Helsinki University of Technology,
Faculty of Electronics, Communications and Automation

Emilia Koskinen

Optimizing Tactile Feedback for Virtual Buttons in Mobile Devices

Master's Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering.

Espoo, January 28th, 2008

Supervisor Professor Marko Nieminen

Instructor Miika Silfverberg, M.Sc.

HELSINKI UNIVERSITY OF TECHNOLOGY **Abstract of Master's Thesis**

Author: Emilia Koskinen	
Subject of Thesis: Optimizing Tactile Feedback for Virtual Buttons in Mobile Devices	
Date: January 28, 2008	**Number of Pages:** 95
Department: Faculty of Electronics, Communications and Automation	
Professorship: T-121 User Interfaces and Usability	
Supervisor: Prof. Marko Nieminen	
Instructor: Miika Silfverberg, M.Sc. (Psych.)	

Touchscreen mobile devices, which do not have a physical keypad or keyboard, have become very popular. In these devices the interaction is done primarily with virtual buttons as all or most of the physical buttons have been removed. Due to this fact these devices have one major weakness compared to the traditional mobile devices: the lack of tactile feedback. This makes the mobile device usage challenging as the user can only rely on visual and audio feedback. Mobile devices are often used in situations where the user cannot devote all his visual attention to the device and the audio feedback cannot be heard. Therefore the absence of the tactility makes the mobile device usage difficult. Adding tactile feedback to touchscreens might solve this problem.

This thesis researches how to design and implement tactile feedback for virtual buttons with the highest level of usability. The research compares two different actuators for producing tactile feedback on the touchscreen: a standard vibration motor and a piezo actuator. The virtual buttons enhanced with tactile feedback features produced with the aforementioned technologies are compared in terms of usability attributes. The usability evaluation is performed using a traditional usability testing method where one participant at a time is doing a pre-defined task with the system. Several studies are conducted including both laboratory and field tests.

The results of the studies show that virtual buttons with piezo feedback provide the highest level of usability. With piezo feedback users performed faster and made fewer errors. The results also found the piezo feedback to be the most pleasant tactile feedback on virtual buttons. Virtual buttons with vibra feedback are the second best option in terms of usability. Virtual buttons without tactile feedback have clearly the lowest level of usability. The results also show that when users are on the move, especially when traveling on the metro, the tactile feedback is even more beneficial.

Keywords: touchscreen mobile devices, virtual buttons, haptics, tactile feedback, usability, usability testing

TEKNILLINEN KORKEAKOULU **Diplomityön tiivistelmä**

Tekijä:
Emilia Koskinen

Työn nimi:
Virtuaalisten näppäinten tuntopalautteen optimointi mobiililaitteissa

Päivämäärä: Tammikuu 28, 2008	**Sivumäärä:** 95

Tiedekunta:
Elektroniikan, tietoliikenteen ja automaation tiedekunta

Professuuri:
T-121 Käyttöliittymät ja käytettävyys

Työn valvoja:
Prof. Marko Nieminen

Työn ohjaaja:
FM Miika Silfverberg

Kosketusnäytölliset mobiililaitteet, joissa ei ole lainkaan fyysistä näppäimistöä ovat nykyään hyvin suosittuja. Näissä laitteissa vuorovaikutus tapahtuu useimmiten virtuaalisilla näppäimillä, koska kaikki fyysiset näppäimet ovat poistettu. Tämän vuoksi kosketusnäytöllisillä laitteilla on yksi merkittävä heikkous perinteisiin matkapuhelimiin verrattuna: tuntopalautteen puute. Tämä tekee mobiililaitteen käytöstä melko haastavaa kun käyttäjä voi luottaa pelkästään visuaaliseen- ja äänipalautteeseen. Mobiililaitteita käytetään useasti tilanteissa, jossa käyttäjä ei voi keskittää katsettaan jatkuvasti laitteeseen ja äänipalaute jää kuulematta, jolloin tuntopalautteen puute tekee laitteen käytöstä hyvin vaikeata. Tuntopalautteen lisääminen kosketusnäyttöön saattaa ratkaista tämän ongelman.

Tämä työ tutkii kuinka suunnitella ja toteuttaa tuntopalaute virtuaalisille näppäimille niin, että saavutetaan korkein käytettävyyden taso. Tutkimus vertailee kahta erilaista aktuaattoria, jotka tuottavat tuntopalautetta kosketusnäytölle: värinämoottoria ja piezo aktuaattoria. Edellä mainittujen teknologioiden avulla tuotetuilla tuntopalautteilla varustettuja virtuaalisia näppäimiä verrataan valittujen käytettävyysattribuuttien suhteen. Käytettävyyden arviointi toteutetaan perinteisellä käytettävyystestimenetelmällä, jossa yksi käyttäjä kerrallaan suorittaa ennalta määrättyä tehtävää laitteella. Tutkimuksessa toteutetaan useita yksittäisiä testejä sekä laboratorio- että kenttäkokeina.

Tulokset osoittavat, että virtuaalisten näppäinten käytettävyyden taso on korkein piezo palautteella: käyttäjät suoriutuivat tehtävästä nopeammin ja tekivät vähemmän virheitä. Piezo palaute koettiin myös virtuaalisten näppäinten miellyttävimmäksi palautteeksi. Värinäpalaute on toiseksi paras vaihtoehto käytettävyyden kannalta, kun taas virtuaaliset näppäimet ilman tuntopalautetta ovat huonoin vaihtoehto. Tulokset myös osoittavat, että tuntopalaute on hyödyllisempi silloin kun käyttäjät ovat liikkeellä, varsinkin metrossa matkustettaessa.

Avainsanat: kosketusnäytölliset mobiililaitteet, virtuaaliset näppäimet, haptiikka, tuntopalaute, käytettävyys, käytettävyystestaus

1. INTRODUCTION

1.1 Mobile touchscreen devices

Mobile devices, those small pocket-sized gadgets, which over 3 billion people carry with them almost all the time, were initially designed for mobile communication. These days many of them are more like small-sized computers, which allow users to read and write email messages, browse the web, listen to music, take pictures, and navigate their way with a map and a GPS. All this can happen anywhere and anytime, which sets special requirements for the usability of these devices.

Usually most mobile devices have comprised a visual screen and a small physical keypad or keyboard but this has changed now. At the moment there are many touchscreen mobile devices on the market and more are coming out all the time. Touchscreens are not a new thing, as they have been widely used e.g. in personal digital assistants, but now they are becoming a mainstream technology in mobile devices. Touchscreens do have their benefits. As the physical keypads and keyboards can be removed there is more space on the surface of the mobile device for larger screens. Also the user interface of the mobile device can be configured according to an application, as it is not dependent on any physical keys. This allows making the graphical UI more suitable and usable for different functions. Nokia N800 Internet Tablet (Fig. 1) is a good example of a typical touchscreen mobile device, which has a large screen without any physical keyboard and the interaction is done with a stylus.

Fig. 1. The Nokia N800 Internet Tablet, a touchscreen device, which uses a stylus for interaction.

Almost all the newest touchscreen mobile devices have one major change compared to the previous mobile devices such as Nokia N800: they are using fingers on the screen for interaction. This seems to be the trend, which touchscreen mobile devices are going towards to, as most manufactures are getting rid of stylus interaction. One well-known finger-operated touchscreen mobile device at the moment is Apple iPhone (Fig. 2).

Fig. 2. The Apple iPhone touchscreen mobile device.

Finger-operated touchscreen mobile devices have one major disadvantage compared to the traditional devices with physical keyboards, namely the lack of tactile feedback i.e. feedback that can be felt. For example when entering text or numbers with virtual buttons, the buttons do not provide any tactile response, that the users are used to experience with physical buttons. Without the tactile feedback on touchscreens, the users can only rely on audio and visual feedback. This makes the mobile device usage more challenging because they are often used in parallel while the user is doing something else like e.g. walking or traveling on a bus. In these kinds of situations users need to fragment their attention for several objects, which makes the interaction with the mobile device more difficult [1]. In mobile situations the visual attention cannot be completely devoted to the mobile device because it is needed to observe the environment. Also in these kinds of situations the audio feedback from the mobile device cannot always be heard because of the noise from the environment. This makes the mobile touchscreen devices with lacking tactility difficult to use in most mobile situations.

Adding tactile feedback to touchscreens might solve this problem. With tactile feedback it is possible to make the virtual buttons feel more like physical ones. The tactile feedback is a good way to confirm the actions to the users especially in situations, where the user cannot look at the screen all the time to see the visual feedback or the audio feedback cannot be heard [2]. Tactile feedback creates also more natural interaction between the user and the device as the human sense of touch is directly connected to the tasks that are performed with fingers. Tactile feedback can be a possible way to improve the usability of touchscreen mobile device interaction.

1.2 Objective of the study and research questions

The problem with touchscreen mobile devices is that they lack the tactile feedback of physical buttons. This study tries to find a good solution for this problem from the user's point of view. The tactile feedback of virtual buttons should be implemented and designed so that it ensures the highest degree of usability to the user. Therefore the objective of this study is to find the optimal way to implement tactile feedback on touchscreens. The study focuses on tactile feedback for virtual buttons, as button interactions are very common in mobile devices. The main research question of this thesis is:

> **What is the optimal solution for virtual buttons tactile feedback?**

To find answers to that question, two approaches, theoretical and empirical, are used. The theoretical approach clarifies what is already known about designing tactile feedback for touchscreen interactions. The empirical approach researches tactile feedback by conducting several usability studies. In the empirical studies two technologies are used to generate tactile feedback on a touchscreen device, piezo actuator and vibration motor. To gain a better understanding of these two alternatives, the usability studies try to find answers to the following questions:

> **Which parameters create the most pleasant tactile feedback for virtual buttons with piezo actuator and vibration motor?**

How does the usability of virtual buttons differ when using piezo feedback, vibra feedback or no tactile feedback at all?

How does the usability of virtual buttons differ as users are on the move when using piezo feedback, vibra feedback or no tactile feedback at all?

1.3 Thesis structure

The structure of this thesis includes a theoretical part and an empirical part. The theoretical part consists of chapters 2 and 3 and the empirical part of the chapters 4, 5 and 6. The chapter 2 provides a basic understanding of human sense of touch, haptic perception and it also introduces existing interfaces and devices with tactile feedback. The chapter 3 presents the concept of usability and usability testing methods in more detail. It also introduces the earlier research of tactile feedback on touchscreens, including the research methods and findings. The chapter 4 highlights the importance of this study and introduces the methods used in the usability tests. The following chapters 5 and 6 report the methods in more detail and the results of the conducted usability studies. The chapter 7 presents the conclusions and discussion of the research and recommendations for future research.

2. HAPTICS

This chapter first examines haptic perception and the most relevant related terms are defined. After that haptic feedback is defined more precisely. Next the kinaesthetic sense is introduced briefly and after that the cutaneous sense is described in detail, as it is the more relevant sense related to this study. Then the differences between active and passive touch are briefly specified. After that the devices, which provide haptic feedback, both desktop and mobile, are introduced. The last subchapters focus on existing research and development of touchscreen mobile devices with tactile feedback.

2.1 Haptic perception

Sense of touch is crucial for human beings; it protects us from injury and provides vital information about the outside world and environment. The word “haptic” means related to, or based on, the sense of touch. It is derived from the Greek word “haptikos” meaning able to touch. Haptic perception refers to perception that is based on the sense of touch and it includes both cutaneous and kinaesthetic perceptions.

Kinaesthetic perception refers to the sensations of stimuli from within the body e.g. the movement of limbs [3]. Kinaesthetic perception implies awareness of static and dynamic body posture. It is based on the afferent information originating within the muscles, joints, skin and efference copy, which is the correlate of muscle efference available to the higher brain centers [4]. Therefore, kinaesthetic perception includes both proprioception i.e. sensing the positions of the limbs and kinesthesis i.e. sensing the movement of the limbs.

Cutaneous perception relates to the sensations that are based on the stimulation of the outer surface of the body by means of mechanoreceptors within the skin and the associated nervous system [4]. Cutaneous stimulation can be further separated into the sensations of pressure, stretch, vibration, temperature and pain. The sensation that is mediated exclusively by cutaneous stimulation is called tactile perception [5].

Terms haptic and tactile are commonly regarded as synonyms of each other but to be precise, the term tactile pertains only to cutaneous perception, excluding the kinaesthetic perception. The Chart 1 summarizes the terminology for haptic perception that is used in this thesis.

Chart 1. The terminology relating to haptic perception (modified from Oakley et al. [6])

Term	**Definition**
Haptic	Relating to sense of touch.
Kinaesthetic	Meaning the feeling of motion. Relating to sensations originating in muscles, tendons and joints.
Cutaneous	Relating to sensations, which arise through direct contact with the skin surface. Includes sensations of pressure, vibration, temperature and pain.
Tactile	Pertaining to the cutaneous perception and more specifically the sensation of pressure and vibration rather than temperature and pain

2.2 Haptic feedback

Haptic feedback is something that the user can feel therefore creating haptic interaction between the device and the user. Haptic feedback provides both cutaneous and kinaesthetic information. It is important to understand the division between these two. Haptic feedback that conveys only the cutaneous information is called tactile feedback, which affects the human's skin surface e.g. by stretching it. Force feedback conveys only the kinaesthetic information by applying force to a human's hand or body and affecting their position and movement [6]. To be precise, when talking about a haptic device it needs to provide both tactile and force feedback. These kinds of devices are only possible in a desktop environment as they are not portable and usually require the user to wear special equipment. In the case of mobile haptics, due to the size and power consumption limitations and the nature of the mobile devices, the feedback is restricted only to tactile feedback and cannot include force feedback. The figure 3 clarifies this division of haptic feedback to tactile and force feedback from the device's point of view and shows which haptic sensation the feedback perception corresponds to.

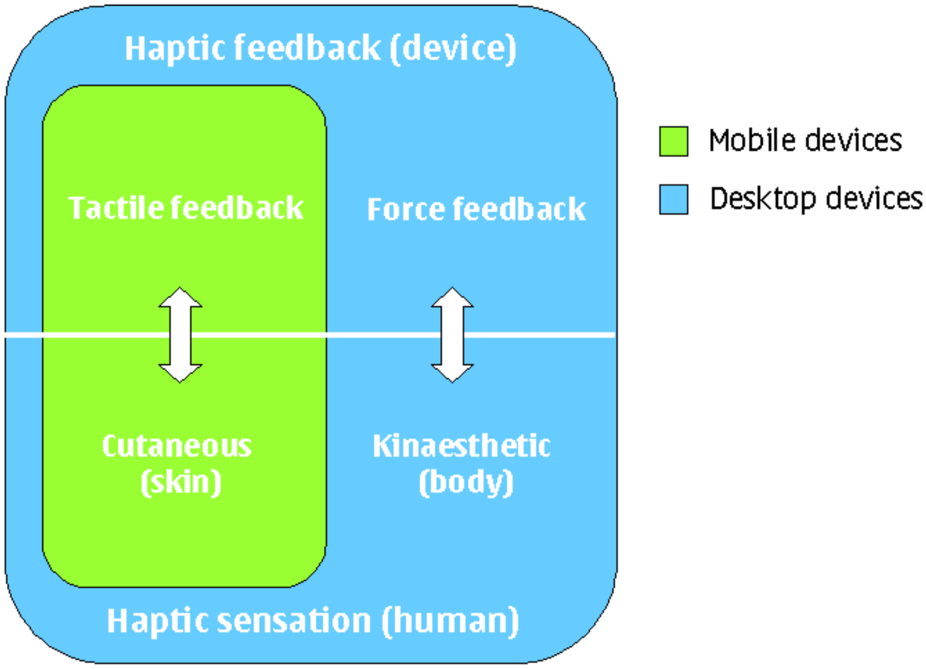

Fig. 3. Haptic feedback contains both tactile and force feedback which create cutaneous and kinaesthetic sensations.

The haptic feedback that is researched in this study activates cutaneous perception by providing sensations of pressure, taps and vibration to the skin. Therefore the term tactile feedback is more appropriate to use to describe the feedbacks that are researched later in the usability studies of this thesis because they contain only the cutaneous output.

2.3 Kinaesthetic sense

Perceiving kinaesthetic sensations like the movement of body parts and body position rely on specialized sensor receptors, which are located in muscles, tendons and joints. These receptors include muscle spindles, tendon organs and joint receptors. Muscle spindles provide information mainly on the length of the muscles or the speed of change in this length. Tendon organs provide information on the level of tension of the muscle and its variation over time. The role of the joint receptors is still being debated but they are now known to provide information about extreme joint positions. It has been suggested that the joint receptors serve mainly a protective function by detecting harmful stimulation. The way in which the kinaesthetic receptor units mediate perceptual outcomes is not well understood, especially when comparing to cutaneous receptors. [7] The kinaesthetic sense is not relevant to mobile devices (Fig. 3); therefore further details are not presented here.

2.4 Cutaneous sense

The cutaneous sensations are experienced through the skin; the largest organ in human body. Through the skin, touch provides information about the physical characteristics of the environment and allows the perception of pressure, texture, shape, temperature and pain [8].

Perceiving the above-mentioned sensations is based on the outermost and visible layer of the skin, called epidermis. The layer of skin beneath the epidermis is called dermis. These two layers contain four major receptors, which each respond to particular kinds of stimulation and associate with particular perceptions [9]. Those receptor structures are Merkel receptor, Meissner corpuscle, Ruffini cylinder and Pacinian corpuscle. There are also two main types of nerve endings found in the skin; free nerve endings and nerve endings, which are incorporated within the receptor structures, mentioned above. Figure 4 shows a cross section of the human skin, including the layers of the skin and the four major receptors.

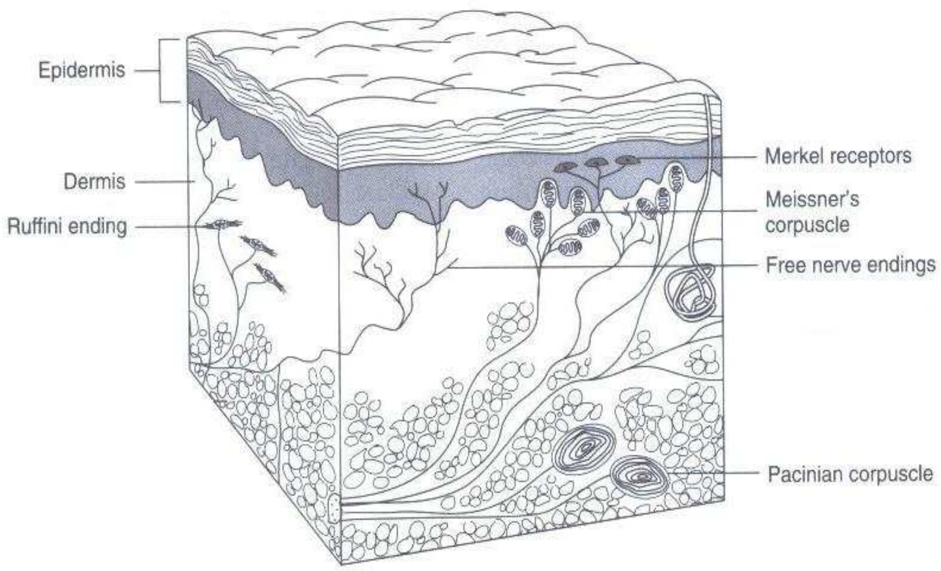

Fig. 4. Cross section of the human skin, including the layers of the skin and the four receptors. [9]

According to how the nerve endings react to different kind of stimuli, they are classified into three receptor categories; mechanoreceptors, thermoreceptors and noiceptors [3]. Mechanoreceptors are divided further into two categories based on their speed of adaptation, i.e. rapidly adapting (RA) and slowly adapting (SA). Mechanoreceptors respond to indentations of the skin, associating for example sensation of pressure, vibration and skin stretch. Meissner corpuscles and Pacinian corpuscles are classified as rapidly adapting (RA) mechanoreceptors and Merkel receptors and Ruffini cylinders are classified as slowly adapting (SA) mechanoreceptors. Thermoreceptors are free nerve endings with small receptive fields which respond to temperatures or changes in temperature, associating sensation of cold or warmth. Noiceptor receptors respond to stimuli, which damage the skin, for example intense heat or strong pressure.

