MD = 1.5, $p < 0.01$) number presentation styles.

For the ratings of the difficultness, a 2 × 3 two-way (speed × number presentation style) ANOVA showed a statistically significant main effect of number presentation style ($F(2, 46) = 8.1$, $p < 0.001$). Post hoc pairwise comparisons showed that the participants rated the Arabic number presentation style as easier than the Roman (MD = 1.1, $p < 0.05$) or the Location based (MD = 1.7, $p < 0.001$) number presentation styles.

4. DISCUSSION AND FUTURE WORK

We developed a fully haptic number keypad making use of the limited haptic capabilities available in the phones today. We were able to recreate similar haptic edge effects with a consumer model phone, as done in an earlier work with a prototype device [8] by transforming input parameters for piezo electric actuators applicable for rotation motor actuator. By using the number representation models actuated with a single rotation motor actuator, we were able to create haptic number entry solutions based on existing mental representations for the numbers. Using these models we achieved smaller error rates with a single actuator and around the same error rates than in an earlier solution making use of multiple actuators [12].

Interestingly, the comparison of the models of haptic number representations did not reveal any significant differences in the measured performance, but still it had an effect in the subjective evaluation and the user's experience of how well the task was performed. Thus, even if the measured performance does not support the issue that any of the models would be better than another, subjective ratings suggest that the most familiar Arabic number model with the slower speed would be better for real applications. Also, when it is known that with an attractive design people tend to value usability of the device over performance only [9], subjective ratings should be taken into account in the design.

Our results support the earlier research where it has been shown that existing literal coding, like Braille [10] can be represented with haptics. Also, our results support the results reported earlier that in the recognition of tactile stimuli, rhythm [3] and waveform modulation [4][6] would be good parameters.

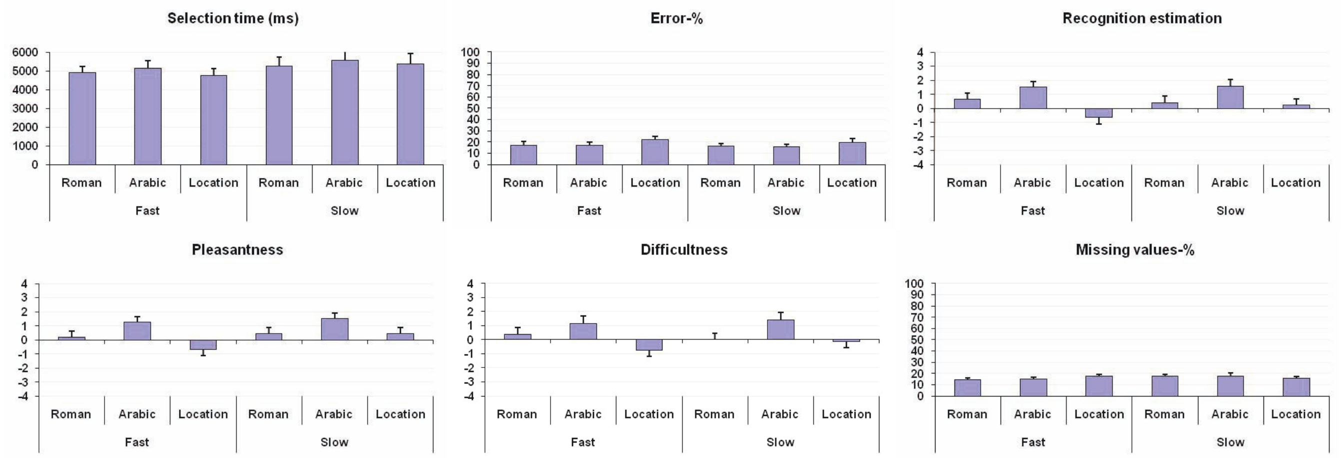

Figure 2: From top left to bottom right: Selection times (ms) for individual numbers. Error-% of the number typing. Subjective estimation of the recognition rate. Subjective rating of pleasantness. Subjective rating of difficultness. Missing entries in the data.

Quite high error rate and slow input rate reveal that pure touch based task was demanding. This was also supported by comments of the participants after the experiment. Also, the phone numbers given for users were unfamiliar to them, which made the task harder. Error rate and input speed might be better, if the numbers were shorter and more familiar to the users and if vision would be part of interaction as a supportive modality. As there was no learning phase and novice users were the participants of the study it could be argued that with an appropriate learning time, users would be much more confident with touch interaction and thus, error rate and speed would improve in long-term usage.

Based on the current results, complete blind usage scenarios cannot be recommended for long and unfamiliar numbers. However, using shorter and already known numbers it might be easier to enter them and, thus, they would be more applicable. Also, the problems arose from difficulties to use touch screen with appropriate pressure. This is due to the case that software responded to the touch events, and based on those events, provided haptic feedback. With a weak touch pressure, all the haptic feedback designed to be presented might not have been presented and thus feedback been more confusing, which could have raised the input time and error rate.

5. CONCLUSIONS

Even though the objective performance was not affected by parameters used in the experiment, the users preferred the most familiar Arabic numbers represented with the slower speed. Thus, when representing numbers with haptics, a better choice would be to use the slow Arabic number based rhythmic representation. Based on our experiences, we would recommend interaction schemes that allow at least partial use of sight and use of highly responsive touch screen, where the amount of the pressure required is minimal.

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Paper V

Pakkanen Toni, Raisamo Roope, and Surakka Veikko. (2012). Comparison of Extensive vs. Confirmation Haptic Interfaces with Two Levels of Disruptive Tasks. In *Haptics: Perception, Devices, Mobility, and Communication: International Conference, EuroHaptics 2012*, Tampere, Finland, June 13–15, 2012. Proceedings, Part I. Heidelberg: Springer, 383–394. (Lecture Notes in Computer Science 7282).

