MULTIMODAL INTERACTION: DEVELOPING AN INTERACTION CONCEPT FOR A TOUCHSCREEN INCORPORATING TACTILE FEEDBACK

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Multimodal Interaction: Developing an Interaction Concept for a Touchscreen Incorporating Tactile Feedback

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Preface

This doctoral dissertation describes my project on tactile touchscreen for multimodal interaction, which was conducted from 2007 to 2010 in the Media Informatics and Human-Machine Interaction Work Groups of the Informatics Department at Ludwig-Maximilians-Universität Munich, in collaboration with the User Interface Design Center at Siemens Corporate Technology.

First of all, I would like to extend my appreciation to my academic supervisor, Prof. Dr. Heinrich Hußmann, for his theoretical and technical support and for many valuable discussions. I would also like to thank Prof. Dr. Detlef Zühlke for his willingness to access this dissertation.

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My special thanks go to my family for their tremendous support and unfailing encouragement.

Declaration

I hereby certify that this dissertation is my own original work, produced without improper assistance from others. Any text passages or figures taken from external sources are attributed as such and their sources identified in the References section. This dissertation has not previously been presented for the award of any other degree of any institution.

Bonn, Octorber 1st, 2011

Abstract

The touchscreen, as an alternative user interface for applications that normally require mice and keyboards, has become more and more commonplace, showing up on mobile devices, on vending machines, on ATMs and in the control panels of machines in industry, where conventional input devices cannot provide intuitive, rapid and accurate user interaction with the content of the display. The exponential growth in processing power on the PC, together with advances in understanding human communication channels, has had a significant effect on the design of usable, human-factored interfaces on touchscreens, and on the number and complexity of applications available on touchscreens. Although computer-driven touchscreen interfaces provide programmable and dynamic displays, the absence of the expected tactile cues on the hard and static surfaces of conventional touchscreens is challenging interface design and touchscreen usability, in particular for distracting, low-visibility environments. Current technology allows the human tactile modality to be used in touchscreens. While the visual channel converts graphics and text unidirectionally from the computer to the end user, tactile communication features a bidirectional information flow to and from the user as the user perceives and acts on the environment and the system responds to changing contextual information. Tactile sensations such as detents and pulses provide users with cues that make selecting and controlling a more intuitive process. Tactile features can compensate for deficiencies in some of the human senses, especially in tasks which carry a heavy visual or auditory burden.

In this study, an interaction concept for tactile touchscreens is developed with a view to employing the key characteristics of the human sense of touch effectively and efficiently, especially in distracting environments where vision is impaired and hearing is overloaded. As a first step toward improving the usability of touchscreens through the integration of tactile effects, different mechanical solutions for producing motion in tactile touchscreens are investigated, to provide a basis for selecting suitable vibration directions when designing tactile displays. Building on these results, design know-how regarding tactile feedback patterns is further developed to enable dynamic simulation of UI controls, in order to give users a sense of perceiving real controls on a highly natural touch interface. To study the value of adding tactile properties to touchscreens, haptically enhanced UI controls are then further investigated with the aim of mapping haptic signals to different usage scenarios to perform primary and secondary tasks with touchscreens. The findings of the study are intended for consideration and discussion as a guide to further development of tactile stimuli, haptically enhanced user interfaces and touchscreen applications.

Zusammenfassung

Touchscreens sind heutzutage als Alternative zu Maus und Tastatur in täglichen Gebrauch. Sie kommen insbesondere überall dort zum Einsatz, wo herkömmliche Eingabegeräte keine intuitive, schnelle und präzise Interaktion mit der Anwendung erlauben, wie z.B. bei Fahrkarten- oder Geldautomaten oder bei der Steuerung von Maschinen über Bedienerkonsolen. Wissenschaftlicher Fortschritt beim Verständnis der menschlichen Kommunikationskanäle und das exponentielle Wachstum der Rechenleistung von Computern haben in den letzten Jahren einen erheblichen Einfluss auf die Entwicklung von nutzerfreundlichen, ergonomischen Mensch-Maschine-Schnittstellen bei Touchscreens gehabt, ebenso wie auf steigende Komplexität und Anzahl von verfügbaren Applikationen für Touchscreens. Aber obwohl diese Touchscreens über programmierbare und dynamisch veränderbare Bedienoberflächen verfügen, fehlt für den Benutzer das erwartete taktile Empfinden an der harten und unbeweglichen Oberfläche konventioneller Touchscreens. Die Erweiterung der Bedienoberflächen um informative taktile Signale ist eine anspruchsvolle Aufgabe beim Design von Mensch-Maschine-Schnittstellen, insbesondere für solche, die in Umgebungen zum Einsatz kommen, die durch störende Einflüsse wie z.B. Lärm oder schlechte Sichtverhältnisse gekennzeichnet sind. Der aktuelle Stand der Technik erlaubt, dass menschliche Empfindungskomplexe, wie Tasten und Fühlen, über Touchscreens angeregt werden können. Während die visuelle Wahrnehmung des Menschen stets unidirektional von der Informationsquelle zum Betrachter verläuft, z.B. vom Computerbildschirm zum Benutzer, weist die taktile Kommunikation einen bidirektionale Fluss von Informationen zum und vom Benutzer auf. Der Benutzer nimmt fühlbare Veränderungen der Bedienoberfläche wahr und reagiert darauf. Aus dieser Reaktion resultiert im System eine kontextabhängige Veränderung der Informationen.

Über das taktile Empfinden, ausgelöst z.B. durch Impulse, werden dem Benutzer Signale übermittelt, die den Prozess der Bedienung eines Systems intuitiver werden lassen. Taktile Eigenschaften von Touchscreens sind in der Lage, Defizite der menschlichen Wahrnehmung auszugleichen, speziell bei Aufgaben, die geprägt sind von starker visueller oder auditiver Belastung.

In dieser Arbeit wird ein Interaktionskonzept für Touchscreens mit taktilem Feedback entwickelt, mit Blick auf eine effiziente und effektive Verwendung der Schlüsselmerkmale des menschlichen Tastsinns, insbesondere in Umgebungen, wo durch störende Einflüsse, das Sehen beeinträchtigt und das Hören überbeansprucht ist. Als ersten Schritt zur Verbesserung der Benutzbarkeit von Touchscreens mit Hilfe von taktilen Effekten, wurden verschiedene mechanische Lösungen zur Erzeugung von untersucht, um eine Grundlage zur

Auswahl passender Schwingungsrichtungen für das Design taktiler Benutzerschnittstellen zu gewinnen. Aufbauend auf diesen Ergebnissen, wurde Know-how bezüglich des Designs taktiler Muster entwickelt, um zu ermöglichen, dass echte UI Kontrollelemente durch diese Muster dynamisch simuliert werden können, so dass Benutzer das Gefühl haben, reale UI Element auf einer berührungsempfindlichen Oberfläche zu bedienen.

Im weiteren Verlauf der Arbeit wurden um haptische Merkmale erweiterte UI Kontrollelement untersucht, um den Nutzen taktiler Eigenschaften von Touchscreens bewerten zu können. Dazu wurden haptische Signale auf unterschiedliche Nutzungsszenarien abgebildet, bei denen es um die Durchführung von Primär- und Sekundäraufgaben unter Verwendung von Touchscreens ging. Das Ergebnis der Untersuchungen soll als Anleitung für weitere Entwicklungen von Berührungsreizen, Schnittstellen, die um haptische Merkmale erweitert werden, und Applikationen die Touchscreens nutzen dienen und Anregung zu weiteren Betrachtungen und Diskussionen liefern.

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1 Introduction

As the first sense to develop in the womb and the last one to be lost before death [@20], the sense of touch is well known as being essential to understanding the real world. Via the interactive touch communication channel, humans perform a set of activities accurately generating information on various physical attributes of an object (e.g. temperature, shape, hardness, weight and texture) through sensory systems (e.g. tactile and kinesthetic systems) that encode information on spatial and temporal distribution through the hand. These kinds of touch information guide further activities of the human body. Geldard [85] noted that the sense of touch is the only human sense that interacts with objects by simultaneously actively manipulating them and passively perceiving them. The skin, as the body's largest organ, can provide a rich alternative touch input channel for those whose visual and auditory sensory channels are either disabled or overloaded. The sensitivity of the skin on hands can be exploited as a means of information communication for human-computer interfaces like touchscreens.

There is no easier and more natural way for humans to communicate with a user interface than touching and feeling what they see on a touchscreen as a pointing device [226]; thus on-screen objects need to behave in realistic and physically-based ways. As touchscreens act as both input and output devices, they require no additional work space, have no moving parts and are very durable, affording control simply by pressing the location of a graphical target displayed on the screen. Although touchscreens are efficient for both user input and data display, there are still challenges such as using them in distracting environments or manipulating targets that are smaller than finger width. One of the main drawbacks of the technology is that the smooth surface of a touch-sensitive screen cannot be felt in the same way as a conventional interface with mechanical controls, where click events can be identified and tactile feedback can be passed to the user. A lack of haptic feedback thus makes for an unnatural user experience and demands excessive visual attention to be paid to pressing on-screen UI controls. Several studies [98] indicate that haptic feedback can enhance the realism of interactive systems through more natural interaction with objects and the environment. This study attempts to employ haptic cues that compensate for deficiencies in some of the human senses – especially the visual or auditory senses, which are often heavily burdened and widely prone to impairment – by providing haptic responses conveying information on the properties of objects in computer-generated environments.

As a first step, this chapter will analyze the tactile touchscreen as interaction technology based on its key features, with the aim of understanding the importance of maintaining and improving the quality of the user experience in touchscreen systems. This leads to an analysis of the usability issues raised by present-day tactile touchscreens, which in turn engenders the research questions and elucidates the motivation behind them. Having thus determined the scope of the study, this chapter will outline the wealth of basic knowledge, surveys and applications that form the contextual background.

1.1 Understanding the tactile touchscreen as interaction technology

Properties of tactile touchscreens

Touch characteristics. Tactile touchscreens can consist of multiple touch-sensitive overlays that work using resistance, capacitance, acoustics, optics and mechanical force. They can be touch-operated by a finger or a stylus. As advances are made in understanding the nature of the human sense of touch, tactile touchscreens are gaining prominence thanks to their intuitive design, natural feedback, software flexibility, and cost and space savings, whether on portable or stationary devices.

Property sensing. Current studies have started to add mechanical oscillations about a fixed reference point to produce the feeling of vibration or friction on the smooth surface of the touchscreen. The intention of this is to let users receive confirmation of the successful activation of an on-screen object. If touchscreens were able to produce real object characteristics (such as texture, hardness and roughness) by haptic emulation of the objects concerned, this would mean an improvement in usability that would dramatically increase the potential range of touchscreen applications.

Directness. Like the conventional touchscreen, the tactile touchscreen, as a direct-interaction interface, unites input, output and display in one device. The manipulation of on-screen UI controls is in many ways analogous to touching real-world controls. The execution of interaction tasks with a tactile touchscreen is direct, intuitive and natural. There is very little delay between initiation and accomplishment.

Elementary interaction tasks of tactile touchscreens

The choice of an interaction technology in a certain working environment must be in accordance with user requirements, stating what interaction tasks can best be addressed by what specialized user interface technologies, to enable those tasks to be optimally performed within the constraints of the work environment. Foley et al. [78] identified six types of elemental interaction task for a generic input device:

- *Select* an object by indicating an object from a set of alternatives
- *Text* a symbol sequence by entering symbolic data
- *Position* an object within a defined space in an application by pointing to a screen coordinate
- *Orient* the axes of objects toward one direction within a defined space in an application
- *Path* constructing a continuous series of positions within a defined space in an application

- *Quantify* explicitly a logical entity by specifying an exact numeric value

Current technology has produced tactile touchscreens enabling the manipulation of controls for various compound tasks made up of a series of elemental interaction tasks.

Usability as a hallmark of tactile touchscreen quality

The key factor in the quality of a tactile touchscreen is usability. Nowadays usability, as an important quality aspect informing the design of software as well as hardware, drives the design of tactile touchscreens by focusing on the user's achievement of specified goals with effectiveness, efficiency and satisfaction in a given context of use.

The dialog between the user and the tactile touchscreen is straightforward. The interface displays only the controls and indicators that are relevant to the specific work process in hand. Since tactile touchscreens make manipulation easy and direct, and the interpretation of feedback immediate and natural, users do not have to memorize a complex syntax of tactile effects. Thus the tactile touchscreen can provide an efficient system affording less potential for error and enabling rapid performance of interaction tasks. Card et al. [41] pointed out two basic factors to be borne in mind when evaluating the design of input devices: expressiveness (achieved when the input mechanism conveys exactly and only the intended meaning) and effectiveness (achieved when the input mechanism conveys the intended meaning with felicity, i.e. aptly and pleasingly). Since then, we have developed further criteria by which to evaluate the performance of a user-computer system, including for instance manipulation time, error rate, learning time, task performance, task recall, concentration level, fatigue, and user acceptance. This study develops an interaction concept for a touchscreen incorporating tactile feedback with the aim of increasing usability by leveraging key traits of the human sense of touch.

1.2 Motivation and problem statement

While the number and complexity of applications available on touchscreens is rapidly increasing, interaction between user and screen is still hampered by the limited input and output capabilities of conventional keypads and displays. The touchscreens we generally use possess only smooth and static surfaces which do not recruit the human haptic communication channel. Buxton [40] was the first to observe that graphical touchscreen buttons lack state transitions and thus cannot provide haptic feedback in the same way as real buttons. Without haptics, users have to rely on their visual and auditory channels. The absence of feedback confuses users, as they are not sure whether they have initiated an action or not; it also increases the risk of accidental activation of touch controls. Users thus have to carefully check inputs visually. In particular, such touchscreens raise the problem of whether the user can accurately hit the small controls typically presented on a small screen, because the target controls become occluded by the finger. Though some leading companies have started to leverage the sense of touch through tactile feedback, utilizing such technologies as VibeTonz [@48] and TouchSense [@46] by Immersion Corp. and zTouch from F-Origin [@52], the visual and auditory communication channels are still the ones most often used – and this has been the case for decades.

A computer-driven touchscreen interface incorporating on-screen graphical controls can replace many mechanical controls. These graphical controls are active iconic keys, labeled with commonly available icons, which provide the basic interactions allowing users to manipulate touchscreens. As interest in applying touchscreen techniques grows, a number of questions arise: Do graphical controls perform worse than physical controls? What factors can contribute to the performance of graphical UI controls? How can the mechanical properties of physical controls be simulated using tactile cues in the context of operation? Before answering these questions, there is obviously a need to investigate the mechanical deployment of vibration directions in a touchscreen, with a view to optimizing the usability of tactile feedback: Which vibration direction in a touchscreen prompts the highest tactile sensitivity in users and enables them to feel vibrotactile feedback most effectively?

To summarize an observable trend to date, we can say that touchscreen user interfaces have developed from the original functional and unintuitive systems, equipped only with a touchable surface, to highly natural interactive interfaces involving diverse human communication channels in accordance with human factors and ergonomics principles. By confronting the design challenges that consequently apply to tactile touchscreens, and building on existing research, this study aims to develop an interaction concept for a touchscreen that incorporates human tactile cues to meet user needs in specific usage scenarios, avoiding reliance on visual and auditory interface elements alone. To do this, the key features of the sense of touch must be applied effectively and efficiently.

1.3 Outline of the study

This study starts by reviewing touchscreen development on the one hand and human haptic sensation on the other, focusing on meeting users' needs. Chapter 2 gives an overview of touchscreen development, with the purpose of understanding how touchscreens work, what touchscreens are used for, and which UI controls are typically selected to meet design requirements on touchscreen-enabled displays.

Recent advances in technology now allow us to add haptic feedback to a wide range of software applications running on touchscreens. The glabrous skin at the fingertip, used as the activator for this kind of touchscreen, has very high tactile sensitivity and is most effective for acquiring detailed tactile information [98] [228]. This being so, the functional features of the human hand have to be factored in to guide design and evaluation of effective touchscreens incorporating tactile feedback. Chapter 3 gives an insight into the functions of human haptic sensation and the current development of haptic I/O technologies.

When investigating the quality gained by adding tactile cues into touchscreens, there is a need to compare various sensory modalities available for touchscreen design, such as acoustic and visual cues, with the aim of gaining maximum benefit from the human sensory channels in engineering the user experience on touchscreens. The advantages of using the human tactile communication channel have recently boosted interest in developing tactile touchscreens and their applications.

Based on an analysis of various sensory modalities and a review of related works on tactile touchscreen interfaces, Chapter 4 indicates that the presence of tactile feedback impacts dramatically on the usability of a touchscreen, and further suggests that the design of a platform for tactile touchscreens has to be given specific consideration, with a view to leveraging the human sense of touch to provide the best intuitive tactile effects on touchscreens. An investigation carried out into the perception of vibration directions in touchscreen thus forms the subject of Chapter 5. Drawing on existing studies, Chapter 6 surveys design know-how on tactile stimuli for on-screen UI controls, as the basis for dynamic simulation of mechanical UI controls such as buttons, sliders, knobs and switches. The aim of this work is to find out how tactile cues enhance touchscreens by achieving a quantifiable effect on efficiency and user satisfaction, as well as on reducing error rates.

The findings made in Chapters 5 and 6 then serve as guidance on user-oriented perceptual features to aid in mapping tactile signals to usage scenarios for primary and secondary tasks as described in Chapters 7 and 8. Chapter 9 reconsiders scenario-based application design and further discusses how the results of this study can guide the development of tactile feedback patterns, haptically enhanced UIs and touchscreen applications.

2 Touchscreen technology for interaction design

As early as in 1965, Johnson [123] described a mechanism that could be used for developing a touch display. A significant milestone [36] in touchscreen technology was the "Elograph", an intransparent touch sensor invented in 1971. In 1974, the first true touchscreen was developed by adding a transparent surface to a touch-sensitive graphic digitizer, and sizing it to fit a computer monitor. The touchscreen as a type of display screen has a touch-sensitive transparent panel covering an LCD or CRT monitor. A touchscreen system consists of three components – a sensor panel, a controller and a software driver. To process a user's input, the *sensor panel* and the *controller* sense the touch event and contact location, and the *software driver* then transmits the touch coordinates to the computer's operating system. Touchscreens can exploit both the precision of a stylus and the simplicity of fingertip operation. A stylus is often used to press the small on-screen controls typical of a small screen. Fingertip solutions, because they afford direct contact with objects on the screen without the need for an extra input control device, have become widely popular on touchscreens of all sizes, even on the small screens of handheld devices. This chapter starts out by describing the point-and-select interface of a touchscreen system and the technical solutions commonly used for touchscreens, to serve as a basis guiding interaction design for touchscreen applications.

2.1 Typical touchscreen systems

In the three-state model described by Buxton [38], touchscreens work using two events – contact and release. In state 0, the finger is out of the physical tracking range, as shown in Figure 1. The system doesn't know what is being pointed at until the finger comes into contact with it. When the user presses on the touchscreen, an on-screen object is selected (state 2).

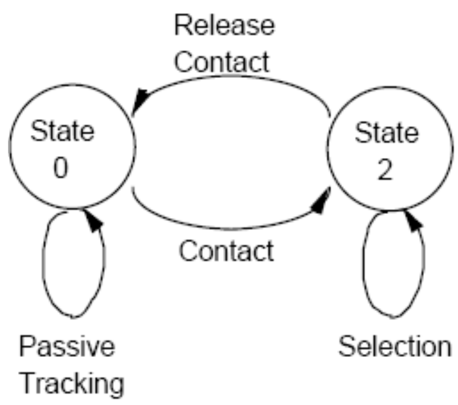


Figure 1: State diagram of touchscreen [38]

As one two-dimensional, directly operated position-sensitive device [39], a touchscreen can be used in all systems where only pointing and selecting tasks need to be performed. When a user points with a finger on a touch-sensitive screen, a selection is made directly from a set of alternatives. Foley et al. [78] stated that a touchscreen allows users to place an object at a particular position, orient the axes of objects toward one direction, define a path and enter values. As an industry mature technology, touchscreen is becoming more versatile, allowing users to perform more than just a simple point-and-select task. The key features of state-of-the art touchscreens that impact on user experience and touchscreen UI design are summarized below.

Pros

- *Direct* pointing to objects offers the most intuitive interaction. There is no intermediate mechanical device and no displacement between input and output, control and feedback, hand action and eye gaze. No physical input device is required prior to making a selection.
- *Fast* access saves time as against maneuvering a mouse to where the user needs it on the screen. Shneiderman [233] identified touchscreens as the fastest pointing devices.
- *Only one surface* between information display and menu choices means that users' control options are reduced. This eliminates learning curves, reduces menu choices and achieves user efficiency and accuracy.
- *Compact* I/O device design saves space by combining display and input space.
- *Ease of cleaning* makes touchscreens good for use in locations where hygiene is important.
- *Ease of learning* and *ease of use* make touchscreens especially suitable for untrained users.

Cons

- *False activation* can be caused by accidental touch. Depending on user pressure and touch sensitivity, a touch might not be accepted or might be double-responded.
- *Contaminants* can reduce the sensitivity of a touchscreen. The screen can also get dirty from fingerprints, making screen content unreadable.
- *Size limitations* are imposed on touch controls by the size of the human finger. Screen controls have to have a minimum size, because the human finger can be too large to point to small objects accurately.
- *Discrete positioning* is inherent to touchscreens as a means of performing discrete serial actions such as typing data – meaning that positioning of the finger is done only after the positional information defining the target has been received. Thus, the user has to lift the finger to reposition for the next input. Repetitive operations such as entering text and numerals may slow down interaction between the user and the touchscreen. Hence, the touchscreen is best for pointing at and selecting objects.

With respect to the strengths and weaknesses of touchscreens, they are best suited to applications which require little or no training, no absolutely accurate positioning, and short textual and numerical data entry. Nowadays, they are often found in situations where intermediate devices (such as keyboards, mice or styluses) can get damaged, lost or stolen, or where reliability is critical because of frequent use. Because there are no physical buttons, knobs or sliders used, touchscreens are especially practical for simplifying pointing tasks in environments subject to vibration or motion such as factories and cockpits. Ease of cleaning and sealing enable touchscreens to be employed in environments where cleanliness is important (e.g. hospitals) or where there is dirt or grease (e.g. factories, restaurants). These properties of touchscreens have made them popular in many applications, as summarized in Table 1.

Area	Application
POI (Point of Information)	Kiosk (advertising, product information) Public information display (city guide, timetable, conference guide, conference message system, museum guide)
POS (Point of Sale)	Restaurant system Retail (cash register) Customer self-service (vending machine, ticket machine, ATM)
Industry	Control panels of machine, remote control
Education / training	Learning system, computer based training
Healthcare	Medical imaging, medical instrument (dentist device)
Labor	Control panels
Consumer market	Telecommunication (PDA, mobile phone, smart phone, laptop, tablet) Household appliance Entertainment (MP3, PMP, Game console) Advanced driver assistance system (satellite navigation device)

Table 1: Area of touchscreen by application

2.2 Technical solutions for touchscreens

When the finger or stylus touches a specific location in an image displayed on a touchscreen, screen-mounted sensors send signals to electronic circuitry which calculates pairs of coordinates suitable for processing by the computer. In this way a touchscreen input is accomplished. Various technical solutions for touchscreen input are available nowadays.

2.2.1 Specific design for interaction technique

The width of the fingertip limits the size of targets on a finger-controlled touchscreen. It is difficult to point precisely at a small target of one or two pixels. Thus, precision mapping of the finger action to the desired target is achieved by various interaction techniques.

Pointing strategy. Potter et al. [200] evaluated three kinds of pointing strategies – land-on, first-contact and take-off. *Land-on* is the simplest strategy that registers only the position of the initial touch. A selection is made as long as a target exists under the initial touch. The *first-contact* strategy refines the *land-on* strategy by allowing users to drag their finger to the target with which the first contact is made. In the *take-off* strategy, the target is selected by removing the finger from the screen. In fact, this strategy employs a *last-contact* technique. The *take-off* strategy produced the fewest errors by a significant margin. Meanwhile, other researches [200] [223] revealed that the *take-off* strategy with a cursor placed ½ inch above the fingertip was less error-prone but slower than the *land-on* strategy.

Other methods employed for precision pointing on touchscreens are the use of physical *cross-keys* to adjust the cursor position pixel by pixel, a graphical *precision handle* technique to amplify the movement precision of the user's fingertip, and a z*oom-pointing* strategy to enlarge the information space to a scale in which one can comfortably point to a target with a bare finger. Albinsson und Zhai [5] discussed the selection of an interaction technique to accomplish different pointing tasks: "When the targets are smaller than a finger width but not at the pixel level, users may select *Take-Off* as their tool. For pixel level precision pointing, *Precision-Handle* shows promising attributes considering speed, accuracy and comfort. Discrete-tapping based *Cross-Keys* is likely to be very exact, suitable for the finest adjustments. When maintaining a complete view is not important, *Zoom-Pointing* can be the best choice."

Some complex strategies are required to provide additional confirmation to prevent accidental activation. For example [224], a *land-on/lift-off* strategy hits the same target when either *land-on* or *lift-off* alone is not adequate. A sequential-touch strategy requires a sequence of touches, the second touch acting as a confirmation.

Scrolling strategy. In the absence of peripheral input devices such as mice and keyboards, scrolling is usually employed to make a selection from within a range of values in the limited physical area of a touchscreen. Scrolling can be performed on a touchscreen by making one continuous movement along a single axis, for example dragging a scrollbar image displayed on a screen. Sometimes repetitive touches on the screen are required to scroll an on-screen object. Comparing the performance of a touchpad scroll zone, a touchpad scroll ring and a mouse scroll wheel, Wherry [272] found that the touchpad scroll ring allows quick and accurate performance of continuous circular movement. Both the touch scroll zone and the touch scroll ring can be implemented on a touchscreen. Because it becomes increasingly difficult to control the touch scroll zone over small distance, the touch scroll ring provides significantly better performance in scrolling tasks. Moscovich and Hughes [177] implemented this kind of touch scroll ring technique to navigate documents.

Navigation strategy. Regarding the manipulation of spatial input devices, Beard and Walker [13] divided navigation into cognitive and mechanical elements - "the cognitive element of navigation is the basic information about the current location of focus and where other areas are located that users carry in memory. The mechanical element of navigation is the use of motor skills to move the user's focus of attention." Partridge et al. [191] summarized existing navigation techniques into five groups: *time-multiplexing, space-multiplexing, proxy-based, WinHop* and *multiscale zoom techniques*. *Time-multiplexing* navigation techniques, such as scrolling, panning and zooming, let users view different regions of a workspace at a series of time points. *Space-multiplexing* navigation techniques allow users to view multiple regions of a workspace. *Proxy-based* techniques have been designed mostly for large screens to "bring representations of distant objects closer to the user's interaction space." *WinHop* techniques allow users to "explore the distant region without actually leaving their current location" using "a space-multiplexing inset window". *Multiscale zoom* techniques combine different zoom functions for maintaining spatial relationships between targets and even retaining object details in the zoomed-out view.

On the basis of the functional solution providing the navigating experience, navigation strategies can be further distinguished into three types: *physical navigation* uses the human finger to move the pointing device to a target object; *logical navigation* uses dialog techniques such as function keys, soft keys, wheels, trackballs, form-based input, prompting and menus for direct manipulation; *local navigation* navigates one element within an object, such as moving one item in a data list (cf. VDI/VDE 3850-3 [252], P.4).

Crossing selection. In a crossing interface [79], an action occurs when the user moves a pointer across a boundary instead of when the user taps within a target. As an alternative to pointing-and-clicking techniques, this solution can be applied not only to finger-controlled touchscreens but also to pen-based computing. Apitz and Guimbretiere [8] suggested using a crossing selection in which there is a fluid transition from one action to another, e.g. selection from a hierarchical menu is supported by the interaction between *target distance* and *continuity of contact*. For targets that are close together, crossing continuously through them may result in fewer selection events than for targets that are farther apart.

2.2.2 Functional characteristics of touchscreen technology

A number of newly invented touchscreen technologies have emerged in recent years because of the high growth of the touchscreen market [@25] [@41]. All touchscreens encode the absolute touch location into corresponding X/Y coordinates rather than the relative position pointed to by a mouse. On the basis of the interaction mechanism through which the user controls the pickup of information by touch, touchscreens can be classified into two major groups: active digitizer and passive touch. An active digitizer, typically used in tablet PCs, requires a dedicated digital stylus to transmit signals constantly from the stylus to the display indicating where the stylus is. A passive touchscreen may make the cursor jump by accidental activation, since most technologies being commonly used in passive touchscreens employ multilayer overlays using electrical resistance, capacitance, acoustic waves, infrared beams or mechanical force.

Resistive touchscreens [@1] are pressure-sensitive. They are constructed from two transparent layers coated with a conductive material stacked on top of each other. In response to the user exerting pressure on the screen, an electrical circuit is formed with the substrate to indicate where the touch is occurring. Four-, five-, seven- and eight-wire designs are usually available for sensing the position of the pressure, depending on the number of wires leading from the touch-screen to the controller. When four wires are used, the contacts are placed on the left, right, top, and bottom sides. When five wires are used, the contacts are placed in the corners and on one plate. Based on the four-wire touchscreen, an eight-wire touchscreen adds sense wires to the end of each of the conductive bars. The seven-wire variation adds two sense lines, as with the eight-wire design, to decrease drift due to environmental changes.

Capacitive touchscreens [@44] coupling between a conductive surface and the user's finger draw a tiny amount of current from the surface. Even before a conductor (such as a bare finger or other conductive stylus) actually makes contact with the touchscreen, capacitance changes that are produced by the action of pointing near the screen may determinate the touch location. *Analog capacitive* (or *surface capacitive*) and *projected capacitive* touchscreens are two main capacitive variations. In *surface capacitive* touchscreens [@21], electrodes at the corners distribute a low voltage across the conductive layer, creating a uniform electric field. The ratio of the corner currents caused by touch is measured to determine touch location. *Projected capacitive* touchscreen uses a sensor grid installed between two glass layers. The touch location is calculated from the changing electrical characteristics of the sensor grid. The grid enables two-finger or even multi-finger touching. Based on capacitive technology, *near field imaging* (NFI) [@27] [@43] employs a patterned coating of transparent metal oxide between two laminated glass layers. An AC signal is applied to the patterned conductive coating, creating an electrostatic field on the surface of the screen. When a conductor comes into contact with the sensor, the electrostatic field is disturbed.

Acoustic wave technology employs ultrasonic waves that travel along the surface of a screen panel; techniques include the *surface acoustic wave* (SAW) and *guided acoustic wave* (GAW) technologies. When a finger or stylus comes into contact with the touchscreen, the wave is interfered with or absorbed. This change in the ultrasonic waves determines the coordinates of the touch event and this information is then sent to the controller for processing. Whereas the SAW touchscreen utilizes waves that travel across the surface of the glass, the GAW solution uses waves that travel through the glass.