Skin sensation information that is received through the touch receptors in the skin is transmitted to the brain through pathways within the body and is processed in the central nervous system (CNS). The brain consists of two hemispheres, which are made up of nerve cells and nerve fibres. Each hemisphere is separated into four wide lobes, which match in position to the bones of the skull below which they are located, i.e. the frontal, temporal, parietal and occipital lobes [3]. The outermost layer of each hemisphere is referred to as the cortex. The area of the brain where the sensation information is processed and which provides the perception of sensations is called the somatosensory cortex and is located in the parietal lobe. Figure 5 shows a simplified diagram of the main structures involved in processing somatosensory information within the CNS.

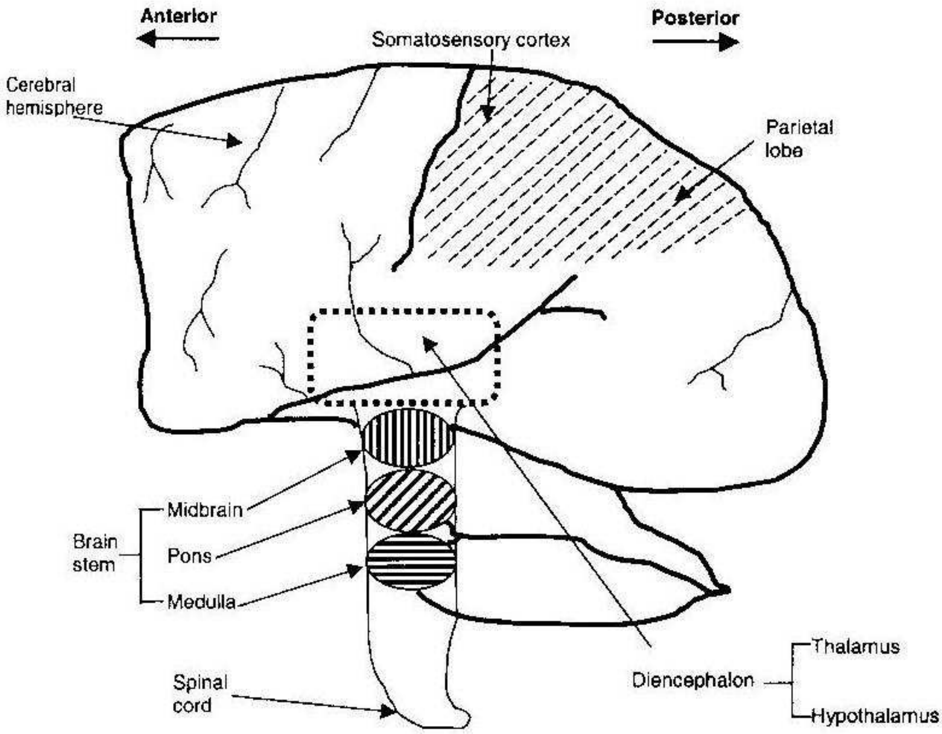

Fig. 5. Simplified diagram of main structures involved in processing somatosensroy information within the central nervous system. [3]

The information received through the touch receptors is transmitted to the brain through two main pathways i.e. dorsal column medial lemniscal system (DCMLS) and anterolateral system (ALS). DCMLS transmits information that is obtained through active exploratory touch and includes information e.g. about vibration and pressure. ALS is a protective system, which transmits information about pain and temperature [10]. In order to reach the somatosensory cortex, the information passes through one of the two processing systems along the spinal cord to the reticular formation in the brain from where it is then transmitted to the thalamus. The thalamus serves as an important integrating centre for input from all sensory systems with the exception of olfactory system [11]. Figure 6 shows a simplified diagram of the somatosensory system.

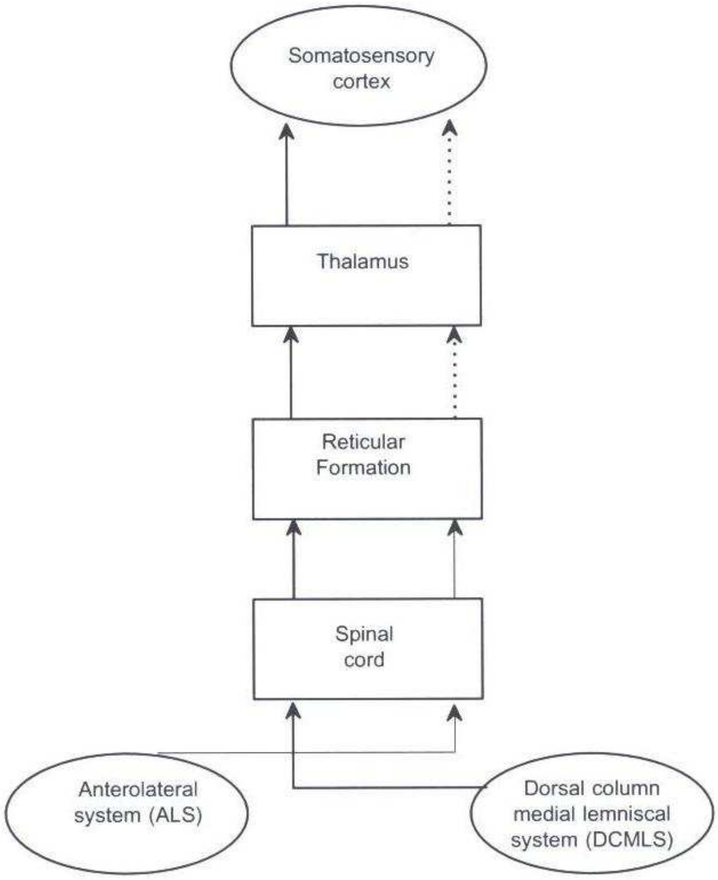

Fig. 6. Simplified diagram of somatosensory system showing the two pathways, Anterolateral system (ALS) and Dorsal column medial lemniscal system (DCMLS). [3]

2.5 Active and passive touch

Active touch refers to the person actively controlling his or her fingers to explore a haptic stimulus e.g. running fingers across surfaces or hitting the mechanical keys on a mobile phone. In passive touch the stimulus is applied to the skin of a passive person. Passive touch is tended to relate to the sensation experienced in the skin which provides information about events at the surface level of human bodies, whereas active touch is tended to relate to the object being touched providing information about objects and surfaces in the environment [12].

Active touch stimulates the receptors in the skin and also in the joints and tendons, which are activated as fingers or hands are moved over an object. Passive touch stimulates only the receptors in the skin. Active and passive touch also differ from each other when perceiving movements of objects. When a hand is moved over the edges and surfaces of an object (active touch), the object is not perceived as moving, even though it is moving relative to the skin. If the object is moved across the skin (passive touch), the object is perceived moving across the skin [9]. The usability studies of this thesis focus on active touch.

2.6 Haptic interfaces and devices

Haptic feedback is mainly used in the desktop environment, but in the past few years new haptic applications, suitable for mobile usage, have emerged.

2.6.1 Desktop haptics

Haptic feedback can be utilized in graphical user interfaces in desktop environments using specific input devices, which provide users with haptic output [13]. The first commercial haptic device was SensAble's PHANTOM [14], a robot arm that is attached to a computer and used as a pointer device (Fig. 7). The user can point virtual objects on the desktop by moving the mechanical arm which provides force feedback as the pointer on the screen touches the objects and creates an illusion that the user is actually feeling the virtual objects with the pointer.

Fig. 7. The PHANTOM haptic device by SensAble technologies.

Logitech has introduced a couple of tactile mice, which work as normal pointing devices but are enhanced with vibration or force feedback [13]. The idea is that the user can feel feedback from the mouse whenever the cursor moves on a clickable object on the screen and also when performing a task, e.g. moving a scrollbar or crossing a window boundary.

There are also various game controllers on the market with haptic feedback features. Especially joysticks and console game controllers are able to push back against the user utilizing force feedback and also feature vibration or rumble to create richer gaming experiences. For example Sony's PlayStation 2 [15] and Nintendo's Wii [16] video game consoles have controllers, which provide this kind of haptic feedback. For most people, these game controllers are the most common haptic devices they have experienced so far.

Haptic interfaces are also used in virtual reality systems, robotics and in medical science for training of minimally invasive procedures and remote surgery using teleoperators [17].

2.6.2 Mobile haptics

There has not been much research & development in the field of mobile haptics, until recently. The area of haptic human-computer interaction has grown rapidly over the last few years. As the technologies have improved and the prices have come down, mobile haptics is gaining more attention. Mobile devices utilizing tactile feedback features have now become possible.

In mobile phones, the most common feature that utilizes the sense of touch is vibration alert [18]. Vibration alerts provide little vibrations to the user to indicate an incoming call or message and are mostly used to enhance the audio feedback to alert users in noisy environments.

The tactile alerts, which can be used to communicate other information also, are called Tactons [19]. They are structured vibrotactile messages, which are used to communicate information non-visually and can enable tactile-only communication of complex information. In addition to caller information, Tactons can indicate the type of call or message being received, or the priority of the call [20].

One other example of utilizing tactile feedback in a mobile device is the Digital Pen (Fig. 8) by Nokia [21]. It is a pen which can store handwritten notes and drawings from a digital paper. It provides the user with vibration feedback e.g. to confirm the written notes to be safely transferred from the pen's memory card to a mobile phone.

Fig. 8. The Digital Pen by Nokia.

2.6.3 Touchscreens with tactile feedback

The research in the field of tactile touchscreens has focused mostly on designing the tactile actuators and adding the tactile feedback to different user interactions with mobile touchscreen devices.

The earliest reported tactile interface for a touchscreen, called Active Click, was developed for relatively large touchscreens where an actuator was attached to the body of the mobile device or the backside of the touch panel [22]. In this solution the user can perceive the tactile feedback by the grasping hand or tapping finger-tip when the touch panel is tapped depending on the location of the actuator. With this design, the actuator vibrates the entire device body.

Poupyrev et al. have presented a tactile interface design for small touchscreens used in mobile devices [23, 24]. In their design users can directly feel the graphical user interface (GUI) controls with their fingers, simulating the feeling of real mechanical controls, e.g. pressing a GUI button on a touchscreen feels like pressing a real electromechanical switch. In their implementation, presenting the tactile feedback directly to the finger, which is interacting with the device, is possible by locating the actuator under the touchscreen. In addition to adding tactile feedback to multiple GUI elements, they also introduced a structure for touchscreen gestures, e.g. dragging a GUI widget on the screen.

Kaaresoja et al. [25] have also presented a mobile device demonstrating tactile feedback for a touchscreen, extending the scope of the earlier work done by Poupyrev [24]. They added tactile feedback to four different applications: numeric keypad, text selection, scrolling and drag and drop.

Virtual buttons are the most common user interface element to which tactile feedback has been added. In addition to providing the user with a feeling of a button press, other information about the buttons can also be communicated with tactile feedback. Nashel et al. [26] presented a technique to add tactile cues of real buttons to virtual buttons displayed on mobile devices with touchscreens. In their design, the user is able to feel that his finger is over a button and if he presses it but also which button is under his finger.

2.6.3.1 Tactile touchscreen technologies

In the usability studies of this thesis, two different kinds of tactile actuators are used to produce tactile feedback on the touchscreen; standard vibration motor and piezo actuator.

Standard vibration motors (Fig. 9) are widely used in most mobile phones to produce vibration alerts. Vibration motor functions by spinning an eccentric mass with a small electric motor [23]. Vibration motors produce usually strong tactile effects, as the vibration induces a movement of the whole mobile device and are therefore ideal to be used for alerting the user. The weaknesses of a vibration motor as a tactile actuator are the significant latency and the limitations in displaying amplitudes and range of frequencies.

Fig. 9. Standard vibration motor.

Piezo actuator is constructed of electro-strictive piezoceramic material, forming a flat, brass plate that is curved into a cup shape by the constricting ceramic component (Fig. 10). The material on the top has an opposite polarity to that on the bottom, so when a signal is applied, the entire structure bends [23]. Piezo is often called a ”bending motor” actuator. The piezo actuator can be used to move a screen window or cover parts of mobile device. The movement is very small, approximately 100 micrometers but its high speed makes it easily detectable to the human touch. Piezo actuators enable tactile feedback on a specific area of the mobile device. With piezo actuator enhanced touchscreens, users can experience the illusion of local actuation although in reality the entire screen moves [27]. The benefits of piezo actuator are that they can be manufactured in various sizes and number of layers. But most importantly piezo actuator is fast and allows controlling both the amplitude and the frequency of the tactile feedback at the same time.

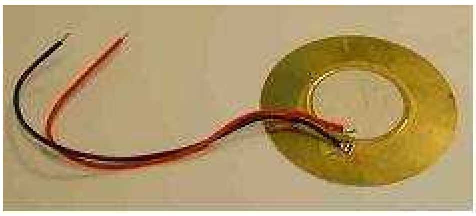

Fig. 10. Piezo element.

There are also other components that can be used to produce tactile feedback, e.g. voice coils and loudspeakers but vibration motor and piezo actuator are the most promising technologies at the moment.

2.6.3.2 Touchscreen mobile devices with tactile feedback

At the moment there are only a couple of commercial mobile devices with touchscreens that have tactile feedback features. LG's Prada phone [28] and a couple of Samsung phones [29] are using Immersion's VibeTonz System [30] to provide tactile feedback for touchscreen interactions. The VibeTonz System uses different kinds of vibration motors to produce tactile cues in user interface features.

Another touchscreen mobile device with tactile feedback is Sony's Navitus [31], an integrated remote control with touchscreen that presses back against the user's fingertips to confirm commands. Navitus (Fig. 11) uses TouchEngine [32] tactile actuator, which is constructed as a sandwich of multiple layers of piezo elements.

Fig. 11. Sony Navitus, an integrated remote control.

3. USABILITY

This chapter begins with defining the concept of usability and continues by introducing different usability evaluation methods. After that usability testing methods are introduced in detail, clarifying also the special needs of usability testing of mobile devices. Then the methods and findings of previous usability studies researching tactile feedback on touchscreen mobile devices are introduced.

3.1 Definition of usability

Human-computer interaction (HCI) studies the interaction between people and computers. In HCI the goal is to improve the interaction by making computers to better fulfill user needs and make them more usable, in other words to have good usability. There are several definitions of usability but all of them have similar fundamental philosophies. Usability is commonly related to how well a product applies to the intended use and how well it fulfills user's needs and goals.

International standard ISO 9241-11 [33] defines usability as "The extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use." ISO clarifies also effectiveness further as the accuracy and completeness with which users achieve specific goals, efficiency as the accuracy and completeness of goals in relation to resources expended and satisfaction as the comfort and acceptability of the system.

According to the ISO 9241-11 standard, usability is about the effectiveness, efficiency and satisfaction but it is also influenced by the users who are using the product, the goals they are trying to do with the product and the context of use where and how they are using the product. Therefore it is obvious that usability is not a single, one-dimensional property of a product but a combination of several factors.

Nielsen [34] defines usability to consist of multiple components and associates it with five usability attributes; learnability, efficiency, memorability, errors and satisfaction. Learnability means that the system should be easy to learn so that it is possible to use the system effectively as quickly as possible. Efficiency means that the systems should be efficient to use, so that once the user has learned the system, a high level of productivity is possible. Memorability implies that the system should be easy to remember, so that the user does not need to learn the use all over again after a break from using the system. Errors should be avoided so therefore the system should have a low error rate. If the user makes errors, it should be easy to recover from them. Satisfaction implies that the system should be pleasant to use, so that users are subjectively satisfied when using the system.

According to Nielsen [34], a product which is easy to learn, efficient to use, easy to remember, has low error rate and satisfies the users, can be regarded to have good usability.

There are slightly different terms used when defining usability attributes, depending on the preferences of the author. Shackel [35] for example defined usability with four attributes; learnability, effectiveness, attitude and flexibility. Preece et al. [36] on behalf referred usability consisting of learnability, throughput, flexibility and attitude. Regardless of what terms are used to describe the usability attributes, it is more important that the attributes are measurable. If the product achieves the set measurements, it can be said that the product fulfills also an acceptable level of usability.

In the usability studies of this thesis the considered usability attributes are efficiency, errors and satisfaction adapted from Nielsen [34].

3.2 Evaluating usability

3.2.1 The purpose of evaluation

The primary goal of usability evaluation is to improve the usability of the product that is being evaluated. International standard ISO 13407 [37] clarifies that usability evaluation can be used to provide feedback during the design process, assess whether the user and organizational objectives have been met and to monitor long-term use of the product or system. Therefore the purpose of usability evaluation is not just to identify the possible usability problems but to consider other usability aspects of the product also. The main goals are usually to evaluate whether the set usability targets have been achieved and to receive user feedback in a form that can be used to improve the design of the product.

Before carrying out any evaluation, the goals need to be set. Chapter 3.1 defined different usability attributes which can be used as the criteria for judging the usability of a product. Assigning metrics to those attributes, allows to determine the usability of a specific system. Usability attributes need to be prioritized based on the product's target user group, intended use and context of use. Those attributes might not be the same for different users working in different environments and on different tasks. Therefore it is important to recognise which attributes are most crucial when identifying usability of a given product and how they can be expressed in measurable ways.

To evaluate the system thoroughly it is necessary to gain both quantitative and qualitative information. Quantitative data is useful because data can be validated statistically and it allows detailed analysis of the data. Qualitative data concentrates more on opinions and feelings of the users. Usability metrics can be used to gain quantitative data and those are useful for evaluating the performance of the system. However, a good system is not just about ensuring that both the device and the user perform as efficiently as possible, but it needs to create a positive emotional experience to the user as well and therefore needs to satisfy the user [38]. That is why qualitative data is essential for usability evaluation.

3.2.2 Usability evaluation methods

There are several different methods to evaluate usability and new methods are still being designed. There are also various ways to categorize these methods but the most common classification is to divide usability evaluation methods into two categories; expert evaluations and user testing, according to user involvement [34].

Expert evaluation is the inspection of a product or system in terms of its usability, usually done by a usability specialist or human factors specialist. The specialist evaluates the system against certain accepted rules, for example usability principles, usability heuristics or usability guidelines. There are several different methods to conduct an expert evaluation, for example heuristic evaluation, guideline review, standard inspections and cognitive walkthrough, to name a few. [34, 38]

Heuristic evaluation is usually conducted by a small set of evaluators who independently examine a user interface and look for problems that violate some of the predefined usability guidelines also referred to as usability heuristics, developed by several authorities. Guideline review is also done by a usability specialist who checks that the system conforms to the guidelines set by the system's platform. Guidelines should ensure that systems are internally and externally consistent. Standards inspections are design reviews done by a usability expert to determine whether the system conforms to the particular standards that have been set for it by the specification. Cognitive walkthrough is carried out by an usability expert who inspects the user interface by going through a set of task with the view of imitating user performance and endeavouring to discover what problems the user might encounter.