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Comparison of Extensive vs. Confirmation Haptic Interfaces with Two Levels of Disruptive Tasks

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Abstract. In the car environment there are more and more complex infotainment systems, which are used with touchscreens, even by driver while driving the car. While it is known that secondary tasks have a negative impact to the driving safety, there is a lack of information, if haptics can be used to make this interaction safer. In this study we compared two haptically enhanced user interfaces with two levels of user distraction: Commonly used *confirmation haptic* interface, and *extensive haptic* interface, where all possible information was provided with haptics. In the experiment participants entered four-digit numbers, while driving or watching video. Input speed, input error rate, driving errors and subjective experiences were recorded. The results showed that there were no significant performance differences between the user interfaces, but the extensive haptic interface helped to reduce the number of driving errors. Participants did not have significant preference differences between the user interfaces.

Keywords: Haptic feedback, User interaction, Distracted user, Driving user

1 Introduction

Human being is by nature a multimodal and multitasking being. While we perform a main task, like cooking, we use touch together with short glimpses to perform secondary tasks. It is easy for us, for example, to grab ingredients with the help of touch, while we keep our concentration in the cooking. This unfortunately is not the reality with modern mobile touch devices, where interaction metaphors are similar to real world interaction. A problem arises here, when it is known that interaction with mobile devices in the mobile contexts is usually split in small fragments, while users have to pay attention to the environment [7]. They use devices by direct touch and manipulate virtual elements, but without the haptic feeling of the elements on the screen. However, many of the modern devices have tactile actuators, which could make it possible to create haptic representation for graphical user interface elements. This approach would make it possible to add haptic information cues for the users of the devices to describe the items they are manipulating.

This problem with interaction without help of haptic cues is emphasized in the car environment, where users should have their concentration in the main task: driving. It

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has been shown that using the mobile phone and having additional cognitive load has a negative impact to the driving safety [2][4] and that impact is even larger than impact of natural conversation in the car between the driver and passenger [2]. Thus, under no circumstances it cannot be recommended to use mobile phone or other non-driving related devices while driving a car. However, it is known that people tend to use mobile phones while driving [15] and that even awareness of increased risk of crashing does not predict intention to use the mobile phone while driving [14]. This leads to the question, how use of touchscreen devices in the car could be made safer while the user's attention should be in the driving.

The aim of this study was to find out, if the extensive haptic interface would help the users with the tasks, if the distraction level impacts the usefulness of haptic interface and how the user preference about user interfaces is impacted by conditions. This information would provide a needed knowledge, if the secondary tasks in the car environment can be made safer to perform with the help of haptics.

2 Related work

While evaluating usefulness of haptics under cognitive load [6], it has been found that when supporting a scrollbar and a progress bar with haptics, performance improvement could be found, but with simple haptics in a button task similar improvement could not be found. Also it has been found that cognitive load does not have significant effect on the performance. This leaves an open question, could supporting extensive haptics help with button-based tasks. Also in the experiment [6] cognitive load was added as a secondary task, and impact of the interaction with device to the other task was not evaluated. Thus, the question remains, if using haptics with touch screen interaction can improve performance in a second task used to distract the interaction and to create cognitive load. Also an open question is, if haptics can positively affect the performance impact caused by more demanding cognitive load.

By using individual haptic textures with number keypad for each number buttons, number input accuracy was improved compared to simple haptic feedback which was the same for all the buttons. However, this was with the cost of input speed [13]. These results support the idea to have informative extensive haptics in the user interface to achieve lower error rate rather than faster interaction speed.

In the car environment, where safety has to be first priority, multimodal feedback could provide possibilities to minimize the need of visual attention to the secondary devices. Especially, haptics play an important role in the car environment by providing eyes-free interaction scenarios [1].

Users also prefer multimodal feedback in touch screen interaction, while driving [9] and have subjective feeling that haptics helps them to drive better, even though this was not seen at actual driving performance [10]. Thus, using haptics together with vision was preferable by the users, but it did not help them actually improve the driving safety. Considering simple confirmation only haptics used in these experiments, the question remains, if with more extensive task specific haptics, the driving task could be supported better.

In the car environment with a simple task, menu selection by using rotating knob, also there couldn't be found beneficial impact with adding haptics to the interaction. Neither task performance nor driving safety was significantly improved, but by using haptics only condition performance was reduced [12]. These results support the approach to experiment with more complex interaction, like number input in our experiment and allowing partial use of gaze to support the task completion. The question remains, if more complex tasks can be supported with haptics so that user performance is impacted positively.

In an experiment, where visual, audio-visual, haptic-visual and audio-haptic-visual feedback was compared [5], it has been found that tri-modal condition reduces the driving errors, while bi-modal conditions did not reach statistical significance. Although, haptic-visual condition reduced the measured workload participants felt (Nasa-TLX workload score). Thus, it could be assumed that while haptic-visual condition reduces the workload of the driver, with more descriptive and helpful haptic interface the gain for driving errors might be larger. This assumption is supported by an experiment [3], where mean standard deviation from given drive line was reduced both with audio-haptic and visual-haptic navigational guidance.

The results seems promising with the more complex haptic input device with number button interface, which provides possibility to find the buttons on the screen with dragging finger on the screen and push them to select. Even though there was no statistical confirmation, a trend in the data indicated that a system mimicking physical buttons could improve user performance and driving safety [11].

These results from earlier experiments support the idea to approach the touch screen interaction in the car environment with task-specific, extensive and informative haptic user interface in demanding primary task and use the touch screen as a secondary task. In our experiment, we compared such an interface with traditional confirmation haptic interface and varied the primary task demand, to find out if more demanding task would benefit more from the more advanced interface.