Infrared (IR) touchscreens are activated before the touchscreen is actually contacted. This solution works on a similar principle to that of acoustic wave technology, but relies on a grid of invisible vertical and horizontal beams of infrared light that detect the interruption over the screen surface. Because of very high light transmittance in this touchscreen solution, an IR touchscreen requires minimal pressure to activate, but can be easily interfered with by surface contaminants and ambient light. For example, if a surface contaminant is thick enough to intrude into the optical grid, the IR touchscreen may deliver wrong information on the position of a touch event to the controller for processing. In comparison to the IR touchscreen, **optical imag-**

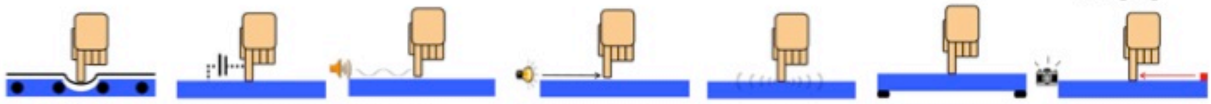
ing technology [@30] [@31] utilizes image sensors (such as cameras) placed at the corners of the screen panel to track any object close to the panel when detecting the interruption of infrared backlights traveling over the surface of the touch panel. Each pair of image sensors identifies the location and measures the size of the touching object by registering it in the form of shadows.

Bending wave technology measures detected mechanical vibrations (bending waves) within the glass substrate that occur due to a touch; techniques include *acoustic pulse recognition* (APR) and *dispersive signal technology (*DST). Electronic signals interpreted from the mechanical vibrations are encoded to calculate touch locations. In contrast to the transducers used for both sending and receiving waves in surface wave technologies, the piezoelectric transducers used in APR technology [@4] convert the acoustic waves generated by a touch to an electronic signal. This signal is then matched with a prerecorded acoustic profile to identify the position of the touch. The DST solution [@18] detects passively the mechanical vibrations created by a touch on the screen surface. The touch location is then calculated using complex algorithms.

Strain gauges mounted on the four corners of a touchscreen to measure pressure along the Z axis and sense position along the X and Y axes constitute a further kind of touchscreen solution. When a user presses the touchscreen, transducers such as piezoelectric sensors calculate the forced applied, and output voltages caused by pressure on the strain gauges are encoded into the appropriate X/Y coordinates defining the touch location.

Each touchscreen technology features certain attributes that impact on usability in a particular environment. Key attributes such as activation type, image clarity, touch accuracy, calibration drift, response time and contaminant resistance have to be taken into consideration when selecting a touchscreen solution to meet product design requirements. Table 2 provides a detailed comparison of key characteristics and specifications among seven mainstream technologies with regard to what challenges are involved with each touchscreen solution and what touchscreen technology types are most competitive.

Recently touchscreen designers and developers have introduced touchscreen technologies incorporating multi-touch capabilities to simultaneously recognize two or more touch positions. Some multi-touch display techniques can be integrated into any touchscreen solution. Some of them need additional sensors to help triangulate simultaneous inputs [36].



	Resistive	Capacitive	Acoustic Wave	IR	Bending Wave	Strain Gauge	Optical Imaging
Pro	• activated with any stylus • low cost • low power consumption	• high durability • high image clarity and touch accuracy	• very high image clarity • high durability – all glass panel	• highest light transmittance • activated with any non-transparent object • one time factory calibration	• very high image clarity and touch accuracy • activated with any stylus • one time factory calibration	• very high image clarity • activated with any stylus	• highest light transmittance • activated with any stylus • very high touch accuracy • one time factory calibration
Con	• reduced optical clarity • periodic recalibration • damaged by sharp objects	• requires bare finger or conductive stylus • periodic calibration	• not completely sealable • interfered with by contaminants • cannot work with hard-tip stylus	• lower touch resolution (limited by number of LEDs) • interfered with by contaminants and ambient light	• has not been proven for reliability, durability and usability • false activation by noise	• has not been proven for reliability, durability and usability	• interfered with by contaminants

Table 2: Comparison touchscreen technology

2.3 Basic considerations for designing touchscreens

Because the human finger is used as a direct pointing device in touchscreen applications, a touchscreen user interface is different from an indirectly controlled UI (such as a mouse-controlled UI) due to limitations imposed by physical constraints. For example, it is difficult to point at graphical targets that are smaller than finger width (e.g. when selecting a 1 or 2 pixel target) because of the "low resolution" of the fingertip [5] [223]. The usability of a touchscreen, as reflected by its ability to accommodate users' personalized requirements and to provide a solution offering distinctive features, is always key to influencing a user's perception of touchscreen quality. Several studies [273] [195] have surveyed conditions that may affect pointing accuracy when using touchscreens. Meanwhile, a number of guidelines provide touchscreen-specific design principles to assist in striking a balance between functional richness and user-focused design, resulting in joy of ownership and use of touchscreen systems. For instance, the Association of German Engineers and the Association for Electrical, Electronic & Information Technologies together [252] presented fundamental rules for user-friendly design of finger-operated touchscreens. The Interaction Design Guide for Touchscreen Applications [@23] offered recommendations for finger-controlled touchscreen applications. Touchscreens generally involve special positioning requirements due to ergonomic considerations.

Screen placement. A touchscreen should be set up to allow the user a good view of the display, and to prevent arm or neck fatigue as well. Depending on the users' location relative to the graphical target displayed on the screen, touch biases that are introduced by parallax lead to consistent discrepancies between the locations where users want to touch and where they actually touch [19] [195] [223]. Parallax caused by the distance either between the touch surface and the display or between the user and the touch surface [195] [274] is a challenge for designing touchscreen-based applications. Many studies addressing this issue [17] [19] [252] have therefore recommended that the screen be mounted perpendicularly to the user's line of sight since this results in diminished touch bias, as shown in Figure 2 (a).

Another ergonomic aspect of touchscreen placement that needs to be considered is whether the angle of inclination can cause arm or neck fatigue. Touchscreens are not recommended for tasks that require holding the arm up to the screen frequently or for long periods of time. It is usually suggested that a touchscreen be positioned in the lower region accessible to the user's hand in order to reduce arm fatigue [233], or that it be located as high as at eye level to relieve neck strain (see Figure 2 (a)). A screen mounted at a 30–45 degree angle from the horizontal is considered as the best preference achieving the lowest perceived fatigue [2] [221], as shown in Figure 2 (b). When the graphic display of a touch display is

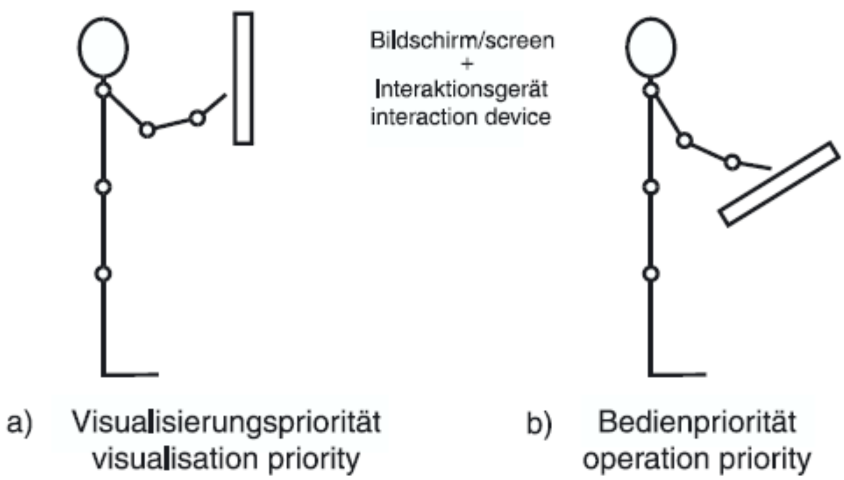
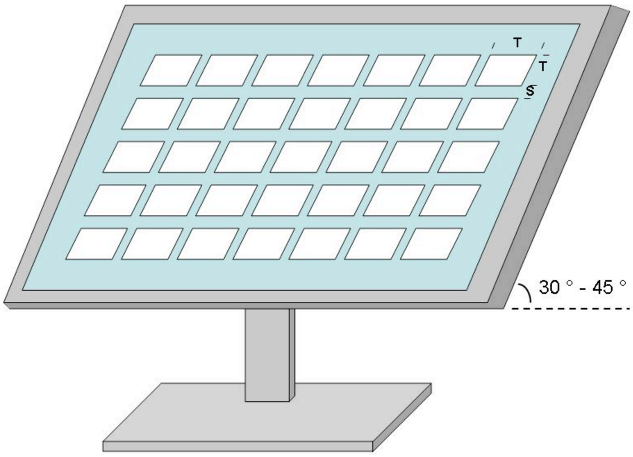


Figure 2: Touchscreen position ([252], p10)

Target size. In view of the low pointing accuracy due to fingertip size and the touch bias caused by parallax, an appropriate target size is required to allow accurate target touches. A number of studies [16] [224] used Fitts' Law to choose target size, and assessed how target selection time was influenced by increasing the target size and by adjusting the space between targets. However, the studies on target size on touchscreen displays came up with different results, as summarized in Table 3. Hall et al. [98] and Pfauth et al. [195] recommended that the minimum key size should be 26 mm per side for a square and 22 mm per side for a rectangle. Sears and his colleagues indicated that the pointing strategy used impacted selection of the target size. They considered that the minimum target size required was about 20 mm per side when using the take-off strategy [223], while the minimum size identified for the land-on strategy was about 22.7 mm per side [221]. Parhi et al. [190] stated that the optimal target sizes for one-handed thumb use of touch-sensitive handheld devices would be at least 9.2 mm for single-target pointing tasks and 9.6 mm for multi-target tasks. Several guidelines have suggested target sizes based on current research. For example, NUREG-0700 [184] states that touchscreen buttons should not be bigger than 38 mm; MIL STD 1472 F [176] stipulates that rectangular screen buttons should have a height of at least 15 mm and a width of at least 25 mm; VDI/VDE 3850-3 [252] specifies that the diameter of circular screen buttons should not be less than 20 mm. In addition, touchscreen technology can impact the selection of target size [287], as shown in Table 4.



	T (target)	S (separation)	Resistance
min	16 mm (1) 15 mm (2) 20 mm (5, 6) 26 mm (3) 15 mm x 25 mm (rectangular buttons (6))	3 mm (1, 2, 5) 5 mm (6)	0.25 N (1, 2) (for alphanumeric keys (5)) 0.97 N (for numeric keys (5))
Preferred	13 mm (1) 22 mm (4) 25 mm (vibrating environments or gloves(5))		
max	20 mm (circular buttons (6)) 38 mm (1) 40 mm (2)	6mm (1, 2)	1.5 N (1, 2) (for alphanumeric keys (5)) 3.89 N (for numeric keys (5))

Table 3: Touchscreen design considerations
((1) [176], (2) [184], (3) [98], (4) [195], (5) [10], (6) [252])

	Height of target	Width of target	Separation	
			Horizontal	Vertical
Resistive	10 mm	20 mm	10 mm	5 or 10 mm
IR	13 mm	19 mm	10 mm	10 mm

Table 4: Target size and separation of touchscreen technologies [287]

Layout of targets. In order to reduce cognitive load, on-screen targets should be presented in a similar way across different displays. Basic functions such as QUIT, BACK and CANCEL should be placed in consistent locations from one screen to the next. As regards touchscreen ergonomics, it is difficult to select targets that are arranged close to the edge of the screen. Moreover, there is a risk that on-screen information may be obstructed by the user's hand and arm while activating a target. Thus, designers of UIs to be displayed on a touchscreen should consider how big the screen will be and what screen area will need to be crossed. The information obstructed by right-handed users is different from that obstructed by left-handed users. Users usually tend to touch the targets that are located toward the sides of the screen and slightly below the center of the screen [287]. Targets arranged at the bottom right of the touchscreen are more suited to a right-handed person, whereas it is comfortable for a left-handed person to touch the targets located at the bottom left. In addition, the targets arranged within one screen need to be as few as possible in number and to have a separation distance between them ranging from 3 mm to 6 mm [176] [184].

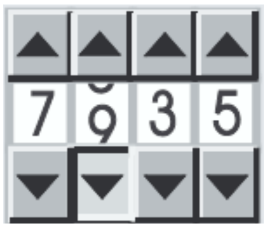
Response time. The touchscreen system needs to respond fast enough to let the user know that the computer has received the input. Touchscreen response time should be less than 100ms [176] [212]. If the system is too slow showing a selection that has been made, this may confuse the user into making an undesired input or delaying the next input. If the response occurs too quickly, users may fail to notice it; in this case, some other form of feedback (e.g. acoustic or haptic feedback) can be used to indicate that the target has been successfully pressed.

Screen resistance. Depending on the touchscreen technology used and the application concerned, force may be required to activate certain touchscreens. Thus, some guidelines stipulate requirements for the force to be applied to touchscreens [10] [176] [184], as shown in Table 3.

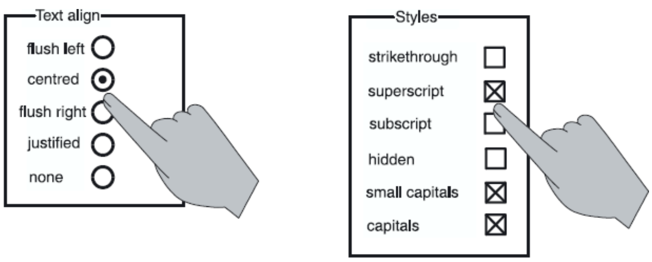
2.4 Controllable dialogue elements for touchscreens

A touchscreen, as a direct-pointing device, is not a mouse substitute and cannot perform all mouse-driven functions. Normal mouse features such as the right button or scroll wheel are missing on the touchscreen. Certain operations such as dragging and double-clicking and the manipulation of certain dialog elements such as dropdowns, scrollbars and multiple windows tend to reduce user comfort and impair efficient performance. Aspects of touchscreen operation such as finger size and arm fatigue due to frequent and lengthy use have to be taken into account when designing controllable dialog elements (or control elements).

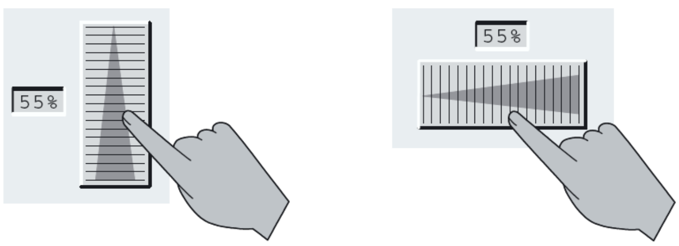
Value input. Touchscreens provide an on-screen virtual keyboard or keypad replacing the physical equivalents to input textual and numerical values. Commonly used keyboards arrangements are the QWERTY layout, an alphabetical variants using keys from A to Z, or a 12-key keypad. As alternatives, character recognition systems such as Graffiti and Unistrokes have been developed for stylus-controlled direct input on handheld devices, while handwriting recognition for finger-controlled input can be employed on any size of touchscreen. Special applications require specific control elements to enhance touchscreen usability. Alphanumerical values can be entered by means of toggle-wheel switches (see Figure 3 (a)) or via an on-screen keyboard. As shown in Figure 3 (b), radio buttons, check boxes and dropdown menus are suitable for entering binary values or for selecting a single value or multiple values from a list. Incrementing or decrementing a value by dragging a slider- or scrollbar-like control element, or by moving along an analog scale, is particularly suitable for input of discrete or continuous values. Sometimes an additional digital indicator is used to display the current value, as in Figure 3 (c).



(a) Numerical input with a toggle-wheel switch ([252], P16)



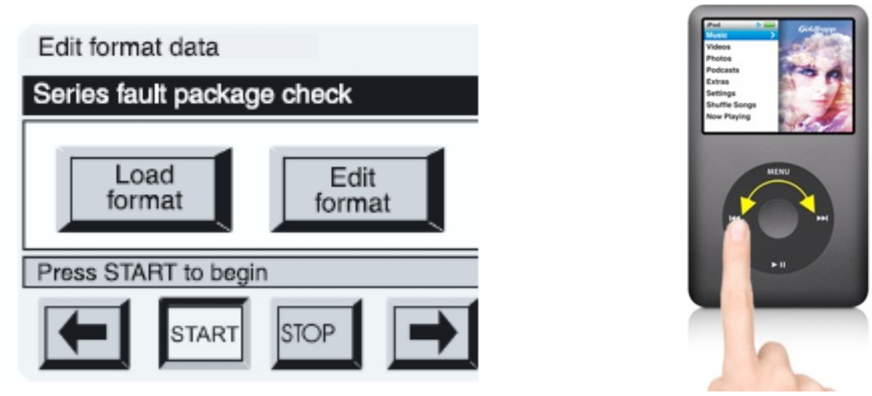
(b) Discrete-value input using radio buttons and check boxes ([252], P. 17)



(c) Analogue input in vertical and horizontal directions ([252], P16)

Figure 3: Virtual control elements for value input

Navigation and selection. The control elements displayed on the screen for navigation tasks are usually designed in the same way as their physical equivalents such as jog wheels or simple buttons indicating directions, as shown in Figure 4. Sometimes, an additional button that can be implemented as either a soft key or a physical key is required for selection tasks. The format and labeling (both textual and graphical) of these control elements must clearly indicate their functional operation to prevent erroneous activation.



(a) (b)

Figure 4: Navigation and selection on a touchscreen (a. Navi-key ([252], P.18); b. iPod scroll wheel)

Hierarchies. Touchscreens are not generally good at presenting hierarchies in response to direct finger input. But because tabs provide easy access to all items on the same hierarchy level, they are often chosen to display items in a two-level hierarchy on touchscreens. When searching for items in a hierarchy, a tree structure comprising expandable nodes can be used on a touchscreen to enable the user to point a path through a multi-level hierarchy.

2.5 Multimodal solutions for touchscreens

Unlike the physical control elements, touchscreens in common use to date are unable to offer haptic or acoustic feedback. Since humans are naturally skilled at performing perceptual and motor tasks, these skills can be exploited in real-time virtual environments integrating multiple communication modalities such as 3D graphics, stereo sound and haptic feedback. The interaction component of a state-of-the-art touchscreen user interface is capable of involving multiple sensory channels, i.e. the visual, auditory and haptic channels. For example, when an on-screen button is pressed, users can see a changed 3D effect on the button, hear a computer-synthesized sound and feel a "click".

Graphical display. Touchscreen interfaces in general use to date enable only graphical interaction with the content of the display. Graphical elements not only represent the outlines of targets, but also highlight state changes. Interaction with this kind of interface thus prompts the brain to recognize shape outlines, thereby creating the illusion of realistic, functioning objects on the screen. The states of a target (e.g. selectable, deselectable and even visibly pressure-sensitive) can be conveyed by for example changing the color of the target or shadowing it. Consequently this kind of touchscreen increases the demands made on users' visual attention in comparison with a physical device.

Acoustic solution. Acoustic feedback can assist in reducing the need for visual attention to a touchscreen. It is an appealing alternative for touchscreen when the screen is occluded by a hand or stylus. Acoustic feedback significantly enhances the performance (operating speed) of touch-screen [155]. Different sounds could be used for different functions to replace the need for a visual confirmation for some tasks. Acoustic feedback can be used to warn users in some critical situations, where the users don't need to absolutely rely on the visual attention. However, the environment sound can result in interfering with receiving auditory stimuli and even enhancing cognitive loading on users' auditory attention.

Haptic feedback. The majority of today's touchscreen applications employ the visual modality (2D/3D display) and sometimes the auditory modality (interactive sound). As a further enhancement, haptic feedback has been starting to gain recognition in manipulation-intensive applications on touchscreens. Haptic feedback integrated into a touchscreen can provide information on virtual objects such as contact geometry, smoothness, hardness, weight, inertia and so on, in such a way as to simulate their physical counterparts.

In chapter 4, the sensory solutions used in touchscreens will be further compared in different use environments.

Innovations in touch technology and ergonomic design are enhancing the viewing and touch experience on touchscreens. This chapter has described typical touchscreen systems, summarized the technical solutions commonly used, and analyzed the design considerations and touch scenarios to be applied when designing touchscreen applications. This constitutes an attempt to strike a balance between technical features influencing touchscreen selection, functional richness informing the development of touchscreen solutions, and user-focused considerations driving the design of touch interaction. This dissertation focuses on touchscreens that use the human finger as a direct pointing device. The discussion in this chapter will guide the remainder of this dissertation in selecting touchscreen hardware and developing interaction design in different touch application scenarios.

3 Haptic sensing and control

When designing a touchscreen concept incorporating tactile cues, it is necessary to consider the general background behind such systems. To this end, this chapter reviews past studies relating to haptics. It begins by describing and classifying perception by touch. A review of the literature follows, discussing a significant number of publications concerning haptic interfaces. Finally, haptic technology is surveyed together with its dimensional information, in order to gain a perspective on what it can offer the user. Today, haptics is more than ever a developing multidisciplinary field that is as important to psychology and neuroscience as it is to robotics and virtual reality.

3.1 Principles of haptic operation

The term haptics, which derives from the Greek word *haptikos* meaning *pertaining to the sense of touch (*from *haptesthai* – to *touch* or *contact),* was first introduced by Revesz in 1931 [9]. It refers to one important channel of human sensory information through which the body interprets physical sensations. Today it relates to the science of sensation and manipulation through the touch modality and often to technology that integrates touch sensations into the human-machine interface [45].

The study of perception through touch plays a critical role in the design and construction of haptic interfaces. Zhang and Canny [285] stated that a haptic interaction system needs to include a human operator, a haptic interface (haptic device or haptic display), a graphic display and a programmable environment. The human operator makes physical contact with an active mechanical device by pushing, rotating or some other mechanism. A haptic interface utilizes a haptic rendering technique to provide the human operator with a response in the programmable environment enabling manual exploration and manipulation of objects, which can be presented in a real-time graphic display. Haptic information is intensely interdisciplinary and involves the following domains [21] [76]:

Human haptics refers to the psychophysical and neurophysiological study of the sensory and cognitive capacities (e.g. attention, motivation and learning) relating to the human sense of touch and to physical interaction with the external environment. This knowledge is crucial to the effective design of haptic interfaces. In particular, since people gather haptic information from their surroundings using their hands, the properties of the hand should be considered when designing a new interface.

Machine haptics combines the fields of mechanical and electrical engineering in particular to study artificial touch technologies. It involves the design of mechanical devices which replace or augment the human sense of touch, and includes their configuration, electronics and sensing, and their communications with the computer controller. They share the property of being programmable and can be passive or active. Passive haptic devices were classified into two categories by Hayward et al. [106]: one type having controllable brakes and the other relying on constraints involving velocity. Active devices working with force apply the energy exchanged between a user and the machine as a means of controlling the feedback that is delivered. These active devices in turn fall into two categories – either the actuators act as a source of force (a variable of effort) and then position is measured, or the actuators act as a source of position and then force is measured.

Computer haptics is concerned with developing paradigms, algorithms and software which run on a host computer to control the mechatronic haptic display. These usually combine with computer graphics to model and render virtual objects in a real-time environment.

Multimedia haptics addresses touch-based interaction with multimedia applications and systems using different media forms such as audio and video. The design of interfaces coordinating different types of media may enhance user experience.

Haptic interaction brings the above domains together to accomplish a particular interaction task, as illustrated in Figure 5. Haptic interfaces engage users to communicate by applying forces, vibrations or motions. As a user manipulates the end effector, grip or handle on a haptic device, encoder output is transmitted to an interface controller at very high rates. Here the information is processed to determine the position of the end effector. The position is then sent to the host computer running a supporting software application. If the supporting software determines that a reaction force is required, the host computer sends feedback forces to the device. Actuators (motors within the device) apply these forces based on mathematical models that simulate the desired sensations. For example, when simulating the feel of a rigid wall with a force feedback joystick, motors within the joystick apply forces that simulate the feel of encountering the wall. As the user moves the joystick to penetrate the wall, the motors apply a force that resists the penetration. The farther the user penetrates the wall, the harder the motors push back to force the joystick back to the wall surface. The end result is a sensation that feels like a physical encounter with an obstacle. Human sensory characteristics impose much faster refresh rates for haptic feedback than for visual feedback.

Subsequently, multidisciplinary studies on haptics, involving subjects such as psychophysics, biomechanics, neuroscience, motor control, mathematical modeling and stimulation, and software engineering, supported the development of haptic interface technology.

3.2 The human haptic perception system

It is crucial, especially for the haptic interface designer, to understand how the biomechanical, motor, cognitive and sensory subsystems involved in human haptic sensation work. There is a strong link between these subsystems. Klatzky and Lederman [139] described the processing of human haptic perception as shown in Figure 6. The receptor units in the sensory subsystem, such as cutaneous, thermal and kinesthetic sensors, have a highly developed hierarchy. They respond to different stimuli from the environment by undergoing electrical and biochemical changes. The sensory information that is converted from the environmental stimuli is transmitted by the nervous system to the brain to be further processed. The brain strives toward an interpretation with respect to personal interests, past experiences and goal intrigue. The subsequent motor commands that are sent out by the brain activate muscles, resulting in body motion which in turn updates the sensory information. Human haptic perception carries on this kind of processing loop when exploring and manipulating objects.

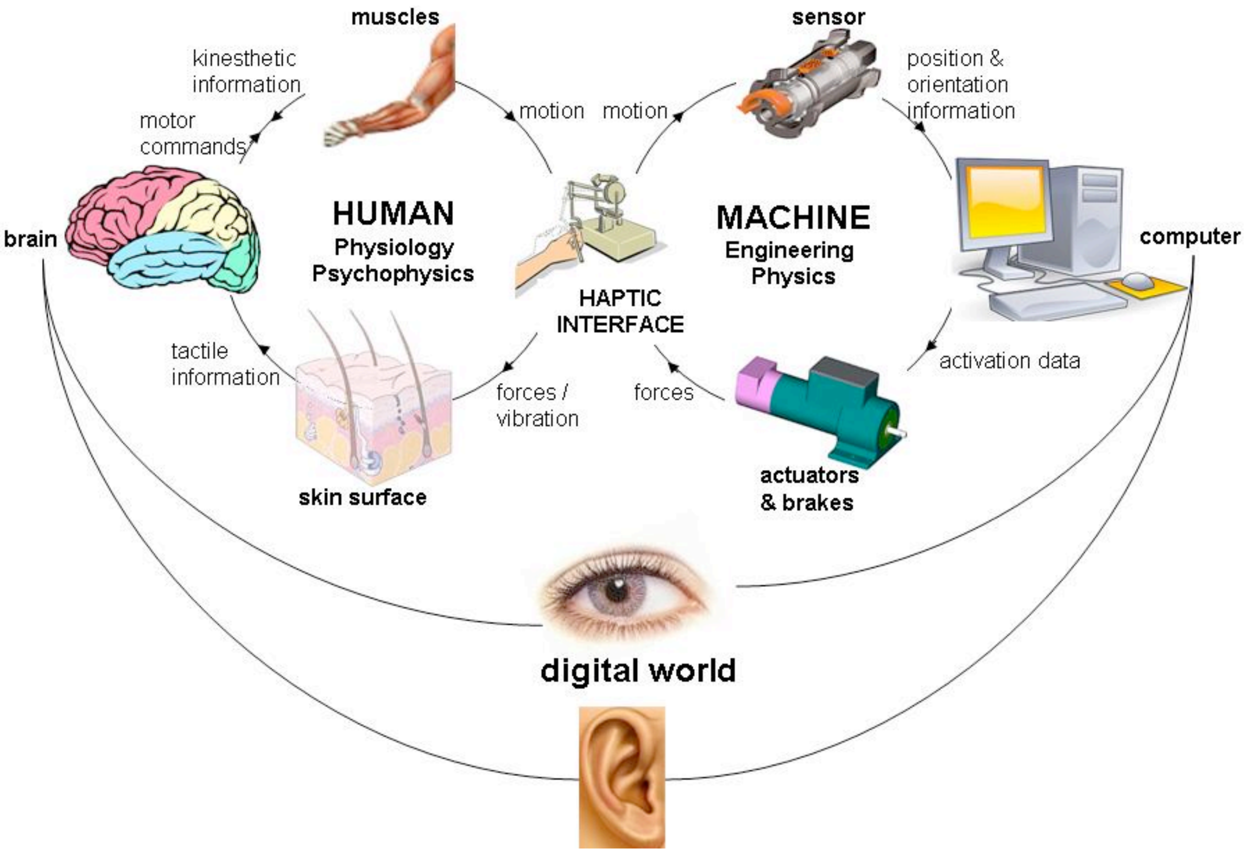


Figure 5: Interaction design of human, machine and haptic interface in physical and digital world[1]

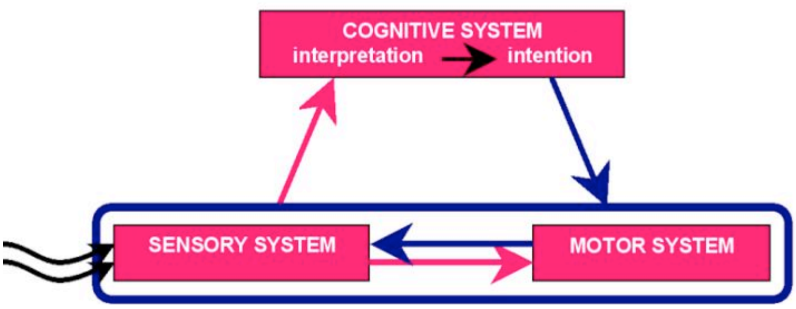


Figure 6: Description of haptic loop [139]

[1] Based on the figure showed in the paper "Human and Machine Haptics" [238].

The haptic sense is differentiated into tactile and kinesthetic stimulations, or a combination of both. Human beings use the tactile and kinesthetic sensory channels to perform manual tasks as part of the activities of daily life. The tactile receptors under the skin surface respond to sensations of light and heavy pressure, weak and intense vibration, low and high temperature and lesser and greater pain. Some motor receptors provide information on movement direction, joint angle and limb position. Haptic perception is the result of the combination of cues provided by tactile and kinesthetic receptors during active manipulation of objects. The cues originating from tactile receptors while stimuli are presented to a stationary observer constitute passive touch. Goldstein [91] integrated the categories of haptic perception in psychophysiology into the "haptic-somatic system", in comparison to the general definition of the "haptic system" or the "tactile-haptic system" [45] [95].

3.2.1 Encoding of human haptic information

The mechanical and physiological characteristics of the sensory receptors of the skin define and constrain the sensitivity of the skin to the environment. The skin is the largest and the heaviest organ of the body. The human subjective sensations of touch designate the ability of the skin and muscles to recognize an object. Two major layers include the epidermis (outer or cuticle) and the dermis (inner or sclera) as shown in Figure 7. The epidermis plays a role in protecting the body. Thus this insensible part "functions as an intermediary, condensing raw sensation into interpretable signals" ([102], P. 88).