Expert evaluation methods are useful for evaluating a system or a product without the need for end-user involvement and are therefore cheaper and faster. However, the evaluation is only as good as the experts who are conducting it and the methods they use.

User testing with real users is still regarded to be the most fundamental usability method since it provides direct information and feedback from users on how they can perform with the system, what problems they might have with it and how they experience the system. There are also different types of user testing methods, which differ from each other in terms of the number of the participants, the role of the observing usability specialist and the formality of the performed tasks. The user testing conducted in this study can be referred to traditional usability testing, where one participant at a time is doing a pre-defined task with the system. This type of testing is introduced more precisely in the following chapter.

3.3 Usability testing

Usability testing refers to techniques for collecting empirical data while observing test users using the product to perform representative tasks. The aim of usability testing is to measure how well users can actually use the product. Usability testing can be divided into four types of tests, namely exploratory, assessment, validation and comparison [39].

Exploratory usability tests are performed early in the development process in order to evaluate the effectiveness of a design concept in its early stages. Usually the test user is given a prototype and asked to perform tasks using it. Assessment usability testing is performed early or midway through the development process where the test user is performing tasks with a functional prototype. The focus of assessment usability tests is more on specific aspects of product operations. Validation usability tests are performed late in development process in order to verify the product is usable by collecting performance data. Testing focuses on the most particular aspects of the product. Comparison usability testing is the evaluation of two or more prototypes or final products. The comparison test is not associated with any specific point in the product development life cycle. The usability testing conducted in this thesis uses comparison tests and the used methods are explained in more detail in the chapter 4.2.

3.3.1 Reliability and validity

A good usability test is reliable and valid. A reliable result is consistent and repeatable. A result can be considered reliable if the same result would be achieved if the test was repeated over and over again [40]. The reliability of usability tests is problematic because of the individual differences between test users and the variability in their performance [34]. This variability requires greater numbers of participants to be recruited into a sample, in order to maintain the same level of confidence. Standard statistical tests can also be used to indicate the reliability of the results [34]. Validity means whether the test really reflects the usability results that were meant to be tested. It refers to the relationship between the test and reality. Validity depends on test conditions, participant selection and tasks being as close as possible to actual conditions [40]. Achieving a high level of validity requires methodological understanding of the test method that is used.

3.3.2 Measures

In a usability test both performance and subjective measures can be collected. Performance measures are counts of actions and user behaviors that are observed, for example the time to finish a task and the number of total errors. Performance measures are quantitative and they depend naturally on the product in question. Subjective measures refer to people's perceptions and opinions and may be either quantitative or qualitative. To receive quantitative subjective measures it is common to use different kinds of questionnaires. There are a variety of common types of formats of close-ended questions to use in questionnaires. Likert scales and semantic differentials are good examples of those, as they are most often found in questionnaires. Likert scales are scales on which the participants register their agreement or disagreement with a statement and the judgements are quantified typically on a 5-point or 7-point scale. Semantic differentials are scales on which the participants are asked to register the degree to which they favor one of two adjective pairs. As an example of a semantic differential, users could be asked to rate how easy or difficult the product is to use on a 5-point or a 7-point scale. The response is quantitative though the judgement is subjective [41]. Interviews are the best way to receive qualitative subjective data. Also the comments made by test users during the test are a good source for information. The thinking-aloud method is ideal for gaining spontaneous comments from participants, where they are encouraged to continuously talk while they work with the system. By verbalizing user's thoughts, it is possible to understand how the user views the system [34].

3.3.3 Test users

Test participants should represent the real users as much as possible in order to achieve high level of validity in the results, as mentioned already earlier. It has to be carefully considered who the users of the product are and what kind of characteristics they share. The number of participants should also be decided, which depends on do the results need to be statistically significant. Nielsen [34] suggests that five would be the number of users that are necessary when running a usability test. Rubin [39] on behalf prefers a minimum of eight participants in a test to rule out the effect of individual differences of the test subjects.

3.3.4 Test tasks

The test tasks should be as representative as possible of the real tasks of the product. The task should also cover the most important parts of the product and it's user interface. When planning the test tasks it is important to determine which tasks are the most important to include in the test. The tasks should be small enough to be completed within the time limits of the test, but not too small that they become trivial. The test tasks should also be specified in detail and the processes for carrying out the tasks should be in place. [34, 38, 39]

3.3.5 Test environment

Usability tests can be conducted in various environments but usually they are conducted in the usability laboratory or in the user’s real environment.

Usability laboratory is a special room, which is dedicated to usability testing, and it is equipped with special equipment. Usability laboratories typically have soundproof, one-way mirrors separating the observation room from the test room, which allows the usability specialists to observe the user without disturbing him or her. A typical usability laboratory is equipped with several video cameras, which can be used to show an overview of the test situation and to focus in on the user and the user interface of the product. This equipment makes it easy to observe the user interacting with the system. However, a well-equipped usability laboratory is not an absolute necessity for usability testing; even a regular office room can be converted into a usability laboratory. [34, 38]

A usability test that is conducted in the user’s environment, in a natural setting, such as an office, home or other type of realistic environment, is called a field study or a field test. A field test gives a much better idea about the context in which the product will be used compared to the laboratory test. Testing conducted in the field makes it possible to view the system as part of the user’s total environment and allows to observe the other contacts and interactions that cannot be seen in a laboratory test. The benefit of a field test over a laboratory test is above all the exposure of the product to actual working conditions. On the other hand, the disadvantage is the loss of control over the data collection. [38, 39]

3.3.6 Pilot test

Before conducting the real usability tests, a pilot test should be carried out. The aim of the pilot test is to test the test itself. Pilot tests reveal problems with the test plan, the equipment, the test tasks or the procedure. It often uncovers incomprehensible instructions for the test tasks that can be easily misinterpreted. Likewise, questionnaires used for subjective satisfaction rating will often need to be changed based on the pilot tests. The pilot test also allows the test conductor to practice carrying out the test. Usually, one or two pilot test users are enough but more might be needed for large tests. The ideal pilot subject would belong to the same user group as the real test users but more important is that the participant does not belong to the testing team. [34, 39]

3.3.7 Usability testing of mobile devices

The key essence of mobile devices is that they are mobile and can be used almost everywhere. Often when the user is using the device, he or she is doing something else at the same time, e.g. walking, running or traveling on the bus and engaging in almost any of the multitude of activities of which human beings are capable [41]. This makes the usability testing of mobile devices more complex and challenging.

Usability testing of mobile devices is an emerging area of research in the field of HCI and new techniques for evaluating mobile systems are introduced at the very moment. However, there is still no agreement on the best evaluation technique for mobile devices. A recent survey [42] showed that 71% of evaluations on mobile human-computer interaction were laboratory based and very few of those involved special techniques being applied to meet the challenges of evaluating a mobile device. When usability testing is conducted in a laboratory, control and collection of high-quality data is not a problem. The greatest disadvantage is the lack of realism. Usually a solution for this problem has been introduced by recreating or simulating the real context of use in the laboratory. However, it is impossible to immitate all the factors that influence the usage of mobile devices in real life situations. The factors are for example the effects of mobility of the user, the varying lightning and noise levels and other distractions [43]. It is very important to test mobile devices in as a realistic setting as possible to receive valid results.

Field testing has been shown to be superior in evaluating usability of mobile devices. Duh et al. [44] reported a study comparing laboratory testing and field testing when evaluating usability of a mobile device. They conducted the test in laboratory setting and then repeated it in the field where test users traveled on the train when performing the test tasks. The results showed that there were many more types and occurences of usability problems found in the field than in the laboratory. Some of the problems related only to the device being used in the field, which could not have been found using conventional laboratory test. The only way to really see how the mobile device will work in practice is to use it in real conditions [45]. Therefore when testing usability of mobile devices, field testing should always be considered.

3.3.8 Usability testing of tactile mobile touchscreen devices

3.3.8.1 Methods

There are only few reported studies that have researched the effect of tactile feedback on the usability of touchscreen interactions.

Fukumoto et al. [22] carried out a short evaluation of their Active Click tactile touchscreen interface. They used a simple calculation task for entering numbers with a Calculator application. They compared number entry with tactile feedback presented when a button was pressed and number entry without the tactile feedback, where audio feedback was presented instead. The test was conducted both in silent and noisy situations. Users used their fingers to press the buttons on the touchscreen. The methods they used were not more deeply reported. Poupyrev et al. [24] conducted several informal usability tests with 10 colleagues to investigate the effects of adding tactile feedback to touchscreen GUI elements. They did not report the methods they used in those tests.

Brewster et al. [46] conducted a laboratory and a field test comparing standard virtual buttons to ones with tactile feedback added in text entry task. They tested a touchscreen keyboard with a stylus on an HP iPAQ PDA. The iPAQ did not include any tactile actuator so they added an external vibrotactile actuator on the back of the PDA. They used two tactile stimuli; one to indicate a succesful button press and another one to indicate an error. In the laboratory test, test users were seated and holding the PDA in their left hand and the stylus in their right hand. Participants were given poems to type in with the standard visual buttons and buttons with tactile feedback for 10 minutes each. They measured the amount of text entered, the total number of errors made and the number of errors that were uncorrected by users. In the field test, participants sat in a seat on an underground train while performing the same test task. After the test, participants were asked to fill in a questionnaire to gather qualitative data.

Recently, Leung et al. [47] conducted an usability test to evaluate touchscreen GUI elements with tactile feedback under a varying cognitive load. They used a Nokia 770 Internet Tablet prototype enhanced with tactile feedback features. The test included number entry task, progressbar task and scrollbar task where users interacted with the device with a stylus. Auditory tasks were used to cognitively load participants while they were performing the actual test tasks. The response time, accuracy and self-reported performance were measured. After the test, a questionnaire was used to collect users feelings and opinions about the tactile feedback. The test was conducted in a laboratory.

3.3.8.2 Findings

Fukumoto et al. [22] found that tactile feedback can improve the usability of touchscreen devices, especially in noisy environments. The results showed that the task time was reduced 5% with the tactile feedback condition compared to the audio feedback condition in a quiet situation and 15% in a noisy situation. Poupyrev et al. [24] reported that in their informal usability tests, tactile feedback was exceptionally well-received and was most effective when the GUI elements needed to be held down or dragged on the screen.

Brewster et al. [46] found that in the laboratory test participants could perform much better with tactile feedback; they entered more text, made fewer errors and noticed more of the errors they made. In the field test, tactile feedback was a bit less beneficial. There was however, significantly more errors corrected with tactile feedback than without it, even more than in the laboratory. The qualitative workload results showed that participants strongly favoured the tactile feedback condition. Based on these results, Brewster suggests that tactile feedback is an easy way to improve usability of touchscreen device’s interaction.

Leung et al. [47] reported that participants were able to complete given tasks significantly faster with the haptically augmented progress bar and scroll bar. Users also perceived an increase in their performance with the added tactile feedback. All participants responded that they found the tactile feedback to be useful and helpful.

4. USABILITY TESTING IN THIS THESIS

This chapter justifies the importance of the usability studies of this thesis and introduces the used methods.

4.1 The importance of this study

At the moment, many new mobile devices with touchscreens are coming out, and there is still much more to come. According to one market forecast [48], there will be rapid growth in the touchscreen phone market and by the year 2012, as much as 40% of all mobile phones are using touchscreen technology. From the usability point of view, touchscreens have one major weakness, the lack of tactility. At the moment the interest in haptics is evolving as the problem of tactility has been recognised. In the previous chapter it was found that there are still only few touchscreen mobile devices with tactile feedback. New devices with tactile feedback are launched but so far they are all using the same solution, a vibration motor to provide vibration cues as means of tactile feedback. There are only a few reported formal studies researching the effects of tactile feedback for mobile touchscreens. Although this field is gaining more attention, there is still little known how to design tactile feedback on touchscreens.

The studies, presented in the following chapters try to gain a better understanding of how tactile feedback should be designed for virtual buttons in mobile devices. The first studies examine which parameters create the most pleasant tactile stimuli for virtual buttons with piezo actuator and vibration motor technology. Then the two found most pleasant tactile feedbacks are compared in terms of usability. To gain a better understanding of the effects of tactile feedback on the usability of virtual buttons in mobile devices, the same comparison is done also in the field to take into account the other factors that might affect the mobile device usage.

This research is essential, as there are no reported studies that have researched the pleasantness of tactile feedback on touchscreens that is generated by a vibration motor or a piezo actuator. There has been no studies that have compared the tactile feedback generated by piezo actuator to tactile feedback generated by vibration motor in the laboratory nor in the field. Lastly there are also no thoroughly reported formal studies that have researched the effects of tactile feedback when using a finger on a touchscreen for interaction.

4.2 Methods

In the following subchapters the methods used in the studies of this thesis are introduced on a generic level. The chapters 5 and 6 introducing the studies, explains also the realization of the methods.

4.2.1 Preliminary studies

The two preliminary studies, piezo pleasantness study and vibra pleasantness study, were conducted to find the most pleasant tactile stimuli for piezo and vibra enhanced virtual buttons. Piezo pleasantness study researched also if audio feedback from piezo actuautor biases the evaluation of the feedback pleasantness.

4.2.1.1 Measures

The studies measured the subjective perceived pleasantness of the tactile feedbacks using a pairwise comparison method. The method is used to compare alternatives in pairs and to judge which of each pair is preferred. It can be used to order items along some dimension such as preference [49]. In these studies the used dimension was the perceived pleasantness of the tactile feedback.

4.2.1.2 Statistical tests

Different statistical tests can be used to test if the results are statistically significant, which means that there is low probability that the difference was due to chance [40]. Traditionally differences are considered to be significant if they occur by chance less than 5 percent of the time (p=0.05).

The data from both preliminary studies was analyzed with nonparametric Kruskal-Wallis test and the multiple pairwise comparisons were Bonferroni corrected. To examine the integration between tactile and audio stimuli, pairwise comparison were made for the two data sets with Mann-Whitney U test.

Mann-Whitney U test is a nonparametric statistical test, used to compare differences between two samples. It tests the null hypothesis that two samples come from the same population, e.g. having the same median. If two samples do not fulfill the null hypothesis, there is a statistical significant difference between the samples. [40]

Kruskal-Wallis test is a nonparametric statistical test, used to compare differences between three or more samples. It tests equality of medians among samples. It is an extension to Mann-Whitney U test to analyze the statistically significant differences between three or more samples. [40]

Bonferroni correction is a mathematical correction originally utilized to reduce falsely significant results in statistical analyses. If n independent hypotheses on a set of data are tested, then the statistical significance level that should be used is n times smaller than usual. In order to guarantee that the overall significance level is still at the same level, Bonferroni correction has to be used. [50]

4.2.2 Comparison laboratory study

The comparison laboratory study researched the effect of tactile feedback on the usability of virtual buttons and compared the most pleasant piezo and vibra feedbacks found in the preliminary studies and the no tactile feedback condition.

4.2.2.1 Test

The usability test conducted in this study was carried out as a comparison test. The comparison test methodology involves side-by-side comparison of two or more alternative designs. Performance data and preference data are collected for each alternative, and the results are compared. The comparison test is typically used to establish which design is easier and better to use, or to better understand the advantages and disadvantages of different designs. [39]

4.2.2.2 Test environment

The test was conducted in an office room, which was used as a usability laboratory. Because of the limitations of the prototype, the test could only be carried out in laboratory setting, since the device needed to be connected to a laptop during the test.

4.2.2.3 Test task

The task that test users needed to perform was a number entry task. Number entry is a very common activity and is based on button pressing, which is one of the most basic interaction techniques of all. The task was similar to the ones that other haptic researchers have also used in their studies [22, 51].

4.2.2.4 Measures

The study evaluated usability of tactile feedback enhanced virtual buttons by gathering data about three usability attributes; efficiency, errors and satisfaction. Efficiency is usually expressed as the time required to perform a given task [34]. Here the efficiency was measured as the time to type in three numbers. Errors are usually expressed as an error rate i.e. how often do errors occur. Here the term accuracy was used instead of errors and it was measured as the degree of incorrect number entries. Satisfaction can only be studied by asking the users [34]. Questionnaires and interviews are good methods for that. Satisfaction was measured in this study using satisfaction questionnaires with a 1-7 Likert scale and a 1-7 semantic differential and an open interview.

4.2.2.5 Statistical tests

The data was analyzed with the nonparametric Kruskal-Wallis test and the multiple pairwise comparisons were Bonferroni corrected. Kruskal-Wallis test and Bonferroni correction were introduced already earlier.

4.2.3 Comparison field study

The comparison field study researched the effect of tactile feedback on the usability of virtual buttons in a realistic use as users were on the move and compared piezo, vibra and no tactile feedback conditions.

4.2.3.1 Test

The same kind of comparison test methodology was used as in the comparison laboratory study introduced earlier.

4.2.3.2 Test environment

The test was conducted both in a laboratory and in the field. Two situations were selected for the field tests, walking and traveling on a metro train. The metro has been found to be a good platform for testing tactile feedback on mobile devices, as noise levels and light levels vary dramatically and also vibration and movement are very changeable [46]. Others have also tested tactile feedback while walking [51].

4.2.3.3 Test task

The same number entry task was used as in the comparison laboratory study allowing to compare the results between the two studies.

4.2.3.4 Measures

The same measures were also used to evaluate the usability of the tactile feedback enhanced virtual buttons: efficiency, accuracy and satisfaction.

4.2.3.5 Statistical tests

The data was analyzed with single factor ANOVA. Paired t-test was also used to compare differences between single feedback conditions. ANOVA, analysis of variance, is the statistical analysis method, which tests for differences among two or more independent groups. The equivalent nonparametric test is Kruskal-Wallis test. The paired t-test is used to compare two population means. The equivalent nonparametric test is Mann-Whitney test. ANOVA and t-test are parametric statistical tests, which require that the populations are normally distributed and/or are homogenous in their variance. [40]

5. PRELIMINARY STUDIES

5.1 Piezo pleasantness study

5.1.1 Objective of the study

The objective of the study was to research the subjective perceived pleasantness of different tactile feedbacks and to find the most pleasant tactile stimulus for the virtual button in a piezo enhanced touchscreen. The piezo technology produces audio feedback while actuating in addition to tactile feedback. The test consisted of two parts to find out if audio feedback biases the evaluation of the pleasantness of the tactile feedback.

5.1.2 Test method

5.1.2.1 Test equipment

The study was made with a mockup handheld touchscreen device (Fig. 12) enhanced with tactile feedback features, which is the same kind of mobile device that Kaaresoja [25] has presented in his paper. The tactile stimuli were generated with a robust and simple bending bimorph placed under the touch display module. The touch screen was displaying two virtual buttons A and B (Fig. 13) which gave tactile feedback when pressed.

Fig. 12. Touchscreen device enhanced with tactile feedback.

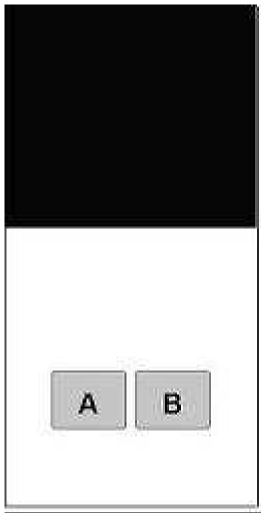

Fig. 13. Test application displaying two virtual buttons, A and B.

5.1.2.2 Test stimuli

The tactile stimulus was generated by a piezo actuator solution, which enables the production of various pulse shapes, with displacement on a scale of several hundred micrometers. The modulation of the stimuli was done by controlling the driving voltage and the current of the piezo actuator and thereby altering two parameters, the rise time and the displacement amplitude (Fig. 14).