3 Experiment

In this study, we compared use of two different haptically enhanced user interfaces with two levels of distraction. There was a commonly used *confirmation haptic* number keypad and an *extensive haptic* number keypad, where all possible information was provided also with haptics. Participants had a task to enter four-digit numbers to the phone, while either driving in a simulated environment, or while watching a video.

3.1 Participants

12 voluntary participants (all male) participated in the experiment (mean age 28 years, range 18-42 years). 11 of the participants were right-handed by their own report.

3.2 Experiment setup

In the experiment the Playstation 3™ game Grand Tourismo 5 Prologue™ was used to simulate driving. A Logitech driving force GT wheel controller was used as the driving wheel. The car from the game used for driving was the Daihatsu Copen ’02, which had a top speed approximately of 160 km/h, and the track driven was a simple oval track, Daytona. In the game the guideline for optimal driving track was on and shown on the track. The touch screen device used in the experiment was a Nokia X6 touchscreen phone with a capacitive screen and a rotation motor actuator, which was used for generating the haptic feedbacks. Picture of the experiment setup is shown in Figure 1.

Fig. 1. Experiment setup

The tasks were to enter four-digit numbers to the phone with two levels of haptics provided with the phone. Other one was currently common confirmation haptics. Thus, a short pulse was provided, when a number was selected. The other was extensive haptic number keypad, where all possible information was provided with rhythmic haptic pulses. Thus, there were feedbacks for the edges of the buttons, for the texture, for the push down event and release event of the button. Also numbers were presented with haptic feedback when participant stopped the finger on top of the number button.

Haptic feedbacks used in this experiment were the same, as has been used earlier in the experiment investigating haptic number representation models [8]. The number model used in this experiment was the best rated model from that experiment, slower speed Arabic number representation. The haptic feedbacks used can be found in Table 1. Numbers were composed by repeating haptic pulses: for number one there was one pulse, for number two there was two pulses, and so on. There was a 100 ms pause between the pulses and to help recognition of larger numbers the pulses were grouped in groups of five by having a 200 ms pause after the fifth pulse. Number representation was repeated with a 500 ms delay.

Table 1. Haptic parameters of haptic feedback used in the experiment. (P) Proportional power, (rd) rotation direction, (t) rotation time, and (Pause) between pulses.

	P (%)	*rd*	*t (ms)*	*Pause (ms)*	*P (%)*	*rd*	*t (ms)*
Number pulse	100	↑	50				
Edge in	100	↑	35	10	100	↓	25
Edge out	100	↑	35				
Texture	5	↑	2				
Pushdown	100	↑	35	50	100	↓	25
Release	100	↑	50	10	100	↓	25

The experiment was videotaped with two cameras to the single video file, so that the mobile phones interface and participants face was seen in the video. From the video it was controlled that participants interacted with the phone following instructions and did not perform the number entry task by gaze. The driving from the game was saved to the video repeat file and driving errors calculated out of the video. The mobile phone recorded the input to the phone, and input error rates and input speed was collected from the data.

3.3 Procedure

Before the experiment tasks, the participants were introduced to the haptic user interfaces used. They were allowed freely to try out the interfaces, until they told that they understood how the user interfaces work and what kind of haptic feedback they provide.

In the experiment the task for the participants was to enter four-digit numbers to the phone, while both, driving or watching earlier recorded error free driving at the same track with the same car and speed as in driving task from a video repeat file. Before the tasks a baseline driving was done with the same condition without any additional tasks. Tasks were done twice, once with each haptic interface. Participants entered ten four-digit number sequences in each condition and numbers were given for the participants from the laptop screen below the game screen. Numbers were given for input in half way of both straight stretches in the oval track, at the finish line and at the depot entrance. When a new number was given, laptop provided small sound effect to notify participants. Participants were instructed to enter the numbers without any delay. Thus, participants drove five and a half laps in each condition and entered 40 digits to the phone.

Participants were instructed to drive as fast as the car used could and follow the guideline shown in the road as exactly as they could. Driving errors were counted from the deviations from the guide line in the road. They were also asked to hold the phone down on the knee during the experiment, as seen in Figure 1, and not to enter numbers by watching the phone screen. They were however allowed to take a short glimpse down to the phone, if it was necessary for understanding the location of the finger on the number keypad.

In the video task, participants were instructed to keep their eyes in the video and not to perform the number input task by watching the phone screen. They were told that they may glimpse the screen same way as in driving condition, if needed, to check were the finger is on the keypad, but not to input the numbers by using the gaze. Thus, the usage of the gaze was synchronized with the driving task.

All the participants followed the given instructions as asked. Thus, participants did not see the phone screen, otherwise than turning their eyes out of the screen showing the driving interface, i.e. out of the driving path. They also kept the speed asked and in cases of accidents, immediately raised the speed back to the top speed.

Order of the conditions was counterbalanced for the elimination of the learning effect. Also the numbers used were randomized so that all the digits repeated evenly and the same digit sequences were not repeated for the participant. Also same digit was not used within the same four-digit number, so that participants had to move their finger on the screen and find the correct number button every time.

After each task, the participants answered to the questionnaire from that combination of haptic level and distraction level. Nine point bi-polar scales were used for the answers to the questions. Questions asked were: "How well you think, you could enter the numbers", "How pleasant the number keypad was to use", "How easy the use of the number keypad was", "How demanding the task in total was", "How easy the user interface was to understand" and "How much there was haptic feedback to support the task". Also there was asked with three point bi-polar scale a question "Would you use this kind of number keypad in your phone, if it was available".

3.4 Data analysis

Within-subjects repeated measures analysis of variance (ANOVA) was used for statistical analysis. If the sphericity assumption of the data was violated, Greenhouse-Geisser corrected degrees of freedom were used to validate the F statistic. Bonferroni corrected pairwise t-tests were used for post hoc tests.