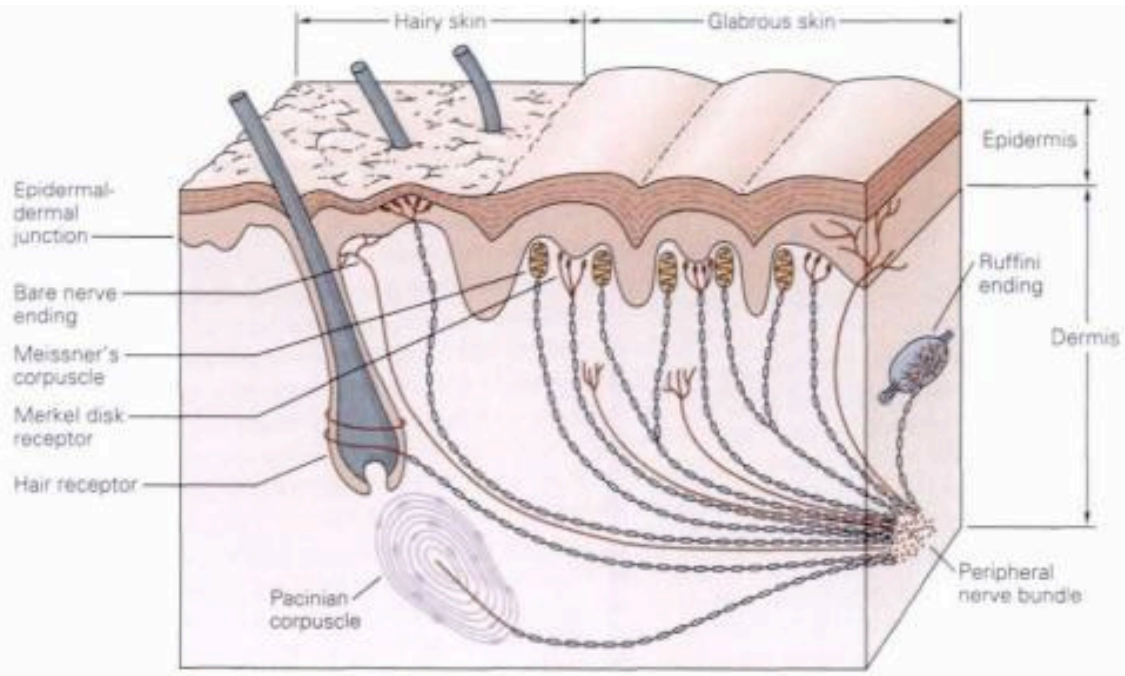


Figure 7: The location and morphology of mechanoreceptors in hairy and hairless (glabrous) skin on the human hand ([132], P. 433)

Structural and functional characteristics Various types of sensory receptors determine different aspects of how impulses are perceived through the skin. The location and depth of receptors within the skin affect how an impulse acts on them. These receptors are classified by function and include *mechanoreceptors* which respond to mechanical deformation to recognize the size, shape, and texture of objects and their movement across the skin, *thermoreceptors* which receive information on changes in skin temperature, and *nocioreceptors* which are responsible for pain or itching. The mechanoreceptors either discharge ongoing stimulation slowly (slow-adapting, SA) or respond to steady stimulation rapidly in order to detect velocity, acceleration or jerk-sensations (rapid-adapting, RA). Depending on the size of the receptive field, SA and RA units can be further classified into Type I (small) and Type II (large). Glabrous skin and hairy skin have different mechanoreceptors. Major types of mechanoreceptors include Merkel's disks, Meissner's corpuscles, Ruffini endings und Pacinian corpuscles (named after their discoverers [55]). Hairy skin has an additional type of receptor, namely the hair-root plexus (or follicle) that detects movement on the surface of the skin [34]. Merkel's disks, Meissner's corpuscles and Ruffini endings are located in the upper regions of the dermis, whereas Pacinian corpuscles lie deep in the dermis and fatty tissues. Free nerve endings serve as pain receptors that are present throughout the body.

Features	Skin mechanoreceptors			
	Merkel's disks	Ruffini endings	Meissner's corpuscles	Pacinian corpuscles
Location	Superficial Dermis (Shallow)	Basal Epidermis (Shallow)	Dermis and Subcutaneous (Deep)	Dermis and Subcutaneous (Deep)
Channel type	Nonpacinian III	Nonpacinian II	Nonpacinian I	Pacinian
Adaptation rate	Slow adapting I (SA-I)	Slow adapting II (SA-II)	Rapid adapting I (RA-I)	Rapid adapting II (RA-II)
Frequency range	0,3 – 3 Hz	15 – 400 Hz	3 – 40 Hz Vibration <~ 80Hz	500 Hz – 1000Hz Vibration ~40 – 500Hz
Function	Sustained Pressure	Skin stretch / movement of joint	Velocity, Tap	High frequency vibration
Receptive field size	Small	Large	Small	Large
sensory distribution in the hand	25%	19%	43%	13%

Table 5: Functional features of skin mechanoreceptors [91] [98] [169]

Table 5 summarizes the functional features of skin mechanoreceptors in terms of location, sensorial adaptability [34], frequency range, functionality, receptive field and density of distribution. *Merkel's disks* (SA-I), disk-like nerve endings, produce a long but irregular discharge rate to respond best to pressure [34]. *Ruffini endings* (SA-II) operate best as detectors of skin stretch and temperature changes, but can also detect the movement of joints. Merkel's disks and Ruffini endings are of the slow adaptation type. *Meissner's corpuscles* (RA-I) have the highest density of the hand receptors and serve as velocity detectors of skin deformation, providing feedback for gripping and grasping functions. They lie just below the epidermis [34]. *Pacinian corpuscle*s (RA-II) are extremely sensitive to acceleration and high-frequency vibration. Meissner's corpuscles and Pacinian corpuscles are categorized as rapid-adapting receptors, which have such a fast rate of impulse decay that in a very short time the stimulus becomes undetected.

Skin sensitivity The sensitivity of the skin to haptic stimuli varies over the body. Sherrick and Craig [228] concluded that, because of the high density of receptors and the large amount of available cortical space responsive to excitation in the frontal facial region and the hands of humans, these regions possess the highest sensitivities, with maximum sensitivity occurring at the fingertips and lip borders. This is consistent with the development of the hand and the finger as the specialized "haptic organs".

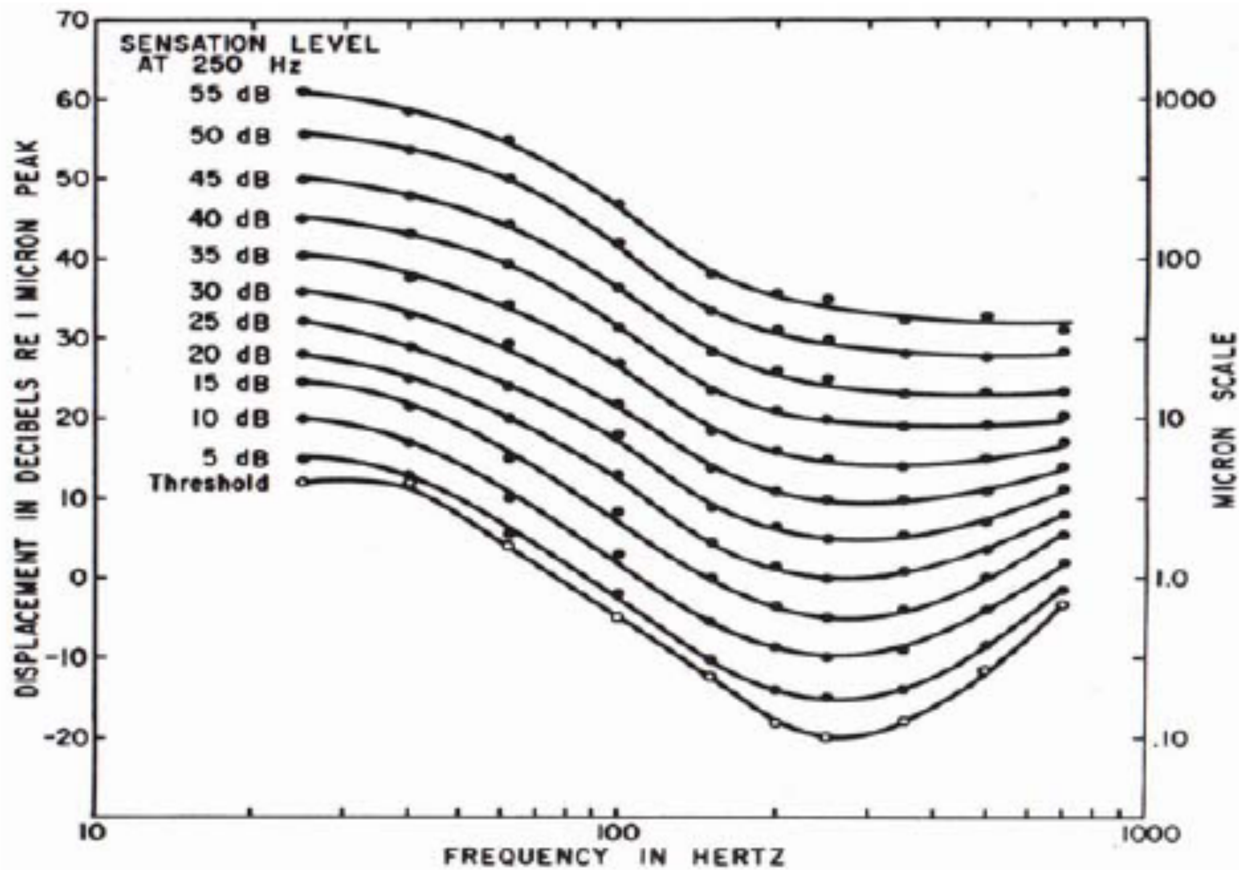


Figure 8: The absolute threshold of mechanical vibration at the fingertip [257]

For the purpose of quantifying haptic sensation, the minimal touch energy detected by the skin determines the so-called *absolute threshold*. A number of studies have measured the absolute threshold for mechanical vibration of the fingertip as a function of frequency [28] [136] [228] [255] [256] [257]. The human haptic system is commonly sensitive to the frequency range of 10 to 1000 Hz. The threshold of sensitivity to vibration varies as a U-shaped curve, with a minimum value at around 250 Hz, as shown in Figure 8. Shrerrick & Craig [228] found that the frequency range of 10 to 50 Hz featured prominently in measurements of the absolute threshold. Kyung et al. [150] measured the best spatial sensitivity in the 1-3 Hz and 18-56 Hz frequency ranges. Burdea [34] noted that absolute threshold values vary from 80 mg on the fingertips to 150 mg on the palm. Depending on vibration frequencies, the threshold of vibrotactile sensitivity on the fingertips is 5 to 10 times greater than the absolute threshold.

Spatiotemporal resolution Human haptic perception can make both spatial and temporal discriminations, unlike the visual and auditory communication channels, which are superior in spatial and temporal adaptation respectively. RA-I receptors (Merkel's disks) are more sensitive than the SA-I receptors (Meissner's corpuscles), but have a poorer spatial resolution. RA-II receptors (Pacinian corpuscles) have essentially no spatial acuity in comparison to the other mechanoreceptors because of their deeper location in the skin. Burdea [34] indicated that the SA-I and RA-I receptors (Meissner's corpuscles and Merkel's disks) in the hand have small receptive fields and provide accurate spatial localization; conversely, the SA-II and RA-II receptors (Pacinian corpiscles and Ruffini endings) have large receptive fields and low spatial localization.

The spatial resolution of the human haptic sensation can be measured by a two-point discrimination threshold, which is the minimum distance between a pair of nearby stimuli that the human being can consistently distinguish. The two-point discrimination threshold for the fingertips is 0.9 mm without any lateral movement [265]. If the stimuli at these two points are located much closer than this threshold, they tend to overlap. Weber defined a mathematical relation between the size of the change in stimulus magnitude and the just noticeable intensity, which came to be called the *Weber ratio*. As the fraction of the *Weber ratio,* the *difference limen* (DL) [34] was determined to be about 0.14 for static pressure and about 0.2 for impulse (tap) stimuli and vibrations. Sherrick and Craig [228] used a so-called *two-point limen* for testing the minimum haptic spatial acuity. The average separation distance of a two-point limen on the fingertip is approximately 2.5 mm, and the spatial localization error is a circle of about 1.5 mm radius.

The temporal sensitivity of the fingertip can be defined by the *successiveness limen* (SL) [34], which is the time threshold needed to detect two consecutive stimuli. When two events are presented to the skin close in time, the human being may feel them as one stimulus. Mechanoreceptors have a relative small SL value of approximately 5 msec; by comparison, the SL value for the eye is 25 msec, and that for the ear is 0.01 msec [34] [55]. Burdea [34] suggested that a time interval of 20 msec is required in order to allow the order of two stimuli to be perceived. However, when the time interval is greater than 150–200 msec, the delay may reduce sensitivity in detecting the second stimulus.

Sensory information Human sensory characteristics and manipulatory abilities obviously play a key role for the design of a good haptic interface. The human haptic sense is multi-functional and encompasses a hierarchy of modular subsystems. Regarding the information the haptic system obtains, Gibson [88] classified human haptic perception into six subsystems of cutaneous touch (stimulation of skin without movement of muscles or joints), haptic touch (stimulation of skin without movement of the joints), dynamic touch (stimulation of the skin plus movement of the joints and the muscles), temperature touch, painful touch, and oriented touch (skin stimulation plus vestibular stimulation). The process of perceiving objects that conveys sensory information to the brain involves somatic feeling via the *cutaneous sensory system* as well as the manipulation of objects through the *kinesthetic sensory system*[2]. The fundamental differences between these two systems are presented in Table 6. The cutaneous sensory system receives and transfers information through receptors innervating the skin and allows surface textures and qualities to be felt. The means of stimulation include pressure, vibration, heat, cold, smoothness, or pain. The state of the arms and the movement of the limbs are addressed by the kinesthetic sense. The kinesthetic receptors are mostly embedded in the muscle fibers, the tendons and the joints, and provide information on body forces and motions. In much of the literature, this kind of perception is referred to as deep sensibility or proprioception. Robles-De-La-Torre and Hayward [211] reported that the perception of object shape is dominated by force cues.

type / criterion	**cutaneous sense**	**kinesthetic sense**
Stimulus	skin	bodily movements
Mode	passive	passive, active
Receptor	mechanoreceptor, thermo receptor, chemo receptor, nocioreceptor	proprioceptor
Location of receptor	skin	muscle fibers, tendons, joints
Sensibility	Visceral / surface	deep
Sensation	texture, pressure, puncture, roughness, temperature, softness, shape, stretch, wetness, vibration, rigidity	weight, force, hardness, motion, velocity, limb position, inertia
Information	fine grained details of an object	larger scale details of an object
Feedback	tactile feedback	force feedback
Actuator	motor (offset mass-vibrator), electrical simulation, micro-in	electric motors, brakes, pneumatic system, hydraulic system, SMA, piezo crystals, heat pumps

Table 6: Comparison of haptic senses ([129], p.53)

The human haptic system uses both cutaneous and kinesthetic input information gained through conscious manipulation to recognize objects. For example, when a user presses number keys on a phone, the position of the fingers is perceived by kinesthetic sensors. Simultaneously, information on material properties of the keys, such as texture, roughness and rigidity, is obtained through the cutaneous sense. Following this, the information on surfaces, object properties and spatial relations that is sent by the kinesthetic and cutaneous sensors is converted into neural codes to be analyzed by the brain in order to recognize, identify and control the object.

[2] Klatzky and Lederman [141] classified the sensory systems, based on their afferent inputs, as cutaneous, kinesthetic and haptic systems, with the haptic system using combined inputs from both the cutaneous and kinesthetic systems. They identified five different "modes of touch" based on the research of J.J. Gibson: tactile (cutaneous) perception, passive kinesthetic perception, passive haptic perception, active kinesthetic perception and active haptic perception.

3.2.2 The role of movement in haptic perception and haptic exploratory style

A number of studies on touch have stressed the role of movement in haptic perception. In fact, haptic perception depends heavily on successive movements. As early as 1925, Katz [148] stated that the surfaces and shapes of objects and the distances between them can be perceived, recognized and distinguished only through movement. Appelle [9] concluded that, to understand haptic perception of geometric properties such as extent, orientation, curvature and proportion, it is important to examine the information obtained through movements in terms of the path taken by the fingertips. A number of geometrical illusions are subject to the kind of haptic inspection used [29] [69] [81] [275]. What is called haptic illusion arises when the brain fails to take account of the relative motion and pressure that humans perceive between the fingertips and objects that are in contact with them.

Revesz and Gibson were deemed – like Katz – to be pioneers in their influence on modern haptic research. According to Revesz [208], dynamic touch with a moving hand tends to understand object form and material while static touch detects thermal properties. He distinguished simultaneous touch (involving inspection of a form and its parts in a single act) from successive touch (occurring whenever an object or its parts are touched in separate acts distributed over time) [9]. The distinction between active and passive touch was drawn by Gibson [87] [88] to explain how the perceiver controls the pickup of information by touching[3]. Active touch allows the perceiver to explore objects via actively controlled movement, whereas passive touch is imposed on the perceiver by some outside agency. Based on Gibson's mechanism of perceiving objects, Loomis and Lederman [163] divided touch modes into five categories: tactile, active and passive kinesthetic, and active and passive haptic perceptions. Passively guided and actively controlled movements have been widely discussed as distinguishing factors in the quality of haptic perception. A few studies have compared active and passive exploration of two- and three-dimensional haptic stimuli, but the results are contradictory [87] [107] [108] [168] [210] [244]. Chapman [49] analyzed three factors influencing the results of comparisons: (1) performance in tactile discrimination tasks used by most studies depends on the subject's ability to perceive relative, and not absolute, differences between inputs; (2) performance may be affected by velocity of movement; (3) active touch achieves enhanced performance through voluntary movement.

The manipulation of objects usually has to involve both active and passive touch. Touching itself is a serial exploratory process where a perceptual image is gradually filled in or updated as we touch the environment. Gibson [87] described these exploratory touching movements as feeling, grasping, rubbing, groping, palpating, wielding, and hefting. The human hand, as a versatile organ[4], is the major instrument used to explore and manipulate objects. To understand haptic activity, a number of studies observed the behaviors of perceivers' hands while engaged in haptic

[3] Haywards et al. [106] summarized two kinds of haptic devices: passive and active devices.

[4] Humans use fingers to show emotion, depict ideas, and point to objects, but also to read Braille, speak in sign languages and write poetry. Hands are such incredibly gifted communicators that they always bear watching.

exploration. Napier [181] divided the movements of the human hand into *prehensile movements* (by which an object is seized and held partly or wholly within the compass of the hand), and *non-prehensile movements* (in which no grasping or seizing is involved but by which objects can be manipulated by pushing or lifting motions of the hand as a whole or of the digits individually). Moreover, he differentiated the prehensile movements of the human hand with respect to functional and phylogenetic perspectives: *power grip* (which uses relatively strong muscles to hold an object as in a clamp between the flexed fingers and the palm to provide high stability) and *precision grip* (which uses smaller and weaker finger muscles between the flexor aspects of the fingers and that of the opposing thumb). The technology company Novint has explored a variety of grip types that easily plug into their haptic device Falcon to provide users with more realistic gaming experiences, as shown in Figure 9.

Figure 9: Novint grip types [@29]

In relation to the type of information that associates hand movement pattern and object knowledge, Klatzky and Lederman [139] proposed the term *exploratory procedure* (EP) as a "stereotyped movement pattern having certain characteristics that are invariant and others that are highly typical." Six different EPs of the human hand were proposed [142], as illustrated in Figure 10. They described back and forth "lateral movements" for recognizing texture, perpendicular pressure on an object for apprehending hardness, keeping the hand static on an object for investigating temperature, unsupported holding for measuring weight, enclosure for coding global shape and size (volume), and contour following (i.e. scanning an object part for part with the fingers) for exploring the exact shape.

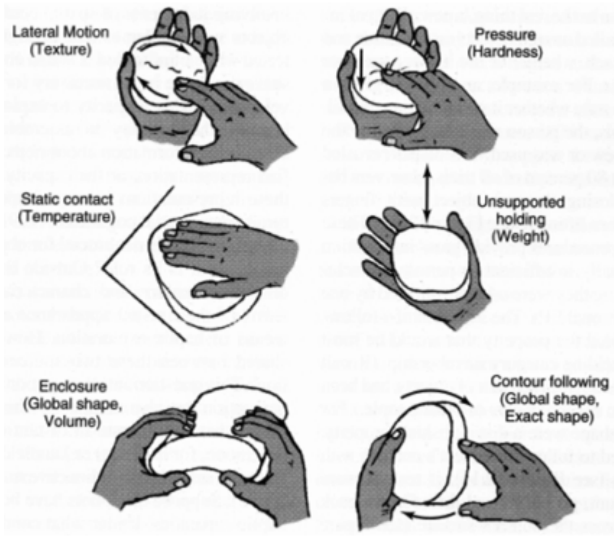


Figure 10: Typical exploratory procedures of the human hand [139]

Knowledge of the characteristics and capabilities of the human skin is essential not only for designing today's conventional haptic interfaces, but also for studying the value of adding tactile properties to touchscreen interfaces and developing haptically enhanced user interfaces within the scope of this dissertation.

3.3 Machine-controlled haptic interface

A machine-controlled haptic interface is a programmable feedback device driven by hardware and software, in which mechanical variables are designed and constructed to generate mechanical signals that stimulate the human kinesthetic and cutaneous sense channels, so as to make specific use of the bi-directional exchange of information between user and machine. Haptic interfaces [21][@38] can be viewed as having two functions: (1) to measure the positions and/or contact forces of any part of the human body and (2) to display contact forces and positions to the user according to their spatial and temporal distributions. The design of haptic interface mechanisms can limit or affect human motor abilities that transmit and receive haptic information.

3.3.1 Haptic tools

Haptic technology allows the user to experience computer-controlled haptic signals through a variety of tools such as gloves, styluses, joysticks and driving wheels. Haptic tools are physically attached to computer-controlled mechanisms that generate the haptic signals.

It is necessary to identify the specific requirements influencing the design of haptic tools, such as the sensing and commanding bandwidth of the human hand, motion range capability and portability. Shimoga [230] found that the sensing and commanding capabilities of the human hand are asymmetric, meaning that tactile and kinesthetic stimuli can be sensed much faster than they can be given in response. The sensing bandwidth of 20–30 Hz for input force signals is much larger than the commanding bandwidth of 5–10 Hz applied to output force commands, while tactile information sensed by human fingers can be up to 10,000 Hz. Kunesch et al. [149] found that rapid hand and finger movements are typically performed at frequencies of 4–7 Hz. The motion range is the range of the tactile stimuli sensed, or the maximum force divided by the haptic interface friction coefficient.

A few research efforts into haptic tools have attempted to achieve optimizations of workspace, portability and stability. The workspace within which a haptic tool can be moved is constrained by the mechanism of the haptic device: a tool can be only moved as far as its mechanism allows. Typical workspaces are three-dimensional, with volumes of the order of 100 cm^3 or larger [94]. One way to distinguish between haptic tools is by their basic locations, for example [73]: (1) body-based or wearable devices, which usually use gloves, suits or exoskeletons that track the position and posture of hand and joint angles measured relative to the mount point or (2) ground-based devices such as force-reflecting joysticks, mice, steering wheels and linkage-based devices, which solidly connect to the "real world" by both sensing certain actions of the hand and providing force reflection or vibration feedback through the desktop. Haptic interfaces usually use desktop or portable special-purpose hardware to provide tactile and force feedback information. Some advanced technologies such as wearable computers, novel actuators and haptic toolkits enhance the practical application of haptic interfaces.

3.3.2 Haptic I/O technology

Current research into haptic technology includes the development of novel technologies for sensors and actuators, the design of computer architectures for fast computation of physical models, and the development of algorithms for real-time control of devices that provide haptic rendering capabilities.

Every haptic interface enables manual touch interactions with real and programmable environments through haptic feedback, namely tactile feedback or force feedback. Tactile feedback interfaces and force feedback interfaces can function as stand-alone solutions, or they can be integrated with other solutions. The quality and appropriateness of the ensuing "feel" may be very important in determining a device's effectiveness and acceptance.

3.3.2.1 Tactile interface technology

Tactile interfaces stimulate the skin's sensory responses to provide the illusion of direct contact with an object, by perturbing the skin through tactile characteristics such as surface texture, roughness and temperature, and are ideally suited to enhancing situational awareness. For instance, Dosher et al. [71] compared smooth versus rough actively-explored icons and found that rough haptic icons are more easily detected by a human subject than smooth icons of the same size. Early tactile interface devices involved sensory substitution to replace vision or audio for users with a sensory impairment. Cheng et al. [50] described an experiment evaluating the effect of vibrotactile sensory substitution on user performance during a grasping task with delicate virtual objects. Wall and Brewster [265] divided tactile interfaces into three categories comprising electro-cutaneous, thermal and mechanical stimulations. Electro-cutaneous tactile stimulations create touch sensation by passing a small electric current through the skin, while mechanical tactile stimulations accomplish this by actively deforming the skin via tactile actuators. Thermal interfaces utilize thermal sensors to induce programmed thermal tactile sensation.

Tactile interfaces can be categorized by stimulus method or by sensor characteristics. Shimoga [231] distinguished five main approaches to generating tactile interaction sensation, namely through visual, pneumatic, vibrotactile, electrotactile and neuromuscular stimulations. He defined that visual stimulations present graphical representations of tactile information, while the neuromuscular stimulation approach provides signals directly to the user's neuromuscular system. By contrast, electrotactile, pneumatic and vibrotactile stimulations all present information directly to the skin, and yield stimuli that are perceivable by the tactile sense. Burdea [34] distinguished tactile sensing technologies with respect to sensor characteristics such as signal linearity, hysteresis, repeatability and range: linear sensors maintain constant sensitivity over the measurement range; hysteresis represents the difference in sensor output in response to input when a sensor is gradually put through a full loading and unloading cycle. When the repeatability of the sensor is high, the measured input value remains accurate.

Tactile interfaces exploit different tactile actuators to produce interaction sensations of friction, vibration, shearing, stretching, pressure, indentation and heat through direct contact with the skin surface. The various mechanical actuation technologies used in tactile interfaces are driven mainly by electromagnets (solenoids or voice coils) [@9] [@12] [@24] [@36] [97] [193], motors [72] [160] [219] [232] [250] [263], piezoelectricity [68] [105] [109] [153] [193] [201] [207] [241] [277], shape memory alloys (SMAs) [180] [245] [253] [268], pneumatic systems [57] [75], rheological fluids [97] [262], capacitive silicon [59] [60] [61] [114] [157] [183] [218] [274], or heat pump systems based on Peltier modules [116] [278] [279]. McGrath [172] classified these tactile actuators into four main types: electro-cutaneous, rotary inertial, linear and pneumatic actuators.

When selecting and optimizing a design for a tactile interface, account has to be taken of several important parameters involved in conveying meaningful sensation information to a user in a controlled environment, such as actuator amplitude range, power consumption, frequency range and human perceptual characteristics. Pasquero [@33] and Benali-Khoudja et al. [15] have given a good overview of existing tactile interfaces. The designed tactile interface needs to be tuned to the human perceptual system. This dissertation focuses on developing vibrotactile stimulation generated by cost-effective electromagnetic actuators to let virtual objects be actively explored by human fingers.

3.3.2.2 Force feedback technology

Force feedback technology works by using mechanical actuators to measure the movement of the effector and transmit forces to the user. Force-sensing objects in the programmable environment provide input for the real-time computation of forces which are then sent to the actuators so that the user feels them simultaneously. The actuator technologies commonly used today are electrical motors [@16] [113] [122] [134] [170] [286], electroactive polymers [11] [@50] [51] [144] [146] [204] [264] [284], hydraulic pistons [162] [198], pneumatic muscles [@6] [@37] [33] [124] [196] [209] [248] [254] and SMA [147] [237] [266] [276]. Other technologies, such as magnetostrictive devices [27] [62] [173], piezoelectric motors [66] [103] [133] [157] [173] and polymeric gels [251] [259], often have unique and desirable features for specific stimulation applications, but are still under development.

The selection of an appropriate actuator is critical to generating an effective haptic interface. There are a number of requirements that need to be taken into consideration: device weight, force output range, system stability, physical location and cost. Burdea [34] reviewed the actuators available for force-transmitting interfaces and ranked them with respect to their power-to-weight ratios (see Figure 11) and mechanical bandwidths (see Figure 12). The power-to-weight ratio measures the strength and lightness of a given actuator. The recommended lowest power-to-weight ratio would be 100 W/kg [34]. Mechanical bandwidth refers to the frequency range of the forces that can be reflected to the user. In principle, small and precise movements require higher-frequency feedback than large and more powerful movements. The need to present a human user with a higher degree of spatial frequency detail has led to the use of physical forces and torques as implemented in force feedback interfaces to convey haptic information to the user.

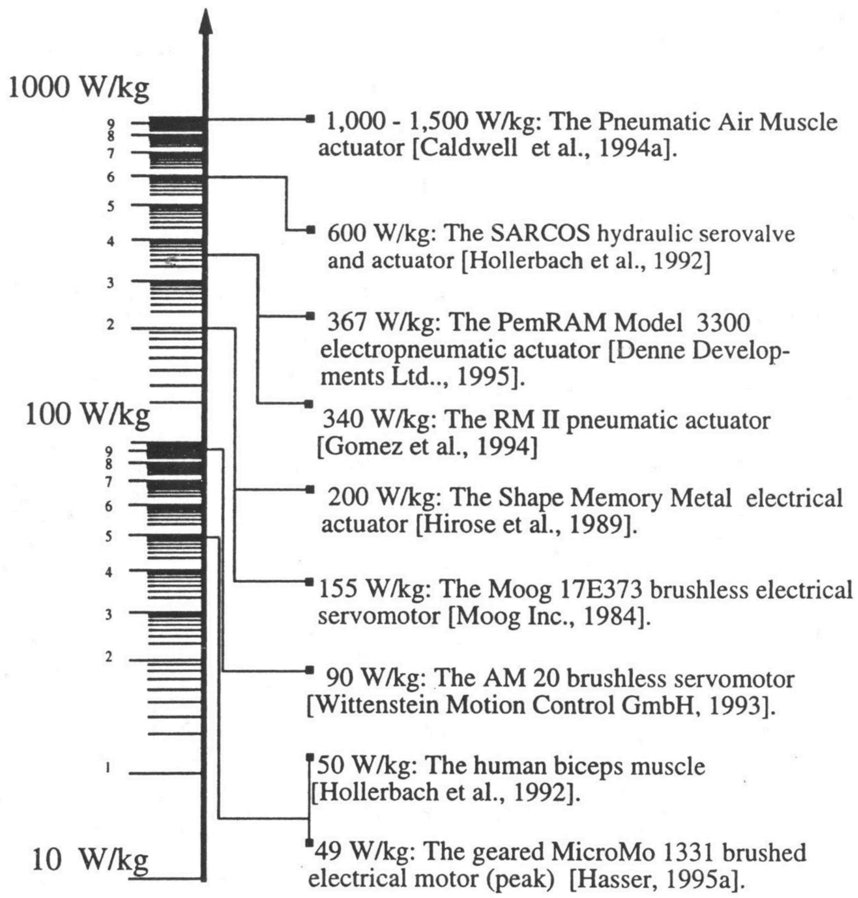


Figure 11: Power-to-weight ratio of haptic feedback actuator ([34], P. 72)

In addition to actuator quality, other key characteristics are also crucial to designing a good force feedback interface serving a specific application, such as the number of degrees of freedom, interface workspace, structural friction and stiffness, and the force exertion capability of the interface.