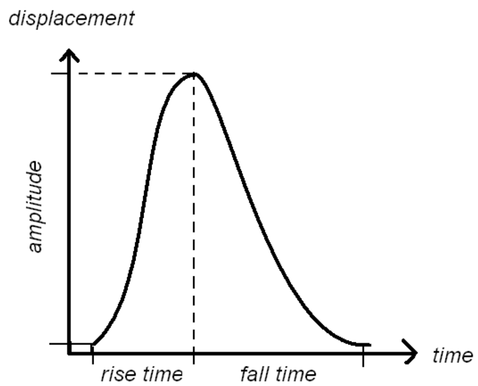

Fig. 14. The stimuli were generated by changing rise time and displacement amplitude. The fall time was fixed to 5ms.

Seven different feedback stimuli were composed altering the amplitude and rise times of the feedback pulses. The different feedback stimuli were chosen according to the previous user study results [52]. The previous study researched the subjectively perceived strength of the physical pulse, and all the seven chosen feedback stimuli were rated on a 1-to-5 rating scale between 2 and 4 by the test users. On the scale 1 meant weak, 2 quite weak, 3 moderate, 4 quite strong and 5 strong.

The three different maximum current values through charging resistors used in the study were 46 mA / 4.7 kΩ, 180mA / 1.2 kΩ and 17 mA / 13kΩ (Chart 2).

The piezo actuator also produces sound while actuating. The audio feedbacks were not separately designed, but the intrinsic sounds generated by the piezo actuator were used as stimuli. The maximum sound levels associated with stimuli varied between 42 dB to 61 dB at a 35 cm distance from the device (Chart 2).

Chart 2. Stimuli parameter values

Stimulus	Resistor (kOhm)	Current (mA)	Drive time (ms)	Decibel level (dB)
A	1,2	180	0.125	61
B	1,2	180	0.25	60
C	4,7	46	0.63	49
D	13	17	1.38	42
E	4,7	46	1.38	46
F	4,7	46	2.75	45
G	13	17	4.13	42

5.1.2.3 Test participants

10 participants took part in the study; six males and four females. The age of the participants varied from 23 to 39 years, average age being 29 years. All the test users were right-handed and they all used their right hand's thumb to press the virtual buttons on the touchscreen.

5.1.2.4 Test design

The test consisted of two parts, one part with tactile and audio stimuli and the other part with tactile stimuli only. In the tactile only part, the audio stimuli were excluded as test users wore headphones to hear typical street noise from the tape and not the audio feedback at all.

Altogether, seven different physical stimuli were tested with a pairwise comparison method, which constituted 21 different pairs. These 21 stimuli pairs were repeated two times in a randomized order resulting to a total of 42 stimuli pairs. A single feedback, e.g. stimulus B, was compared pairwise twice with each of the six other stimuli. Accordingly, every stimulus was evaluated 12 times per user.

5.1.3 Results of the tactile & audio study

The Figure 15 below shows the mean values and 95% confidence intervals for subjective evaluations for the pleasantness of the different tactile and audio feedbacks. The results show that four feedbacks were evaluated as the most pleasant feedbacks, stimuli C, D, E and F.

The results showed that feedbacks A and B differ from feedbacks C, D, E and F, in terms of statistical significance. Also feedback E differs from feedback G. The significance level is 0.000 and the Bonferroni corrected significance level is .0024.

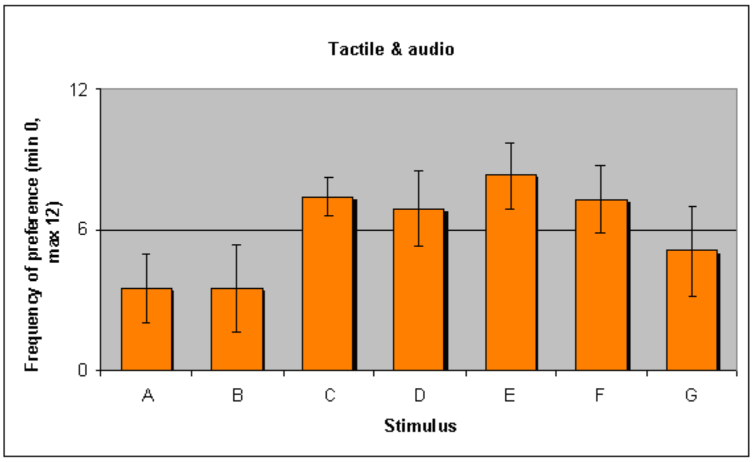

Fig. 15. Mean values and 95% confidence intervals for the subjective evaluations of the feedback pleasantness for the different tactile & audio feedbacks.

5.1.4 Results of the tactile only study

The Figure 16 shows the mean values and 95% confidence intervals for subjective evaluations for the pleasantness of the different tactile feedbacks. The results show that feedbacks E and F were the most popular ones according to the users' evaluations of the pleasantness of the feedbacks.

The results showed that feedbacks E and F differ from feedbacks A, D and G in terms of statistical significance. The significance level is 0.007 and the Bonferroni corrected significance level is .0024

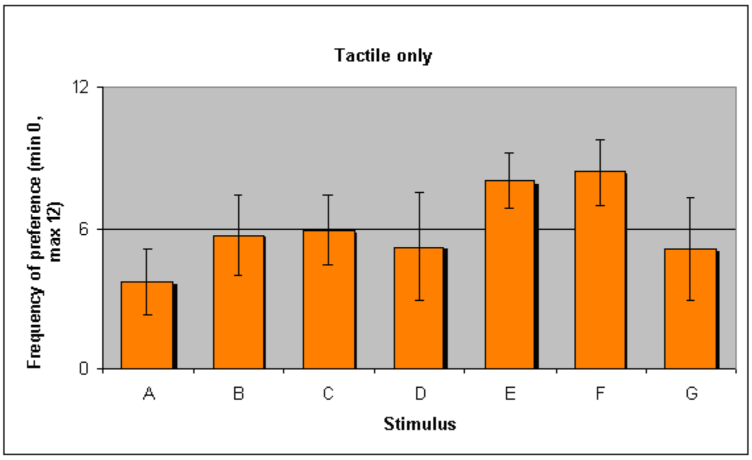

Fig. 16. Mean values and 95% confidence intervals for the subjective evaluations of the feedback pleasantness for the different tactile only feedbacks.

5.1.5 Comparison of tactile & audio and tactile only studies

The pairwise comparisons of the tactile & audio condition and the tactile only condition show that there were no statistically significant differences in the pleasantness evaluations. The differences visible in the Figure 17 were not statistically significant but the audio seems to have some effect on the subjectively perceived pleasantness of the tactile stimulus.

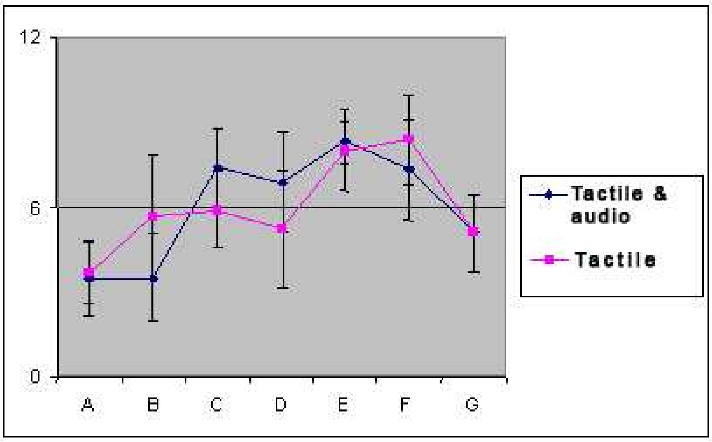

Fig. 17. The pairwise comparisons between two conditions.

5.1.6 Conclusions

The study clarified the subjectively perceived pleasantness of tactile feedback on a touch screen, and the impact of audio feedback on perceived tactile feedback pleasantness. It was noticed that the feedbacks generated with 46 mA current were perceived most pleasant compared to the other feedbacks. Therefore it is suggested that the present three intensities of the 46 mA maximum current feedback should be used for the tested touchscreen device in virtual button use cases. These parameters cannot be directly generalized to all touchscreen devices because different physical device characteristics might impact the optimum feedback parameters. However, these parameters can be considered indicative for other touchscreen devices.

The pairwise comparisons between the two conditions showed no statistical differences between the tactile & audio and tactile only conditions. However, the results suggest that the audio feedback could impact the subjectively perceived pleasantness of the tactile feedback in a way that perceived pleasantness is reduced, especially when the audio feedback is loud. This was predictable, since in the previous studies [52] the audio feedback was noticed to bias the tactile feedback intensity evaluations in a way that stimuli which have higher sound levels were biased more than stimuli that have lower sound levels. However, the conditions between the intensity study [52] and the pleasantness study were different, as in the intensity study the audio feedback was totally excluded, but in the pleasantness study the audio feedback was only masked with random street noise.

5.2 Vibra pleasantness study

5.2.1 Objective of the study

The objective of the study was to research the subjective perceived pleasantness of different tactile feedbacks and to find the most pleasant tactile stimulus for the virtual button in a vibra enhanced touchscreen.

5.2.2 Test method

5.2.2.1 Test equipment

The study was made with a mockup handheld touchscreen device (Fig. 18) enhanced with tactile feedback features. The tactile stimulus was generated by a vibration motor solution, where a vibrator component was placed under the touch display module. The touchscreen was displaying two virtual buttons A and B (Fig. 19) that gave tactile feedback when pressed.

Fig. 18. Touchscreen device enhanced with tactile feedback.

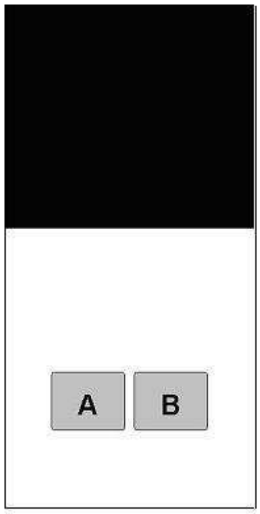

Fig. 19. Test application displaying two virtual buttons, A and B.

5.2.2.2 Test stimuli

The modulation of the stimuli was done by altering one parameter, the drive time. Six different feedback stimuli were composed. The six different feedback stimuli were chosen by empirical method where it was noticed that when the drive time is less than 10 ms, the feedback is far too weak and when the drive time is over 24 ms, the feedback is disruptively strong. Therefore the six different drive times varied from 10 ms to 24 ms (Chart 3).

Chart 3. Stimuli parameter values

Stimulus	Drive time (ms)
A	10
B	13
C	16
D	19
E	21
F	24

5.2.2.3 Test participants

10 participants took part in the study; nine males and one female. The age of the participants varied from 23 to 44 years, average age being 28 years. All the test users were right-handed and they all used their right hand's thumb to press the virtual buttons on the touchscreen.

5.2.2.4 Test design

Altogether 6 different physical stimuli were tested with a pairwise comparison method, which resulted in 15 different pairs. These 15 stimuli pairs were repeated three times in a randomized order resulting to a total of 45 stimuli pairs. A single feedback, e.g. stimulus B, was compared pairwise three times with each of the five other stimuli. Accordingly, every stimulus was evaluated 15 times per user.

5.2.3 Results

The figure 20 below shows the mean values and 95% confidence intervals for subjective evaluations for the pleasantness of the different tactile feedbacks. There is a clear trend that the stimuli in the mid range are more preferred.

The results showed that stimulus A differs from stimuli C and D, and stimulus F differs from stimuli B, C, and D in terms of statistical significance; the significance level is 0.004 and the Bonferroni corrected significance level 0.0033.

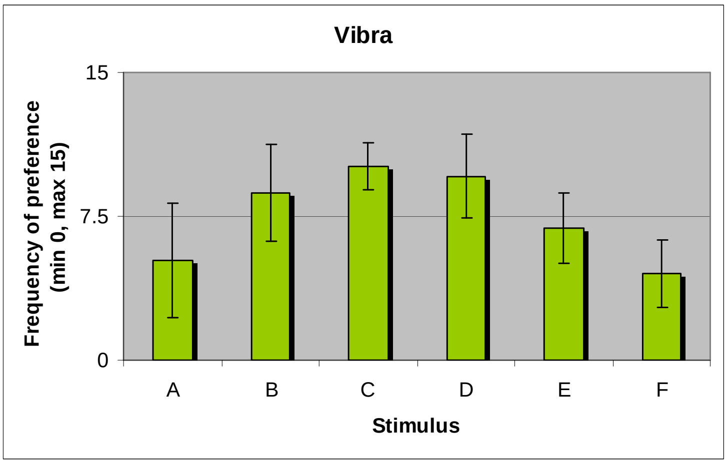

Fig. 20. Mean values and 95% confidence intervals for the subjective evaluations of the feedback pleasantness for the different stimuli.

5.2.4 Conclusions

The study clarified the subjectively perceived pleasantness of tactile feedback on a touchscreen. It was found out that the vibra feedbacks generated with 13, 16, and 19 ms drive time, respectively, were perceived most pleasant compared to the other feedbacks. The feedback generated with 16 ms drive time was rated slightly more pleasant than the other two feedbacks and the evaluations had less variance. Therefore it is suggested that the 16 ms feedback should be considered when using vibra as a tactile feedback technology in touchscreen devices. This result cannot be directly generalized to all touchscreen devices because different physical device characteristics might impact the optimum feedback parameters. However, this result can be considered indicative for other touchscreen devices.

6. USABILITY STUDIES

6.1 Comparison laboratory study

6.1.1 Objective of the study

The aim of the study was to research how tactile feedback affects the usability of virtual buttons by comparing the efficiency, accuracy and subjective satisfaction of touchscreen keypad with piezo feedback, vibra feedback or no tactile feedback at all in a realistic task, which was based on button pressing.

6.1.2 Test method

6.1.2.1 Test equipment

The study was made with the same mockup handheld touchscreen devices, which were presented in the preliminary studies of this thesis, see chapter 5. The devices were connected to a laptop via two cables, one for transferring the display to the device and the other for transferring the data related to the touchscreen. The touchscreen was displaying a virtual phone keypad (Fig. 21), which gave tactile feedback when a button was pressed. The test application was written in Java.

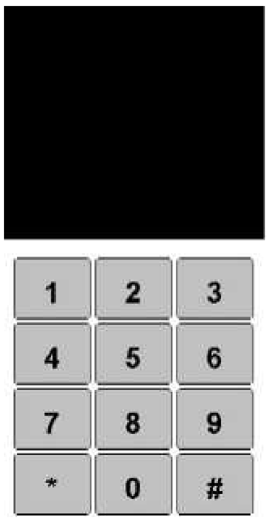

Fig. 21. Test application was displaying a virtual phone keypad.

6.1.2.2 Piezo feedback

In this condition the tactile stimulus was generated by a piezo actuator solution. The piezo stimulus was chosen according to the preliminary study results where the chosen feedback stimulus was evaluated as the most pleasant feedback by the test users.

The drive current value through the charging resistors used in the study was 46 mA / 4.7 kΩ and the drive time was set to 1.38ms. The audio feedback generated inherently by the piezo actuator was not separately designed, but it was used as part of the stimulus. The sound level associated with stimulus was 46 dB at 35 cm distance from the device (Chart 4).

Chart 4. Parameters for piezo stimulus

Stimulus	Resistor (kOhm)	Current (mA)	Drive time (ms)	Decibel level (dB)
Piezo	4,7	46	1.38	46

6.1.2.3 Vibra feedback

In this condition the tactile stimulus was generated by a vibration motor solution. The vibra stimulus was chosen according to the preliminary study results where the chosen feedback stimulus was evaluated as the most pleasant feedback by the test users. The drive time of the feedback was set to 16ms (Chart 5).

Chart 5. Parameters for vibra stimulus

Stimulus	Drive time (ms)
Vibra	16

6.1.2.4 No tactile feedback

In this condition there was no active tactile feedback, only the natural sensation that the user gets when she or he touches the touch-sensitive screen surface.

6.1.2.5 Participants

Altogether 12 participants took part in the study. There were seven males and five females participating. The age of the participants varied from 21 years to 49 years, the average age being 30 years.

Nine of the test users were right-handed and they used their right hand's thumb to press the virtual buttons on the touchscreen. The other three were left-handed and they used their left hand's thumb respectively.

All the test users were very familiar with using a mobile phone; nine of them have used a mobile phone for over five years and three of them about 3-5 years. Most of the test users entered phone numbers using their phone keypad only a few times a month and a couple of users entered numbers daily. All of the test users wrote on an average 3 SMS text messages daily.

Almost all the test users do not want to use keypad tones in their mobile phones. Only two test users have keypad tones always on in their mobile phone and the rest of the test users take them always off.

Six of the test users use a device with a touchscreen (e.g. Nokia 770 Internet tablet) everyday. Two of them use touchscreen devices (PDA) only once in a while and the last four users have never used a device with a touchscreen.

6.1.2.6 Test procedure

The test was conducted in an office room, where the test users were sitting in silence while using the touchscreen device. The test consisted of three test cases; one with piezo feedback, one with vibra feedback and one without tactile feedback. The test user's task was to key in the three numbers which appeared on the display at once and then press the # -button using the virtual phone keypad (Fig. 22). There were altogether 55 different three digit number series in one test. All test users repeated the test three times and did the test once with vibra feedback, once with piezo feedback and once without tactile feedback. The test order, in which the test users did the test, was varied between users. The test application measured the time from the first keypress to the keypress of the # -mark and it also wrote the numbers the test user entered into a results file.

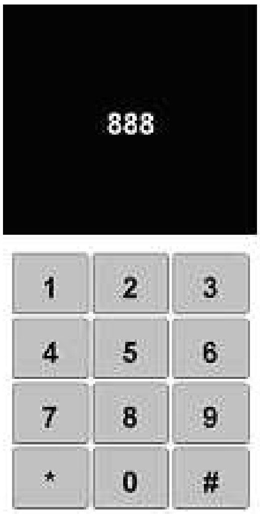

Fig. 22. Three numbers appeared on the display at once and user's task was to key in these numbers and press # -mark using the virtual keypad.

Before the test, users were advised with following instructions:

> *"Soon you will see a virtual keypad on the display. Your task is as follows: Three numbers appear on the display at once. You key in these numbers and press the hash (#) mark. Key in quickly but with the speed suitable for you. Try to avoid errors. If you happen to make an error, don't make a correction but just continue the task. The test will take a couple of minutes and we will repeat it three times. The device tells you when the test is finished."*

Before starting each test case, there was a short rehearsal where test users could try to key in a few three digit number series.

During the test, users were holding the device in portrait mode with their both hands and pressing the virtual buttons on the touch display with the other hand's thumb (Fig. 23).

Fig. 23. Users were holding the device with their both hands and pressed the virtual buttons with their other hand's thumb.

After the test there was a short questionnaire and interview concerning the subjective satisfaction and the characteristics of the experienced pleasantness of the keypad use.

Users were asked to rate their degree of agreement with the following statements using a 1-7 rating scale, where 1 meant totally disagree and 7 totally agree:

a) This keypad is pleasant to use.

b) I felt myself comfortable when using this keypad.

c) Pressing the keypad buttons felt just like pressing physical ("real") buttons.

d) I always knew that the device received my keypress.

e) I would like to buy a device with this kind of keypad.

After the questionnaire users were asked to explain why the keypad was pleasant or unpleasant to use, depending on how they rated the keypad in the questionnaire. Users were also asked for other comments on the keypad use.