The driving errors were categorized to three categories: 1. *Small driving errors*, where the driving was unstable, but the car did not move out of the given track to drive more than a little bit (less than the car's width), *i.e.* "Instability in the driving". 2. *Medium driving errors*, when the driving path was lost and the car moved out of the given track more than the car's width, *i.e.* "A lane switches error". 3. *Large driving errors*, when the control of the car was completely lost, *i.e.* "An accident".

Non-parametric Friedman's rank test was used for statistical analysis for the data from the driving errors. Non-parametric Wilcoxon signed-ranks tests were used for pairwise comparisons of results within each task.

4 Results

Means and standard error of the means (S.E.M.s) for the ratings of the number input errors and number selection speed are presented in Figure 2. For the ratings of the number input errors, a 2 × 2 two-way (haptic feedback level × distraction level)

ANOVA showed a statistically significant main effect of distraction level $F(1, 11) = 11.5$, $p < 0.01$. The main effect of the haptic feedback level or the interaction of the main effects was not statistically significant. Post hoc pairwise comparisons showed that the participants made less input errors while watching video, than when driving $MD = 9.3\%$, $p < 0.01$. For the ratings of the number selection times, a 2 × 2 two-way (haptic feedback level × distraction level) ANOVA showed a statistically significant main effect of haptic feedback level $F(1, 11) = 15.0$, $p < 0.01$. The main effect of the distraction level or the interaction of the main effects was not statistically significant. Post hoc pairwise comparisons showed that the participants entered the numbers faster with confirmation haptic user interface, than with extensive haptic user interface $MD = 1561$ ms, $p < 0.01$.

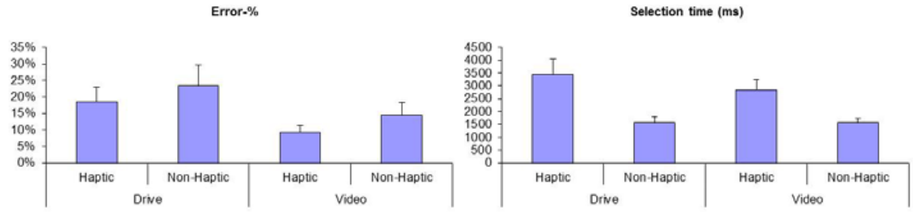

Fig. 2. Number input error-% and selection times.

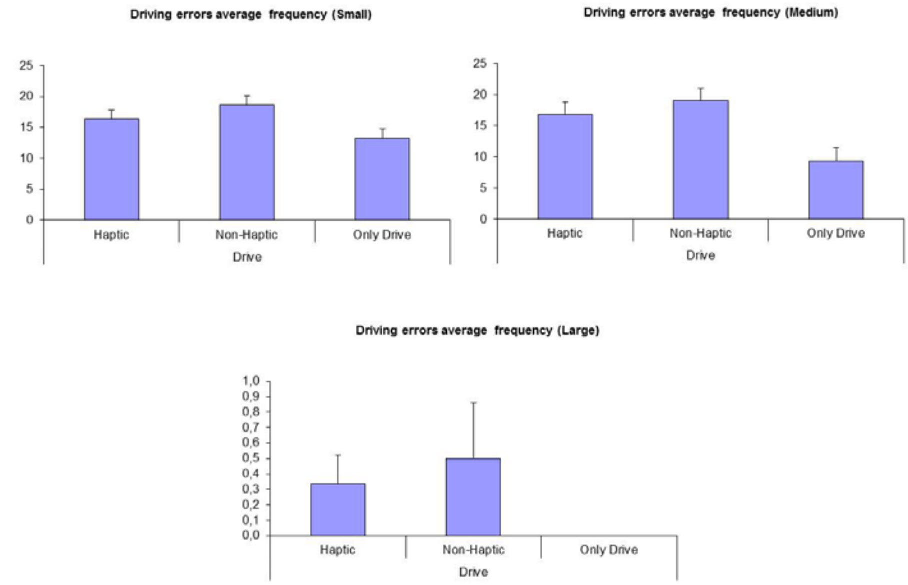

Fig. 3. Driving errors.

Means and S.E.M.s for the driving errors are presented in Figure 3. Friedman's rank test showed a statistically significant effect of the haptic level within small driving errors $X^2 = 20.6$, $p < 0.001$ and within medium driving errors $X^2 = 19.7$, $p < 0.001$. The differences within large driving errors were not statistically significant.

For the small driving errors Wilcoxon singed ranks tests showed that there was less driving errors with the extensive haptic interface $Md = 16.5$ than with the confirmation haptic interface $Md = 18.5$, $|Z| = 2.8$, $p < 0.01$, but still more than with the driving only condition, without any distraction $Md = 14.5$, $|Z| = 2.8$, $p < 0.01$. There were more driving errors with the confirmation haptic interface Md = 18.5 than with the driving only condition, without any distraction $Md = 14.5$, $|Z| = 3.1$, $p < 0.01$.

For the medium driving errors Wilcoxon singed ranks tests showed that there was less driving errors with the extensive haptic interface $Md = 18.0$ than with the confirmation haptic interface $Md = 21.5$, $|Z| = 2.4$, $p < 0.05$, but still more than with the driving only condition, without any distraction $Md = 11.0$, $|Z| = 3.0$, $p < 0.01$. There was more driving errors with the confirmation haptic interface Md = 21.5 than with the driving only condition, without any distraction $Md = 11.0$, $|Z| = 3.0$, $p < 0.01$.