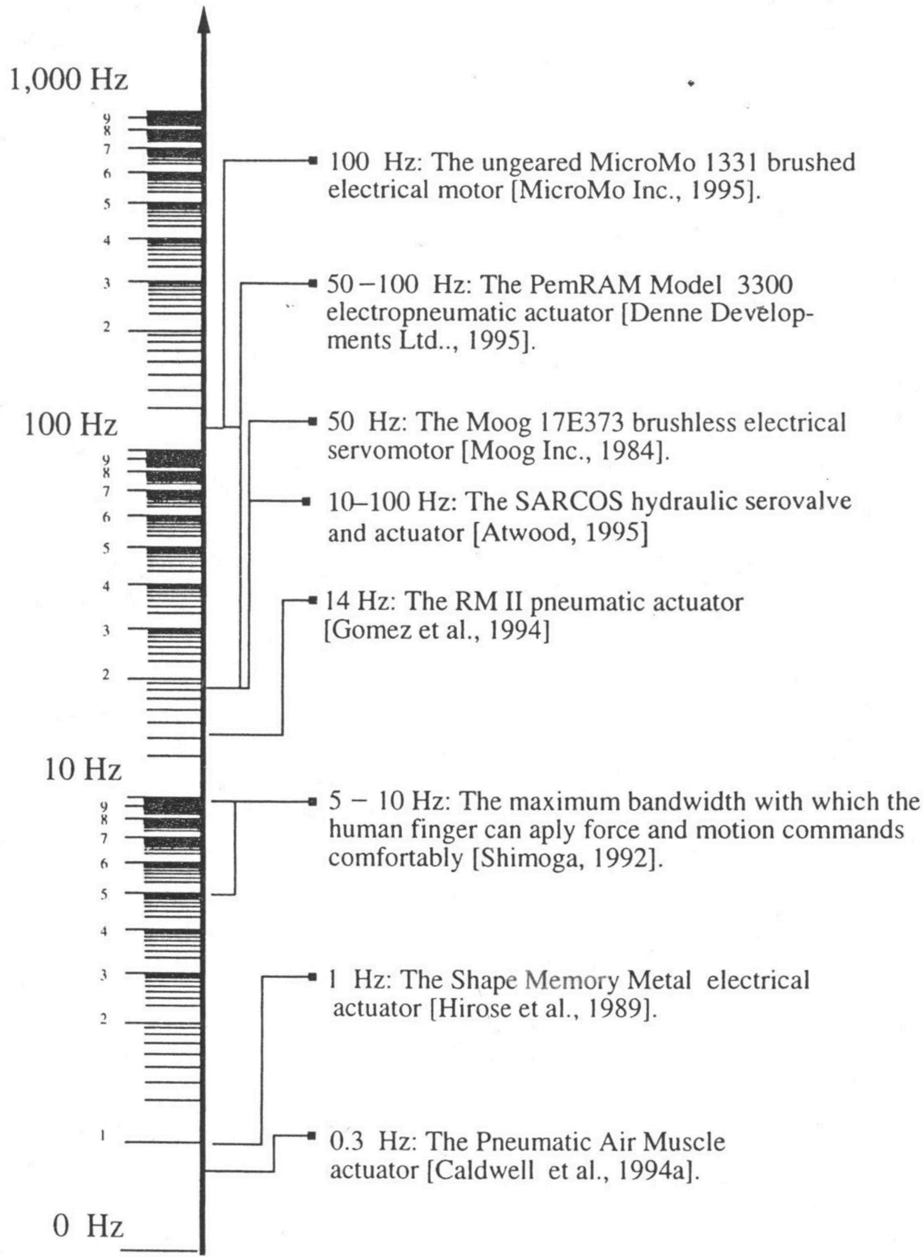


Figure 12: Haptic feedback actuator comparison based on mechanical bandwidth ([34], P. 73)

Force feedback devices can move in varying ways and are therefore often described by the number of independent directions of motion or force present in the device or body interface – this is called DoF (degrees of freedom). A device with multiple DoF simultaneously utilizes dimensions of spatial position and orientation, which can include right-left movement (X axis), up-down movement (Y axis), forward-backward movement (Z axis), roll (rotation about the Z axis), pitch (rotation about the X axis), and yaw (rotation about the Y axis). DoF can refer both to how a device keeps track of position, and to how a device outputs force [46]. For example, a single DoF device utilizes one direction of movement and can thus create an orthogonal force along one actuated axis; while an object with 6 DoF haptic rendering is free to move in three translational and three rotational directions. Cybergrasp [@17] is an exoskeleton device that fits over a 22 DoF CyberGlove (in comparison, a human hand provides 22 DoF with nineteen bones – five in the palm and fourteen in the fingers). The number of DoF is often used as a measure of the quality of the force feedback produced by a given interface.

Force feedback interfaces can be classified into three categories [42] [153] [283]: isometric, elastic and isotonic. An isometric interface offers infinite resistance to measured forces applied by a user and does not move perceptibly. The velocity corresponding to each applied force is computed by the interface. An elastic interface offers varying resistance to applied force; its resistance increases with displacement, until finally the force proportional to its displacement forces the interface to return to a neutral position. An isotonic interface offers zero or constant resistance and works by tracking a user's movement. Unfortunately, a force command that a force feedback interface receives is not the same as the force output that the interface produces and a user in turn feels. Thus, friction loss needs to be low, so that the requisite forces commanded by the computer are not resisted by the interface before the user senses them. The accuracy of force attitude requires the mechanoreceptors to be given precise information about the detention and friction forces between skin and object. Shimoga [230] concluded that the sensitivity of a force feedback interface must be at least 10 times greater than that of the human hand in sensing a force of 0.5 N or a pressure of at least 0.2 N / cm^2.

Force feedback interfaces can take many forms, most commonly that of a robotic manipulator with the ability to exert forces on a human user. There are dozens of studies on force feedback interfaces. Some of these focus on ground-based devices as alternative or supplemental input devices to the mouse, keyboard or joystick, including stylus-based devices like SensAble's Phantom [215] [217], which consists of a small robotic arm with three revolute joints. Other studies investigate body-based exoskeleton devices such as the Rutgers Master II [34] [152], which transmits a 16N force to four fingers finger via a haptic glove. When evaluating these force feedback interfaces, effective interaction with the actuator, the intended influence of the DoF, minimized structural friction and the capability to exert force toward a user are often considered as components of coordination accuracy and operation speed.

3.4 Software-driven computer haptics

Basdogan and Srinivasan [12] defined computer haptics as "concerned with the development of software algorithms that enable a user to touch, feel, and manipulate objects in VEs through a haptic interface". As an important part of a haptic interface, a computational system driving the sensors and actuators generates signals that are relevant to a particular application to provide computer-controlled tactile and kinesthetic feel. In this context, the key component of a haptic interface is the software that generates and calculates in real-time the torque commands needed to simulate physical modeling aspects of virtual haptic feedback and define the features of haptic virtual environments and haptic virtual objects. This software relies on fast computation of haptic collision detection, surface deformation and penetration between virtual models, which requires an update rate of around 1 kHz for stable interactions [12]. Bidirectional, programmable touch interaction involves using human tactile and kinesthetic sensory channels that respond to spatio-temporal distribution of shape, texture and forces on the hand to offer haptic rendering capabilities. The computational task in haptic rendering is usually mapped onto a data processing hierarchy consisting of several computing units and communication channels to convert high-level mathematical models into actual physical forms such as texture and pressure. As proposed by Hayward et al. [106], a model can be developed to represent certain haptic characteristics, which can then be transformed computationally into perceptual and motor stimuli. Thus, a computer-controlled haptic interface involves designing real-time mechanical systems, rendering algorithms and modeling human sensation and user-object interaction.

Computer haptics is usually concerned with haptic properties of objects and surfaces such as geometrical features (size and shape) and material characteristics (hardness, texture, stickiness, weight and curvature). A user moves a haptic interface, which is coupled to virtual objects, while a haptic rendering algorithm detects collisions and computes appropriate collision forces that correspond to haptic geometrical and material properties. A haptic rendering procedure is made up of periodic updates, as shown in Figure 13. When any contact occurs, collision detection algorithms provide the necessary information for calculating appropriate force and position. A response force is computed and converted to an actuation command to drive the actuators using force response algorithms. Control algorithms return the force to the user to achieve the desired haptic effect. And then the state of virtual objects is updated within the context of the haptic interaction.

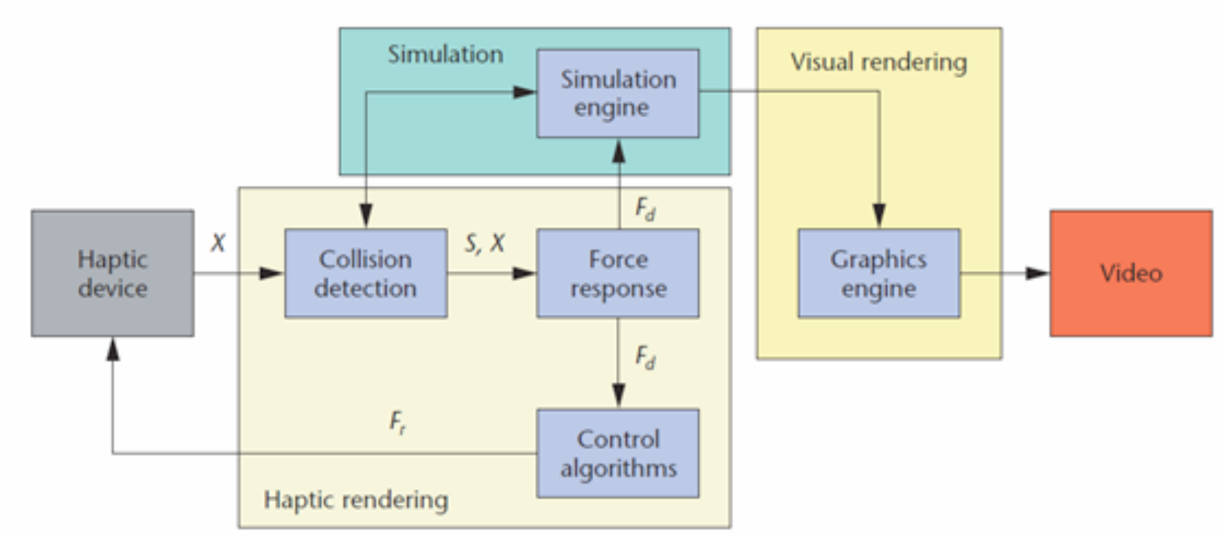


Figure 13: Common procedures in haptic rendering applied to VE [@51]

The human haptic system can be stimulated through haptic interfaces in this computer-controlled manner to enable manual interaction with virtual environments [73] [137] or with teleoperated remote systems [138] [188] [234]. In order to improve usability across a variety of complex interaction tasks on the computer, these computer-controlled haptic interfaces support the performance of real-world exploration and manipulation tasks by receiving motor action commands from touch operation of a tool and by displaying appropriate images back to the user. Therefore, the engineering of a software-generated haptic experience focuses on the development of algorithms and software for creating virtual objects by combining them with different forms of human perception, with the aim of reducing hardware complexity and representing such virtual objects efficiently to the user.

3.5 Collection of dimensional information in haptic exploration

Haptic interfaces measure human hand positions and contact forces applied directly to the skin or the body, but also provide simultaneous feedback to the operator through haptic exploration processing. This kind of processing, which encodes dimensional information present in the haptic interface, can be categorized into three types [140].

One-dimensional linear and circular motion

Single-axis-actuated controls such as scrollbars, mouse wheels, knobs and sliders utilize linear or circular motion to provide a simple means of inputting elements for complex tasks. For example, a physical linear input device SlideBar [52] was designed for a one-dimensional scrolling task with provision of passive haptic feedback. Rotary controls, such as the haptic knob Twiddler [6] and the Haptic Wheel [20] can be programmed with a wide variety of tactile sensations. Different touch effects associated with rotary input, such as detent, barrier, hill and different levels of friction, vibration or force, as shown in Figure 14, can be leveraged to provide further programmable sensations matching the context of use of specific interface controls. These controls concentrate on the adjustment of positions and forces on a single axis.

Two-dimensional rendering on a plane

Haptic interfaces allow users to sense an object's substance (e.g. planar dimensional texture and contour, or three-dimensional size and shape) using a stylus or mouse-type interface to compare value changes along the x and y axes simultaneously, such as a 2D haptic mouse (e.g. Immersion Wingman, Microsoft Sidewinder and Logitech iFeel) [23] [48] [115], a 2D haptic trackball [54] [74] or a joystick [101]. For example, a 2D vibrotactile glyph [22] was designed to describe the position, direction and intensity profile of a visual object. The interface can accurately render a vector force required to provide location information in a defined workspace, for instance to identify the edges of shapes in images [187] [189]. Likewise, a two-dimensional haptic interface is capable of representing a three-dimensional [90] [100] [280] or even a four-dimensional [284] contour or shape.

Figure 14: Haptic effects library for programmable rotary modules [@42]

Three-dimensional free motion

A three-dimensional virtual environment offers an unparalleled repertoire of motions to explore data, thereby enabling some difficult design problems to be solved. The stylus [77] [110], the glove [178], the mouse [42] and finger input [214] [227] are the most common forms of touch input allowing the user to sense and manipulate three-dimensional information associated with a visual object. Complex haptic interfaces can track position and movement in different ways and can provide contact forces in those same directions. For example, a 3 DoF haptic device tracks position and movement in the right-left, forward-backward and up-down Degrees of Freedom, and returns forces in those same DoF. Such a device is usually used to deliver three-dimensional information on an object to allow users to experience complex 3D haptic interaction. Too much freedom of movement, however, becomes inefficient: for instance, using a 15 DoF input device to track 3D information is obviously over-engineered and may be a source of unnecessary errors.

Since humans are naturally skilled at performing perceptual and motor tasks in a three-dimensional space, these skills can be exploited for real-time interaction in a virtual environment, enabling users immersed in a realistic-looking world to immediately sense simulated physical objects with familiar haptic properties such as shape or surface texture. Considering the intricacy involved in a body-based or ground-based haptic interface interacting with virtual objects, a tactile feedback interface that detects vibration and forces directly by finger touch, without the need for any extra handheld device, could reduce complexity of mechanism and provide a space- and cost-effective solution for applying haptic sensation to human interaction. This informs the central idea of this dissertation, which investigates tactile feedback technology with a view to enhancing the usability of haptic applications across a variety of interaction tasks performed using a touchscreen.

4 Improvement of haptic quality in touchscreens

Haptic technology opens up the possibility of making touchscreens feel natural by adding a whole new range of sensory feedback in order to improve the accuracy and efficiency of touchscreen manipulation. The first part of this chapter compares the different modalities of sensory information employed to facilitate interaction with touchscreens, focusing on the visual, auditory and tactile cues. The aim of this is to analyze the limited sensory modalities available for the design of user interfaces, with a view to effectively exploiting feedback via the human sensory channel to maximize usability in manipulating a touchscreen. In addition, a review of related studies is conducted to provide a sound basis for the development of an effective touchscreen incorporating tactile feedback. There then follows a discussion of a number of features conducive to interaction design and usability optimization for tactile touchscreens, based on past studies and various standards.

4.1 Comparison of solutions employing various sensory modalities for touchscreens

A touchscreen system mapping feedback information to various sensory channels - visual, auditory and haptic - can reinforce the original message, but also hinder the right message. This depends on application design and the usage environment.

The visual channel offers most of the sensory feedback required to complete a task via a graphical representation. The interaction between user and touchscreen is usually limited to producing changes in visual appearance. This can lead to a heavy burden on the visual sense, which may even become overloaded. Also, visual cues can sometimes become insufficient in a dark or bright environment.

An alternative to displaying more noticeable visual feedback for touchscreen controls that are likely to be occluded by a hand or stylus is to use an acoustic solution. Auditory stimuli built in to confirm the completion of an operation, or to signal an error, have often been exploited as ancillary cues to improve touchscreen performance, as described in chapter 2.5.2. But acoustic feedback lacks privacy, as it can be misinterpreted by other users or drowned out by environmental sound. In a quiet environment such as an open-cubicle office, audio cues can also be distracting to other users.

Thus, tactile feedback is an appealing alternative in that it provides a private response channel for each user. Klatzky and Lederman [141] proposed that an object’s material properties (roughness, hardness and temperature) are conveyed more effectively by touch, whereas geometric dimensions (size and shape) are better perceptible by vision. This being so, visual stimulations can be used to imply tactile information, indirectly, while neurological stimulation – by means of an appropriate set of devices – can apply electrical stimulation directly to the brain in order to create the illusion of tactile stimuli [185]. However, adequate tactile sensations are not easy to implement since they necessitate modifying the touchscreen or embedding additional tactile transducers.

	Visual	Auditory	Tactile
Pro	Noticeable in a small area	Noticeable all around	A largely private channel for each user in a multi-user or audio-visual distracting environment
Con	Can be occluded by a hand or stylus	Can interfere with other people in a multi-user area; can be impeded in a noisy environment; can cause disturbance in a quiet environment	Can be perceived only by direct contact

Table 7: Comparison of visual, acoustic and tactile modalities for touchscreens

In some environments and situations, one modality alone may not be able to provide satisfactory interaction with a touchscreen user interface. “Environment-impaired” users can benefit from a well-designed application in which the appropriate modalities can be used as desired. In certain situations, the burden on the human visual and auditory systems can grow so heavy that the user is distracted from focusing on the main activity. Examples include a worker operating a control panel in a noisy environment, someone driving a car in heavy traffic or a doctor wearing gloves and working in an antiseptic and visually demanding environment.

In fact, none of these three kinds of sensory modalities is so primitive in terms of interaction that it is subservient to another. Vitense et al. [260] investigated the impact of visual, audio and tactile feedback on user performance. Their results indicated that haptic feedback increased the total task performance time but reduced the target highlight time (i.e. the time that began when initial cursor contacts with target and ended when cursor release), and that audio feedback increased target highlight time. Furthermore, they proposed that haptic feedback and visual feedback used either alone or in combination with each other are more beneficial than audio feedback alone or in any bimodal combination, and that the combination of all three feedback modalities actually reduces user performance. By means of using a combination of modalities (non-speech audio, tactile and pseudo-haptic) for small-target acquisition, Cockburn and Brewster [63] found that the combination of audio and tactile was not as good as when each of them was used alone (reduced targeting time). Popescu et al. [199] stated that “multisensory feedback is not just the sum of visual, auditory and somatic feedback, since there is redundancy and transposition in the human sensorial process.”

The various modalities can be usually merged in such a way as to avoid any one modality becoming overloaded, so that the weaknesses of one modality can be offset by the strengths of another in order to effectively improve usability. A touchscreen can synchronize tactile effects with display and sound changes to create a more engaging, multisensory experience. Consequently, designers of such touchscreens involving multiple perceptual communication information should consider the usage environment and avoid sensorial overload.

4.2 Related research and application on haptic touchscreens

The importance of haptic sensation for touchscreens, in particular those that have only hard and static surfaces, has been generally recognized. Purely visual feedback in touchscreens cannot satisfy the requirements of precise and fast motor control, while acoustic feedback is subject to the constraints of the usage environment. Therefore, quite a few studies have examined the value of adding tactile properties to touchscreens. An understanding of the design of vibrotactile stimuli, of the skin's response to vibrotactile stimulation, and of touchscreen-based UI and widget design is essential to the development of effective touchscreens incorporating tactile feedback. The discussion in this study focuses on vibrotactile sensation in glabrous skin.

4.2.1 Adding tactile feedback to touchscreens

Because of the flat surface of a touchscreen, users cannot be offered a click sensation as if they were operating real mechanical controls. The idea of adding tactile feedback to touchscreens was proposed as early as 2001 [83]. "Active Click" produced a click feeling by supplying a single pulse or a short burst signal via an electric actuator or vibration transducer attached to the housing or the back of the touchscreen. The operation time in a tactile-enabled touch panel can be reduced by about 5% in silent situation and 15% in noisy situation. Other studies have used a small actuator to offer a click feeling, such as an electromagnetic actuator (TouchEngine [203]) and an ultrasonic vibrator [246], tactile-enabled by physical actuators placed directly on the backside of a handheld device. Some handheld touchscreens [151] [154] have been developed which rely on a pen-like haptic stylus to provide tactile feedback while the user is drawing and touching objects on the touchscreen without direct finger manipulation.

Several studies have examined the value of adding tactile properties to touchscreens. Akamatsu et al. [4] found that tactile feedback had a greater effect in reducing highlight time (i.e. the time between initial cursor contact with the target and cursor release) than either audio or visual feedback alone, or any combination of modalities. A number of studies have indicated that the presence of tactile feedback on touchscreens reduces operating time and work errors, thereby enhancing task completion and general usability [25] [79] [83] [112] [201]. Some recent investigations of the effects of tactile properties in touchscreens [25] [112] [158] have revealed that tactile feedback reduces cognitive load, thereby enabling users to pay more visual and auditory attention to multitasking situations. Haptic touchscreen GUI elements provide confirmation of the selection made without any need for visual feedback.

4.2.2 Structured messages delivered by haptic communication

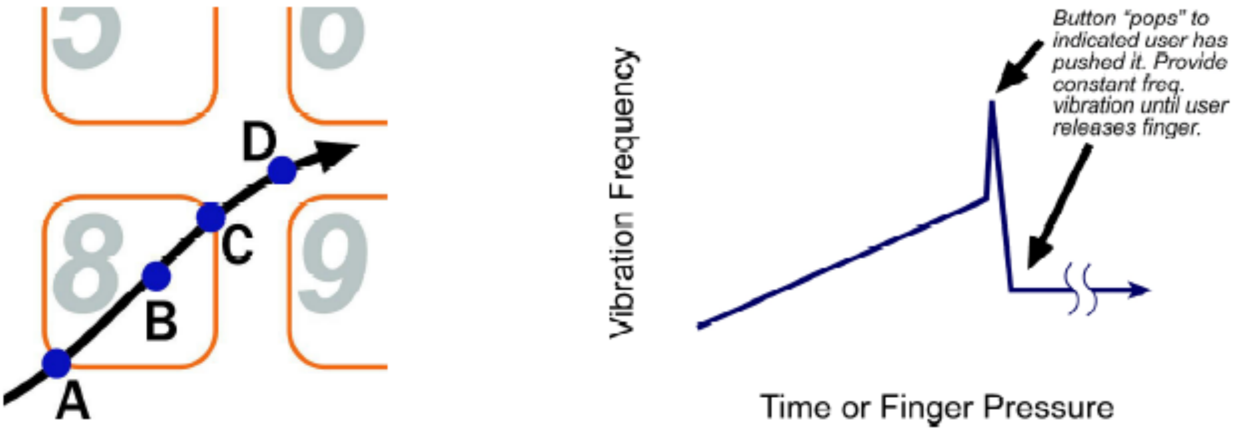
Icons incorporating artificial haptic patterns, such as haptic icons, hapticons and tactons, have used to be analyzed to understand how human skin receives haptic messages. Hapticons or haptic icons [6] [166] are described as abstract haptic signals rich in perceptual information that are typically delivered via simple electromechanical means. These signals may have varying degrees of structural complexity. They share with their graphical and auditory counterparts the function of communicating low-level, abstract information such as the state of an event, the function of an object or the occurrence of an event. Brewster and Brown [24] define Tactons as “structured, abstract messages that can be used to communicate messages non-visually”. They are, therefore, quite similar to haptic icons with the difference that they result from the general philosophy behind “earcons” (auditory icons) and make use of concepts typically associated with music and speech synthesis (e.g. rhythm, vibration, pitch). Pasquero [192] indicated that haptic or tactile icons must (1) be easy to learn and memorize, (2) carry evocative meaning or at least convey a discernible emotional content, (3) be universal and intuitive, (4) support increasing levels of abstraction as users become expert through repeated use. Chan et al. [47] found that seven haptic icons could quickly and easily be learned in the absence of workload. They evaluated users’ ability to identify the haptic icons in the presence of varying degrees of workload.

Haptic icons encode information by manipulating simultaneously several parameters of vibrotactile stimuli in order to control synthetic properties and convey abstract messages of tactile perception. Brown and Brewster [25] [27] [30] [31] proposed the basic vibrotactile parameters frequency, amplitude, waveform, duration, rhythm and body location as spatiotemportal patterns in tactile interface design. Further, they described three types of tactons: compound tactons (combining different tactons to create compound messages), hierarchical tactons (with properties inherited from tactons at higher levels in a so-called tacton tree) and transformational tactons (encoding several properties or pieces of information using different parameters).

The Multidimensional Scaling (**MDS**) technique was used by MacLean and Enriquez [166] to determine how haptic icons can be constructed utilizing frequency, magnitude and waveform. They suggested that **frequency** played a dominant perceptual role among a set of time-invariant parameters. Rabinowitz [206] found that performance on **intensity** was most affected, and performance on **contactor area** least affected, by simultaneous variations in the other dimensions. The human tactile system has been shown to be relatively insensitive to **waveform,** suggesting that the perceptibility of vibrotactile **frequency** is largely due to temporal cues rather than spectral properties. **Waveform** has therefore been excluded as a parameter for use in designing tactile devices [242]. However, a complex **waveform** generated by sinusoidal amplitude modulation (e.g. a 250 Hz sinusoid modulated by a 30 Hz sinusoid) [30] [111] achieves higher average recognition rates than frequency and amplitude modulation. **Rhythms** [31], which are created by grouping together vibrotactile pulses of different durations and leaving gaps, have been proved to be a very effective parameter. **Temporal** variation of vibrotactile stimulation has been studied in three groups: (1) the burst duration of the stimulus, (2) the pulse repetition rate and (3) the number of pulses [126]. Duration range of 50 – 200 ms shows the best perceptibility [129]. The ability to identify a tactile pattern improves as duration increases from 80 to 320 ms [242]. The information of haptic communication serve as basic parameters that can be further studied with a view to developing haptic messages on touchscreens.

4.2.3 Haptically enhanced widgets design

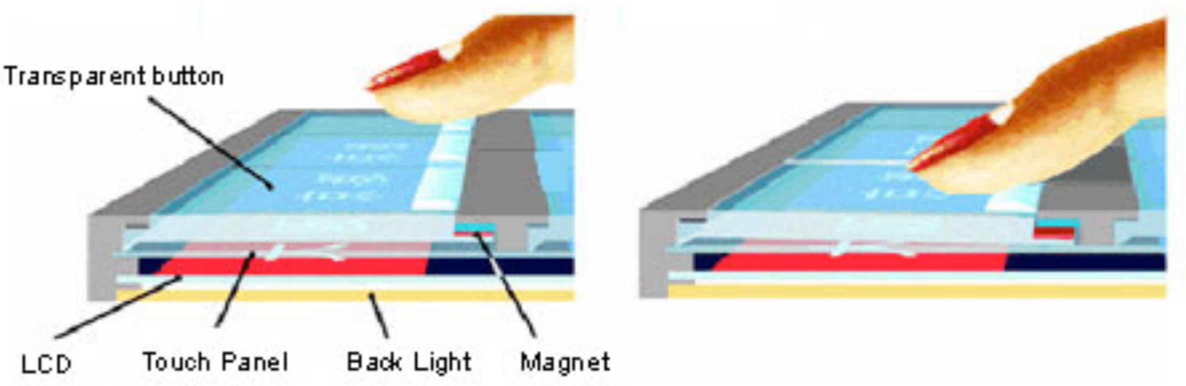
It has been confirmed that haptic feedback, especially active force feedback, effectively improves task completion times and enhances manual interaction with a GUI [212] [269]. This has been exemplified by widgets that attempt to make manipulative use of haptics to enhance 3D interaction with a computer [175] [236]. Programmable force-displacement curves have been applied to simulate pushbuttons on a haptic display [70]. Some strategies have tried to add the tactile cues of physical buttons to virtual buttons. Nashel and Razzaque [182] implemented two kinds of tactile virtual buttons. Firstly, they added a pulse when the finger moves onto a button and when it moves off again, and low amplitude vibration when the finger moves across the button (Figure 15 (a)). Secondly, they interpreted continuous presence of the finger over the button as pressure (Figure 15 (b)). A research group [112] at the university of Glasgow added different vibrotactile feedbacks to an iPhone prototype in response to the events “finger down”, “finger up”, and “finger touches the edge of touchscreen key.



(a) (b)

Figure 15: Tactile cues of physical buttons on virtual buttons [182]

“SurePress” [@39] and “UnMouse” [@34] [@47] employed the whole touchscreen as one big pushbutton with tactile feedback added. A “CC switch” placed mechanical transparent switches over a touchscreen, as shown in Figure 16. When the transparent plate that lay over the panel was pressed with a force exceeding the attracting force between the magnet and the magnet substance, the transparent plate falls towards the touch-sensitive panel to make the user sense the “click” feeling of a pushbutton.



(1) "OFF" state (2) "ON" state

Figure 16: Structure of CC switch [@13]

In additional, there have been several reports of attempts to realize soft surface touch interfaces using transparent elastic materials to provide tactile feedback to onscreen widgets. A silicon-based tactile sensor [59] [60] [156] [243] [274] using capacitive transduction possesses mechanical properties. "PuyoSheet" and "PuyoDots" [82] placed a sheet of soft-gel film over a touchscreen and five soft-gel dots on the back of a handheld device to provide a button-click feeling. "GelForce" [261] and "ForceTile" [130] utilized gel on a tablet display to move, push or pinch projected images. "PhotoelasticTouch" and SLAP widgets [271] used rear projection underneath silicone and acrylic interfaces.

4.2.4 Touchscreen-based UI

As MacLean and her colleagues [167] state in their studies of HCI design in conjunction with tactile feedback, a touchscreen system incorporating tactile cues contains a tactile renderer, a tactile driver and a tactile effector. Users can both transmit and receive tactile information on screens simultaneously.