The questionnaire statements and the interview questions were all the same after each test. Lastly, after the interview, test users were asked for their general preference for the tactile feedbacks by asking them to rate each feedback on a 1-7 scale with 1 meaning poor and 7 meaning excellent.

6.1.3 Results

6.1.3.1 Average task time

The figure 24 below shows the mean values and 95% confidence intervals for the time to enter three digits and the hash (#) mark in milliseconds with different tactile feedbacks. The results show that the keypad with piezo feedback was the fastest to use. The task took 4% longer time with the keypad with vibra feedback and 7% longer with the keypad without tactile feedback.

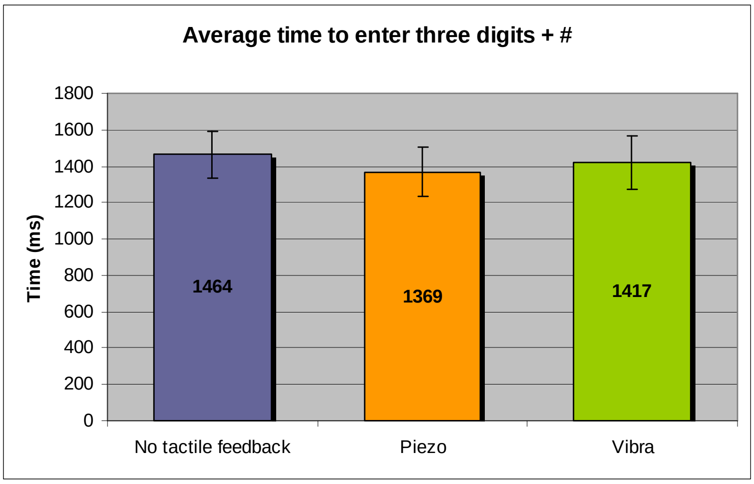

Fig. 24. Mean values and 95% confidence intervals for time (ms) to enter three digits and hash (#) mark.

The Kruskal-Wallis test showed that the results do not differ from each other in terms of statistical significance. The significance level is 0.076 and the Bonferroni corrected significance level is .0167.

6.1.3.2 Average error rate

The figure 25 below shows the mean values and 95% confidence intervals for error rates with different tactile feedbacks. The results show that there were least errors done with the keypad with piezo feedback. With the keypad with vibra feedback and the keypad without tactile feedback, the average error rate grew 38% and 23% respectively.

It should be noted that due to prototype malfunction some errors were recorded even though the user pressed correctly. Therefore, error values close to zero were impossible to obtain with the test equipment.

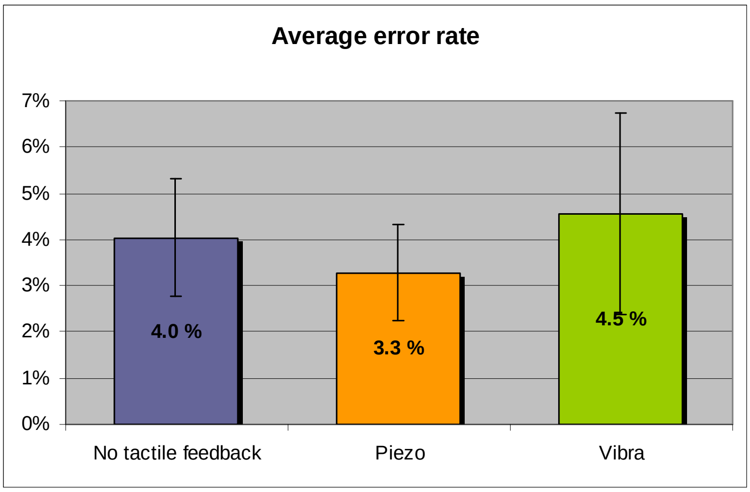

Fig 25. Mean values and 95% confidence intervals for average error rate

The Kruskal-Wallis test showed that the results do not differ from each other in terms of statistical significance. The significance level is 0.979 and the Bonferroni corrected significance level is 0.0167.

6.1.3.3 Subjective satisfaction

The figure 26 below shows the mean values and 95% confidence intervals for degree of agreement with the statements on a 1 (totally disagree) -7 (totally agree) scale.

The results show that the keypads with piezo and vibra feedback were rated higher than the keypad without tactile feedback. Also the keypad with piezo feedback received slightly higher score in all five statements compared to the keypad with vibra feedback.

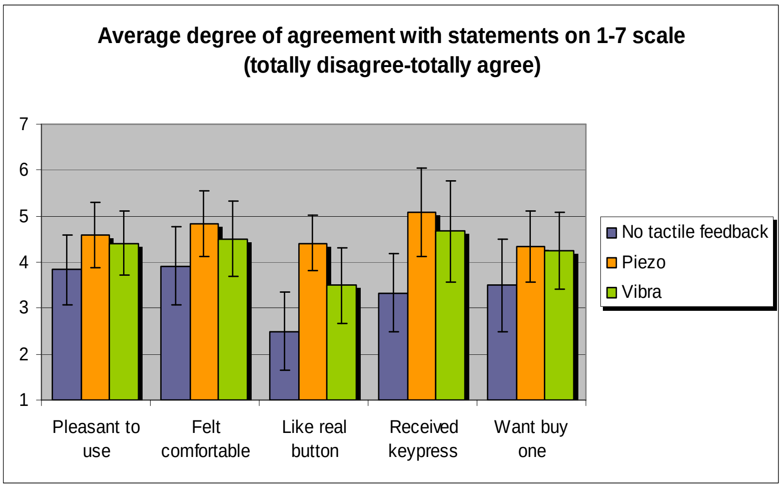

Fig. 26. Mean values for degree of agreement with statements on 1-7 scale.

6.1.3.4 General preference

The figure 27 below shows the mean values and 95% confidence intervals for general grade given by the test users. The results show that the keypad with piezo feedback was rated higher than the keypad without tactile feedback and the keypad with vibra feedback.

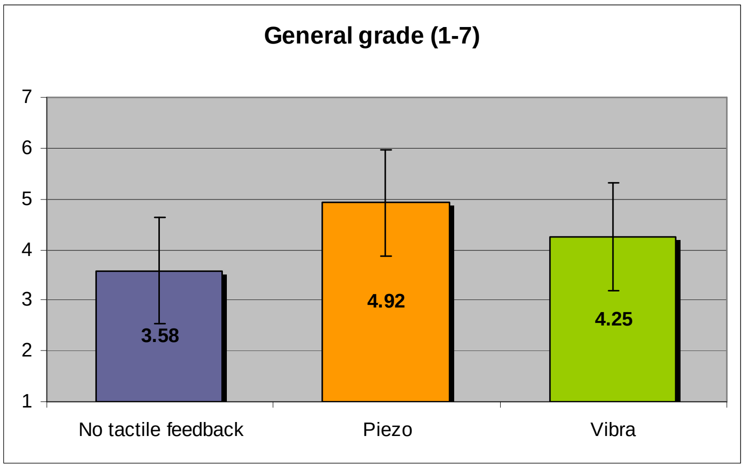

Fig. 27. Mean values and 95% confidence intervals for the general rating on 1-7 scale.

6.1.3.5 Interview

The results from the interview showed that on average, users preferred the keypad with piezo feedback compared to the keypad with vibra feedback and the keypad without tactile feedback, because it gave the most natural feeling of a real button. Vibra feedback was commented to be too strong, because it vibrated the whole device, but it was better than without any tactile feedback. A couple of users told to prefer still vibra feedback to piezo feedback. Below are some comments from users.

Comments on the keypad without tactile feedback

> *"I made many mistakes because I didn't feel pressing the button. It would have needed a sound feedback."*

> *"I didn't know was my keypress taken or not so I had to look at the display all the time."*

> *"This was terrible to use, I didn't like it at all."*

> *"This felt better to use because there wasn't any sound coming from inside the device."*

Comments on the keypad with piezo feedback

> *"This one had best feeling. The feedback was quick and I could key in the numbers faster."*

> *"I didn't like the sound, it was quite unpleasant."*

> *"This one felt good. It reminded me of a real button."*

Comments on the keypad with vibra feedback

> *"When I pressed the button the vibration felt very weird. It would be very disturbing when e.g. writing some long text message."*

> *"The feedback was too long. I noticed the vibration still when I had already taken my thumb up from the button."*

> *"This one felt ok. It had very soft feeling. The sound wasn't too loud either. I liked it."*

6.1.4 Conclusions

The study researched the effect of tactile feedback on the usability of virtual buttons by comparing the efficiency, accuracy and subjective satisfaction of the touchscreen keypad with piezo feedback, vibra feedback or no tactile feedback at all. It was found that the keypads with tactile feedback were more efficient and more pleasant to use than the keypad without tactile feedback in this use case. Therefore the results suggest that tactile feedback improves the usability when entering numbers with virtual buttons using fingers on a touchscreen.

The results also showed that the keypad with piezo feedback was faster to use than the keypad with vibra feedback. Also the error rate was lowest with the keypad with piezo feedback. Results showed that the keypad with piezo feedback received the highest scores in the satisfaction questionnaire in all the five statements compared to the keypad with vibra feedback and the keypad without tactile feedback. Lastly, the keypad with piezo feedback also received the highest score in the general grade given by the test users compared to the keypad with vibra feedback and the keypad without tactile feedback. Although the individual metrics did not show statistically significant differences in this study, it can be safely concluded that piezo is the preferred method for producing tactile feedback for a touchscreen. Vibra is slightly but consistently less preferred, while no tactile feedback is clearly the worst option.

It is important to note that due to the variation in the results, a minority of users would prefer vibra or no tactile feedback. However, when making a generic touchscreen tactile feedback solution, it can be clearly recommended to use piezo.

6.2 Comparison field study

6.2.1 Objective of the study

The aim of the study was to research how tactile feedback affects the usability of virtual buttons in more realistic use and to find out if the results from the Comparison laboratory study, presented in the earlier chapter, transferred to the real environment, when users are on the move. The controlled setting in the Comparison laboratory study is almost an exact opposite of the use of mobile devices in the real world where people use them while on the move and in noisy environments. To research the effect of tactile feedback in a more realistic setting, test users repeated the test while walking up and down a corridor and traveling on a metro train, simulating more realistic usage scenarios. The study compared the efficiency, accuracy and subjective satisfaction of a touchscreen keypad with piezo feedback, vibra feedback or no tactile feedback in a realistic task, which was based on button pressing.

6.2.2 Test method

6.2.2.1 Test equipment

The study was made with a prototype touchscreen device, which is a Nokia 770 Internet Tablet (Fig. 28) enhanced with tactile feedback features. The large touchscreen was displaying a virtual keypad (Fig. 29) that gave tactile feedback when pressed. The test application was written in Python.

Fig. 28. Nokia 770 Internet Tablet enhanced with tactile feedback features.

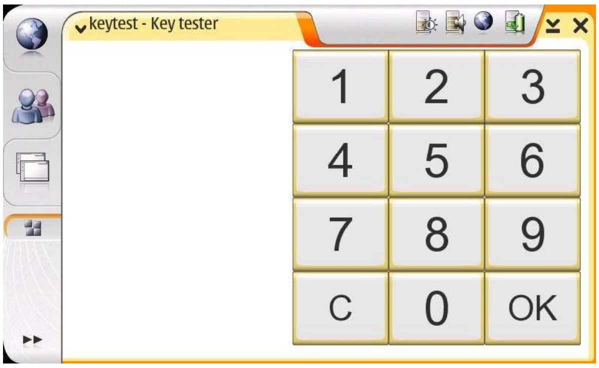

Fig. 29. The touchscreen was displaying a virtual keypad.

6.2.2.2 Piezo feedback

The tactile feedback was generated with a piezo actuator solution. Two piezo discs were placed under the touch display module (Fig. 30), providing the tactile feedback.

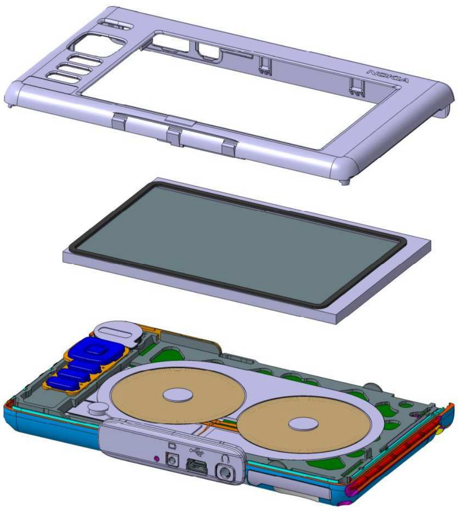

Fig. 30. Two piezo discs placed under the touch display module.

The piezo stimulus could not be chosen directly according to the preliminary study, which researched the subjectively perceived pleasantness of the piezo feedback. This is because the touchscreen device used in this study was not the same as in the earlier study and the piezo feedback design is dependent on the mechanical design of the device [53]. However, results from the preliminary study were used as a basis for finding the matching parameters to create the most pleasant stimulus for piezo feedback in the Nokia 770 prototype touchscreen device.

The value for the charge voltage used in the study was 200 V and for the charge resistor 6.57 kΩ. The charge time of the stimulus pulse (Fig. 31) was 0.5 ms and the discharge time was 4 ms. The audio feedback generated inherently by the piezo actuator was not separately designed, but it was used as a stimulus. The sound level associated with stimulus was 42 dB at 30 cm distance from the device (Chart 6).

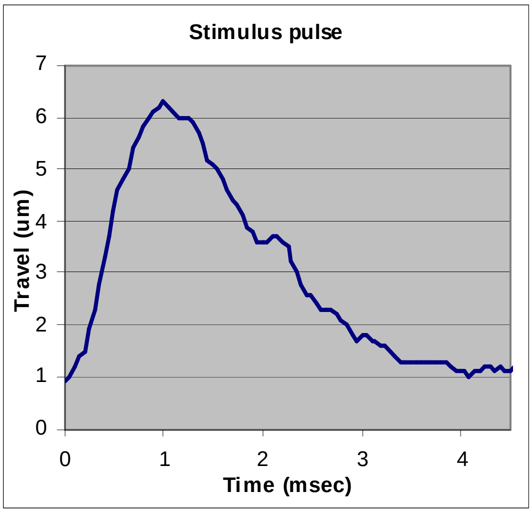

Fig. 31. Piezo stimulus pulse

Chart 6. Parameters for piezo stimulus

Stimulus	Charge voltage (V)	Charge resistor (kOhm)	Charge time (ms)	Discharge time (ms)	Decibel level (dB)
Piezo	200	6.57	0.5	4	42

6.2.2.3 Vibra feedback

The tactile stimulus was generated by a vibration motor solution where a vibrator component was placed under the touch display module.

The vibra stimulus could not be chosen directly according to the preliminary study, which researched the subjectively perceived pleasantness of the vibra feedback, because the touchscreen device used in this study was not the same as in the earlier study. However, results of the previous study were used as a basis for finding the matching parameters to create the most pleasant stimulus for vibra feedback in the Nokia 770 prototype touchscreen device.

The drive time of the stimulus pulse (Fig. 32) was set to 18 ms and was afterwards slowed down by driving the vibration motor in the opposite direction for 10 ms (Chart 7).

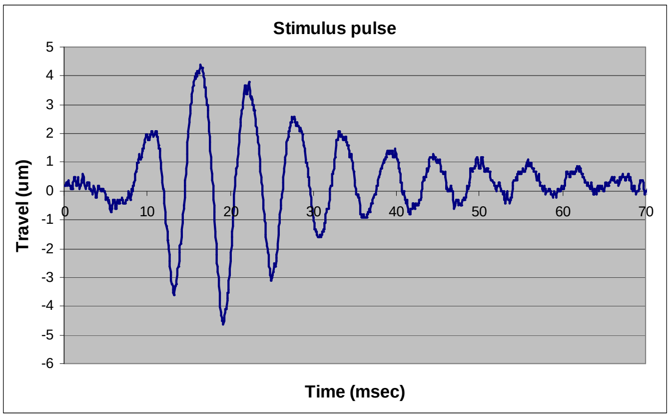

Fig. 32. Vibra stimulus pulse

Chart 7. Parameters for vibra stimulus

Stimulus	Drive time (ms)	Drive time in opposite direction (ms)
Vibra	18	10

6.2.2.4 No tactile feedback

In this condition there was no active tactile feedback, but only the natural sensation that the user gets when she or he touches the touch-sensitive screen surface.

6.2.2.5 Participants

Altogether 12 participants took part in the study. There were seven males and five females participating. The age of the participants varied from 24 years to 45 years, the average age being 31 years.

All of the test users were right-handed and they used their right hand's thumb to press the virtual buttons on the touchscreen.

All the test users were very familiar with using a mobile phone; all of them have used a mobile phone for over 5 years. Most of the test users entered phone numbers using their phone keypad only a few times in a month. A couple of test users entered a few phone numbers weekly and a few test users entered 5-10 phone numbers daily using their phone keypad. All of the test users wrote on an average 5 SMS text messages daily.

Three of the test users use a device with a touchscreen (e.g. Nokia N800 Internet tablet) everyday. Three of them use touchscreen devices (PDA) only occasionally and the final six users do not use any device with a touchscreen.

6.2.2.6 Test procedure

The test consisted of three parts; laboratory, walking and metro. The laboratory part was used as a baseline that can be compared to the walking and metro parts. In the laboratory part, test users were sitting in silence in an office room while using the touchscreen device (Fig. 33). In the walking part, test users had to walk up and down a long L-shaped corridor in an office building while using the touchscreen device (Fig. 34). The route was 70 m long and very quiet; there were no other people walking during the test. Once test users reached the end of the corridor, they turned and walked back to the start, continuing to do laps and entering numbers until the test was finished. In the metro part, test users were sitting in a seat on the metro train while using the touchscreen device (Fig. 35). The test order, in which the test users did the different parts of the test, was changed between the users and is presented in Chart 8. Sound levels were measured in each test environment and the measured ranges can be found from Chart 9.

Fig. 33. In the laboratory part users were sitting in a chair in an office room while using the touchscreen device.

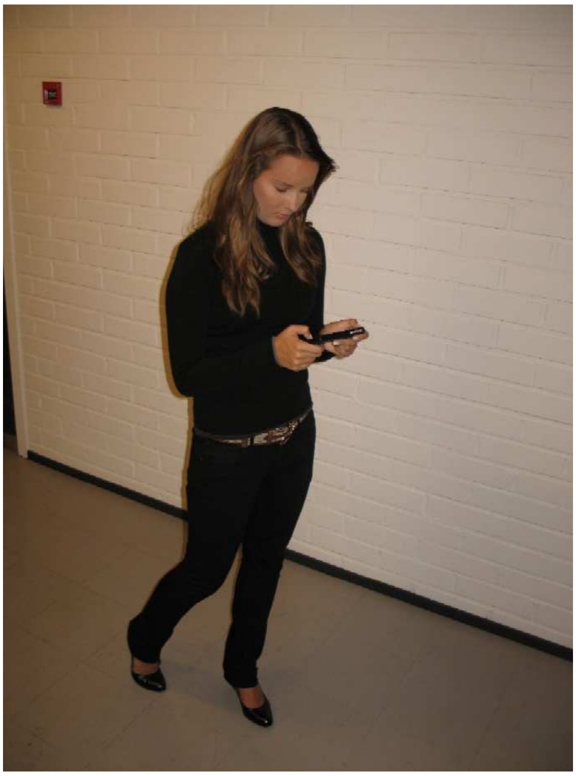

Fig. 34. In the walking part users had to walk up and down a corridor while using the touchscreen device at the same time.