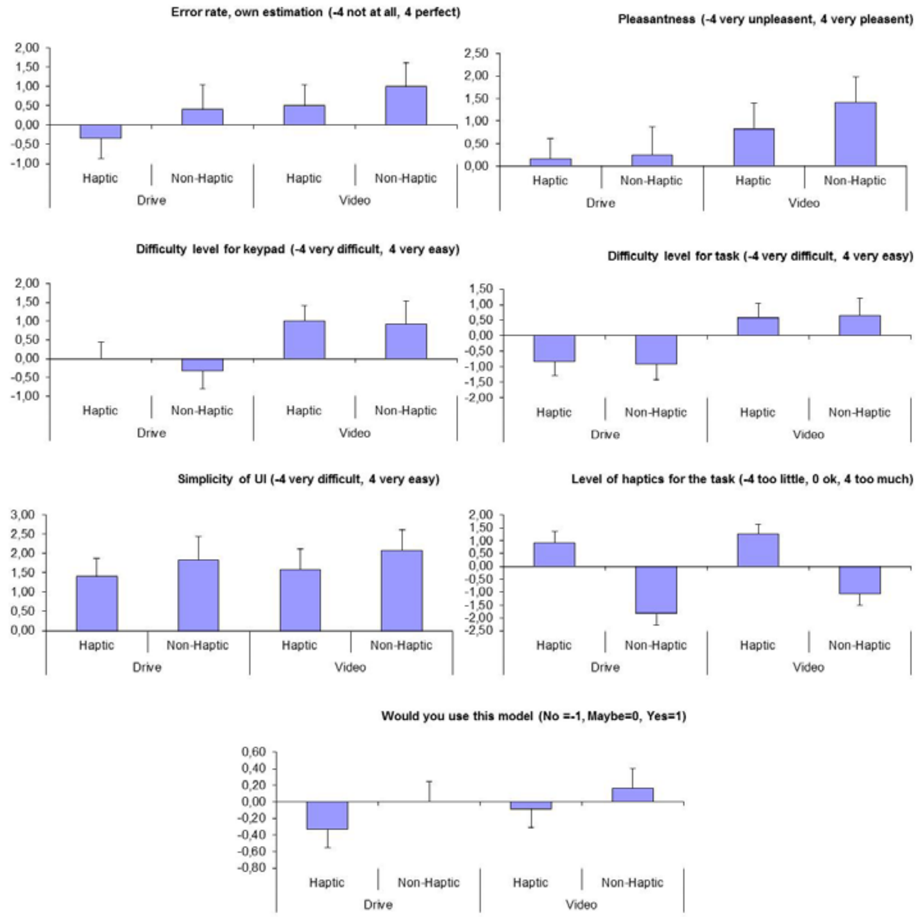

Fig. 4. Subjective evaluations.

Means and S.E.M.s for the ratings of the subjective evaluations are presented in Figure 4. For the ratings of the question "How easy the use of the number keypad was", a 2 × 2 two-way (haptic feedback level × distraction level) ANOVA showed a statistically significant main effect of distraction level $F(1, 11) = 13.3$, $p < 0.01$. The main effect of the haptic feedback level and the interaction of the main effects were not statistically significant. Post hoc pairwise comparisons showed that the participants thought that using the keypad was more difficult while driving, than while watching the video $MD = 1.1$, $p < 0.01$.

For the ratings of the question "How demanding the task in total was", a 2 × 2 two-way (haptic feedback level × distraction level) ANOVA showed a statistically significant main effect of distraction level $F(1, 11) = 18.6$, $p \leq 0.001$. The main effect of the haptic feedback level and the interaction of the main effects were not statistically significant. Post hoc pairwise comparisons showed that the participants thought that the driving task was more difficult than the task to watch the video, when using the phone keypad at the same time $MD = 1.5$, $p \leq 0.001$.

For the ratings of the question "How much there was haptic feedback to support the task", a 2 × 2 two-way (haptic feedback level × distraction level) ANOVA showed a statistically significant main effect of haptics level $F(1, 11) = 35.2$, $p < 0.001$. The main effect of the distraction level and the interaction of the main effects were not statistically significant. Post hoc pairwise comparisons showed that the participants thought that level of the haptic feedback was more sufficient for the task with extensive haptic user interface than with user interface with confirmation haptic interface $MD = 2.5$, $p < 0.001$.

The main effects of the other subjective rating questions were not statistically significant.

5 DISCUSSION AND FUTURE WORK

In this experiment we evaluated how the level of haptic support and task environment difficulty level impact to user performance and satisfaction. In the present study, the main task was to drive or watch the video. The numeric input with the phone was done as a secondary task.

As our results show, with a descriptive extensive haptic interface, where haptic feedback is supporting the task, the errors in the main task, driving, were reduced. This differs from the result in earlier research [10] [12] [5], where the impact for the driving safety could not be found, while using more simple haptic interfaces than in this experiment. These results support the preliminary view, based on the trend in the data that versatile haptics supporting the task well enough can impact the driving safety [11] and the results that task specific visual-haptic and audio-haptic feedback help drivers to drive more stable [3].

However, it is crucial to notice that in both conditions there were significantly more driving errors, than with the baseline driving without any additional tasks. Thus, these results do not support the view that using the mobile phone should be allowed while driving. But, if the users do it anyway [15][14], using the appropriate haptic interface could make the use of touch screen systems safer, than using them with simple confirmation haptics only. Our results also support adding haptic feedback in in-car touch screens and other systems used while driving.

Regarding the performance results on the numeric input task, the earlier results [6] indicating that cognitive load did not have a significant impact in the performance were not repeated. In the present experiment the input error rate was impacted by the task demand level. However, in this experiment the more demanding task was considerably more demanding than cognitive levels used in Leung's [6] experiment. Thus, in the driving condition, demand is so high that it will reduce secondary task's performance. Based on this, rising error rates should be taken into account in user interface design for the car environment.