To provide tactile feedback, a few of studies have applied soft buttons or combined moving parts (such as pop-up button) so as to remain the most basic mechanical interaction action behavior on touchscreens. For instance, researchers [@45] at Carnegie Mellon University have developed pneumatic buttons that pop out from a touchscreen surface. The screens are covered in semi-transparent latex, which sits on top of an acrylic plate with shaped holes and an air chamber connected to a pump. When the pump is off, the screen is flat; when it is switched on, the latex forms concave or convex features around the cutouts, depending on negative or positive pressure. One type of haptic surface using the FEELEX system [120] provided a new solution to the touchscreen-based user interface, in which an actuator array deforms the flexible screen onto which the graphical image is projected. Leung et al. [158] indicated that designing haptic feedback for GUI elements running in the background does not interfere with using other GUI elements. Furthermore, haptic solution led to favorable subjective reactions.

4.2.5 3D touch surface

In addition to the application of touch effects to traditional X- and Y-axis touch panels, some attempts to add pressure information to form a 3D interface have been reported. IBM TDB [43] described a type of three-axis touch-sensitive panels implementing Z-axis control that involved adding an additional layer beneath the X and Y surface. Some work has involved the use of piezoresisitivity, piezoelectricity [121] [206] and capacitive sensing [80] [89] [240] to measure the local force applied to the surface on the Z-axis.

Guided by these existing studies on the exploitation of the human sense of touch to meet user needs when using touchscreens, this dissertation will further investigate how to develop haptic stimuli and UI applications that allow users to literally “feel” the interface controls (e.g. buttons and scrollbars) with which they interact. This is intended to aid the mapping of haptic signals to different touchscreen-based usage scenarios.

4.3 Quality design for haptic touchscreen

Touchscreen design incorporating tactile cues is a task which sets out to achieve goals at multiple levels, in a given context. The starting point is a functional requirement which demands that designers not only analyze the environment of use, such as a workplace, but also that they select the best currently available technology, and that they evaluate the validity of their envisioned designs in real-world tests with actual users. In the process of developing a touchscreen with haptic feedback, touchscreen-based scenarios constitute the input method that determines what sets of onscreen UI elements are needed for direct manipulation, while feedback for user perception and system responses to user actions are output via the user interface through the human tactile channel, conveyed by such factors as vibration stimulus, impulse emission and temperature change. In order to structure the design model with real potential users of the system in mind at all times, a number of system properties must be targeted when designing and evaluating a tactile touchscreen.[5]

- **Touch-reliable:** The application environment and the users’ experience dictate selection of the best touchscreen solution (see 2.2.2). Designing tailor-made tactile touchscreen-based applications avoids errors caused by technology and ergonomics.
- **Response-fast:** The system should always give immediate tactile feedback to the user in regard to what action is being taken. Latency, or a time lag, between a user pushing a control and the system responding can cause user confusion and control instabilities.
- **Task-suitable:** Too much functionality makes the touchscreen-based applications complicated and confusing users. Spatio-temporal representations conveyed via the tactile

[5] The summarized eight points are based on ISO 9241-11 “Guidance on usability” and ISO 9241-10 “Dialogue principles”. ISO 9241-10 presents seven general principles for designing dialogues between users and information systems: suitability for the task, self-descriptiveness, controllability, conformity with user expectations, error tolerance, suitability for individualization and suitability for learning.

and kinesthetic channels should match the physical properties of the information provided by the visual and auditory displays.

- **Understandable:** When an application is manipulated to accomplish basic tasks for the first time, user can be quickly apprehensive as to what it does and how to use it. Feedback information should be clearly presented, easily distinguished, self-explaining and felt as natural.
- **Navigable:** The system should tell users where they are in the application through visual, tactile or auditory feedback. At the same time, it is necessary to provide clear and direct navigation, for instance, to return to the home screen or switch to another screen.
- **Conformable to expectations:** To avoid causing user confusion and cognitive overload, the quantity of tactile information (e.g. intensity levels) should not be too high. For example, it is recommended that a haptic system should use no more than four different intensity levels [45]. Unpleasant tactile feedback can be used as a warning or alarming sign.
- **Error-tolerant:** The application should allow to UNDO erroneous actions.
- **Enjoyable:** Tasks should be accomplished without undue effort or stress. A well-designed system makes users feel good about using it.

With a view to maximizing the usability of tactile touchscreens, the eight properties listed above will serve as a guide to designing tactile stimuli for the UI controls, touchscreen UIs and hardware designs developed as part of this dissertation. As discussed in Chapter 3, vibrotactile feedback has particular advantages in certain kinds of sensing tasks, such as detecting events for the purpose of manipulating and controlling a hardware system. Exploiting the human tactile channel as a medium for active manipulation of a touchscreen makes use of several psychophysical, cognitive and emotional characteristics which allow access to the physical dimensions of a touchscreen and permit better understanding and control of a touchscreen system. To take best advantage of the human haptic channel and make the design touch-reliable, this study first surveys the perception of vibration direction in touchscreens, the results of which can serve as a guide to devising a mechanical touchscreen arrangement ensuring maximum utilization of tactile effects. Using a tactile touchscreen that vibrates in the direction most effectively sensed, haptically enhanced UI controls are investigated with the aim of emulating physical controls and enhancing user experience by simulating a natural response on the part of the UI controls and arranging them in an optimal layout. These haptically enhanced UI controls are then implemented in prototype applications facilitating further investigation into interaction design for tactile touchscreens used for primary and secondary tasks. The following chapters expound in detail the development of this interaction concept for tactile touchscreen interfaces.

5 Perception of vibration direction in touchscreens

Current market-ready technologies used with touchscreens allow vibrotactile feedback in order to give users a sense of perceiving physical graphical controls. In order to properly optimize the usability of touchscreens through tactile effects, it is necessary to investigate mechanical arrangements for displacement of tactile touchscreens with a view to effectively exploiting the key features of the human sense of touch. This chapter is based on a paper by the author on investigating perception of vibration directions in touchscreens, published in the proceedings of the IASTED HCI conference [161].

As shown in Figure 17, a touchscreen in principle can move in three mutually perpendicular directions. When users press a touchscreen, horizontal movement of the touchscreen stretches the skin and the tactile receptors under the skin along the left-right horizontal direction of the X axis or in the forward-backward horizontal direction along the Y axis. However, the skin is compressed when the touchscreen moves along the vertical Z axis. This study provides quantitative research into user sensitivity to a touchscreen vibrating in three different directions.

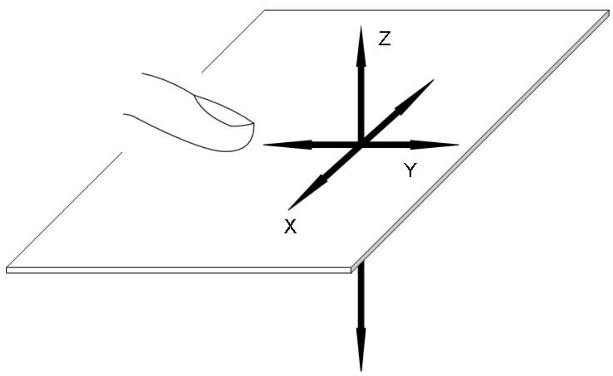


Figure 17: Different translational movements of touchscreen

Some works [197] [239] have claimed that the active lateral movement of the skin across the surface recruits the "vibration sense", which may have a higher acuity than the "pressure sense" of passive touch. Appelle [9] argues that the manipulation of objects is neither exclusively active nor passive, and is neither exclusively cutaneous nor kinesthetic; in fact, passive stimulation is also caused when a user runs a finger over the surface of a touchscreen moving in any one of these three translational directions. Warren [267] concludes that blind people may have a good understanding of vertical movement; by the reverse token, it is worth investigating how normally sighted humans interpret haptic spatial information. So a systematic insight into the perceptibility of the passive stimulations attributable to these three spatially defined variants of touchscreen surface motion is key to enhancing the usability of tactile effects in touchscreens.

The human tactile system is commonly sensitive to the frequency range of 10–400 Hz [30], with maximum sensitivity around 250 Hz. In comparison to the human auditory system, which has a range of 20–20,000 Hz, the skin is relatively poor at frequency discrimination [112]. Kyung et al. [136] measured the best spatial sensitivity in human skin within the 1–3 Hz and 18–56 Hz ranges. Since 1–3 Hz is too slow to permit a tactile touchscreen to be felt, we chose the frequency range of 18–56 Hz as our focus. The vibrotactile actuators we used have a limited frequency range of 15–80 Hz, which covers the optimum 18–56 Hz range. The experiment we conducted provided a quantitative measurement determining which vibration direction is better perceptible at the frequency range of 15–80 Hz.

5.1 Experiment setup

Perceptual thresholds [98] for touch depend on location, stimulus type, and timing. Actuator design must consider these thresholds to ensure that human mechanoreceptors receive the tactile stimulus. Electromagnetic motors and arrays of pins are commonly used actuators in vibrotactile display. Two bass shakers (4Ω, 80W, 120x40mm)[6] [@10], in the form of small, low-cost and low-power electromagnetic motors with a frequency range of 15 to 80Hz, were used as vibrotactile actuators in our experiment.

The tactile stimuli tested were run with two equivalent setups A and B. Each of them used one cubic box made of acrylic glass mounted on a bass shaker. The prototype, as shown in Figure 18, was set up with three mutually perpendicular thick wooden boards, to which setups A and B were fixed.

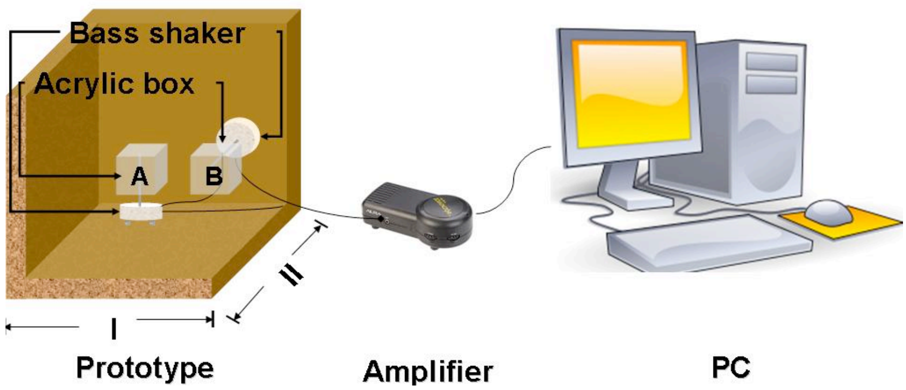


Figure 18: Hardware setup of the prototype and functional connection

Two bass shakers and an audio power amplifier [@9] (18-1400Hz, 200x65x100mm, sinus output 16W) were connected in series. The amplifier was set to a level that could be sensed clearly. We chose the volume level of 4 (out of a maximum 10 volume levels) for the experiment. The bass

[6] In the physical world, auditory and haptic perceptions share significant similarities. These similarities can enlighten us as to haptic actuator selection and stimulus design. In this work, the actuators used for the experiment incorporate bass shakers that have cost- effective and power-efficient electromagnetic motors.

shakers were driven by the amplifier, which was plugged into a computer sound card. Thus, low frequency signals were generated by the sound card, amplified by the power amplifier, and subsequently converted to both low frequency sounds and vibrations, which could be felt on the surface of the acrylic boxes.

Setups A and B generated the vertical and horizontal motions respectively. Setup A could only be moved vertically along the Z axis. Setup B generated horizontal motions along the X axis when the prototype was aligned with side I, and along the Y axis when it was aligned with side II.

In order to keep the setups A and B equivalent, we measured the vibrations on the surfaces of the acrylic boxes A and B, which are produced from the base shake A and B. Firstly, a microphone was placed on a tripod 1m away from the middle point of the surface of acrylic box A, vibrated setup A, and recorded the sound. We did record the sound from the surface of acrylic box B in the same way. If the sounds from setups A and B were not the same, we adjusted them until both recorded sounds were the same.

5.2 Research method

Stimuli: In this experiment, the single-frequency acoustic waves generated by CoolEdit2000 transmitted vibration to the surfaces of the two fixed cubic boxes. Van Erp's suggested [249] that frequency difference for encoding tactile information should be at least 20% between levels, while intensity difference should be not more than four levels. Thus, the tactile stimuli tested were presented as sinusoids at frequencies of 15Hz, 30Hz, 58Hz and 80Hz. The amplitude was not used as a parameter, because reducing amplitude could degrade perception of other parameters or render the signal undetectable, while increasing it too far could cause pain [@10] [25][128]. When the amplitude of a constant-frequency vibrotactile signal grows, the perceived frequency increases [128]. Because of the interaction of frequency and amplitude in perceived vibrotactile frequency discrimination, Brown et al. [25] suggested that amplitude and frequency should be combined into a single parameter to simplify design. Carter and Fourney [45] concluded that, where tactile information is encoded temporally, the stimuli must be at least 5.5 ms apart and have an interval of at least 10 ms between them. The stimuli in this experiment were formed by grouping three such monophasic sinusoids of the same duration and leaving one interval of one second between them, as shown in Figure 19. Each pulse frequency was run in the three different vibration directions.

Participants: Sixteen subjects, six women and ten men, took part in the experiment. The ages ranged from 26 to 57 years with the mean age of 34. They were all employees, internees and consultants at Siemens Corporate Technology. All were right handed, with no known hand disorders, and used their right hands.

Procedure: In order to limit evaluation to human haptic perception, participants were asked to wear a pair of ski goggles covered with thick black paper, and a headset emitting constant noise during the experiment. Thus participants could see nothing and felt as if they were in a noisy and distracting environment. The test observer led the hand of each participant to the surface of the acrylic box each time a test was initiated.

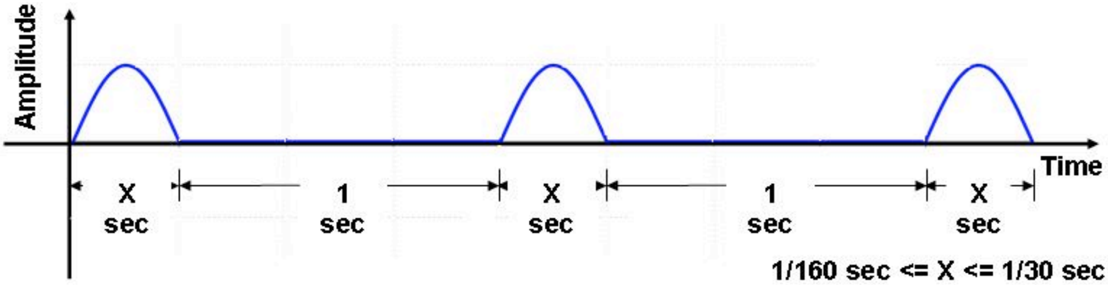


Figure 19: Stimuli with 3 half-cycle sine waves

Participants were asked to compare three stimuli each time and make a decision on which stimulus felt clearer and pleasant. Every participant completed four sets of stimuli. Each set of three stimuli had the same pulse frequency, but a different vibration direction along the X, Y or Z axis. Participants could choose to sense each stimulus up to three times.

Furthermore, this experiment surveyed whether the skin can differentiate and compare different frequencies generated by the actuators that were used in the experiment, and whether perception of motion would be more sensitive as frequency increased up to 58 Hz. In the pilot survey, it was predicted that vertical vibrations would be sensed more correctly than horizontal vibrations. For this reason, in the last part of this experiment all stimuli took the form of vertical vibrations. Three pairs of stimuli were presented. Each pair of stimuli had two different frequencies. Participants were asked to compare the two stimuli and indicate which stimulus felt more intensive.

5.3 Subject evaluation

Sets of data were gathered to determine how often one vibration direction was preferred over the others in terms of its intensity.

The mean value of the rate of preference for each vibration direction was plotted, to compare which one was best perceptible, as shown in Figure 20. A Friedman test showed a significant difference in performance ($\chi^2 = 11.236$, $p = 0.004$). Meanwhile, the lower standard deviation for the vibration along the X axis also implied that the perception of lateral skin stretch along the X axis is less sensitive than that of lateral skin stretch along the Y axis and that of vertical skin pressure along the Z axis. Thus, the perception of vertical vibrations is more sensitive than that of horizontal vibrations at the 15-80 Hz frequency range.

The number of times that participants chose to sense each stimulus is also worth investigating in relation to the three directions of vibration. The statistical analysis used was a standard two-way ANOVA analysis, based on the critical values of the F distribution, where alpha = 0.05. The ANOVA shows that there are significant differences in sensitivity ($F = 6.4 > F(2, 30) = 3.32$, $p = 0.005$). As shown in Figure 21, the number of times chosen to sense lateral skin stretch along the X axis is the lowest among that of the three vibration directions, whereas lateral skin stretch along the Y axis is the direction that participants most asked to sense repeatedly.

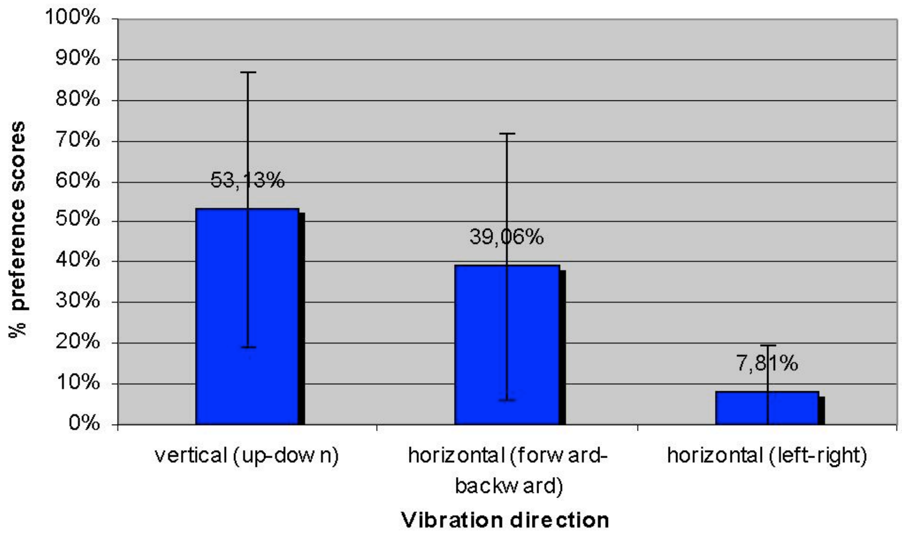


Figure 20: Perceptibility of the three vibration directions (with standard deviations)

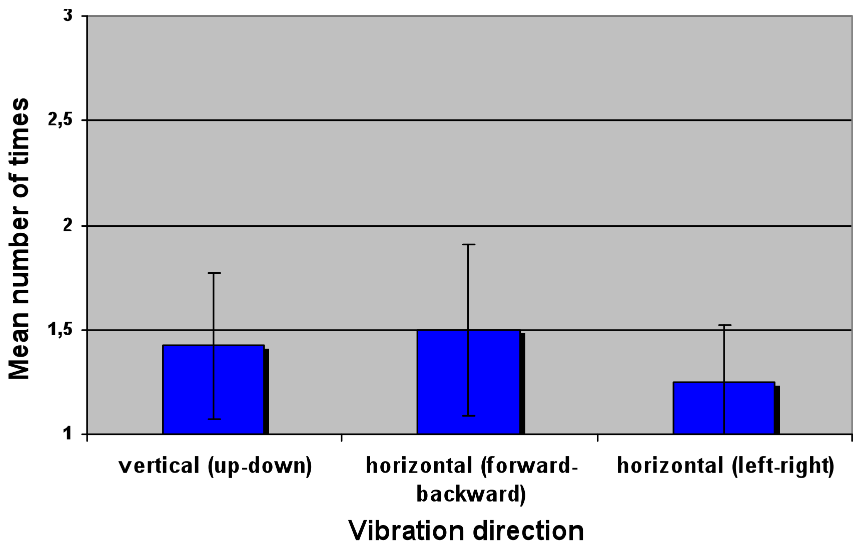


Figure 21: Number of times chosen to sense stimulus in the three vibration directions (with standard deviations)

During the last part of this experiment, participants' responses regarding the comparison of two frequencies were gathered. Figure 22 illustrates the individual rates of preferences for each frequency.

The measure of how intensively one frequency was sensed rises, when the frequency increases from 15 Hz to 58 Hz. But the perceptibility of motion decreased when the frequency is increased from 58 Hz to 80 Hz. These experimental results are in accordance with those of past studies on vibrotactile spatial acuities in showing that the sensitivity of the human skin gradually decreases as the frequency of vibration increased over 50 Hz [86] [150].

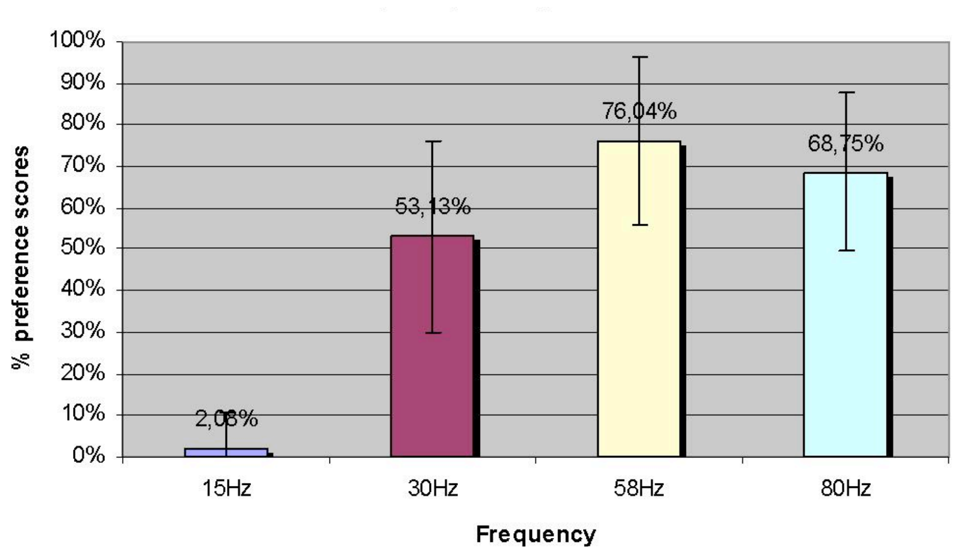


Figure 22: Perceptibility of four different frequencies (with standard deviations)

5.4 Discussion on the test results

During the user test, few participants found difficulty in selecting the best stimulus from one set of three stimuli presented in different directions, in particular when they were asked to compare horizontal vibrations along the X axis. This indicates that the vertical direction of motion can be identified more clearly than the two horizontal ones. Some participants complained that exact directions of motion were not clearly recognizable. This shows that perception of the differences between the directions is easier than recognition of the exact direction.

In fact, participants pressed the surface of the acrylic boxes with varying force. This could impact on the clarity with which the vibration directions were sensed, thus increasing or decreasing the number of times chosen to sense each stimulus. The number of times chosen to sense the stimulus at a frequency of 80 Hz is clearly higher than at 15 Hz, 30 Hz and 58 Hz, indicating that the stimulus can be sensed only weakly when the frequency is increased to 80 Hz. Future work should investigate whether and how the frequency delivered influences sensitivity to the vibration direction, in particular when the frequency range is higher than 80 Hz.

The results of the last part of this experiment showed that the perceptibility of frequencies on the fingertip was not linear. The higher-frequency stimuli are better suited to the human ability to identify vibrotactile stimulations. This finding is taken into account in the design of haptically enhanced UI controls in the next chapter.

5.5 Conclusion on designing vibration direction in touchscreens

The experiments described in this chapter measure human sensitivity to spatially defined variants of motion in the surface of a touchscreen, with a view to maximizing the usability of tactile effects in touchscreens. In fact, the sensitivity of the human fingertip to the vibration direction in a touchscreen depends heavily on the successive processes taking place on the moving surface of the touchscreen. The perceptibility of vibration is therefore determined by the characteristics of the stimuli used in touchscreens. Multiple factors such as frequency, amplitude and time need to be investigated as a basis for offering high-quality tactile feedback. The findings made provide guidance for choosing suitable vibration directions and stimulus designs for the tactile touch-screens involved in the further investigations pursued in this dissertation. Moreover, they are intended to serve as a guide to further research into hardware design for tactile touchscreens – i.e. how to build a tactile touchscreen to provide users with the type of vibration they are most sensitive to – and as an input to the development of touch interaction in different usage scenarios, with the aim of effectively exploiting the key characteristics of the sense of touch.

6 Design of haptically enhanced UI controls

When a physical control is pressed, users see the state of the control with the aid of its three-dimensional position, sense its displacement and the force applied to it with the aid of the physical form of the control, and even hear the feedback provided by the mechanical trigger (detent). In order to simulate the natural haptic response that physical input devices provide, and which is missing on a touchscreen, software-triggered feedback has started to be developed for onscreen controls. Previous studies [25] [112] [201] [202] have shown that adding tactile feedback can improve the usability of user interfaces on touchscreens. However, there are few studies that report where the best places are to add haptic feedback to optimize usability, and in particular how to integrate haptic feedback into graphical UI controls (or widgets), or even how to define the basic components of touchscreen UIs. This chapter presents some standard graphical UI controls and describes how haptic feedback can be added with a view to simulating physical UI controls and thereby maximizing the usability of touchscreen UIs.

6.1 Basic considerations for the design of haptically enhanced UI controls

A UI control represents a complete command in terms of the semantics of user operation. Haptically enhanced UI controls in touchscreens need a clear, effective and consistent design. The haptic effects used in such UI controls are based on structured haptic messages from haptic or tactile icons (see 4.1). These encode information by manipulating the parameters of cutaneous perception. Various dimensions of information can be represented in a single haptic or tactile icon by encoding each dimension in a different vibrotactile parameter, such as frequency, amplitude, duration or waveform. With a view to ensuring that haptically enhanced UI controls improve usability effectively, one critical aspect of designing haptic effects for UI controls lies in selecting the parameters to be applied to vibrotactile stimuli and determining which range of values is best perceptible and how varied those values should be. In this study, the multidimensional information comprised in vibrotactile parameters was used as a basis for designing onscreen UI controls, with a view to determining how best to generate haptic icons varied along one or more of the dimensions available, such as frequency, amplitude, waveform and duration.

6.2 Principles of the perception of UI controls

Digital UI controls are actually a set of visual, auditory and haptic representations of physical objects or actions. The principles for designing both discrete action and continuously variable UI controls on touch-based screens are derived from the mechanical manipulation of physical controls combined with the dynamic simulation of haptic sensation.

The button is one of the UI controls most commonly used to trigger a discrete action, whereas the knob and the slider are employed as continuously variable controls to provide a perceptible means of manipulating parameters. The large size of the knob and the slider may require them to accommodate more functions, but well-designed haptic feedback can keep their operation intuitive. When modeling a task or process within a dynamic system, rendering such UI controls as haptic elements can maximize information delivery, thereby improving the usability of the interface design.

6.2.1 Perceiving the click feeling of a pushbutton

Pressing a pushbutton till it clicks can be conceived of as an elemental one dimensional positioning task. The click feeling of a mechanical pushbutton can be perceived in a simple way - one bit of pressure being sensed, namely push or release as shown in Figure 23. State 0 is the start position - the pushbutton is not pushed down, so there is no effect. When the button is depressed, resistance force may rise as the stroke length increases. When the button is fully pushed, the finger perceives a click feeling due to a rapid change in resistance force as the button enters state 1. When finger releases, the button restitutes to the state 0.

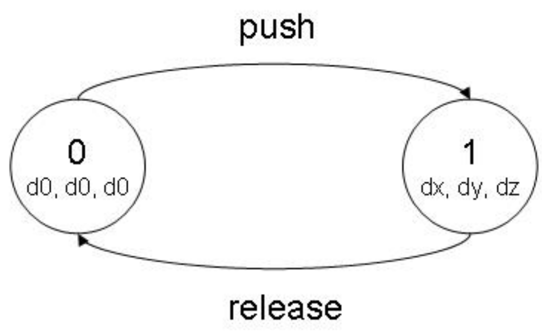


Figure 23: State 0-1 transition of pushbutton

The click action of a button can be described as consisting of three main phases: 1) as the button is pushed down, resistance increases; 2) when the button hits bottom, it stops; 3) when the button is released, haptic feedback provides a click. In order to simulate physical buttons, these three phases of the button's click action need to be taken into consideration.

The feel of pressing a virtual pushbutton has been defined as an initial resistive force that increases linearly with displacement, followed by a triggering action and a sudden decrease in resistive force [175]. Tashiro et al. [246] analyzed the relationship between reaction force and changing stroke length in mechanical buttons, as shown in Figure 24. They produced the click feeling of a button utilizing ultrasonic vibration with an amplitude of a few micrometers.

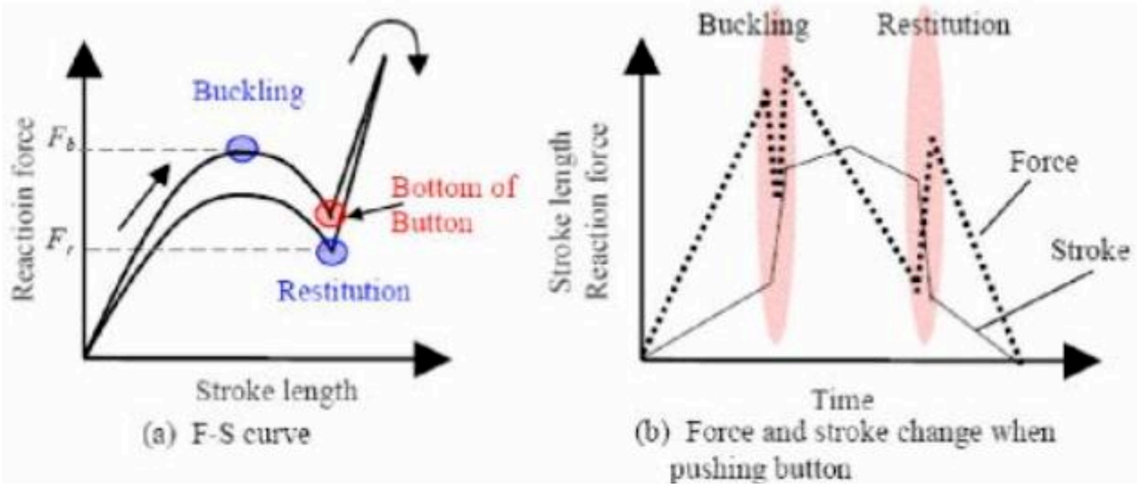


Figure 24: Image of F-S- curve and timescale change of F-S characteristic of pushbutton [246]

Doerrer et al. [70] demonstrated that the force used for haptic feedback in pushbuttons needs to be at least 1.5 N. Table 4 in chapter 2 summarizes some results of investigating the minimum and maximum force that apply to a graphical button, which can range from 0.25 N to 3.89 N. This would have to be taken into account in designing a perceptible click feeling for a pushbutton on a touchscreen.

6.2.2 The two states of checkbox and switch button

A checkbox or a switch button usually has two states: selected and unselected. In comparison with a pushbutton, a checkbox undergoes no physical variation. It is one kind of graphical UI control that conveys its selection state visually. As shown in Figure 25, state 1 represents the switching position. The system moves the switch button into state 2 when the finger moves up. So the button switches on. It is this state 2 that distinguishes the switch button from the simple button.