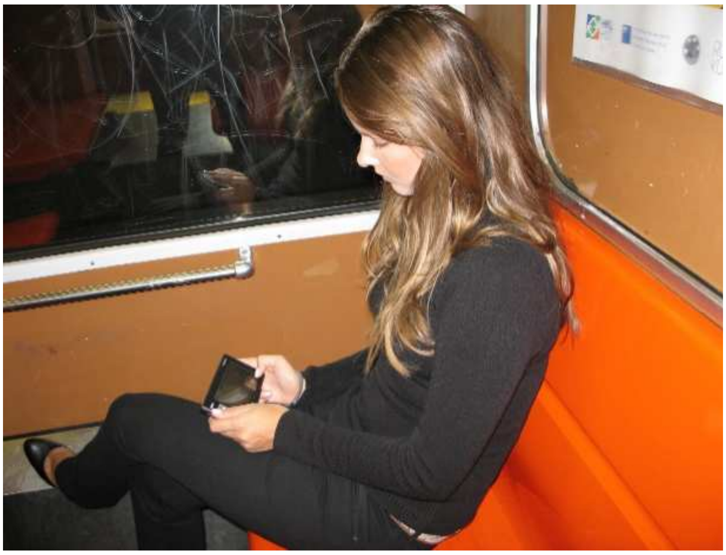

Fig. 35. In the metro part users were sitting in a seat on the metro train while using the touchscreen device at the same time.

Chart 8. The order in which users did the different parts of the test, where L=Lab, W=Walking and M=Metro.

1	2	3	4	5	6	7	8	9	10	11	12
L	W	M	W	L	M	L	W	M	W	L	M
W	L	W	M	M	L	W	L	W	M	M	L
M	M	L	L	W	W	M	M	L	L	W	W

Chart 9. Sound level ranges for each test environment

Laboratory	Walking	Metro
37-40 dB	45-58 dB	58-84 dB

Each part included three test cases; one with piezo feedback, one with vibra feedback and one without tactile feedback. The test user's task was to key in the three numbers, which appeared on the display at once and then press the OK-button using the virtual keypad (Fig. 36). If the test users made an error while keying in the numbers, they could correct it with the C-button. There were altogether 55 different three digit number series in one test. The test application measured the time from the first keypress to the keypress of OK-button and it also wrote the numbers, the test user keyed in, into a results file.

Fig. 36. Three numbers appeared on the display at once and user's task was to key in these numbers and press OK button using the virtual keypad.

All test users repeated the test three times and did the test once with vibra feedback, once with piezo feedback and once without tactile feedback. The test order, in which the users did the test, was varied between users and is presented in Charts 10, 11 and 12. Before starting the test, there was a short rehearsal where test users could try to key in a few three digit number series. During the test, users were holding the device with their both hands and pressed the virtual buttons on the touch display with their right hand's thumb (Fig. 37)

Chart 10. The test order for different feedbacks for laboratory part, where N=No tactile feedback, P=Piezo feedback and V=Vibra feedback

1	2	3	4	5	6	7	8	9	10	11	12
V	N	P	P	N	V	V	N	P	P	N	V
P	V	N	V	P	N	P	V	N	V	P	N
N	P	V	N	V	P	N	P	V	N	V	P

Chart 11. The test order for different feedbacks for walking part, where N=No tactile feedback, P=Piezo feedback and V=Vibra feedback

1	2	3	4	5	6	7	8	9	10	11	12
N	V	N	V	P	P	P	V	N	N	V	P
P	P	V	N	V	N	V	P	V	P	N	V
V	N	P	P	N	V	N	N	P	V	P	N

Chart 12. The test order for different feedbacks for metro part, where N=No tactile feedback, P=Piezo feedback and V=Vibra feedback

1	2	3	4	5	6	7	8	9	10	11	12
P	N	V	N	V	N	N	P	V	V	P	N
N	V	N	P	N	V	P	N	N	N	N	P
V	P	P	V	P	P	V	V	P	P	V	V

Fig. 37. Users were holding the device with their both hands and pressed the virtual buttons with their right hand's thumb.

Before the test users were advised with following instructions:

Soon you will see a virtual keypad on the display. Your task is as follows: three numbers appear on the display at once. You key in these numbers and press OK-button. Key in quickly but with the speed suitable for you. Try to avoid errors. If you happen to make an error, try to correct it using the C-button. The test will take a few minutes and we will repeat it three times. The device tells you when the test is finished.

There are three parts in this test:

***Lab:** You are at your office using this mobile device. (This office room)*

Walking: *You are using this mobile device while walking. (This building's ground floor)*

Metro: *You are using this mobile device while seated on the metro train. (We'll go to Ruoholahti metro station and take a little journey)*

After each test there was a short questionnaire concerning the subjective satisfaction and the characteristics of experienced pleasantness of the touchscreen use. Users were asked to rate their degree of agreement with the following statements using a 1-7 rating scale, where 1 meant totally disagree and 7 totally agree:

a) This keypad is pleasant to use.

b) I felt myself comfortable when using this keypad.

c) Pressing the keypad buttons felt just like pressing physical ("real") buttons.

d) I always knew that the device received my keypress.

e) I would like to buy a device with this kind of keypad.

The questionnaire statements were the same after each test. In the end, as test users had carried out all three parts, there was an interview containing the following questions:

1) *Now I ask you to compare the touchscreen use between the test rounds. Did you notice any differences using them? Did you prefer some more than the others?*

2) *Was the use different while walking or seated on the metro? Did the environment affect the keypad use somehow?*

3) *Any other comments?*

Lastly after the interview, test users were asked for their general preference for the tactile feedbacks by asking them to rate each feedback on a 1-7 scale with 1 meaning poor and 7 meaning excellent.

6.2.3 Results

6.2.3.1 Average task time - Laboratory

The figure 38 below shows the mean values and 95% confidence intervals for the time to enter three digits and press the OK-button in milliseconds with different tactile feedbacks in the laboratory setting. The results show that the keypad with piezo feedback was the fastest to use. The task took 12% longer time with the keypad with vibra feedback and 14% longer time with the keypad without tactile feedback.

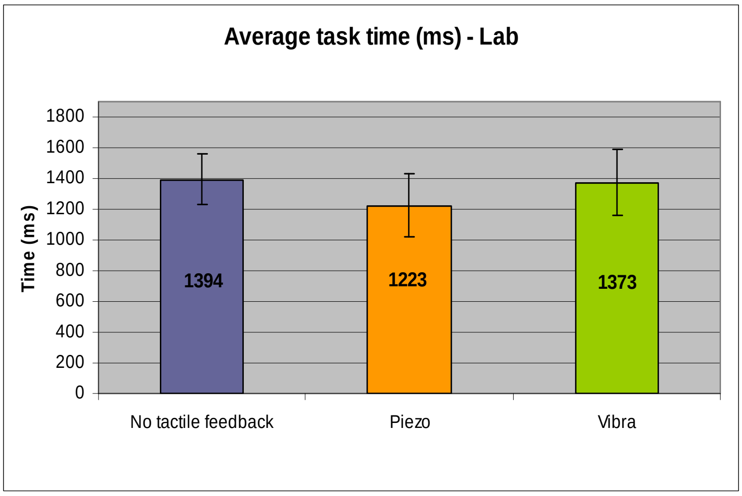

Fig. 38. Mean values and 95% confidence intervals for time (ms) to enter three digits and press OK-button.

The results of the single factor ANOVA test showed that the results do not differ from each other in terms of statistical significance; the significance level is 0.6737.

6.2.3.2 Average error rate - Laboratory

The figure 39 below shows the mean values and 95% confidence intervals for error rates with different tactile feedbacks in the laboratory setting. The results show that there were the least errors done with the keypad with piezo feedback. With the keypad with vibra feedback and the keypad without tactile feedback, the average error rate grew 27% and 73% respectively.

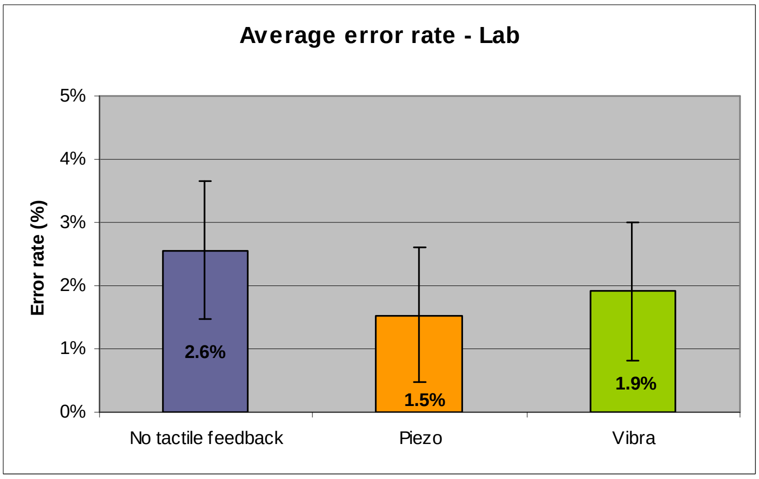

Fig. 39. Mean values and 95% confidence intervals for average error rate.

The results of the single factor ANOVA test showed that the results do not differ from each other in terms of statistical significance; the significance level is 0.4242.

6.2.3.3 Subjective satisfaction - Laboratory

The figure 40 below shows the mean values and 95% confidence intervals for degree of agreement with statements on a 1 (totally disagree) -7 (totally agree) scale.

The results show that the keypad with piezo feedback was rated highest in all five statements, the keypad with vibra feedback came second and the keypad without tactile feedback was rated the lowest.

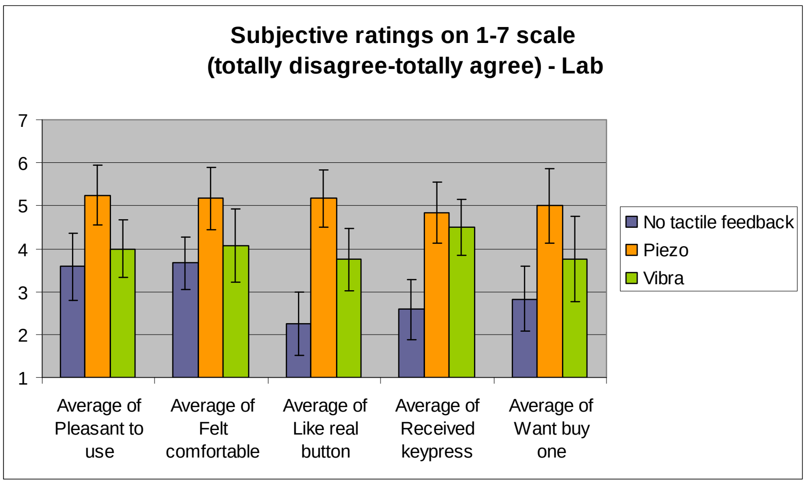

Fig. 40. Mean values for degree of agreement with statements on 1-7 scale.

The results of the single factor ANOVA test showed that the results differ from each other in terms of statistical significance. Therefore the results clearly suggest that the keypad with piezo feedback is more pleasant to use compared to the keypad with vibra feedback and the keypad without tactile feedback; the significance level is 0.0080. Also the virtual buttons with piezo feedback feel more similar to physical buttons when compared to vibra feedback and no tactile feedback; significance level is 0.0000.

With piezo and vibra feedback users are more confident in knowing that the device received their keypress compared to the keypad without tactile feedback; significance level is 0.0001. The results also suggest that users would rather buy a device with a keypad with piezo feedback than a device with vibra feedback or without tactile feedback; significance level is 0.0066.

6.2.3.4 Average task time - Walking

The figure 41 below shows the mean values and 95% confidence intervals for the time to enter three digits and press the OK-button in milliseconds with different tactile feedbacks for the walking part. The results show that the keypad with piezo feedback was again the fastest to use. The task took 7% longer time with the keypad with vibra feedback and 12% longer with the keypad without tactile feedback.

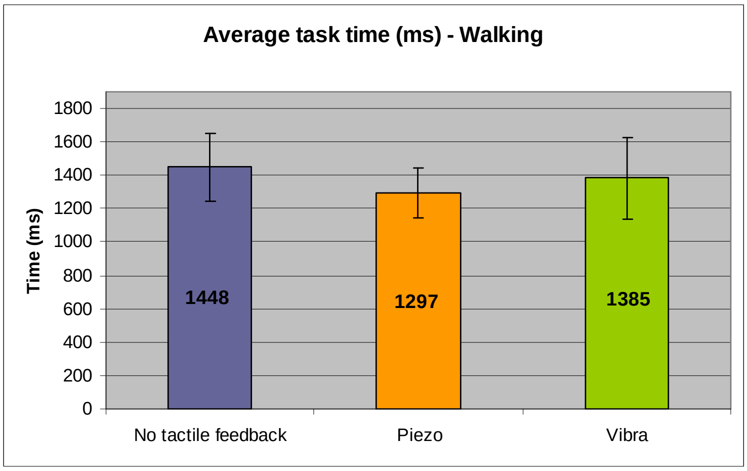

Fig. 41. Mean values and 95% confidence intervals for time (ms) to enter three digits and press OK-button.

The results of the single factor ANOVA test showed that the results do not differ from each other in terms of statistical significance; the significance level is 0.7824.

6.2.3.5 Average error rate - Walking

The figure 42 below shows the mean values and 95% confidence intervals for error rates with different tactile feedbacks for the walking part. The results show that there were the least errors done with the keypad with piezo feedback. With the keypad with vibra feedback and the keypad without tactile feedback, the average error rate grew 27% and 80% respectively.

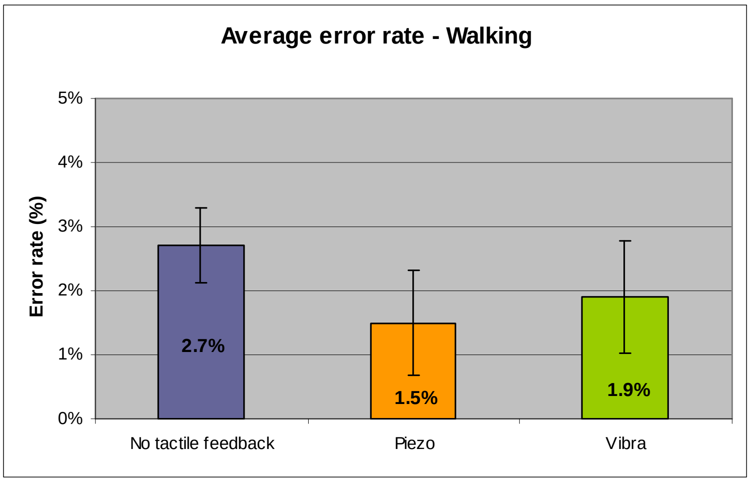

Fig. 42. Mean values and 95% confidence intervals for average error rate.

The results of the paired t-test showed that the keypad with piezo feedback differs from the keypad without tactile feedback in terms of statistical significance; the significance level is 0.0132. Also the keypad with vibra feedback differs from the keypad without tactile feedback; there is a statistical significant difference; significance level 0.0220. Accordingly, the results suggest that the tactile feedback improves the accuracy of the keypad use as users made fewer errors when using the keypads with tactile feedback compared to the keypad without tactile feedback.

6.2.3.6 Subjective satisfaction - Walking

The figure 43 below shows the mean values and 95% confidence intervals for the degree of agreement with statements on a 1 (totally disagree) -7 (totally agree) scale.

The results show that the keypad with piezo feedback was again rated highest in all five statements, the keypad with vibra feedback was rated second highest and the keypad without tactile feedback was rated the lowest.

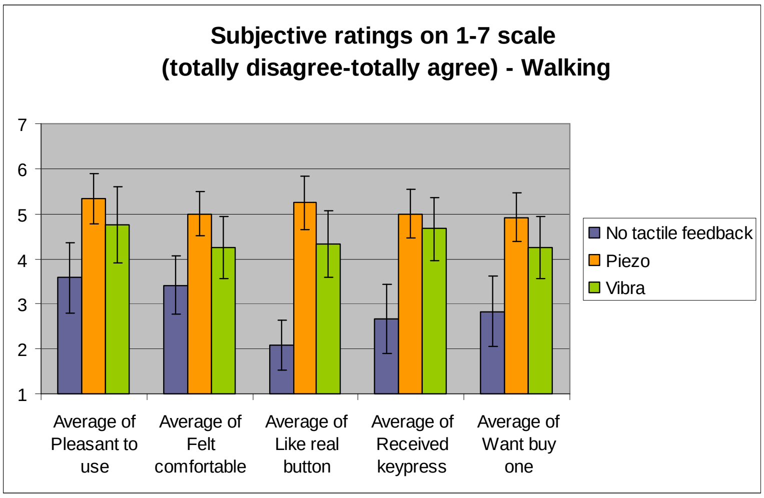

Fig. 43. Mean values for degree of agreement with statements on 1-7 scale.

The results of the single factor ANOVA test showed that the results differ from each other in terms of statistical significance. Therefore the results suggest that the keypads with piezo feedback and vibra feedback are more pleasant to use compared to the keypad without tactile feedback; the significance level is 0.0079. Also the virtual buttons with piezo feedback feel more similar to physical buttons when compared to vibra feedback and no tactile feedback; significance level is 0.0137.

Also, with piezo and vibra feedback users are more confident in knowing that the device received their keypress compared to the keypad without tactile feedback; significance level is 0.0001. The results also suggest that users would rather buy a device with a keypad with piezo feedback or vibra feedback than a device without tactile feedback; significance level is 0.0138.

6.2.3.7 Average task time - Metro

The figure 44 below shows the mean values and 95% confidence intervals for the time to enter three digits and press the OK-button in milliseconds with different tactile feedbacks for the metro part. The results show that the keypad with piezo feedback was again the fastest to use. The task took 5% longer time with the keypad with vibra feedback and 21% longer with the keypad without tactile feedback.

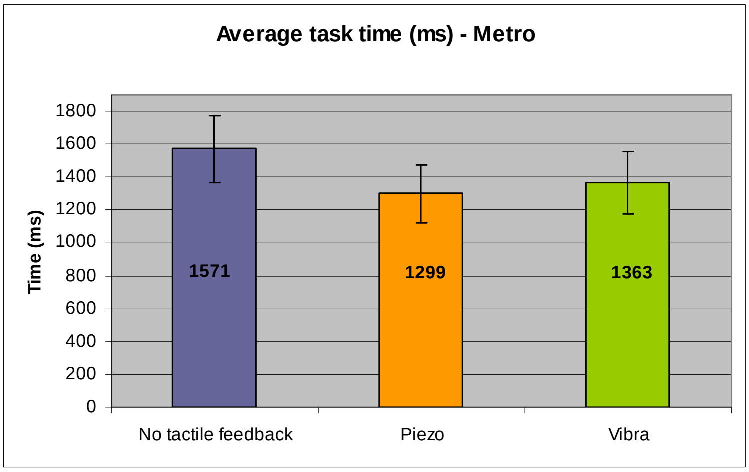

Fig. 44. Mean values and 95% confidence intervals for time (ms) to enter three digits and press OK-button.

The results of the paired t-test showed that the keypad with piezo feedback differs from the keypad without tactile feedback in terms of statistical significance; the significance level is 0.0010. Also the keypad with vibra feedback differs from the keypad without tactile feedback in terms of statistical significance; the significance level is 0.0286. Therefore, the results suggest that the tactile feedback improves the efficiency of the keypad use, as both keypads with tactile feedback are faster to use compared to the keypad without tactile feedback.