The finding that better haptic interface will reduce the input speed [13] was repeated in this experiment. The result on better input error rates in Yatani's experiment was not found in this experiment. However, as can be seen in error rate bars in Figure 2, there is a trend that in extensive haptic interface error rates are getting smaller, even though the difference was not statistically significant. While in this experiment the number of participants was 12, the trend showing smaller error rates might be found significant with a larger sample. Also, the extensive haptic interface was novel and not familiar to the participants, with time and practice the results might get better and users learn interaction strategies to help them to gain more from additional feedback.

From the subjective experience results it can be seen that the participants thought that using the phone while driving was more difficult. Haptic level did not affect to this result, which does not support the initial assumption that haptics might be more useful in a more demanding task environment. The level of haptic support did not affect to the user experience ratings. Interesting in these results was that even though the extensive haptic interface was unfamiliar and provided haptic feedback all the time, it was not considered less pleasant or difficult. Vice versa, the level of haptics was considered to be more sufficient for the task, which supports the result that users prefer multimodal feedback while driving [9].

6 CONCLUSIONS

Based on our results, extensive and informative haptic interfaces supporting the task they are designed for would be recommended for the touch screen interfaces, which are used while driving. The results support the assumption that extensive haptic interface helps the driver to drive safer, even though not as safe as by not using the device at all. The cost of that safer drive is the interaction speed with the secondary system. It can be assumed that extensive haptics helps the driver to perform the secondary task more by touch, less by sight, and thus keep the concentration and eyes more on the road, less on the secondary task.

Extensive haptification of user interfaces cannot make the use of the device as safe as not using the device while driving, so under no circumstances based on these results should use of touch screen systems be recommended while driving! However, providing well designed haptifications for the tasks the drivers manage with touch screens, allowed or not, could make it safer.

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Paper VI

Pakkanen Toni, Raisamo Roope, and Surakka Veikko. (2014). Audio-Haptic Audio-Haptic Car Navigation Interface with Rhythmic Tactons. In *Haptics: Perception, Devices, Mobility, and Communication: International Conference, EuroHaptics 2014*. Proceedings, Part I. Heidelberg: Springer, 208–215.

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Audio-Haptic Car Navigation Interface with Rhythmic Tactons

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Abstract. While car environment is often noisy and driving requires visual attention, still navigation instructions are given with audio and visual feedbacks. By using rhythmic tactons together with audio, navigation task could be supported better in the driving context. In this paper we describe haptic-audio interface with simple two-actuator setup on the wheel using rhythmic tactons for supporting navigation in the car environment. The users who tested the interface with a driving game would choose audio-haptic interface over audio only interface for a real navigation task.

Keywords: Haptic feedback; User interaction; Driving user.

1 Introduction

In the car environment, safety has to be the first priority. Multimodal feedback could provide possibilities to minimize the need for focusing visual attention to the secondary devices. Haptic interaction could provide opportunities for eyes-free interaction [3]. While audio alone is already an eyes-free modality, a question remains, if audio with haptic feedback can help the driver even more. There are also situations where audio is not usable, such as noisy discussion or a child sleeping in the car.

It has been shown that audio-haptic navigation instructions reduce the amount of eyes-off-the-road moments and having haptic feedback delivered jointly with multimodal instructions reduces especially young drivers' cognitive load [6]. Thus, it can be assumed that haptic feedback in multimodal navigation instructions helps the drivers to drive better. However, in an experiment by Kim et al. [6] the navigation task performance was not better with audio-haptic feedback. They had visual feedback used together with audio and/or haptic feedback in all the compared conditions and did not have audio only condition as a baseline. So, a question remains, if audio interface without the visual modality benefits from the use of haptic feedback more.

It has been shown that in visual-haptic navigation using a handheld navigation device resulted with less navigation errors and device interaction distractions with bimodal than unimodal conditions [10]. It has also been shown that a tactile display under cognitive load helped the driver navigate better than when using a traditional navigator interface [1]. Further the cognitive side task was not impacted by the mo-

adfa, p. 1, 2011.

dality [1]. Finally, it has been found that mean standard deviation from the given driving line was reduced with audio-haptic navigational guidance compared to audio only [5]. This indicates that the use of haptic feedback can result with better driving safety. However, with visual-haptic tasks, there have been contradictory results of the effect of haptic feedback on the driving safety. On the other hand tasks using simple haptifications [11][13] have not improved driving safety, while comprehensive haptification [8] did improve it. An interesting question is, if these results can be repeated with haptic feedback used with an audio interface while driving.

Earlier studies have shown that duration and rhythm are good for recognition of distance [12][14] with haptic tactons [2] and that combination of these parameters function better in intuitive recognition of distance while using abstract audio [7]. This can also be assumed to apply to abstract tactile vibration. There is evidence that rhythm is the most effective way to provide information of directions [12]. Also location of actuation on body and moving the actuation from side to side [14] has been found as an effective way to provide direction information. Thus, these results should be taken into account, when designing tactons for tactile navigation instructions. Similar tactons with two pulses, latter encoding information about further-closer, for directions than the ones used in this study with dual actuator setup, have been used, for example, in Pocket navigator [9] with a single actuator. A similar hardware setup with two actuators attached to the wheel was used in a study for continuous feedback [4], where navigation performance was increased by audio-haptic feedback.

The results from earlier experiments support the idea to approach the haptification of audio navigation instructions in the car environment with rhythmic tactons using the intensity and duration of a tacton to encode the information. To investigate if encoded information in comprehensive haptic interfaces is better than just having haptic alert to raise attention, a simple haptic interface was included in the experiment. In our experiment, we compared three conditions in navigation instructions: audio, audio with simple haptic interface to evoke attention, and audio with comprehensive haptic interface which has navigation instructions encoded in haptic feedback.