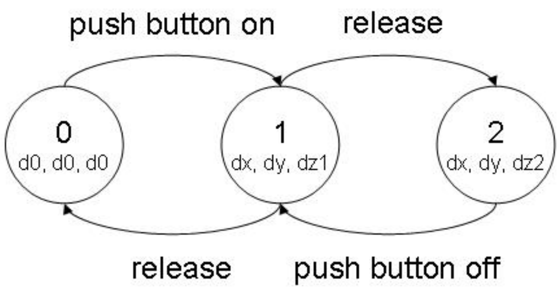


Figure 25: State 0-1-2 transition of switch button

Miller and Zeleznik [175] designed viscosity-driven switches with a quadratic increase in resistance. A resistive force of 20 N per m² is added when the rate of displacement exceeds 200 mm/s, while the viscous force suddenly drops off to zero when the rate of displacement exceeds 600 mm/s. To activate the pressure sensors on the skin, the force should be between 0.06 and 0.2

N per cm² [45]. This could be used for a mechanical setup of a touchscreen to supply a mechanical feeling of manipulating a graphical checkbox or a graphical switch button.

6.2.3 Increasing and decreasing values with sliders and knobs

The slider and the knob are two kinds of UI controls actuated along a single axis. Sliders are used to change input values by linear movement, whereas knobs link value changes to the motion of a wheel turning.

Past studies on haptic technology have utilized orthogonal force sensing to demonstrate a collection of single-axis actuated displays featuring knobs and sliders [236]. The sliding sensation felt when moving a slider [174] can be produced by applying two different spring constants in response to different user force levels, and modulated by using different friction coefficients or alternatively viscosity; Miller also planned to allow the user to click to drag the object perpendicularly to the constraint plane. A volume knob can be characterized as offering little resistance to motion through most of the range of the control, while resistance increases upon nearing the detented off position at the end of the range, and decreases suddenly upon entering the off position.

6.3 Experiment setup

In view of its high touch resolution, durability and reasonably-priced touchscreen technology, a 5-wire resistive touch panel was selected as a platform for investigating the tactile effects of UI controls.

The study in Chapter 5 offers insight into users' perception of directions of vibrotactile feedback. The findings suggest that the best mechanical solution for a tactile touchscreen prototype is vertical vibration. In accordance with this result, a tactile touchscreen prototype vibrating in the vertical direction along the Z axis, as shown in Figure 26, was built to allow further research and development work on tactile touchscreens. Tactile feedback is allowed to exert high-speed control over one or more actuators with varying size and form.

The touch panel [@3] was taped firmly to an 8.4'' TFT LCD module [@28] in 800x600 pixels resolution, which was mounted on four bass shakers [@10] (used as tactile actuators) using copper bars and threaded rods, as shown in Figure 28. In this setup, the spacing between the bass shakers was 11.02 cm along the short side of the touchscreen and 22 cm along the long side, which is in accordance with the spacing of at least 6-8 cm between actuators that was suggested in a past study [126]. The top of the magnet of the bass shaker was positioned 5.5 cm from the surface of the touchscreen. The particle board mounting carrying the bass shakers was fixed to an optical breadboard [@2] in order to isolate any resonance from the hardware components that might distort the original tactile feedback produced by the bass shakers.

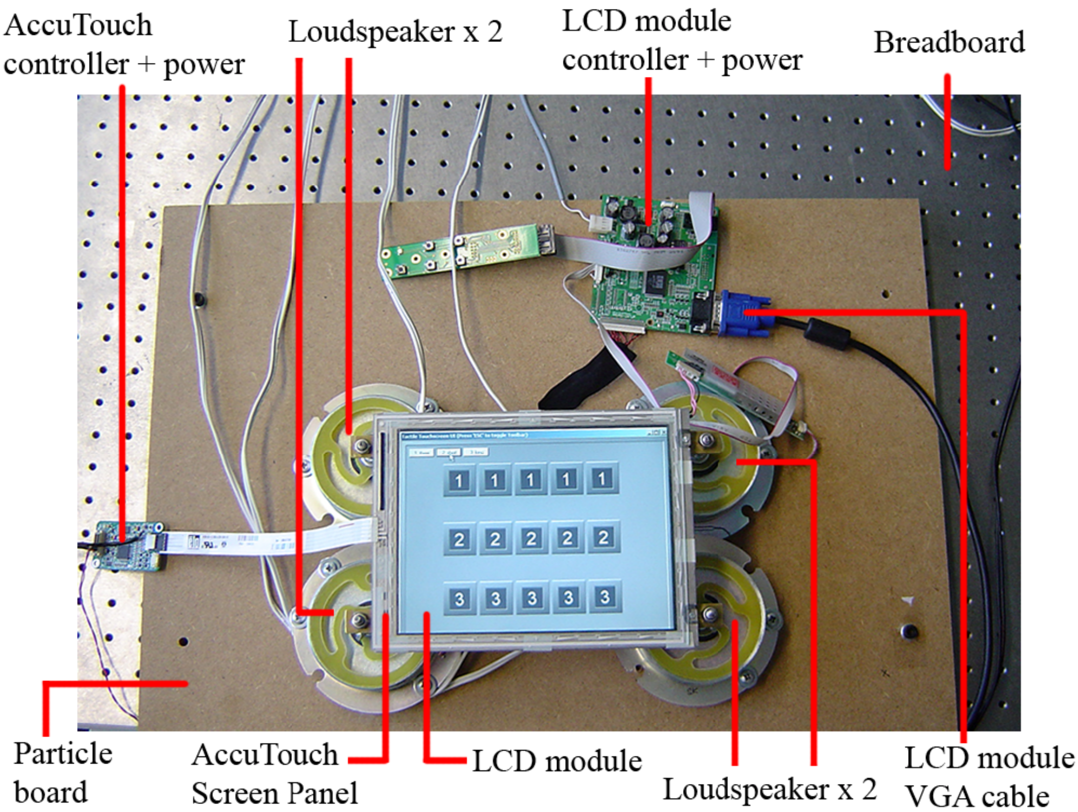


Figure 26: Overview of the hardware platform

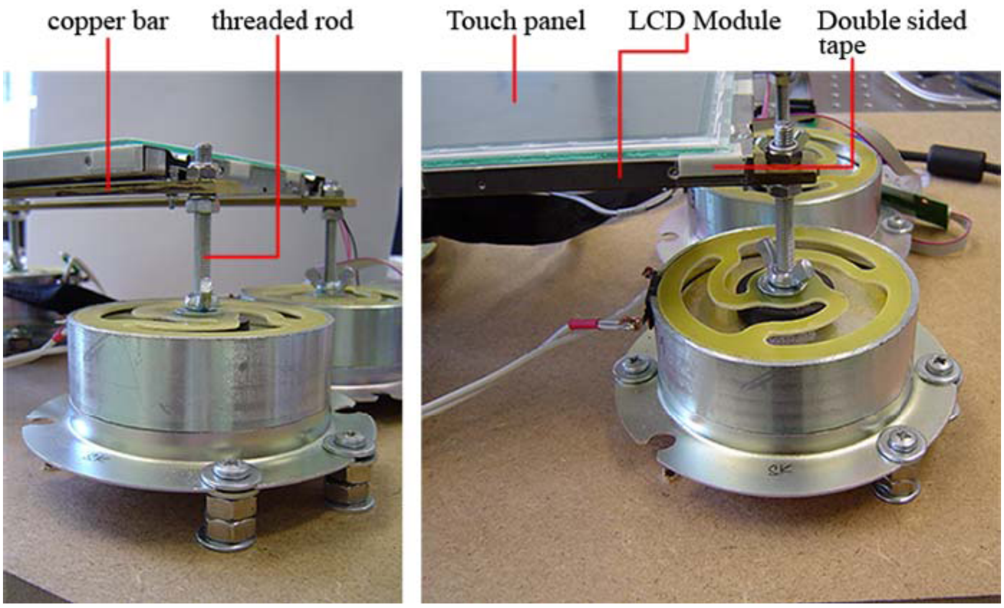


Figure 27: The section of the hardware platform

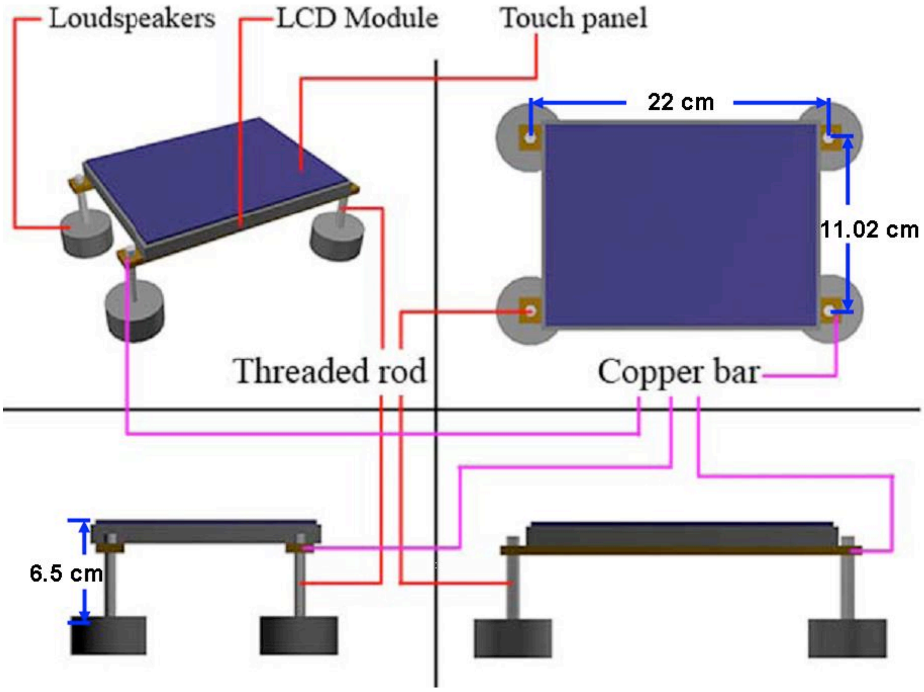


Figure 28: Connection of LCD module and bass shakers

A Pioneer XV-DV515 DVD/CD Receiver (75W, 6Ω per channel) was used as an audio power amplifier. During the experiment, a volume level of 35 (out of a maximum of 60 volume levels provided by the receiver) was chosen as the level that could be sensed most clearly. The bass shakers were driven by the amplifier, which was plugged into a computer sound card. Thus, low frequency signals were generated by the sound card, amplified by the power amplifier, and subsequently converted to both low frequency sounds and vibrations, which could be felt on the surface of the touch panel.

The user interface and the system response events for this experiment were implemented in C#.

6.4 Research design for adding tactile feedback to UI controls

Sensing a mechanical UI control usually involves the perception of resistive force and position change via human kinesthetic and cutaneous cues. Tactile feedback allows users to exert high-speed control over actuators. Pre-programmed tactile effects triggered by actuator movement convey the impression that a graphical widget is moving, seeming to respond to manipulation as if it were mechanical. Accordingly, the aim of this experiment was to develop design know-how focusing on software-controlled tactile feedback patterns to enable dynamic simulation of UI controls such as buttons, sliders, knobs and switches. The technique of delivering tactile information was designed to avoid unintentional activation of the touchscreen. Generally speaking, there are three dimensions of acuity involved in tactile sensing: vibrotactile effect, spatial and temporal change. The thresholds at which humans detect vibration are influenced by frequency, amplitude, duration and waveform. Various combinations of typical widgets, diverse vibrotactile patterns and the individual effects of varying frequency, amplitude and duration were investigated as a basis for dynamic simulation of user interfaces.

6.4.1 Tactile feedback delivery technique

To avoid unintentional activation of the touchscreen, a sequential-touch selection strategy [224] was applied, requiring a sequence of touches to select a target: the touchscreen is first initiated by a press on its surface, then the onscreen widgets are activated by pointing within 1 second. The vibrotactile stimuli are designed to occur right after the target is successfully selected. Prolonged contact with a continuously vibrating touchscreen can lead to desensitization, resulting in user confusion. Providing immediate tactile feedback is therefore critical in designing a user-friendly touchscreen incorporating tactile feedback.

Direct manipulation of a touchscreen generally involves continuously recording the updated location of the current touch point in relation to the initial touch point. Various interaction techniques are assigned to the selection and direct manipulation of onscreen UI controls in this experiment.

Moving onto: moving the finger across the screen into a button's touch area

Moving off: moving the finger out of a button's touch area

Pressing: pushing a UI control in the vertical direction

Rotating: moving the finger around a knob to update the corresponding value

Sliding: dragging a slider by making linear movements

6.4.2 Vibrotactile parameters

Perceptual thresholds for touch depend on location, stimulus type, and timing. Actuator design must therefore consider these thresholds to ensure that human mechanoreceptors receive the tactile stimuli. The tactile effects used in the onscreen widgets are based on structural tactile messages that encode semantic information by manipulating the different vibrotactile parameters such as frequency, amplitude and duration. The stimuli were generated in the form of a sine wave using Cool Edit Pro.

Frequency

As demonstrated with the setup that was devised to investigate perception of vibration direction in touchscreens (see section 5.1), the intensity with which a particular frequency is sensed increases when the frequency is raised from 15 Hz to 58 Hz. But the perceptibility of motion decreases when the frequency is increased from 58 Hz to 80 Hz. This experimental result corresponds to the findings on vibrotactile spatial acuities reported by Kyung et al., who concluded that the best spatial sensitivity is measured in the frequency bands of 1-3 Hz and 18 -56 Hz, and that the sensitivity of the human skin gradually decreases as the frequency of vibration rises beyond 56 Hz. Therefore, the two frequencies of 58 Hz and 80 Hz, having been shown to afford the best spatial sensitivity with our equipment, were chosen as a basis for determining the key parameters for simulation of the haptic behavior of physical buttons, sliders, knobs and checkboxes.

Duration

Temporal acuity for electrocutaneous pulses is best at about 50 ms [125]. Vibrotactile sensitivity grows as stimulus duration increases [125] [242]. The optimal duration of vibrotactile stimuli was suggested to be between 50 and 200 ms [129] [242]. Shorter durations (<50 ms) are not clearly perceptible, while longer durations (>200 ms) can easily become irritating. ISO 9241-1 [117] defines the maximum response time that reasonably supports direct manipulation as 500 ms. In our experiment, durations of 50 ms, 150 ms, 200 ms and 300 ms were used.

Amplitude

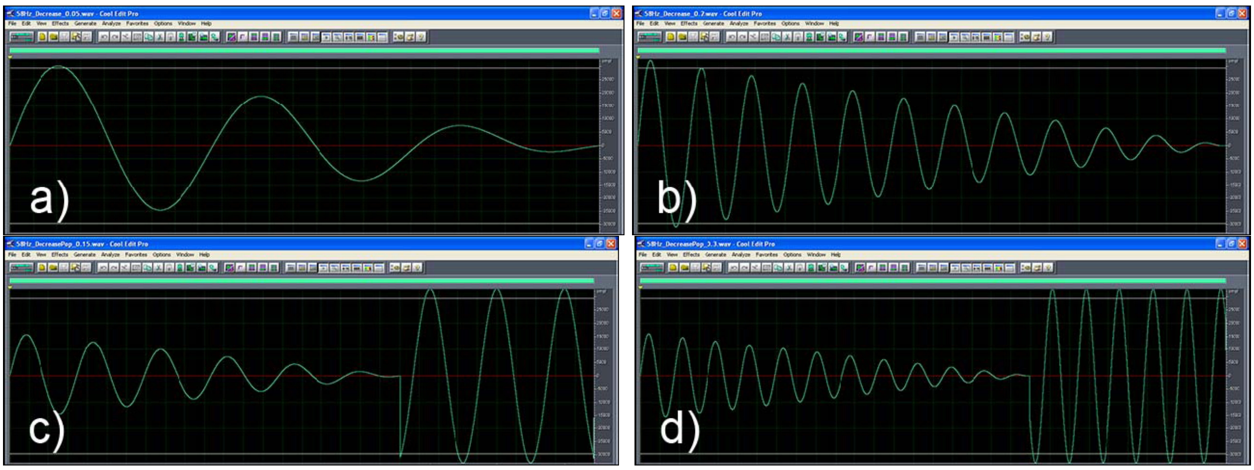
Tactile dynamics can be exploited in designing vibrotactile feedback. Increasing, decreasing and constant stimuli have been proved to be identifiable and distinguishable from each other [32]. The stimuli in this experiment were either modulated by increasing or decreasing amplitude, or kept constant in amplitude, and/or modified by applying a brief intense final impulse.

6.4.3 Semantics of UI controls

Onscreen widgets incorporating tactile feedback are icons that use structured and abstract information to communicate messages in a non-visual or visually and auditorily distracting environment. Also, the nature of contact with the individual UI controls, and the specific differences between them, require additional consideration to be taken of vibration parameters (e.g. frequency, magnitude, waveform and duration) when designing onscreen tactile UI controls.

Pushing buttons

In order to simulate the sensation of pushing buttons on a touchscreen, virtual buttons were tested with twenty stimuli produced by combining sine waves at two frequencies of 58 Hz and 80 Hz with four durations of 50 ms, 150 ms, 200 ms and 0.3 ms, four amplitudes of increasing, decreasing and constant intensity and a brief intense final impulse as shown in Figure 29.



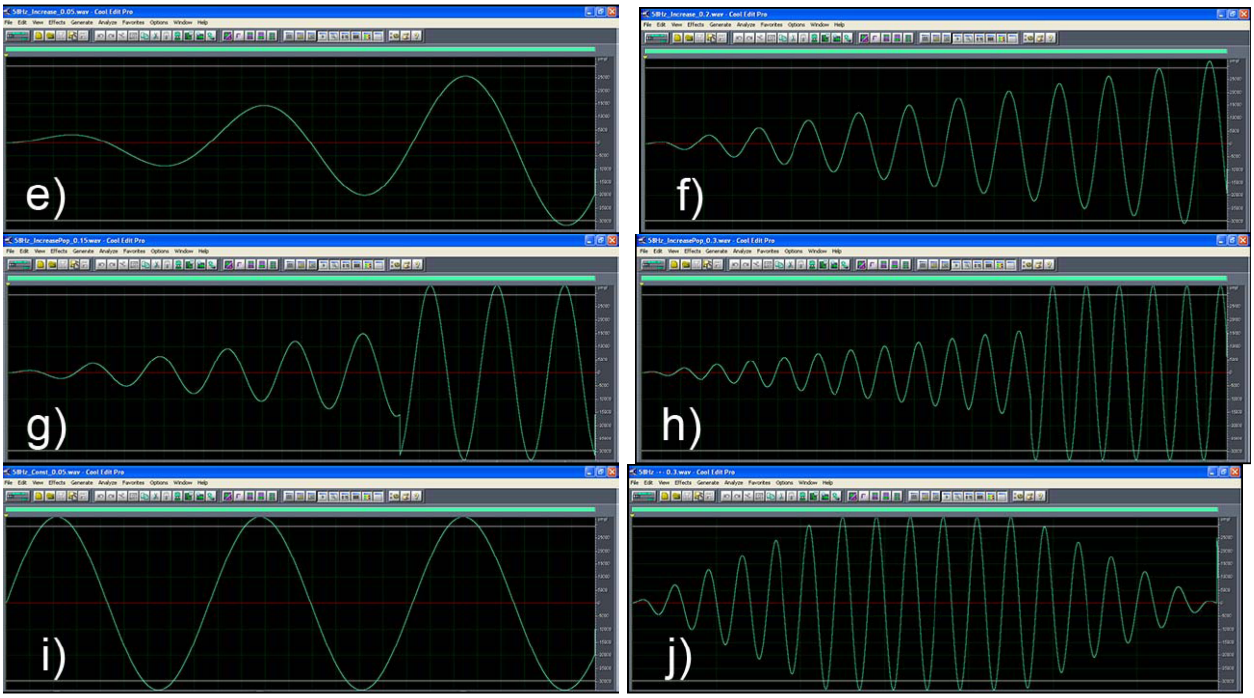


Figure 29: Stimuli at the frequency of 58 Hz

a) 58 Hz, 50 ms, decreasing amplitude;

b) 58 Hz, 200 ms, decreasing amplitude;

c) 58 Hz, 150 ms, decreasing amplitude, with a brief intense final impulse;

d) 58 Hz, 300 ms, decreasing amplitude, with a brief intense final impulse;

e) 58 Hz, 50 ms, increasing amplitude;

f) 58 Hz, 200 ms, increasing amplitude;

g) 58 Hz, 150 ms, increasing amplitude, with a brief intense final impulse;

h) 58 Hz, 300 ms, increasing amplitude, with a brief intense final impulse;

i) 58 Hz 50 ms, constant amplitude;

j) 58 Hz, 300 ms increasing and decreasing amplitude.

Scrolling sliders and knobs

Unlike buttons, sliders and knobs are usually assigned a set of continuous values along one axis. In this experiment, the stimuli were applied in cycles of 150 ms, consisting of 100 ms vibration and 50 ms silence. As shown in Figure 33, three sets of values were used as design features: 1) increasing and decreasing frequencies corresponding to the incremental steps of the slider or knob and played in loop mode; 2) increasing and decreasing amplitudes corresponding to the incremental steps of the slider or knob and played in loop mode; 3) a stimulus applied only when the slider or knob is moved from one incremental step to another to create a range of detent sensations. This experiment aimed to identify the most suitable tactile effects for the virtual slider and knob.

Selecting checkboxes

A checkbox has two states: selected and deselected. This experiment investigated tactile sensation of these two checkbox states by applying two different stimuli: 1) a 58 Hz, 200 ms sine wave of decreasing amplitude and 2) a 58 Hz, 150 ms sine wave of decreasing amplitude with a brief intense final impulse.

6.4.4 Simulation of physical buttons

To give the impression of a button having an edge, three techniques were used to simulate interaction with physical buttons on screens: 1) an impulse when the finger moved onto the button; 2) an impulse when the finger moved onto, followed by an impulse when the finger let go of the button and 3) constant vibration as long as the finger stayed on the button, as illustrated in Figure 30.

The tactile stimulus used in the first and second techniques was an 80 Hz, 200 ms sine wave of decreasing amplitude. An 80 Hz, 200 ms sine wave was used for constant vibration as long as the finger stayed on the button.

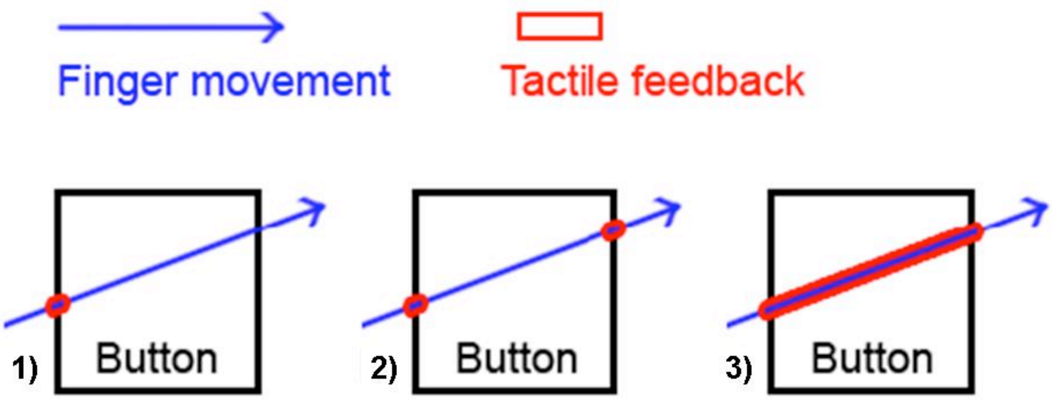


Figure 30: Three interaction techniques applied when the finger moves onto the button

6.5 Research method

6.5.1 Participants

Eighteen subjects, five women and thirteen men, aged between 22 and 58 years (mean = 34), participated in this experiment. The subjects were employees, intern students and consultants at Siemens AG in Munich. All subjects were right handed, with no known hand disorders. They used their right hands for this experiment.

6.5.2 Experiment procedure

During the experiment, participants were asked to wear a headset emitting constant noise so that they could not hear but only feel the vibrations generated by the bass shakers. Use of the human visual channel was allowed. Participants selected the stimuli with which they subjectively felt comfortable as the haptic behavior of the UI controls.

Part I: Semantics of UI controls

Comparison of buttons

Based on past studies on the properties of human tactile perception, Jone & Sarter [128] concluded that, of the available parameters frequency, amplitude, locus and duration, the skin's ability to discriminate between differences in vibration frequency is poor; however, duration is a highly exploitable parameter in this respect. In this part, therefore, duration and amplitude as two parameters for a vibrotactile stimulus – but not frequency – were investigated as to which can better simulate the sensation of a mechanical button. Based on the results regarding the perceptibility of different frequencies in chapter 5, the best perceived frequencies of 58 Hz and 80 Hz were used for our hardware setup in this experiment. Firstly a group of ten buttons with a frequency of 58 Hz were displayed randomly on the screen, as shown in Figure 31 (a). Participants were asked to compare these ten buttons and select the three which were most easily associated with pressing a real button. Following that, a group of ten buttons with a frequency of 80 Hz were displayed, and participants were again asked to select the three which were most easily associated with a real button, as shown in Figure 31 (b). The buttons were designed with a size of 100 x 80 pixels.

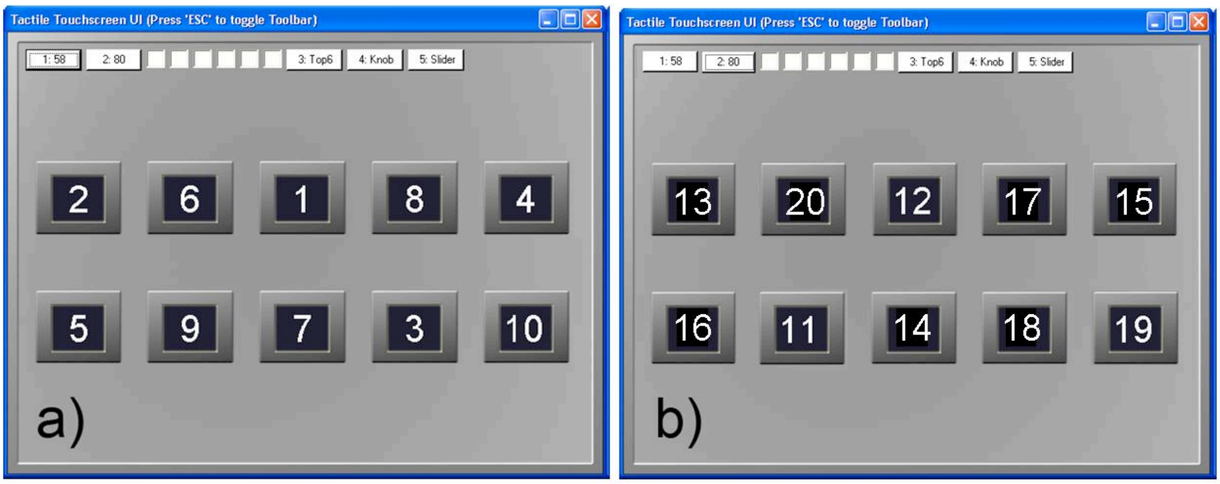


Figure 31: Testing twenty vibrotactile stimuli of buttons

The six selected stimuli, which consisted of three signals at 58 Hz and three at 80 Hz, were then presented randomly on the screen, and participants were asked to rank them according to how well they gave the impression of pressing a real button (see Figure 32).

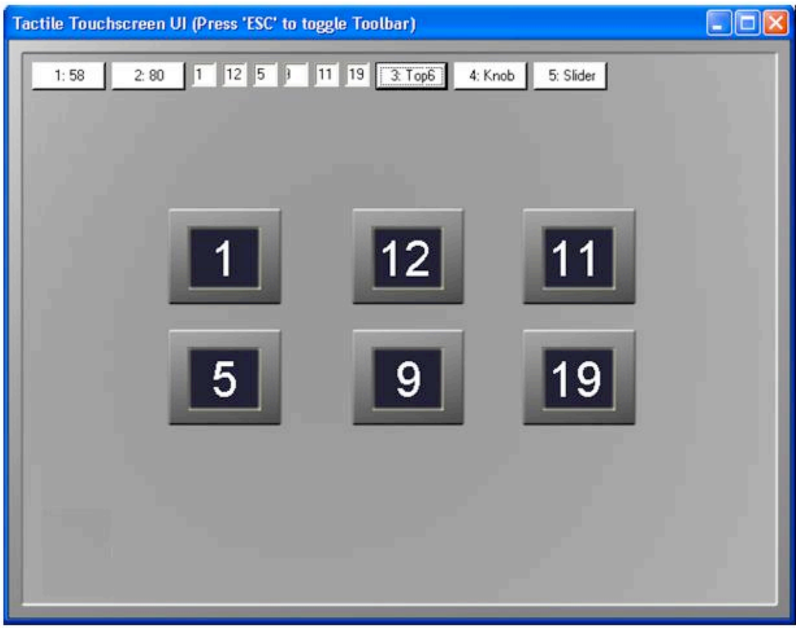


Figure 32: Testing the last six vibrotactile stimuli of buttons

Comparison of knobs

In this part, participants were asked to compare three knobs, the stimuli for which were designed as described in section 6.4.3. To rank the knobs in terms of their vibrotactile feedback, participants were asked to state which they could most easily associate with a physical knob, as shown in Figure 33 (a)).

Comparison of sliders

Three stimuli, as described in section 6.4.3, were assigned to sliders. Participants were asked to compare them and rank them in terms of how easy they were to associate with a real slider (see Figure 33 (b)).

Figure 33: Comparing knobs and sliders

Comparison of checkboxes

Two checkboxes were designed: the first with only one of its two states indicated by a 58 Hz, 200 ms signal of decreasing amplitude; the second with one of its states indicated by a 58 Hz, 200 ms signal of decreasing amplitude and the other indicated by a 58 Hz, 150 ms signal of decreasing amplitude with a brief intense final impulse (see Figure 34). Participants were asked to choose the one that was better to manipulate in a visually and auditorily distracting environment.

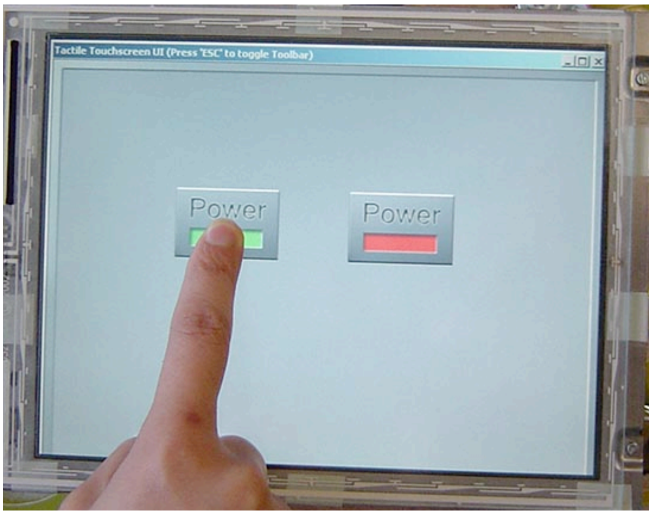


Figure 34: Testing two checkboxes with one and two states
(the colors green and red show the current state of the respective checkbox.)