6.2.3.8 Average error rate - Metro

The figure 45 below shows the mean values and 95% confidence intervals for error rates with different tactile feedbacks for the metro part. The results show clearly that there were the least errors done with the keypad with piezo feedback. The error rate was highest with the keypad without tactile feedback. With the keypad with vibra feedback and the keypad without tactile feedback, the average error rate grew 50% and 183% respectively.

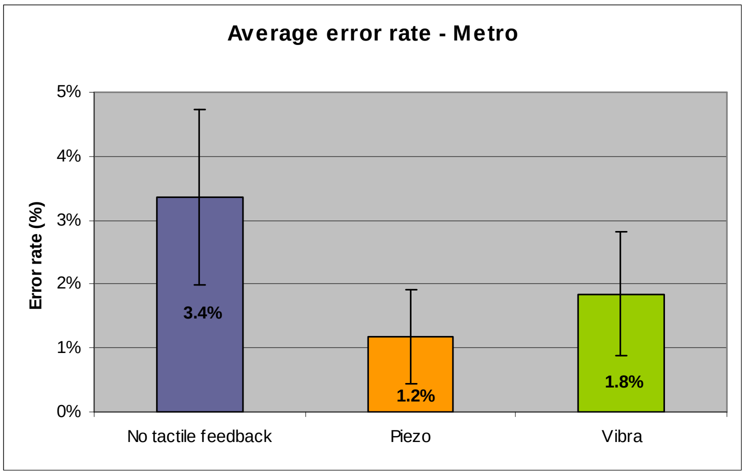

Fig. 45. Mean values and 95% confidence intervals for average error rate.

The results of the paired t-test showed that the keypad with piezo feedback differs from the keypad without tactile feedback in terms of statistical significance; the significance level is 0.0006. Also the keypad with vibra feedback differs from the keypad without tactile feedback; there is a statistical significant difference; significance level 0.0282. Accordingly, the results suggest that the tactile feedback improves the accuracy of the keypad use, as users made fewer errors with the keypads with tactile feedback compared to the keypad without tactile feedback.

6.2.3.9 Subjective satisfaction - Metro

The figure 46 below shows the mean values and 95% confidence intervals for degree of agreement with statements on a 1 (totally disagree) -7 (totally agree) scale.

The results show that the keypad with piezo feedback was again rated highest in all five statements, the keypad with vibra feedback was rated second highest and the keypad without tactile feedback was clearly rated the lowest.

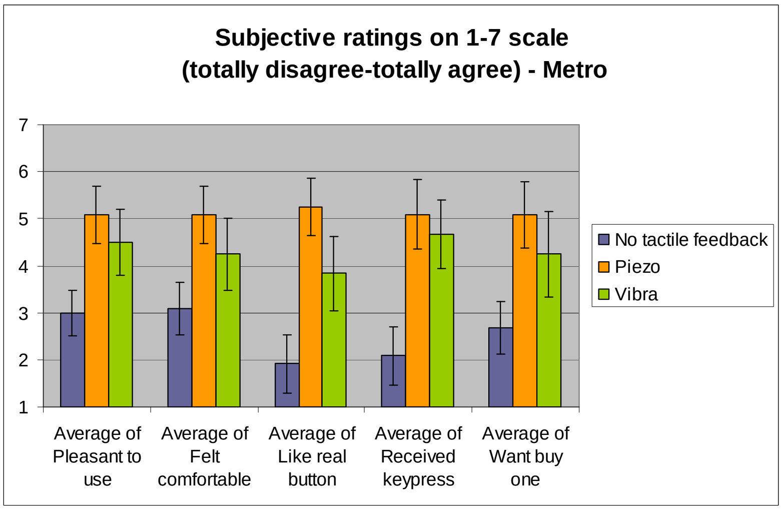

Fig. 46. Mean values for degree of agreement with statements on 1-7 scale.

The results of the single factor ANOVA test showed that the results differ from each other in terms of statistical significance. Accordingly, the results suggest that the keypads with piezo feedback and vibra feedback are more pleasant to use compared to the keypad without tactile feedback; the significance level is 0.0071. Also the virtual buttons with piezo feedback feel more similar to physical buttons when compared to vibra feedback and no tactile feedback; significance level is 0.0000.

With piezo and vibra feedback users are more confident in knowing that the device received their keypress compared to the keypad without tactile feedback; significance level is 0.0000. The results also suggest that users would rather buy a device with a keypad with piezo feedback than a device with vibra feedback or without tactile feedback; significance level is 0.0172.

6.2.3.10 General preference

The figure 47 below shows the mean values and 95% confidence intervals for general grade given by the test users. The results show that the keypad with piezo feedback was rated highest and the keypad without tactile feedback was clearly rated the lowest.

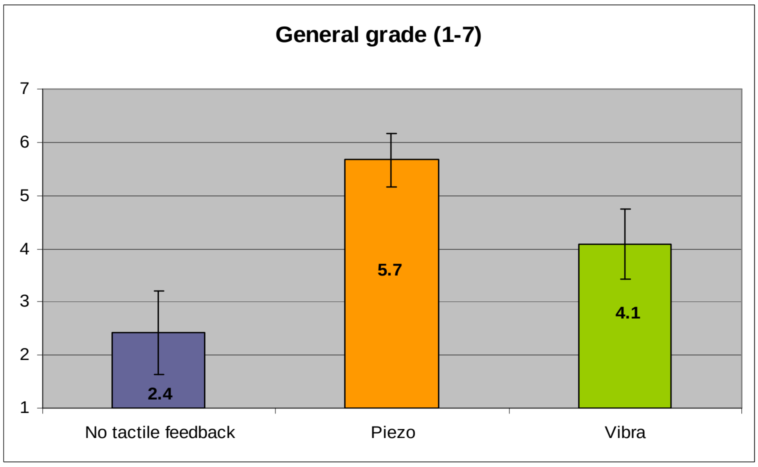

Fig. 47. Mean values and 95% confidence intervals for the general rating on 1-7 scale.

The results of the paired t-test showed that the keypads with piezo feedback and vibra feedback differ from the keypad without tactile feedback in terms of statistical significance; the significance levels are 0.0000 and 0.0231. The keypad with piezo feedback also differs from the keypad with vibra feedback, there is a statistical significant difference; the significance level is 0.0049. Accordingly, the results suggest that users prefer the keypad with piezo feedback to the keypads with vibra feedback and without tactile feedback.

6.2.3.11 Interview

After the test, users were asked to compare the touchscreen use between the test rounds and tell what kind of differences they noticed. Also they were asked if the test environment affected the keypad use somehow.

Many users commented that with the keypad without tactile feedback, they got a very uncertain feeling when using it and seemed to make more errors. Some users commented that when there was no tactile feedback they needed to focus more on the typing and found the lack of tactile feedback very annoying.

Almost all users commented that the piezo feedback feels similar to pressing a real button, which gave them a very natural feeling. Only one user commented that piezo feedback feels too much like a real button and did not want that feeling with touchscreens. Piezo feedback was also commented to be accurate and clear, as users could feel the feedback precisely on their fingertip when pressing the virtual buttons on the touchscreen.

Users commented about the vibra feedback that it was better than nothing but most users said the vibration was a bit disturbing and it could start to annoy in long-term use. Many users commented that the vibra feedback came to the wrong hand, the one that was holding the device and not the one, which was pressing the buttons on the screen. Below there are some user comments about the different keypads.

Comments on the keypad without tactile feedback:

> *"The keypad without tactile feedback was the worst, I would have needed some response that my keypress was taken."*

> "*When there wasn't any tactile feedback, I needed to look at the screen all the time to see if the device received my keypress, I found that very annoying."*

Comments on the keypad with the piezo feedback:

> *"Piezo feedback reminded me of mechanical button, I could feel what I was pressing, that's great!"*

> *"Piezo feedback is accurate and pleasant to use."*

> *"Piezo feedback is a new thing, it's cool and exciting and definitely has a wow-factor."*

> *"This piezo feedback is excellent! I didn't need to guess did the device receive my keypress or not, I just felt it. With this feedback I could type in faster."*

Comments on the keypad with vibra feedback:

> *"Vibra feedback was a bit disturbing but absolutely better than nothing."*

> *"Vibra feedback is in wrong place, not there where I press the button."*
>
> *"Vibra feedback is awful, it vibrates my hold hand and it feels very unpleasant."*

All users commented that when on the move, tactile feedback was the most useful; many users said it to be essential. Most users commented that the keypad without tactile feedback was the worst in every situation but a couple of users told to prefer the keypad without tactile feedback to the keypad with vibra feedback in the laboratory setting. Those users commented that when sitting in silence in an office room, the vibration was too strong and it was more annoying than useful. A few users preferred vibra feedback to piezo feedback while traveling on metro and explained that when it was very noisy and there was a lot of other vibrations also, the vibra feedback was better, it was strong enough and did not disturb anymore. Below are some comments from users about how the test environment affected the keypad use with different tactile feedbacks.

> *"The keypad with piezo feedback was the best one in every situation, I could concentrate on what I saw not what I pressed, it was definitely more pleasant to use."*
>
> *"When walking and traveling on metro, the keypad without tactile feedback was just terrible to use, I needed to concentrate too much on the typing to avoid errors."*
>
> *"The keypad with vibra feedback was best when traveling on metro when there was so much noise and other vibration also."*
>
> *"While on move the keypads with piezo and vibra feedback gave more confident feeling about what I was doing."*

6.2.3.12 Comparing the results of laboratory, walking and metro parts

The figure 48 shows the average task times for different feedbacks for each parts of the test. From the figure it can be seen that the task time remained equal with the keypads with tactile feedback i.e. the keypad with piezo feedback and the keypad with vibra feedback, in all test parts. The task time with the keypad without tactile feedback increased when users were on the move. Especially, in the metro part, the task took 13% longer time than in the laboratory setting with the keypad without tactile feedback.

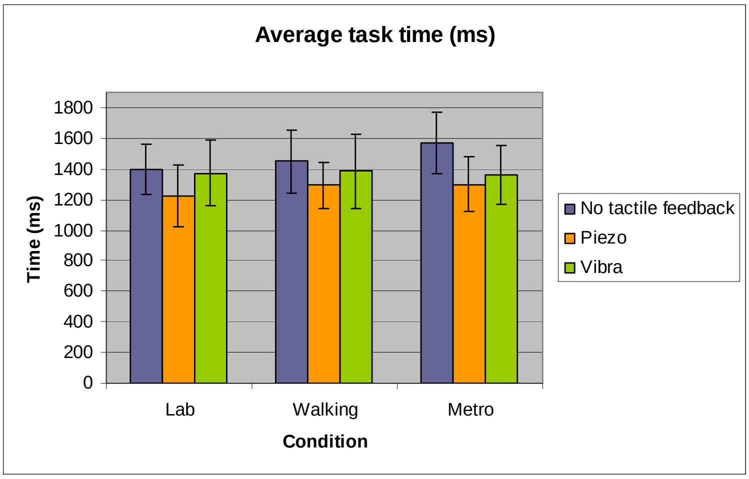

Fig. 48. Mean values and 95% confidence intervals for task times for each parts of the test.

The figure 49 shows the average error rates for different feedbacks for each part of the test. From the figure it can be seen that the error rates with the keypad with piezo feedback and the keypad with vibra feedback remained almost equal in all parts of the test. With the keypad without tactile feedback the error rate grew 36% in the metro part compared to the laboratory part.

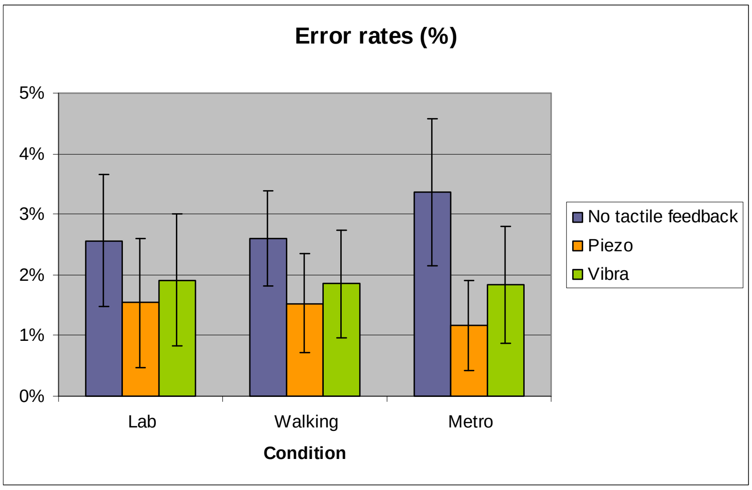

Fig. 49. Mean values and 95% confidence intervals for error rates for each parts of the test.

As the results showed, the tactile feedback was more beneficial when users were mobile. Especially as users were traveling on the metro, the keypad without tactile feedback was clearly slower to use and users made more errors with it compared to the keypads with piezo feedback and vibra feedback.

Figures 50, 51 and 52 show the subjective ratings done after each part of the test. From the figures it can be seen that the keypad with the piezo feedback was evaluated as equally pleasant to use in all parts of the test. The keypad with vibra feedback was evaluated to be more pleasant to use as users were on the move, when walking or traveling on the metro. The keypad without tactile feedback was evaluated the least pleasant to use in all parts of the test and it received the lowest scores in evaluations in the metro part. The results of the subjective ratings showed that users strongly preferred the keypad with piezo feedback.

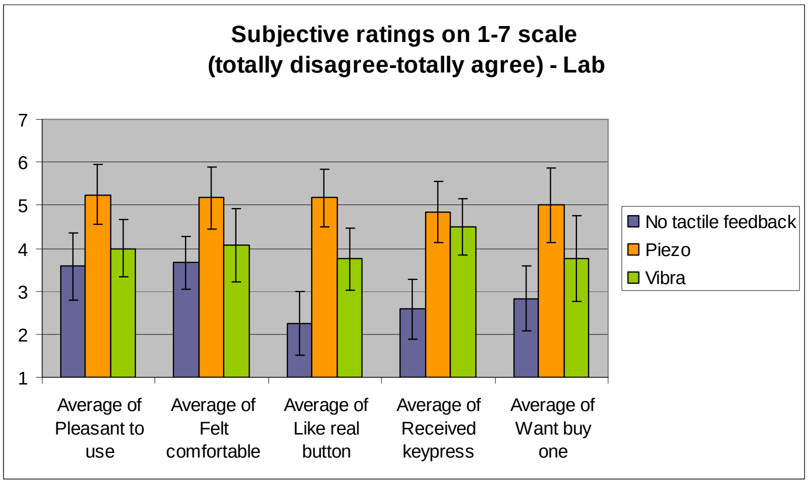

Fig. 50. Subjective ratings for the laboratory part**.**

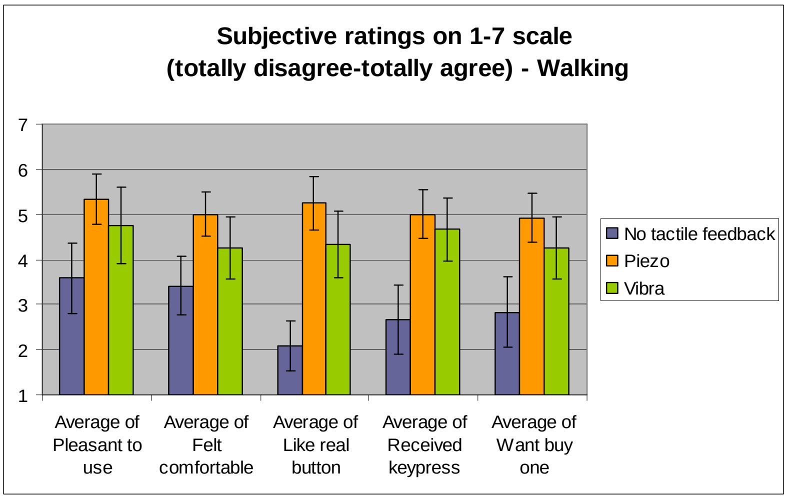

Fig. 51. Subjective ratings for the walking part.

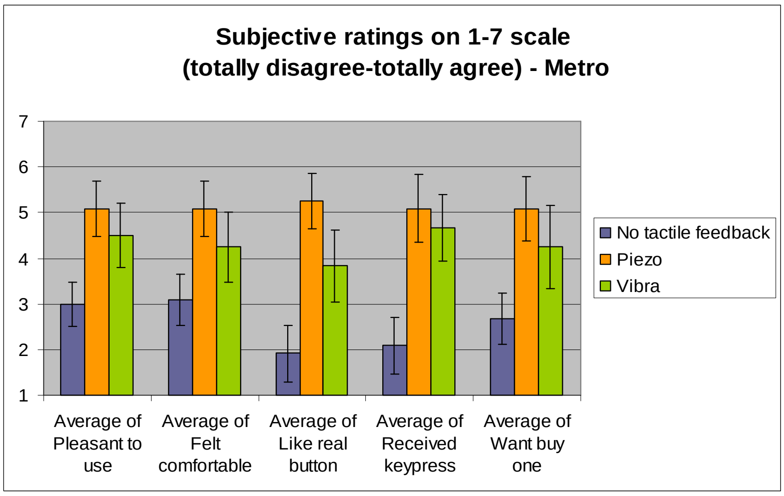

Fig. 52. Subjective ratings for the metro part.

6.2.4 Conclusions

The study researched the effects of tactile feedback on the usability of virtual buttons in a realistic context, when users were on the move. The study compared the efficiency, accuracy and subjective satisfaction of a touchscreen keypad with piezo feedback, vibra feedback or no tactile feedback at all in a realistic task. The test included three contexts; laboratory, walking and metro.

Results from the laboratory part were used as a baseline to compare with the walking and metro contexts. The laboratory test showed that tactile feedback improves the usability when entering numbers with virtual buttons using fingers on the touchscreen. It was found that the keypad with piezo feedback was faster to use than the keypad with vibra feedback in this use case. The results also showed that the error rate was lowest with the keypad with piezo feedback and highest with the keypad without tactile feedback. The results from the subjective satisfaction questionnaire showed that the keypad with piezo feedback was rated highest in all five statements and the keypad without tactile feedback received clearly the lowest score in all five statements.

In the walking context, users walked along a corridor while performing the test task. Results from the walking part showed that the tactile feedback improves the usability when entering numbers with virtual buttons using fingers on the touchscreen. The keypad with piezo feedback was again faster to use than the keypad with vibra feedback in this use case. The error rate was lowest with the keypad with piezo feedback and highest with the keypad without tactile feedback. The results from the subjective satisfaction questionnaire showed that the keypad with piezo feedback was rated highest in all five statements and the keypad without tactile feedback received clearly the lowest score in all five statements.

In the metro context, users were seated on a moving metro train while carrying out the test. Results from the metro part showed that with tactile feedback the keypad was faster to use and had a lower error rate. It was also found that the keypad with piezo feedback was slightly faster to use than the keypad with vibra feedback in this use case. The results showed that the error rate was clearly highest with the keypad without tactile feedback. The results from the subjective satisfaction questionnaire showed that the keypad with piezo feedback was rated highest in all five statements and the keypad without tactile feedback received clearly the lowest score in all five statements.

From the interviews it was found that users favored the piezo feedback; it was said to be most accurate and pleasant to use. The keypad with piezo feedback also received the highest score in the general grade given by the test users compared to the keypad with vibra feedback and the keypad without tactile feedback. The results of the subjective evaluations strongly suggest that the users prefer the piezo feedback to the vibra feedback and to the no tactile feedback.