There is evidence that haptic interface using rhythmic informative tactons can improve the use of visual interface [8] and potentially the same holds for auditory interaction. Audio instructions are a main channel in navigation tasks. Thus, we were interested in studying if similar informative haptic feedback could be used to improve the navigation task. In this paper we describe the interface and haptic navigation instructions and subjective evaluations the users made of usefulness of these modalities. The results are expected to provide knowledge on whether the secondary tasks using audio modality in the car environment can be supported with haptic feedback.

2 Prototype Interface and Evaluation

We compared the use of two different haptically enhanced audio user interfaces and a non-haptic audio interface applying two levels of distraction. In the simple haptic interface a simple haptic burst was used to alert on upcoming audio feedback. In the comprehensive haptic interface all the audio feedback had a corresponding haptic feedback (Table 1). Participants had a task to turn left or right following the given instructions with audio and haptic modalities while driving in a simulated environment under audio distraction with or without a cognitive side task.

In the experiment the PC game Driver: San Francisco™ was used to simulate driving. A Logitech G27 wheel controller with attached 3V pancake vibration motors driven with Arduino Uno was used for driving and providing haptic feedback. Vibration motors were attached to the wheel with acrylic mass (Figure 1). Actuators were located so that they were under the participants' thumbs, when both hands were held on the wheel. The car from the game used for driving was the Cadillac DTS. The task was to drive in the downtown map following given turn by turn instructions.

Fig. 1. The wheel setup including two actuators used for haptic feedback.

Haptic stimuli used were iteratively developed with a similar approach using rhythmic descriptive intuitive tactons as has been used earlier in an experiment investigating a simple and a comprehensive haptification method in visual-haptic user interface [8]. Thus, turning instructions were encoded and represented with rhythmic intuitive tactons varying in pulse duration, pauses between the pulses and the repetitions, and the location of haptic feedback (Table 1). Parameters of pulse durations and pause durations were used to modify the amplitude of the pulse, the intensity of tacton rhythm and the length of the haptic representation to tell distance to the crossing. Every tacton consisted of pulse to right and left actuator and with every command in comprehensive haptic condition they were repeated three times with every turn instruction. For example, turn to left coming further away was given as a 200 ms pulse to the right hand, and then after 150 ms pause a 100 ms pulse to the left hand, repeating this sequence three times with 1500 ms between the repetitions.

	Side	***t (ms)***	***Pause (ms)***	***Side***	***t (ms)***	***Pause (ms)***	***Side***	***t (ms)***	***Pause (ms)***	***Side***	***t (ms)***	***Pause (ms)***	***Side***	***t (ms)***	***Pause (ms)***	***Side***	***t (ms)***
Left far	Right	200	150	Left	100	**1500**	Right	200	150	Left	100	**1500**	Right	200	150	Left	100
Left near	Right	200	150	Left	150	**750**	Right	200	150	Left	150	**750**	Right	200	150	Left	150
Left now	Right	200	150	Left	200	**150**	Right	200	150	Left	200	**150**	Right	200	150	Left	200
Right far	Left	200	150	Right	100	**1500**	Left	200	150	Right	100	**1500**	Left	200	150	Right	100
Right near	Left	200	150	Right	150	**750**	Left	200	150	Right	150	**750**	Left	200	150	Right	150
Right now	Left	200	150	Right	200	**150**	Left	200	150	Right	200	**150**	Left	200	150	Right	200
Simple	Both	200															

Table 1. Parameters for the haptic stimuli, presented as a sequence of three tactons in each line.

2.1 Evaluation

24 voluntary participants (20 male, 4 female) participated in the experiment (mean age 35 years, range 26-52 years). Participants had had a driving license on average 15 years (range 0 to 34 years) and they drove on average 6500 km per year by their own report (range 0 to 20000 km per year).

Turning instructions were given in three counterbalanced blocks: audio only, audio amplified with simple haptic feedback and audio amplified with comprehensive haptic feedback. In both haptic conditions, haptic feedback was given first, followed immediately by audio. Thus, in both haptic conditions haptic feedback worked as an alert telling that audio instructions are coming, but in comprehensive haptic condition information was encoded also in haptic feedback in addition to the audio. Audio instructions for turnings were the following:

- Turn left/right is approaching, given approximately two blocks before the turn.
- Prepare to turn left/right, given approximately one block before the turn.
- Turn left/right now, given when approaching the crossing where to turn.

The experiment was recorded with a HD video camera and a sensitive microphone, so that the driving and all the turning instructions, participant responses etc. could be collected from the video with video analysis. Subjective evaluations were collected between the driving blocks with a questionnaire.

Before the experiment tasks, the participants were introduced to the haptic user interfaces used. They were allowed freely to try out the interfaces, until they told that they understood how the user interfaces work and what kind of haptic feedback they provide. In this phase it was checked that participants could distinguish comprehensive haptic stimuli from each other and recognize what direction was provided. Thus, all the participants did distinguish and recognize the meaning of haptic stimuli.