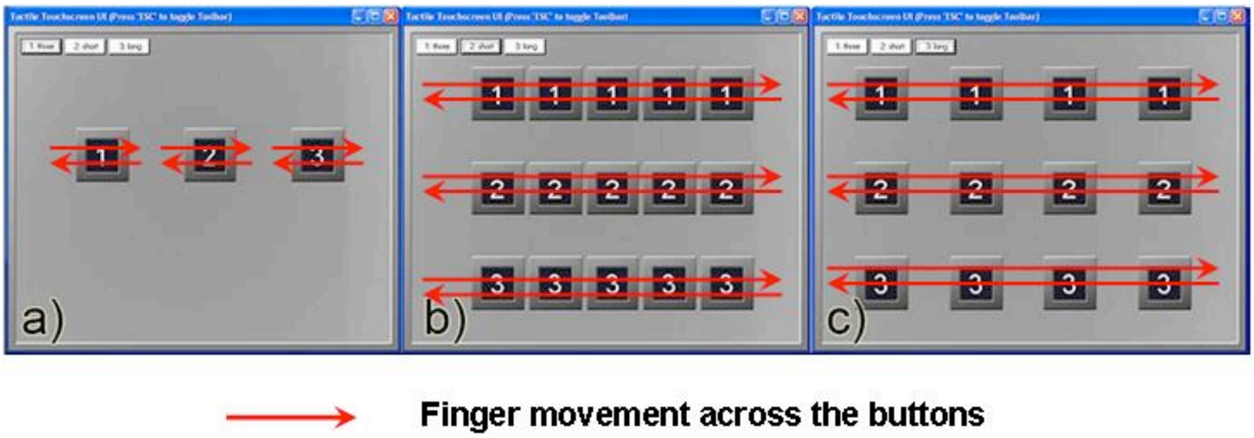


Figure 35: Testing buttons with different distances in rows
(a. three different simulation techniques independing on distance; b. three different simulation techniques with intervening space of 2 mm; c. three different simulation techniques with intervening space of 15 mm)

Part II: Simulation of physical buttons depending on distance

In this part, participants were first asked to rank the three techniques described in section 6.4.4 for simulating the edge of a real button (see Figure 35 (a)). Considering that the space between buttons can impact on conveying the impression of having a button edge, following that, each of these three techniques was presented in the form of two separate button interfaces: one interface where the buttons were positioned very close together in rows with intervening spaces of 2 mm (see Figure 35 (b)), and another interface in which they were set further apart in rows with intervening spaces of 15 mm (see Figure 35 (c)). Participants were asked to compare the techniques by moving their finger along each row of buttons and ranking the techniques presented in terms of how closely they resembled the feel of real buttons.

6.6 Subjective evaluations

Part I: Semantics of UI controls

Buttons

In the first part of this experiment, various stimulus durations (50 ms, 150 ms, 200 ms and 300 ms) were analyzed to determine whether they have any significant effect on the successful simulation of the feel of a button; here the parameters frequency and amplitude were ignored, and the data was sorted purely by duration (see Figure 36). The statistical analysis used was a standard single factor ANOVA analysis, where alpha = 0.05, which shows that there are significant differences in sensitivity ($p = 0.011 < 0.05$). A stimulus of 150 ms meets with the highest preference as a means of synthesizing the feel of a button click.

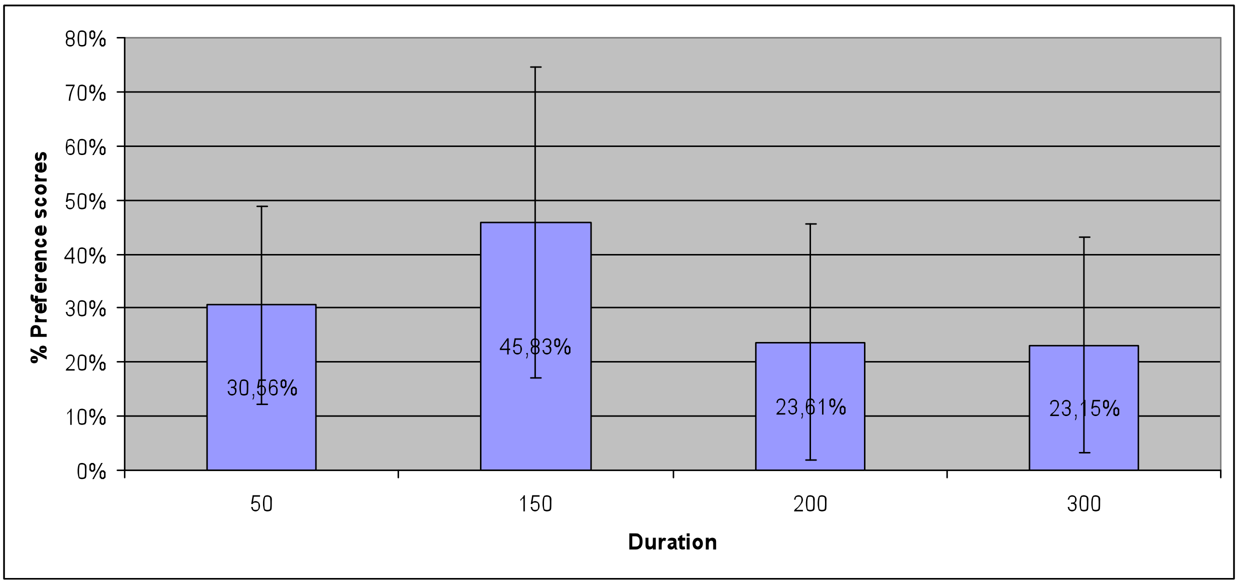


Figure 36: Perceptibility of four durations as a factor affecting the successful simulation of the feel of a button (with standard deviations)

As a second step, various amplitudes, as shown in Figure 37 and Figure 38, were analyzed to determine whether they have any significant effect on the successful simulation of the feel of a pushbutton; here the parameters frequency and duration were ignored, and the data was sorted purely by amplitude. In this step, various amplitudes were grouped into one type with a final impulse and another type without a final impulse (see Figure 37), in order to further determine whether one of two kinds of amplitudes can help to simulate successfully the sensation of pushing a pushbutton. A two-sample t-test assuming equal variances (where alpha = 0.05) shows that there is a significant difference in sensitivity between stimuli with a brief intense final impulse (36.81%) and without (25.46%), with $p = 0.007 < 0.05$. A stimulus with a brief intense final impulse can achieve an increase in sensitivity of 11.35% compared with a stimulus without a brief intense final impulse.

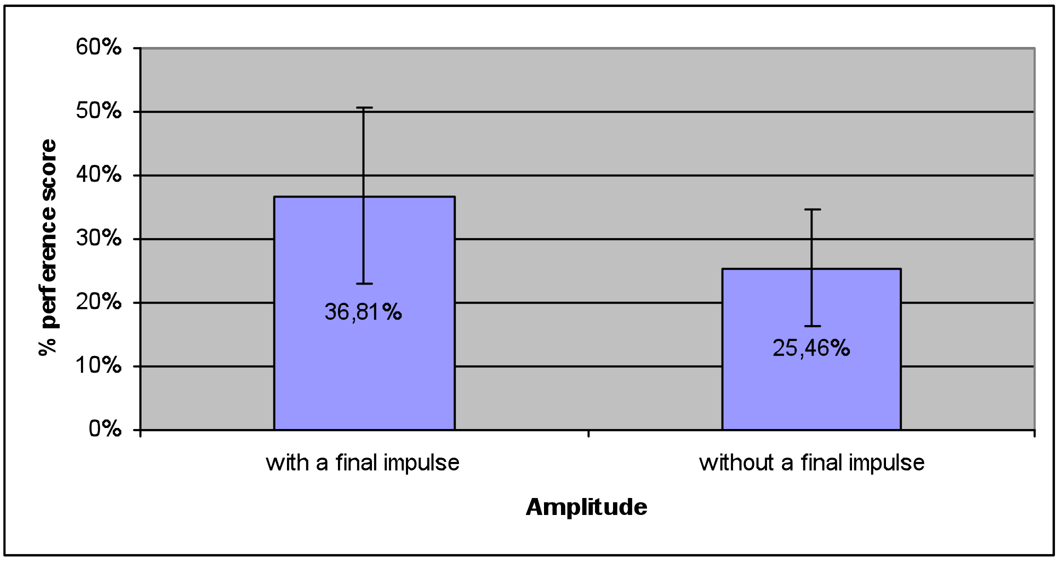


Figure 37: Perceptibility of stimuli with a brief final impulse as a factor affecting the successful simulation of the feel of a button (with standard deviations)

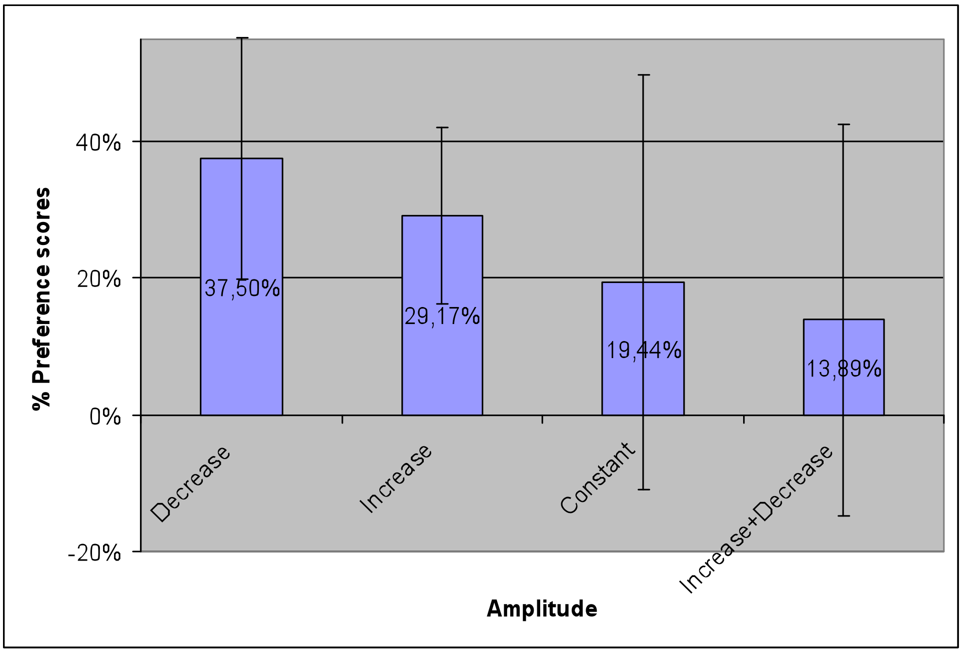


Figure 38: Perceptibility of four different amplitudes for simulating the feel of a button (with standard deviations)

This being so, the amplitudes were further analyzed in relation to whether they were increasing (29.17%), decreasing (37.5%) or constant amplitudes (19.44%), or a combination of increasing and decreasing amplitude (13.69%), as shown in Figure 38. A single-factor ANOVA analysis (where alpha = 0.05) shows that there are also significant differences between mean preferences for increasing, decreasing and constant amplitudes, and for the combination of increasing and decreasing amplitudes ($p = 0.02 < 0.05$).

Sliders

The statistical analysis used here was a Friedman test (see Figure 39), which shows that there is a significant difference in rankings for sliders ($\chi^2 = 14.333 > \chi^2_{0.95}(2) = 5.9915$, $p = 0.001 < 0.05$). A stimulus of changing amplitude met with the highest preference as a means of simulating the feel of a slider in comparison to a stimulus of changing frequency and a stimulus of moving from one incremental step to another.

Knobs

The statistical analysis used here was a Friedman test (see Figure 40), which shows that there is a significant difference in rankings for knobs ($\chi^2 = 19 > \chi^2_{0.95}(2) = 5.9915$, $p = 0.0001 < 0.05$). A stimulus of changing amplitude met with the highest preference as a means of simulating the feel of a knob. Meanwhile, some test participants complained that a stimulus delivered only when the knob was moved from one incremental step to another – while it could create a detent sensation – did not provide the feel of a continuous state change. So this kind of design feature as a means of simulating the feel of a knob is not better perceived than a stimulus of changing frequency or amplitude.

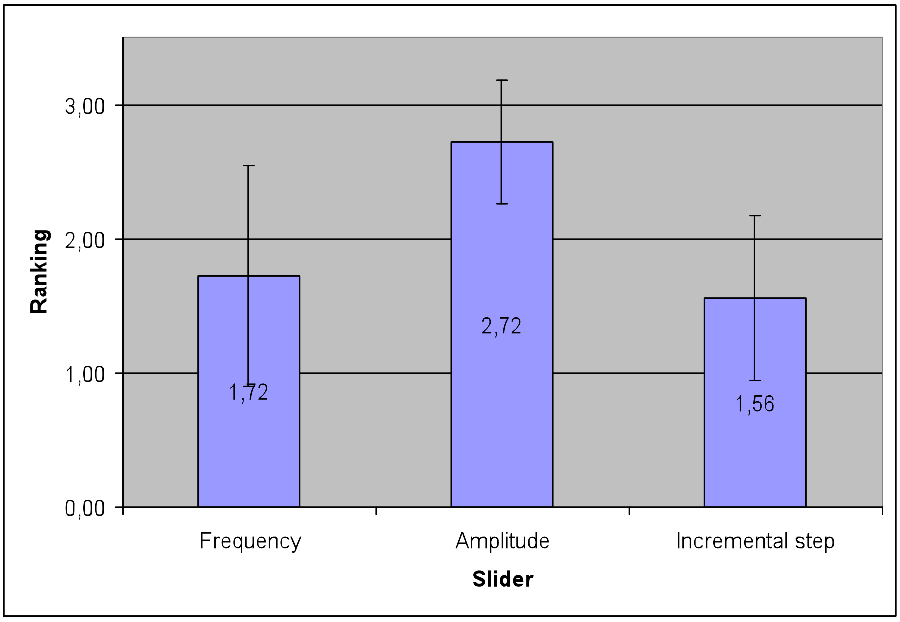


Figure 39: Comparing three different parameters for simulating the feel of a slider (with standard deviations)

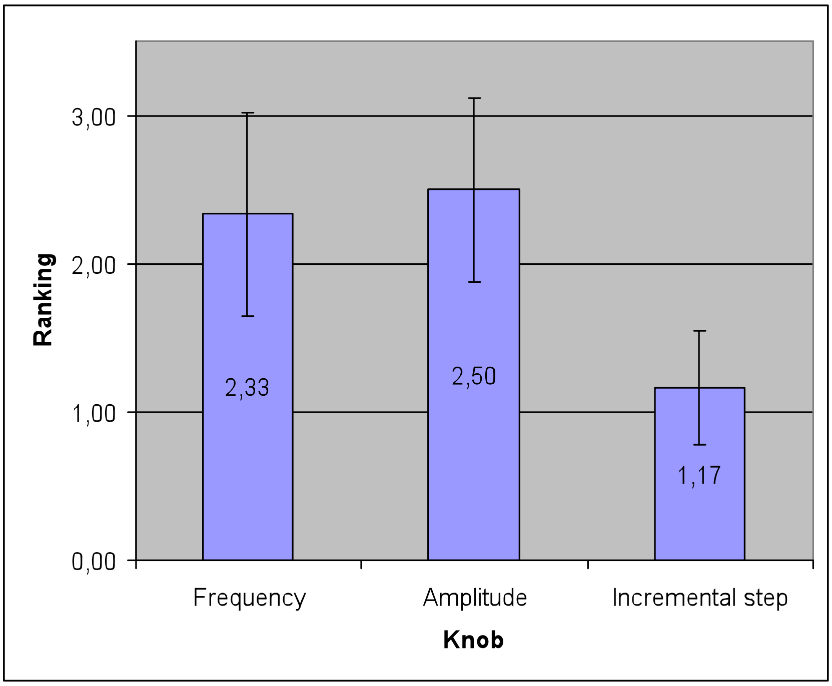


Figure 40: Comparing three different parameters for simulating the feel of a knob (with standard deviations)

Checkboxes

The statistical results of a wilcoxon signed-rank test (p=0.346 > 0.05) suggest that there is no significant difference between a checkbox with the selected state and a checkbox with the selected and unselected states, as shown in Figure 41.

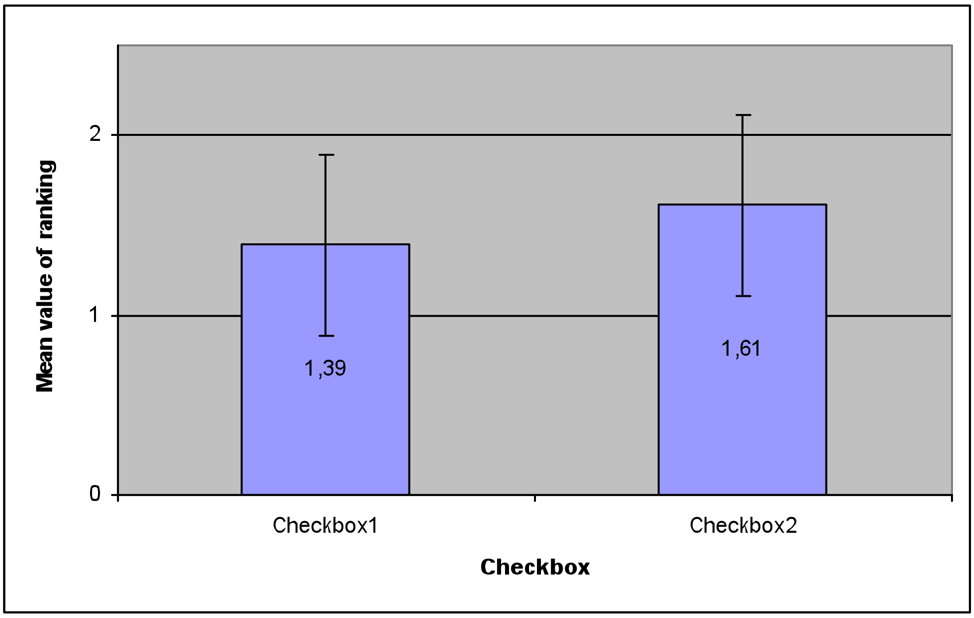


Figure 41: Comparing checkboxes with one and two states (with standard deviations)

Part II: Simulation of physical buttons depending on distance

Firstly in this part, three techniques for simulating interaction with the edges of physical buttons were compared with each other. A Friedman test for three related samples shows that there is no statistically significant difference ($\chi^2 = 0.778 < \chi^2_{0.95}(2) = 5.9915$, $p = 0.678 > 0.05$) among the three techniques examined, as shown in Figure 42. Regarding the second simulation technique, some of participants considered that without a visual cue, they could not distinguish which impulse was for moving onto a button and which impulse was for moving off a button.

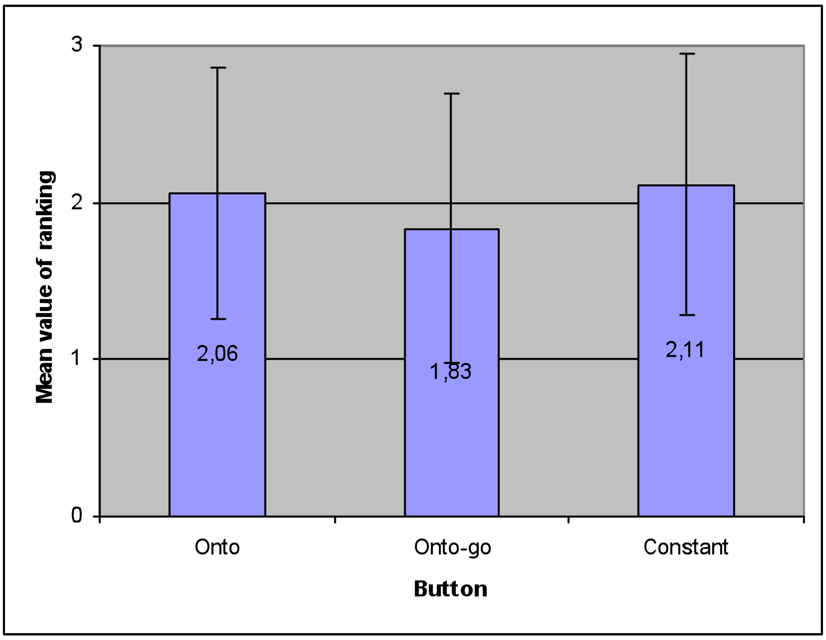


Figure 42: Comparing three different techniques for simulating a physical button (with standard deviations)

Moreover, these three kinds of simulation techniques were compared with a small space and a large space between buttons, as shown in Figure 43 and 44. The statistical analysis used was a Friedman test for three related samples, which shows that there is a statistically significant difference among the three groups of buttons positioned very close together ($\chi^2 = 10.333 > \chi^2_{0.95}(2) = 5.9915$, $p = 0.006 < 0.05$), and that there is also a statistically significant difference among the three groups of buttons positioned further apart from each other ($\chi^2 = 17.333 > \chi^2_{0.95}(2) = 5.9915$, $p = 0.0002 < 0.05$). The results indicated that an impulse delivered when the finger moved onto the button met with the highest preference as a means of simulating the edges of physical buttons set very close together. However, with a large space between buttons, the best usability result was achieved by applying constant vibration as long as the finger stayed on the button, which met with the highest preference as a means of synthesizing the edges of physical buttons positioned further apart from each other.

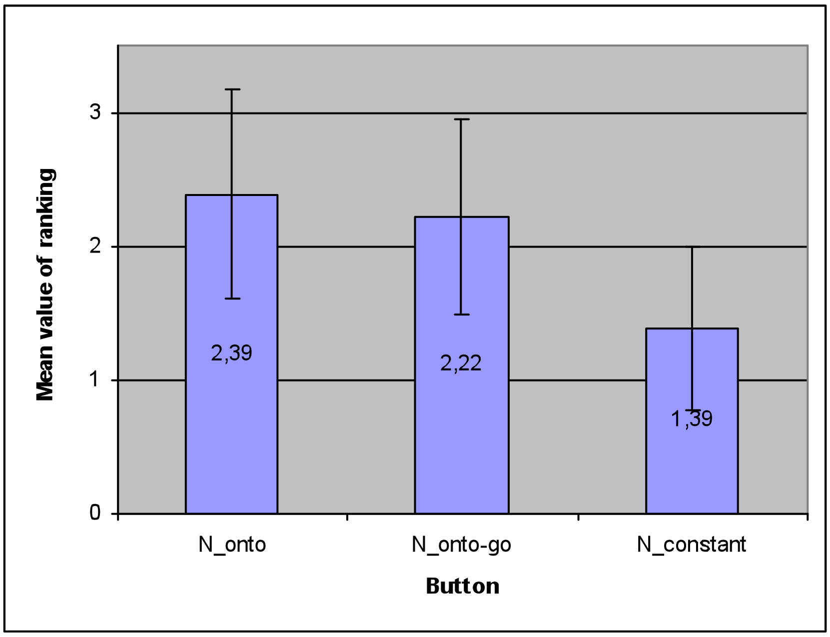


Figure 43: Comparing three different techniques for simulating the edge of physical buttons with a small space between them (with standard deviations)

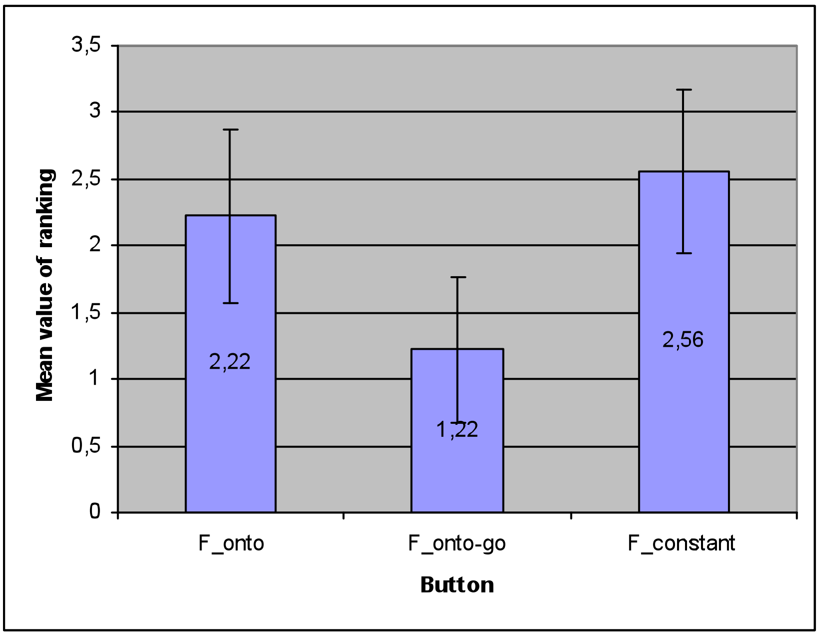


Figure 44: Comparing three different techniques for simulating the edge of a physical buttons with a large space between them (with standard deviations)

6.7 Conclusion on designing haptically enhanced UI controls

By examining the frequency, amplitude and duration of vibrotactile stimuli, the first part of the experiment studied the semantics of perceiving mechanical buttons, sliders, knobs and check-boxes on screen.

A stimulus of 150 ms was shown to be the best duration for synthesizing the feeling of a button click when frequency and amplitude are ignored. This indicates that people only need around 150 ms to react to the feeling of a button click – shorter durations tend to be ignored, and longer durations are perceived as sluggish and are therefore unnecessary. When frequency and duration are ignored, a stimulus with a brief intense final impulse can achieve an increase in sensitivity compared to a stimulus without a brief intense final impulse. A stimulus of decreasing amplitude provided the best perception of seeming to press the button as if were mechanical. Future work with a large group of samples is necessary to further investigate whether a stimulus of a duration of 150 ms combined with an amplitude of decreasing effect and a brief intense final impulse can provide the best sensation of a mechanical button.

As far as sliders and knobs are concerned, a stimulus of changing amplitude was shown to provide the natural feel of moving either a slider or a knob. This indicates that the human tactile channel is more sensitive in identifying an intensity change as representing a set of continuous values along one axis than it is in perceiving differences in vibration frequency, which is in accordance with the findings made on designing tactile displays by Jone & Sarter [128].

As to checkboxes, in general the selected and unselected states of a checkbox can be described as two kinds of button clicks. If the tactile feedbacks for two states of a checkbox have no significant distinction in vibrotactile duration, amplitude or frequency, this will increase cognitive load, making two states of a checkbox hard to discriminate.

The distance between UI controls can be a major factor impacting how to arrange them on the user interface to enable accurate selection. The findings made here revealed that, as a means of simulating the edges of physical buttons, an impulse delivered when the finger moved onto the button enabled clear perception of sets of buttons placed very close together, whereas with a large space between buttons, the best usability result was achieved by applying constant vibration for as long as the finger stayed on the button. This finding will be beneficial in guiding the arrangement of UI controls on a tactile touchscreen.

The typical UI controls reviewed in this chapter, in combination with the individual effects of varying frequency, amplitude and duration, were investigated as a basis for dynamic simulation of physical controls, which in turn will be further investigated in the following chapters.

7 Operation of a touchscreen incorporating tactile feedback when used for a primary task

Because a touchscreen enables users to interact directly with objects displayed and their positions, without the need for any intermediate device, a touchscreen usually serves as an integrated input/output device for the performance of a primary task. A number of studies [25] [82] [112] stated that using a tactile touchscreen for a primary task can enhance the usability and enjoyment of the touchscreen and reduce errors. To complement this, it is necessary to investigate whether a tactile touchscreen can be effectively used in a distracting environment in daily life and also in the harsh conditions of an industrial workshop.

In this chapter, a tactile touchscreen is compared with a touchscreen without tactile cues in a distracting and stressful situation. Furthermore, two sample applications involving a tactile touchscreen are designed in certain usage scenarios, with a view to selecting a touchscreen solution and matching tactile effects.

Furthermore, two sample applications incorporating a tactile touchscreen are designed for specific usage scenarios, the challenge being to select a touchscreen solution and tactile effects that best match the requirements of the situation.

7.1 Experiment design

A 5-wire resistive touch panel was selected as a platform for experiencing tactile effects in UI controls for a primary task. The touchscreen hardware in this experiment was built as illustrated in Figures 26, 27 and 28.

In order to determine whether a touchscreen incorporating tactile feedback results in better usability than a touchscreen that has only a hard and non-responsive surface, a number of standard UI controls were tested in a simulated GUI application consisting of two control modes: a media player control and a room lighting control. The media player control was designed with seven buttons, two checkboxes and one knob, as shown in Figure 45. The pair of buttons at the top left were designed to be displayed permanently on the interface that can be used to switch to the media player control mode as shown in Figure 45 or switch back to the room light control mode as shown in Figure 46. The pair of buttons at the top left of the user interface were used to switch between the media player control mode and the room lighting control mode.

The room lighting control was designed with two buttons, three checkboxes and three sliders, as illustrated in Figure 46. The living room, bedroom and bathroom lights can be turned on/off with the buttons at the top right of the interface. They can also be switched on/off individually with the checkboxes. The pair of buttons at the top left of the user interface are used to switch between the media player control mode and the room lighting control mode.