As the results showed the piezo feedback performed best in all usability metrics used in this study: It was the most efficient and the least error prone condition and it was also favored in all subjective ratings, as well as in the general preference. The vibra feedback was the second best option. The no tactile feedback was clearly the worst option as it performed worst in all usability metrics and was consistently rated lowest.

Tactile feedback was found to be more beneficial as users were on the move, especially when traveling on the metro. The walking part was still a fairly controlled environment as it was very quiet and there were no other people walking. The metro was a more realistic environment, as people use their mobile devices while traveling on trains and buses everyday. It was noisy and the users were subjected to vibrations from the movement of the train. In this kind of situations tactile feedback is suggested to be the most useful, providing the users beneficial information that their keypress was registered among all the distractions in their environment.

Based on the results of this study it can be concluded that virtual buttons with piezo feedback provide the highest level of usability to the user. It is also the preferred feedback producing tactile feedback for touchscreens. Vibra feedback is consistently less preferred, while no tactile feedback is clearly the worst option. Finally, it can be concluded that tactile feedback definitely improves the usability of virtual buttons.

7. CONCLUSIONS AND DISCUSSION

7.1 Conclusions of the usability studies

The main purpose of the usability studies was to find the optimal way to implement and design tactile feedback for virtual buttons.

The two preliminary studies clarified the subjectively perceived pleasantness of piezo and vibra feedbacks. The piezo pleasantness study also investigated the impact of audio feedback on perceived tactile feedback pleasantness. These preliminary studies were carried out to find the most pleasant tactile stimuli for piezo and vibra feedbacks, which could then be compared to each other in terms of usability. It was found that the piezo feedbacks generated with 46 mA current were perceived most pleasant. The audio feedback could have some impact on the subjectively perceived pleasantness of the piezo stimulus in a way that the perceived pleasantness is reduced, especially when the audio feedback is loud. From the vibra pleasantness study it was found that the vibra feedback generated with 16 ms drive time was perceived most pleasant and it also had less variance in the subjective evaluations.

The comparison laboratory study compared virtual buttons with piezo feedback, vibra feedback and no tactile feedback in a number entry task in terms of usability by measuring efficiency, accuracy and subjective satisfaction. It was found that users performed best with piezo feedback; they could enter numbers faster and they also made fewer mistakes. Piezo feedback was also preferred in all subjective ratings. With vibra feedback users could enter numbers faster but they made more errors compared to the no tactile feedback condition.

The comparison field study made the same comparison as the laboratory study, but this time the test was also conducted as the users were on the move; walking along a corridor or traveling on a metro train. In the field study it was found that with piezo feedback users could perform best in all situations, laboratory, walking and metro. With piezo feedback they entered numbers faster and made fewer mistakes compared to vibra feedback and no tactile feedback conditions. Piezo feedback was again ranked highest in all subjective ratings done by the users. Tactile feedback was also found to be more beneficial as users were on the move. Especially when traveling on the metro, without tactile feedback users started to make notably more errors as there was no tactile response to confirm their keypresses.

The results from both the comparison laboratory study and the comparison field study indicate the same conclusion that piezo feedback provides the highest level of usability for virtual buttons.

7.2 Research questions

The usability studies aimed to find answers to the following questions:

What is the optimal solution for virtual buttons tactile feedback?

Based on the results of this study, it is suggested to use piezo actuator as the most optimal solution to produce tactile feedback for virtual buttons.

Which parameters create the most pleasant tactile feedback for virtual buttons with piezo actuator and vibration motor?

The results from the preliminary studies showed that when using a piezo actuator, 46 mA current creates the most pleasant tactile feedback for virtual buttons with the tested touchscreen device. With a vibration motor using 16 ms drive time creates the most pleasant tactile feedback for virtual buttons with the tested touchscreen device. These parameters cannot be directly generalized to all touchscreen devices because the mechanical design of the device impact the optimum feedback parameters. However, these parameters can be considered indicative for other touchscreen devices.

How does the usability of virtual buttons differ when using piezo feedback, vibra feedback or no tactile feedback at all?

It was found that virtual buttons with piezo feedback reach the highest level of usability; they are the most efficient, most accurate and most pleasant to use. Virtual buttons with vibra feedback are the second best option in terms of usability. Virtual buttons without tactile feedback have the lowest level of usability.

How does the usability of virtual buttons differ as users are on the move when using piezo feedback, vibra feedback or no tactile feedback at all?

When users are on the move, especially for example when traveling on the metro, the tactile feedback is even more beneficial. Virtual buttons with piezo feedback provide the highest level of usability; they are the most efficient, most accurate and also most pleasant to use. Virtual buttons with vibra feedback are the second best option; they are more efficient, accurate and pleasant to use compared to virtual buttons without tactile feedback but cannot reach the same level of usability as virtual buttons with piezo feedback. Virtual buttons without tactile feedback have evidently the lowest level of usability.

7.3 Reliability and validity of the results

The results of this study can be considered to be reliable. To ensure the reliability of the results, an adequate amount of participants and different participants for each test were used. Also the results were analyzed using several statistical tests to estimate the statistical significance of the results. The comparison test conducted in the comparison laboratory study was repeated also in the comparison field study. The test setting was exactly the same; only the participants and the touchscreen device were different. Both studies obtained the same results that the piezo feedback improved most the usability of virtual buttons, which points towards a high level of reliability.

The results can be considered to be valid as well. The test participants presented typical users of mobile devices; they all had long experience of using mobile phones. The task that was tested was realistic and a common activity of mobile devices. The feedbacks that were compared in the comparison laboratory study were both first optimized, so that the most pleasant piezo feedback was compared to the most pleasant vibra feedback in order to create an even starting point for the comparison. The comparison field study used the same touchscreen device for both piezo feedback, vibra feedback and no tactile feedback conditions, so the results could not have been dependent on the characteristics of the device. The comparison was conducted both in the laboratory and in the field, so the factors that could not have been tested and taken into account in the laboratory setting were included in the field setting.

7.4 Discussion and future research

The results of this study showed that there is a solution to tackle the major weakness of touchscreens mobile devices i.e. the lack of tactility. It was found that piezo feedback not only improves the user performance but it also leads to a more satisfying experience in touchscreeen interaction. That is not a surprise as people are used to feeling the shapes and textures of physical objects they are interacting with. If taking the touch modality away, it certainly cannot improve the usability of mobile devices and at worst it can become a barrier for the interaction. To make touchscreen interaction more natural tactile feedback needs to be added so that the user is able to really feel what he is interacting with.

Based on the results of the studies, piezo actuator seems to be the best option from the two most promising technical alternatives to provide tactile feedback for virtual buttons. There have been no previous comparisons in terms of usability of tactile feedback produced with a piezo actuator or a vibration motor. However, these two technologies have been compared in technical terms [23] and that comparison also suggests that piezo actuator is the best solution for tactile feedback for touchscreens. The advantage of a piezo actuator is the ability to create a variety of waveforms, which results in a wide spectrum of tactile sensations. With a vibration motor this is not possible.

As piezo feedback provides local tactile feedback it is most suitable for virtual buttons in confirming keypresses, but it could also be used to communicate other information of the buttons, for example the texture and shape of the virtual buttons and the locations of the buttons. One alternative could be to use distinct tactile feedback for different buttons so that the user could distinguish the buttons and controls on the screen only based on the tactile sensations they provide. This could make touchscreen mobile devices also accessible for visual impaired and blind people, as now touchscreens without any tactile feedback are impossible for them to use. Piezo feedback could also be added to many graphical UI elements on the touchscreen besides virtual buttons. For example, sliders and scrollbars could provide different kind of tactile feedback to inform the location of the element but also to provide other information like e.g. the state of the element.

Tactile feedback produced with a vibration motor is less suitable for local feedback on the touchscreen. The results of the usability studies indicated that vibra feedback could be disturbing in button interactions as the feedback cannot be felt only on the screen but it shakes the whole device instead. However, this does not rule out the usefulness of vibration feedback for providing users information that is not directly related to local touchscreen interaction. Traditionally vibra feedback has been used to enhance the phone ringing tone to alert the user in noisy environments and it is very useful for similar purposes to notify the user about other important information. For example as accelerometers are becoming popular in mobile devices it is possible to use gestures for interaction and vibra feedback could be very useful to provide little vibrations to the user and confirm once the gesture was accepted. Also rich gaming is becoming more popular in mobile devices and vibra feedback could be an easy way to make the game experience more fun and exciting as it can provide the same kind of vibrations that the most console game controllers have these days.

A very promising future possibility is to combine both technologies, piezo actuator and vibration motor in one touchscreen mobile device. Piezo feedback could be used for local touchscreen interactions and vibra feedback in alerting purposes, mobile games and gesture interaction. This could make the mobile device interaction more realistic, intuitive and natural, as the device would utilize the user's wide range of tactile sensations.

Another interesting topic for further discussion is the difference between laboratory and field testing when evaluating usability. In this study both methods were used. The results of the laboratory and field study obtained the same outcome; virtual buttons with piezo feedback were most efficient, accurate and pleasant to use. However, the field study revealed even more than the laboratory study. It was found that tactile feedback was even more beneficial as users were on the move, which is an important result when talking about mobile devices. The differences in task times and error rates increased between the tactile feedback and no tactile feedback and reached the level of statistical significance. Also the results based on the subjective satisfaction showed stronger significant differences between the feedback conditions compared to the laboratory study. If the study was conducted only in a laboratory setting, we would not have realized that when users are on the move the lack of tactile feedback starts to really annoy the users and that piezo feedback is clearly the preferred tactile feedback type for virtual buttons. This supports the previous findings on the importance of field testing when evaluating the usability of mobile devices. Especially when evaluating tactile feedback it is very difficult to simulate all the important factors in a laboratory that affect its usage in real life situations, e.g. user's limited visual attention, the movement of the user and other vibrations from the environment. These factors might have a significant impact on the results of the evaluation.

As this study researched only the effect of tactile feedback on virtual buttons, there is still much left to research in the field of tactile feedback for mobile devices. To continue with virtual buttons, more research should be done so that virtual buttons could provide the same kind of tactility that physical buttons provide. Now physical buttons give tactile feedback already before the button has been pressed. Also with physical buttons users are able to feel the shape and the edges of the button without pressing it. It could be one path for future research to focus on how to provide richer tactile feedback for virtual buttons and how this can solve usability issues especially for special user groups such as the visually impaired. Future research could also focus on how to design tactile feedback to other GUI elements as discussed already earlier and how this feedback could improve the usability of touchscreen interactions. Combining different tactile actuator technologies in a single device is also an area that has not been studied before and could result in valuable improvements for touchscreen devices interaction. Little is still known how to best design tactile feedback on touchscreen devices, so there are many fruitful areas for future research in the field of tactile feedback for mobile devices.

8. REFERENCES

[1] A. Oulasvirta, S. Tamminen, V. Roto, J. Kuorelahti, ”Interaction in 4-Second Bursts: The Fragmented Nature of Attentional Resources in Mobile HCI”, in Proceedings of SIGCHI conference on Human factors in computing systems, ACM Press, 2005.

[2] M. Silfverberg, “Using Mobile Keypads with Limited Visual Feedback: Implications to Handheld and Wearable Devices”, in Proceedings of Mobile HCI conference 2003, Springer-Verlag, 2003.

[3] M. McLinden, S. McCall, “Learning Through Touch: Supporting children with visual impairment and additional difficulties”, David Fulton Publishers, 2002.

[4] J. Loomis, S. Lederman, “Tactual perception (Chapt. 31) in Handbook of Perception and Human Performance”, K. Boff, L. Kaufman, J. Thomas, Wiley-Interscience, 1986.

[5] R. Hughes, A. Forrest, “Perceptualisation using a Tactile Mouse”, in Proceedings of the seventh conference on Visualization ’96, IEEE Computer Society Press, 1996.

[6] I. Oakley, M. R. McGee, S. Brewster, P. Gray, “Putting the feel in ‘look and feel’”, in Proceedings of SIGCHI conference on Human factors in computing systems, ACM Press, 2000.

[7] R. Klatzky, S. Lederman, ”Touch (Chapt. 6) in Experimental Psychology, Handbook of Psychology”, A. Healy, R. Proctor, John Wiley & Sons, 2003.

[8] Y. Hatwell, A. Streri, E. Gentaz, “Touching for Knowing: Cognitive psychology of haptic manual perception”, John Benjamins Publishing, 2003.

[9] E. B. Goldstein, “Sensation and Perception, 5th edition, Brooks/Cole Publishing, 1999.

[10] C. Royeen, S. Lane, “Tactile processing and sensory defensiveness” in A. Fisher, E. Murray, A. Bundy, “Sensory Integration: Theory and practice”, Davis, 1991.

[11] L. Goold, J. Hummell, “Supporting the Receptive Communication of Individuals with Significant Multiple Disabilities: Selective use of touch to enhance comprehension”, North Rocks Press, 1993.

[12] J. J. Gibson, “Observations on active touch”, Psychological Review, 69, 1962.

[13] E. Tähkäpää, “Tuntopalaute työpöytäympäristössä”, Tietojenkäsittelylaitos, Tampereen yliopisto, 2003.

[14] SensAble PHANTOM, SensAble Technologies Inc, 2007, http://www.sensable.com

[15] Sony PlayStation 2, Sony Corporation, 2007, http://fi.playstation.com

[16] Nintendo Wii, Nintendo Company, 2007, http://wii.nintendo.com

[17] H. Iwata, "Haptic interfaces (Chapt. 10) in the Human-Computer Interaction Handbook", J. Jacko, A. Sears, Lawrence Erlbaum Associates, Inc., Publishera, 2003.

[18] J. Linjama, T. Kaaresoja, "Värinähälytys, tuntopalaute ja haptiikkamobiililaitteissa", presented at Akustiikkapäivät, 2003, Akustinen Seura Ry.

[19] L. Brown, S. Brewster, H. Purchase, "First Investigation into the Effectiveness of Tactons", in Proceedings of World Haptics 2005, IEEE Press, 2005.

[20] L. Brown, T. Kaaresoja, "Feel Who's Talking: Using Tactons for Mobile Phone Alerts", in Extended Abstracts of CHI 2006, ACM Press, 2006.

[21] Nokia Digital Pen, Nokia Corporation, 2007, http://europe.nokia.com/su-1b

[22] M. Fukumoto, T. Sugimura, "Active Click: Tactile Feedback for Touch Panels", in Extended Abstracts of CHI 2001, ACM Press, 2001

[23] I. Poupyrev, S. Maruyama, J. Rekimoto, "Ambient Touch: Designing Tactile Interfaces for Handheld Devices", in Proceedings of UIST 2002, ACM Press, 2002.

[24] I. Poupyrev, S. Maruyama, "Tactile Interfaces for Small Touch Screens", in Proceedings of UIST 2003, ACM Press, 2003.

[25] T. Kaaresoja, L. Brown, J. Linjama, "Snap-Crackle-Pop: Tactile Feedback for Mobile Touch Screens", in Proceedings of Eurohaptics 2006, 2006.

[26] A. Nashel, S. Razzaque, "Tactile Virtual Buttons for Mobile Devices", in Proceedings of CHI 2003, ACM Press, 2003.

[27] J. Luk, J. Pasquero, S. Little, K. MacLean, V. Levesque, V. Hayward, "A Role for Haptics in Mobile Interaction", in Proceedings of CHI 2006, ACM Press, 2006.

[28] LG Prada phone, LG Corporation, 2007, http://www.pradaphonebylg.com/

[29] Samsung phones, Samsung Corporation, 2007, http://product.samsung.com/cgi-bin/nabc/mobile/wireless_main.jsp

[30] VibeTonz System, Immersion Corporation, 2007, http://www.immersion.com/mobility/touchscreen/vt-system.php

[31] Sony Navitus, Sony Corporation, 2007 http://bssc.sel.sony.com/Professional/navitus/index.html

[32] I. Poupyrev, S. Maruyama, J. Rekimoto, "TouchEngine: A Tactile Display for Handheld Devices", in Extended Abstracts of CHI 2002, ACM Press, 2002.

[33] International standard ISO, "ISO 9241-11:1998: Ergonomic requirements for office work with visual display terminals (VDTs), Part 11: Guidance on usability", International Organization for Standardization, 1998.

[34] J. Nielsen, "Usability Engineering", MA: Academic Press, 1993.

[35] B. Shackel, "Human Factors and Usability in the Human-Computer Interaction", Preece et al., Prentice Hall, 1990.

[36] J. Preece, Y. Rogers, H. Sharp, D. Benyon, S. Holland, T. Carey, "Human-Computer Interaction", Addison Wesley, 1994.

[37] International standard ISO, "ISO 13407:1999: Human-centred design process for interactive systems", International Organization for Standardization, 1999.

[38] X. Faulkner, "Usability Engineering", Palgrave Macmillan, 2000.

[39] J. Rubin, "Handbook of Usability Testing", John Wiley & Sons, Inc, 1994.

[40] C. Nemeth, "Human Factors Methods for Design: Making Systems Human-Centered", CRC Press LLC, 2004.

[41] D. Benyon, P. Turner, S. Turner, "Designing Interactive Systems: People, Activities, Contexts, Technologies", Addison Wesley, 2005.

[42] J. Kjeldskov, C. Graham, "A Review of MobileHCI Research Methods", in Proceedings of the 5th International Mobile HCI conference 2003, Springer-Verlag, 2003.

[43] J. Kjeldskov, J. Stage, "New Techniques for Usability Evaluation of Mobile Systems", International Journal of Human-Computer Studies, Volume 60, Elsevier, 2004.

[44] H. Duh, G. Tan, V. Chen, "Usability Evaluation for Mobile Device: A Comparison of Laboratory and Field Tests", in Proceedings of Mobile HCI conference 2006, ACM, 2006.

[45] J. Goodman, S. Brewster, P. Gray, "Using Field Experiments to Evaluate Mobile Guides", in Proceedings of HCI in Mobile Guides, workshop at Mobile HCI conference 2004, Springer, 2004.

[46] S. Brewster, F. Chohan, L. Brown, “Tactile Feedback for Mobile Interactions”, in Proceedings of CHI 2007, ACM Press, 2007.

[47] R. Leung, K. MacLean, M. Bertelsen, M. Saubhasik, “Evaluation of Haptically Augmented Touchscreen GUI Elements Under Cognitive Load”, in Proceedings of the International Conference on Multimodal Interfaces 2007, ACM, 2007.

[48] S. Robinson, “Touchscreen Technology in Mobile Phones: Ready and Waiting for Blockbuster, Strategy Analytics, 2006: http://www.strategyanalytics.net/default.aspx?mod=ReportAbstractViewer&a0=2961

[49] A. Dean, D, Voss, “Design and Analysis of Experiments”, Springer-Verlag, 1998.

[50] R. Simes, “An improved Bonferroni procedure for multiple tests of Significance”, Biometrika, Vol. 73, 1986.

[51] S. Brewster, “Overcoming the Lack of Screen Space on Mobile Computers”, in Personal and Ubiquitous Computing, Volume 6, Issue 3, Springer-Verlag, 2002.

[52] V. Tikka and P. Laitinen, “Designing Haptic Feedback for Touch Display: Experimental Study of Perceived Intensity and Integration of Haptic and Audio,” presented at the First International Workshop, HAID, 2006.

[53] P. Laitinen, J. Mäenpää, ”Enabling mobile haptic design: Piezoelectric actuator technology properties in hand held devices” in Proceedings of IEEE International Workshop on Haptic Audio Visual Environments and Their Applications, HAVE 2006, IEEE Press, 2006.