Measured Navigation Errors & Subjective Evaluations	*Distraction level*			*Haptic Level*		
Navigation Errors (Measured)	Audio distraction only Sig. Better (MD = 4.7%, $p < 0.01$)					
Driving performance	Audio distraction only Sig. Better (MD = 1.889, $p < 0.001$)					
Distraction level	Audio distraction only Sig. Better (MD = 2.472, $p < 0.001$)					
Comprehension	Audio distraction only Sig. Better (MD = 2.056, $p < 0.001$)					
Navigation performance	Audio distraction only Sig. Better (MD = 1.597, $p < 0.001$)					
Pleasantness	Audio distraction only Sig. Better (MD = 0.819, $p < 0.01$)			Simple Haptic better than Audio (MD = 0.646, $p < 0.05$)		
Measured Navigation Errors & Subjective Evaluations	***Audio***	***Simple Haptics***	***Comprehensive Haptics***	***Audio***	***Simple Haptics***	***Comprehensive Haptics***
Navigation Errors (Measured)	3,33 %	2,92 %	2,50 %	7,08 %	7,50 %	8,33 %
Driving performance	1,38	1,13	1,21	-0,71	-0,75	-0,50
Distraction level	2,21	2,33	2,33	-0,54	-0,13	0,13
Comprehension	2,63	2,54	2,54	0,25	0,50	0,79
Navigation performance	2,21	2,21	2,50	0,25	0,92	0,96
Pleasantness	1,88	2,33	2,46	0,83	1,67	1,71
	Audio distraction only			***Cognitive task and audio distraction***		

Table 2. Significant results and average values of measurements. Navigation Errors as error-%, subjective evaluations on scale -4 (worst) to 4 (best).

In the experiment the task for the participants was to drive using the San Francisco downtown map. They were asked to keep the speed in 45 mph when possible, but to slow down if needed for the safety. During the driving they were given left-right turn instructions in three counterbalanced blocks, with audio only, simple haptic feedback with audio and comprehensive haptic feedback with audio modalities. In each driving block there were ten turns, five to left and five to right. The order of the turns was randomized. If the participant made an error in a turn it was counted as a navigation error and in the next turn the next one was taken from the list of turns. Thus, there was no fixed target for the driving, just ten turns in the given randomized order.

These blocks were repeated twice, with two levels of distraction. The order of distraction levels was counterbalanced. In the lower level, there was only audio distraction which did not require the participant to concentrate on the audio: music and sounds from the game and an audio book playing behind the seat. In the more demanding level, there were simple math tasks coming from the speaker on right side of the seat added to the lower distraction level's audio distractions.

After each drive, the participants answered to the questionnaire from that combination of haptic level and distraction level. Nine point bi-polar scales were used. The questions asked were measuring subjective rating for Driving performance, Distraction level, Comprehension of given instructions, Navigation performance, Pleasantness and Helpfulness of UI. Also was asked, if the participant would use the given modality of instructions in the real car. After each distraction block it was also asked to select which one of these modalities participants would like to use in navigation interface.

Within-subjects repeated measures analysis of variance (ANOVA) was used for statistical analysis. If the sphericity assumption of the data was violated, Greenhouse-Geisser corrected degrees of freedom were used to validate the F statistic. Bonferroni corrected pairwise t-tests were used for post hoc tests. In Table 2 are collected the significant results and in Figure 2 shown the absolute results with the post question, which modality participants would choose for the navigation task in real environment.

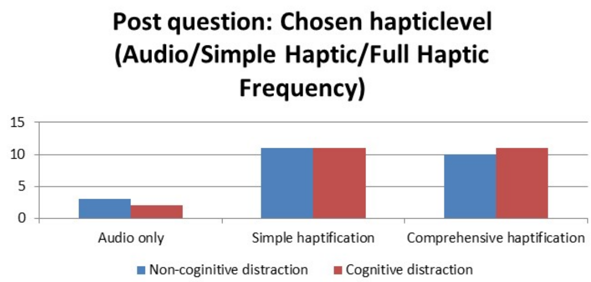

Fig. 2. Which haptic level participants would choose for navigation task?

3 Discussion and Future Work

We presented an audio-haptic navigation interface utilizing a simple and cost-effective setup which utilized rhythmic tactons to present information and evaluated how the level of haptic support and the distraction level affect navigation performance and satisfaction in a navigation task. There were two levels of distraction, one with audio distraction, which did not require attention, and another one with additional cognitive tasks.

While investigating navigation errors, the earlier results with visual-audio-haptic condition [6] were repeated and there was no improvement on navigation errors with haptic feedback added to the audio. However, earlier results showing navigation performance improvement with visual-haptic condition where haptic feedback was added to visual feedback [10] and in visual-audio condition with haptic belt added to navigation support [1] or continuous feedbacks were used [4] were not repeated. In these conditions with the visual element included in feedback, an improvement in the navigation errors was found when haptic feedback was added. This leaves an open question for future research to investigate, if actually the visual element in the navigation instructions under high load conditions is dampening the navigation performance in multimodal context compared to audio-haptic instructions due to requiring visual attention. Also the obvious result was shown, that adding cognitive distraction increases navigation task errors. Future investigation on, how to compensate additional distraction is needed. Also, it could be argued on navigation errors, that when the percentage of errors was so small, the differences did not reach a level of significance. Also in our experiment average navigation error rate was smaller on all conditions, than on those earlier experiments [10][1][4] improving navigation with added haptics. Making the task more demanding in future experiments, could raise the differences between the modalities.

The subjective ratings showed that the participants thought that navigation and driving under more distraction was more difficult. The level of haptic support did not affect the user experience ratings. Interesting in these results was that even though the comprehensive haptic interface was unfamiliar and required interpretation to understand, it was not rated less pleasant or difficult. Vice versa, on post question where participants selected which of the feedbacks they would like to use (Figure 2) almost all would select haptically enhanced audio instructions and half of them comprehensively haptified. Thus, it can be assumed that using comprehensive haptification method in audio-haptic user interfaces would not affect user satisfaction negatively and that users would appreciate haptic interface even though it would not improve the performance.

In this work we have shown, that extremely robust and low-cost haptic device can be used on navigation task by utilizing informative tactons and provide users subjective value, even though performance was not affected. In future research it would be interesting to investigate more complex interactions, based on audio information, than navigation, to find out if haptics can be used to improve performance. Also using other measures, than simple navigation performance, could raise interesting results.

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