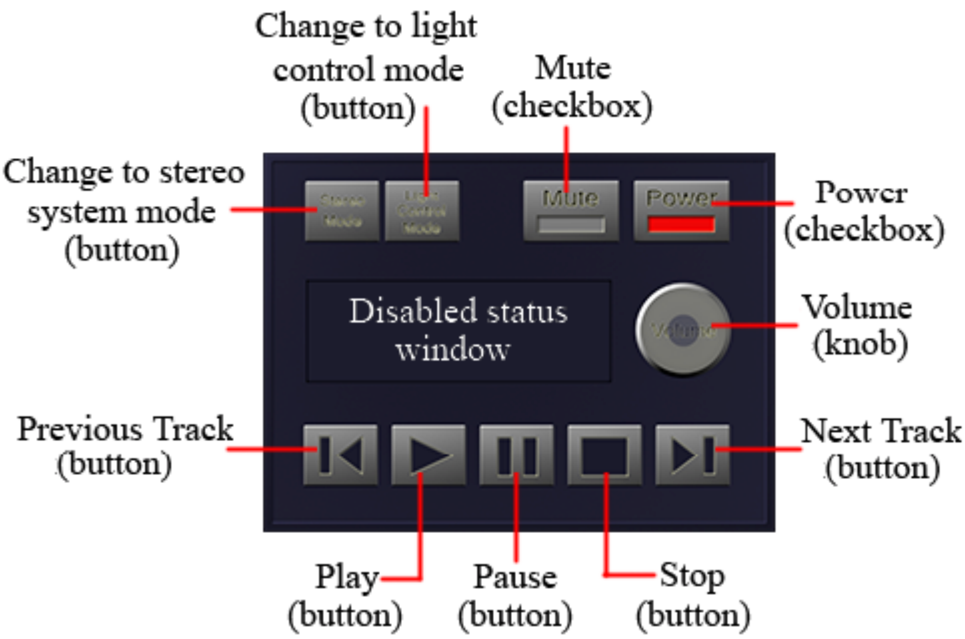


Figure 45: GUI design of a media player control

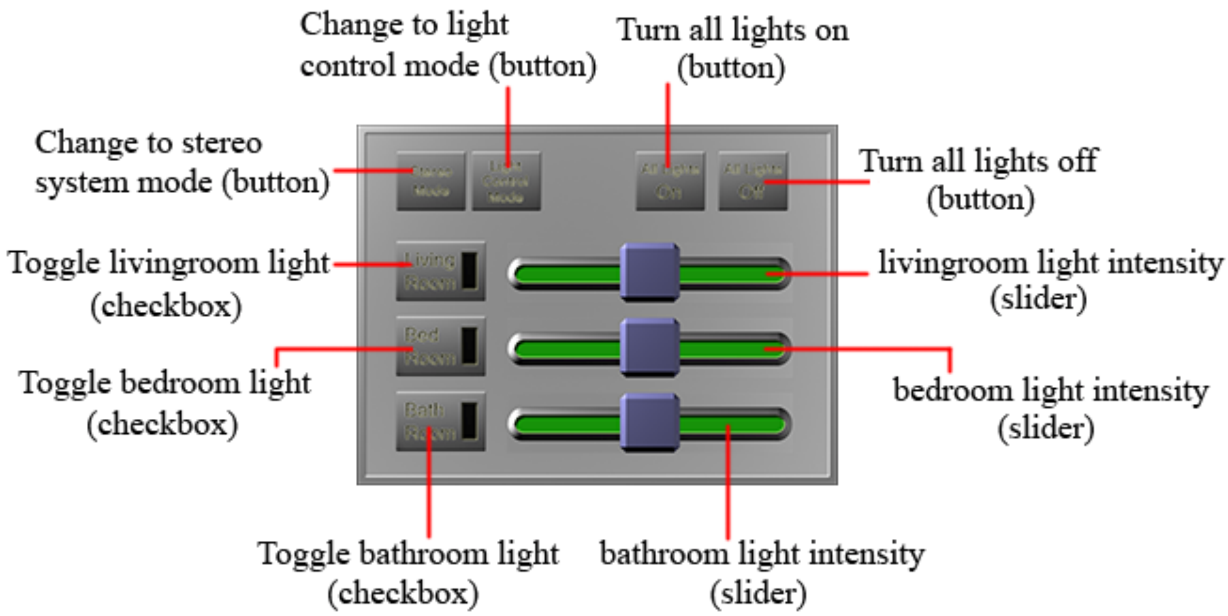


Figure 46: GUI design of a room light control

To simulate attention to a work process, a secondary task was designed to occupy the human visual channel while users were manipulating the tactile touchscreen. For this task, a new letter was displayed randomly every two seconds on the laptop. Figure 47 (1) shows the setup of this experiment: A is the touchscreen with resistive technology which was designed as a device for the primary task and C is an extra laptop on which the secondary task was played. The subject B has to manipulate the touchscreen while using the human visual channel to perform the secondary task presented on the laptop.

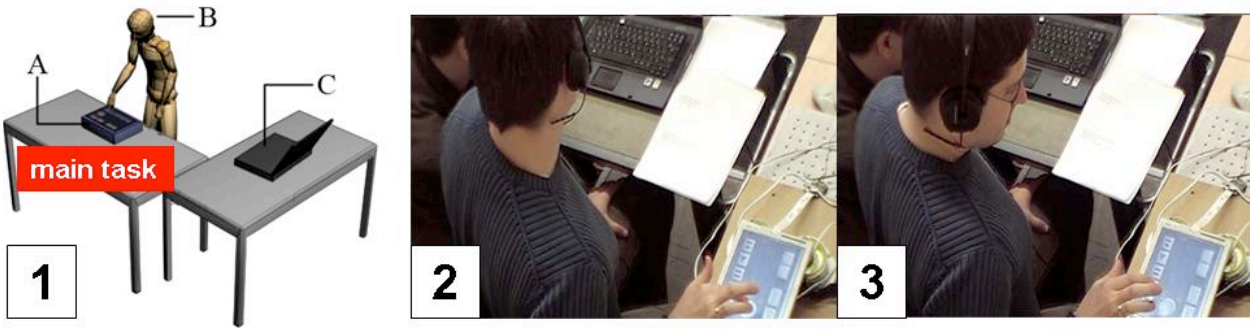


Figure 47: Setup of the experiment to used a touchscreen to perform primary task

During the test, participants were asked to read aloud the letters presented on the laptop (object C in Figure 47 (1)) while they were performing the tasks on the touchscreen (see Figure 47 (2) and 47 (3)). Whenever a test participant read a letter wrongly or missed a letter, the observer pressed the button at the bottom of the interface to record it, as shown in Figure 48. The total number of letters the participant had read so far was displayed at the top left of the interface on the laptop. When the tasks were completed, the system would calculate the number of letters that participants had read wrongly or missed out. The display of random letters could be paused anytime as needed. The system on the laptop was designed to record the time of the start and end of the test and calculate its duration. The duration of any pauses was subtracted automatically by the system from the total duration. The result calculated by the system for one test session was saved automatically as a test block in a txt file, as shown in the following example.

****

Sub Summary

Start Time: 04.12.2008 14:21:17

End Time: 04.12.2008 14:21:31

Duration: 00:00:14.7812500

Wrong Characters: 1

Total Characters: 7

****

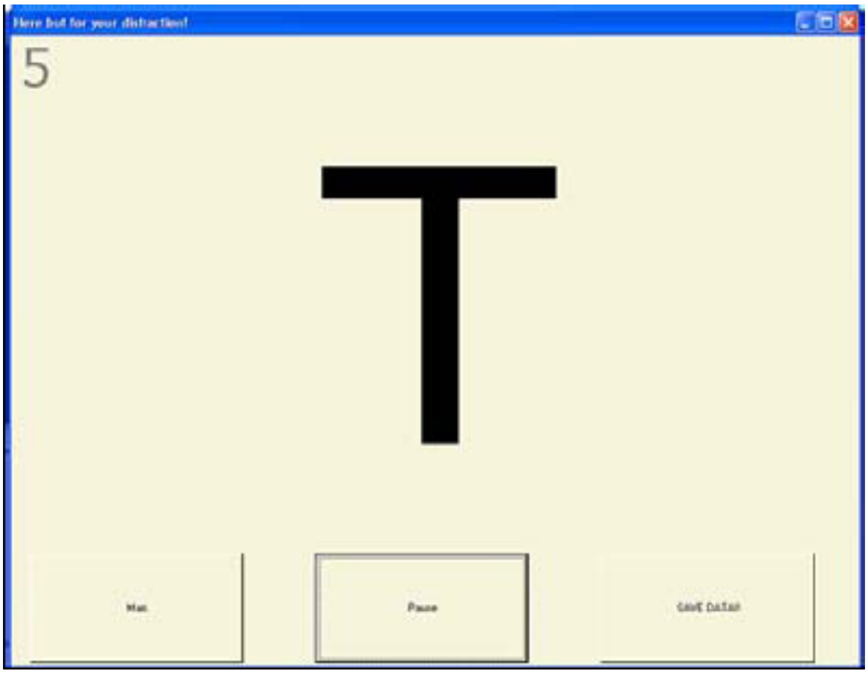


Figure 48: Generation of random letters

7.2 Research method

7.2.1 Participants

Eighteen subjects, five women and thirteen men, aged between 22 and 58 years (mean = 34), participated in this experiment. The subjects were employees, intern students and consultants at Siemens AG in Munich. All subjects were right handed, with no known hand disorders. They used their right hands for this experiment.

7.2.2 Experiment procedure

During the experiment, participants were asked to wear a headset emitting constant noise so that they could not hear but only feel the vibrations generated by the bass shakers. Use of the human visual channel was permitted. The aim of this experiment was to investigate, in a scenario where a touchscreen is used for a primary task, how tactile touchscreen technology can meet user needs in ways that are not currently met by visual and auditory interfaces alone.

Thirty-six commands were grouped into twelve sets. Each set consisted of three commands such as “select stereo mode”, “turn volume to maximum”, “change living room light to maximum” and so on. Participants were then asked to perform these sets of three commands, one set after the other, on the touchscreen. Between the end of one set of three commands and the start of the next, no new letters were displayed on the laptop playing the secondary task.

Each participant completed the test tasks twice on the touchscreen: once with tactile feedback and once without. The first participant started by performing the tasks with tactile feedback, and subsequently performed the same tasks without tactile feedback. Conversely, the second participant first carried out the tasks on the touchscreen without tactile feedback, and then did them again with tactile feedback. This rule continued to determine whether participants started their tasks with or without tactile feedback.

The touchscreen system recorded commands performed, errors made and runtime. An error was recognized when a command was input wrongly or missed out. A repeat input of the same wrong command was recorded as one error only. The following example of a file recorded by the system captures the current mode ("stereo mode" for the media player control or "lights mode" for the room lighting control), the date and the time when the command was performed, the type of UI control activated and the ID number of the UI control (every UI control was coded with an individual ID number.). This example shows that the "mute" checkbox (no. 1) in "stereo mode" was activated wrongly on the touchscreen.

```
***********************************************
+LightsMode | 04.12.2008 14:19:24 | Button: 5
-StereoMode | 04.12.2008 14:19:26 | CheckBox: 1 - False
-StereoMode | 04.12.2008 14:19:27 | Button: 3
-StereoMode | 04.12.2008 14:19:28 | Button: 3
-StereoMode | 04.12.2008 14:19:28 | Button: 3
***********************************************
```

7.3 Subjective evaluations

In order to find out whether a touchscreen incorporating tactile feedback provides better usability than a normal touchscreen with only a fixed, unmoving surface, these two kinds of touchscreens were compared in this test where a touchscreen was used to perform a primary task.

The statistical analysis used – a t-test, as illustrated in Figure 49 – indicated that a touchscreen with tactile feedback produces a significantly lower error rate than a touchscreen without tactile feedback ($p = 0.028 < 0.05$). A tactile touchscreen can achieve a reduction in error rate of about 9.42% compared with a non-tactile touchscreen. However, there is no statistically significant difference between the speed at which the 36 tasks were completed on a touchscreen with tactile feedback and the speed at which the same tasks were completed on a touchscreen without tactile feedback ($p = 0.66 > 0.05$).

In addition, the participants were asked to compare a touchscreen with tactile feedback and a touchscreen without tactile feedback in a group of items that can be grouped into four dimensions of quality [@8]:

- Pragmatic Quality
- Hedonic Quality – Stimulation
- Hedonic Quality – Identity

  and
- Attractiveness

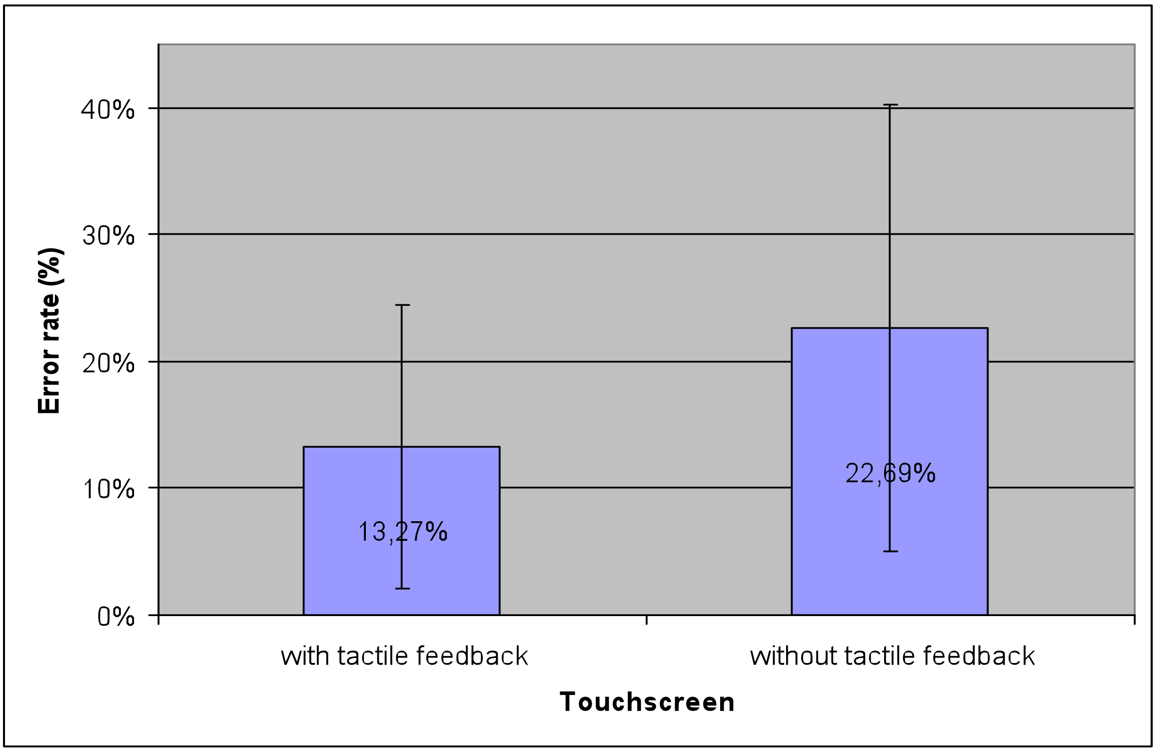


Figure 49: Comparing touchscreen with / without tactile feedback with error rate (with standard deviations)

In all, these dimensions comprise 28 items acting as semantic differentials. Pragmatic quality addresses the practical characteristics of a product in terms of its usability and utility, for example whether it is controllable and trustworthy, whereas hedonic quality addresses the users' desire for enjoyment and for the avoidance of boredom and discomfort. The stimulation aspect of hedonic quality describes whether a product can satisfy users' needs to improve their knowledge and skills, meaning the creative or original characteristics of a product, while the identity aspect of hedonic quality focuses on the ability of a product to facilitate communication in real life, for example, whether a product enables a user to interact purposefully with others. Lastly, attractiveness in an interface will result in greater user satisfaction and preference, insofar as a product is pleasing and comfortable to use. These properties of a user interface influence perceived usability and personal preference for a product. They also give insight into what aspects of the UI of both a tactile touchscreen and a normal touchscreen can be improved. These dimensions of quality are measured by filling out the "AttrakDiff 2" questionnaire based on Hassenzahl et al.'s study [104].

When a touchscreen was used to perform a primary task, the incorporation of tactile feedback clearly enabled better performance with a touchscreen, as shown in Figures 50, 51 and 52. In these figures, touchscreen interaction with tactile feedback is shown to be significantly better at achieving the performance and making users feel more in control. For each dimension of quality, a tactile touchscreen produces a significant improvement in performance compared with a non-tactile touchscreen, as shown in Figure 50.

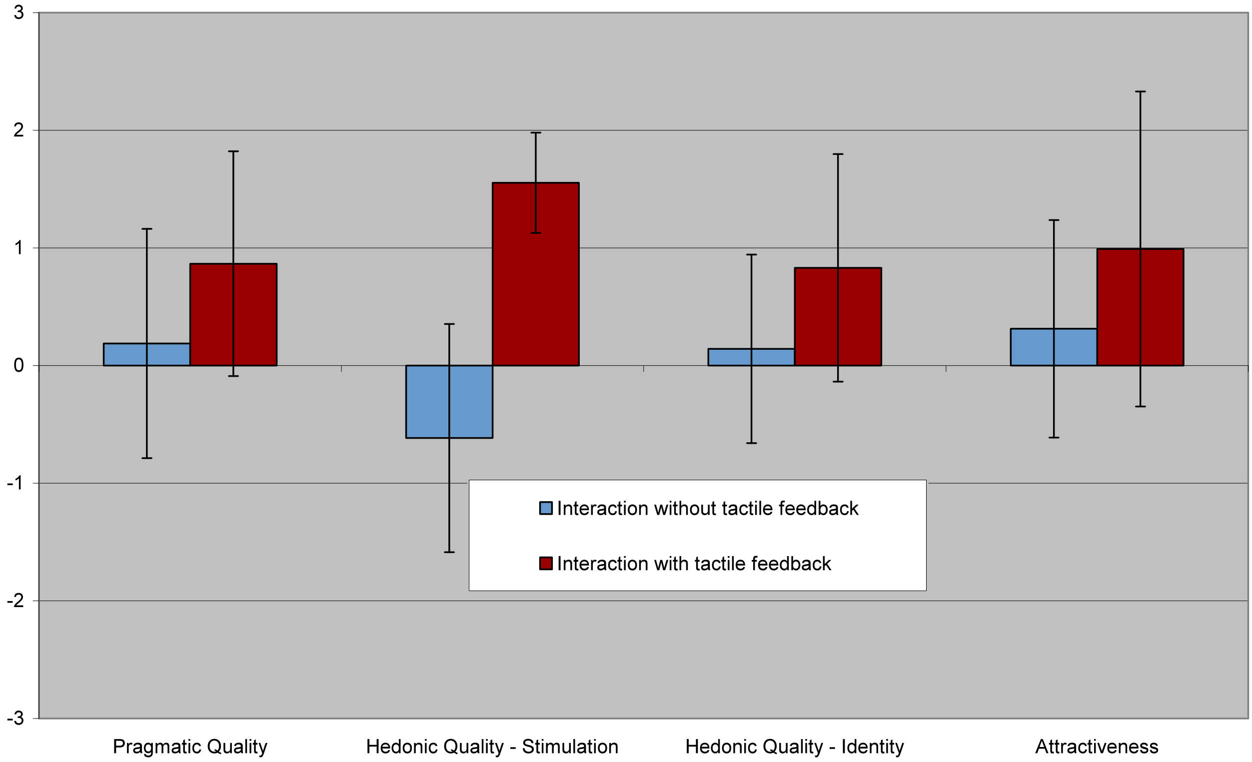


Figure 50: Subjective perception of touchscreen interaction with and without tactile feedback when performing a primary task expressed in four dimensions of Pragmatic Quality, Hedonic Quality - Stimulation, Hedonic Quality - Identity and Attractiveness

Figure 51 shows the result of a comparison of pragmatic, hedonic and attractive qualities according to all twenty-eight criteria. For almost all of participants, it was first time they had used a touchscreen with tactile feedback. Some participants immediately felt that this kind of touchscreen was innovative and easy to control, whereas some of them still needed some time to get used to the tactile stimuli. This suggests that the tactile stimuli can be personalized to satisfy users' individual needs.

In Figure 52, the difference in performance between the two kinds of touchscreens in terms of pragmatic and hedonic qualities is significant. A touchscreen incorporating tactile feedback was rated as more user-oriented than a touchscreen with a hard surface. The test participants acknowledged that a tactile touchscreen is creative and challenging; in particular they felt it distinctly reduced the cognitive burden in a distracting environment as compared with a touchscreen without tactile feedback used to accomplish the same set of tasks.

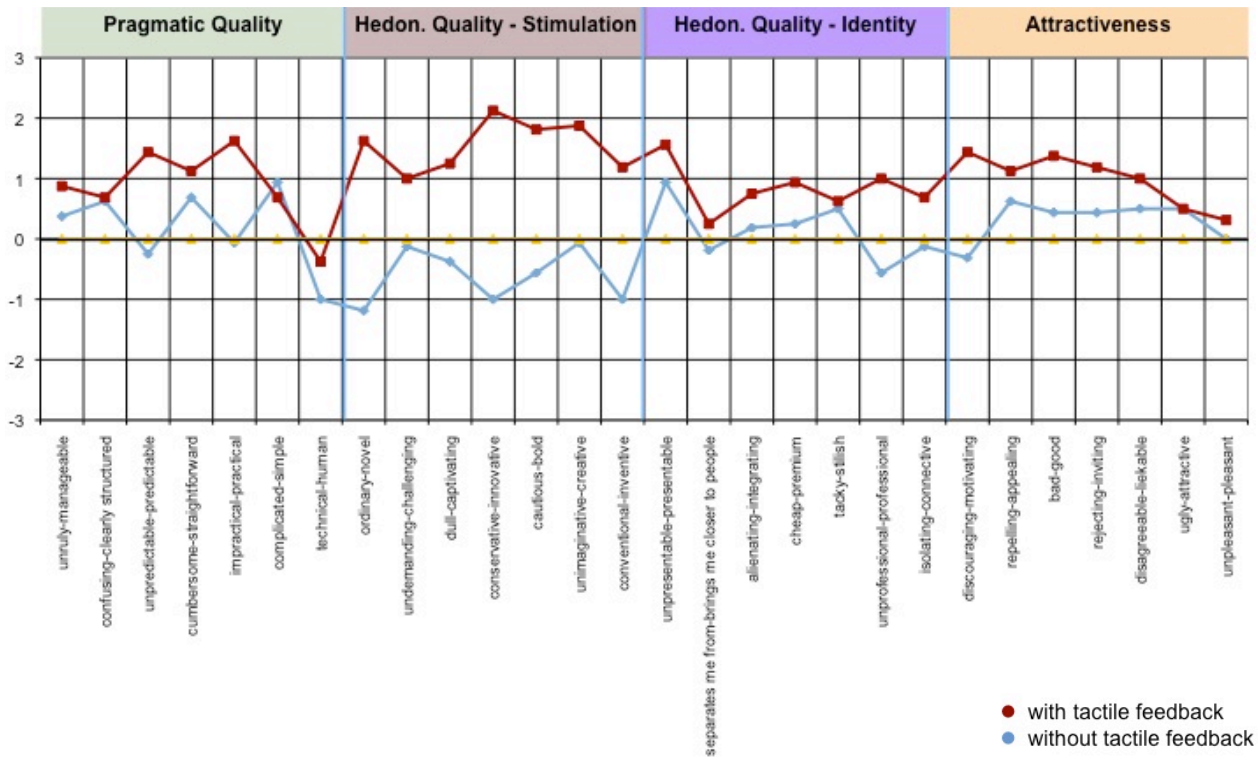


Figure 51: 28 criteria to measure the usability of a touchscreen with and without tactile feedback for a primary task

Figure 52: Portfolio chart comparing to a tactile touchscreen and a non-tactile touchscreen (the green point shows the neutral rating in terms of overall hedonic and pragmatic quality)

7.4 Usage scenario-based design of a tactile touchscreen for a primary task

The design of a touchscreen-based control panel incorporating tactile feedback is based here on usage scenarios and interaction task analysis. A scenario describes a concrete story on using a tactile touchscreen. Task analysis coordinates the interaction tasks to envision activities in the scenarios.

Usage scenarios can be abstracted and categorized to help identify problems and specify the requirements that will be addressed by a new system. Scenario-based design invokes a concrete "to do" situation oriented toward intended users and their needs: it envisions human activity in order to guide selection of a system, technology and UI elements (e.g. widgets) that are appropriate to performing a particular task and reshaping the constituent steps, taking due account of the context of use. Rosson & Carroll [213] described the subsequent process of design specification as involving "activity scenarios" that will be functionally implemented on the system but do not focus on how the system will work or what it will finally look like, "Information scenarios" that provide details of the system information required to carry out the task, and "interaction scenarios" in which user interaction with the task information and the feedback the system provided are elaborated.

Meanwhile, interaction task analysis provides a method of systematically characterizing user activity in order to match the requirements of a system to human capabilities. Interaction tasks envisioned in a concept can be analyzed at multiple levels [7], which usually means that a collaborative requirements dialog needs to be conducted with end users.

Usage scenario-based design builds on an iterative cycle of development activities, which may be understood as a multi-stage problem (see Figure 53) solving process that starts with analyzing the context of use, understanding the utilization of available technology, and evaluating the validity of their assumptions in real-world situations involving actual users. Based on the requirements determined in the design process, prototypes are created to evaluate whether the specification is functionally, visually and technically attuned to requirements. The feedback from that evaluation provides guidance in re-analyzing and redesigning the system, i.e. finding out what to improve and how to do it. This enables designers to elaborate problems, refine specifications and continuously consolidate design ideas.

A touchscreen-based design incorporating tactile feedback needs to consider realistic use context and users' capabilities as reflected in the scenarios, as well as user behavior and experience as determined by analysis and modeling of well-specified tasks. Touchscreen-based scenarios can suggest sets of widgets for direct manipulation. Feedback as to what is happening on the user interface can be displayed on a status bar or by a new content conveyed through tactile events such as vibration, impulse emission or temperature change. To arrive at a user interface that is clear to feel, efficient to work with, easy to learn and pleasant to use, the usage scenario-based design of a tactile touchscreen focuses on user-oriented instead of technology-oriented methods.

The selection of touchscreen solutions for particular applications depends on how users employ a system to accomplish work tasks and other activities. The applications considered in this section, which are potential product solutions for Siemens Building Technology and Automation devices, will be discussed as examples to how to use touchscreen to perform a primary task.

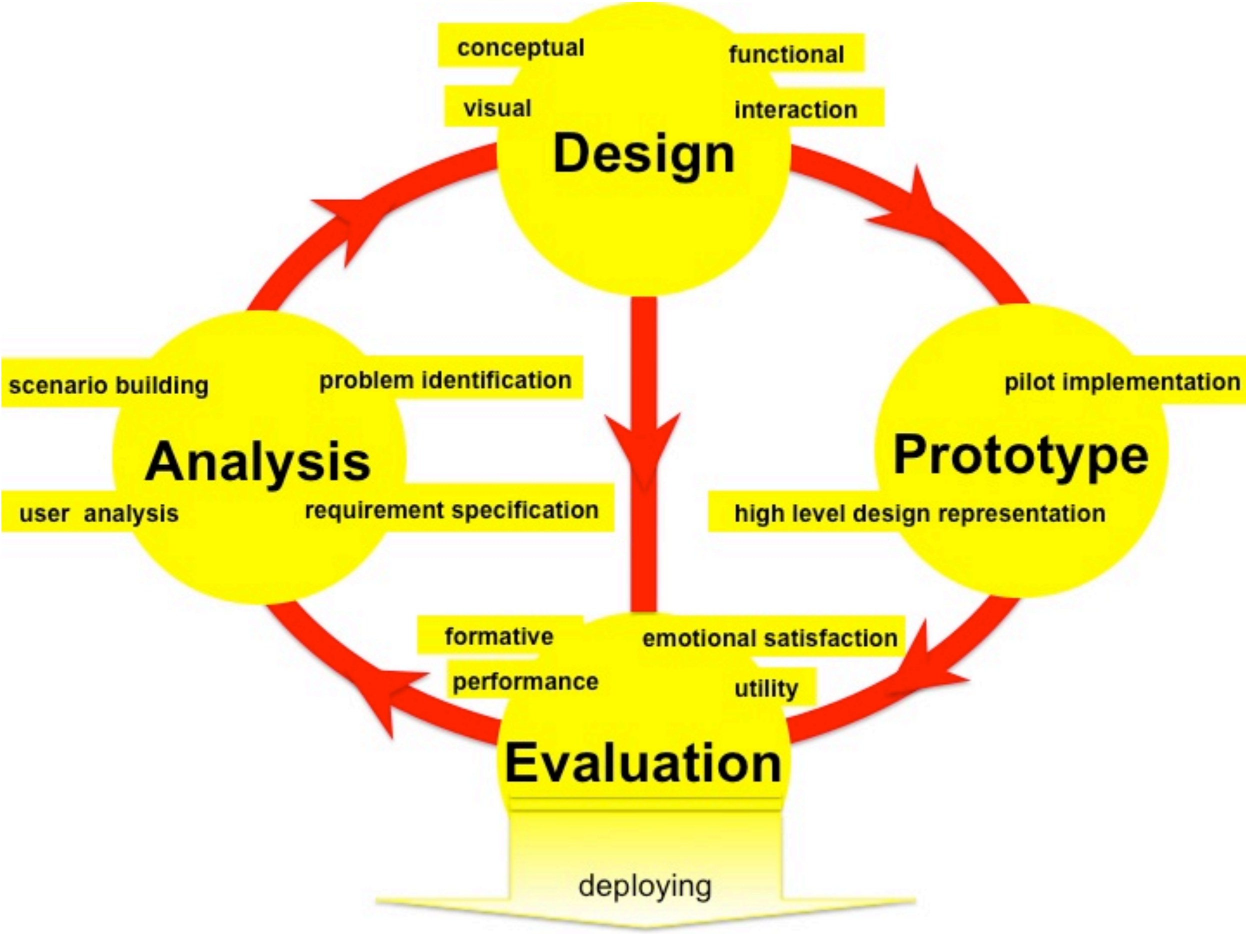


Figure 53: An overview of scenario-based design

7.4.1 Example I: Tactile touchscreen for building technology

The human-machine-interface of a touchscreen for applications in building technology should provide very simple content and interaction for everybody (including novice and expert users). A touchscreen-based interface is, for instance, used to control a room air conditioning system, in which selecting a digital on/off button switches the system on/off or pressing digital up/down keys changes the temperature in room. When performing these tasks, users are interested in the results of manipulating graphical UI controls for the air conditioning control system, but not in the process leading to those results. They don't want to be concerned with long-term retention or fully understand the system behind the touch control surfaces. They have little interest in understanding the technical aspects of controlling the system. The more sophisticated the surface of the touchscreen system, the more complex is the system users have to operate. Tactile feedback provides significant quantities of information through human haptic channel, which helps to ensure that users are not confined to simple notifications, and which makes the systems more intuitive to operate.

Cost-effectiveness, stable operation, energy-efficiency and ease of control will be the key criteria in choosing the most suitable touchscreen technology for building technology devices. An example of a user interface in this field of application is a tactile panel designed to communicate control actions for an elevator system in an office building. Because it is easy to change the size, style and appearance of graphical UI controls according to use context and screen size, the controls can be customized to display several combinations of objects and actions, which would be cumbersome with just physical buttons. As a simple and inexpensive solution, a resistive touch panel without display can be used in this example.

To understand the use of a touchscreen-based device in building automation, consider the following scenario:

NKK Int., which has achieved a meteoric rise from a medium-sized travel agency six years ago to a market leader in holiday travel, acquiring an airline and a number of competitor travel agencies along the way, has issued an invitation to submit design proposals for a planned luxury resort in Bali, Indonesia. Mr. Rogers, who worked with NKK in its infancy six years ago, arrives to present a proposal on behalf of his company Ries-Rolls Design Office, which is treating the project as a major high-profile business opportunity. On Wednesday at 9.45 am, Mr. Rogers arrives in a state of anxious anticipation at the New World Building, where NKK has only recently taken over a splendid suite of offices to meet Ms. Lion, NKK's project manager, who made the appointment last Friday with him for 10 am. When he enters the elevator, he is relieved to see that the control panel shows clearly which company is accommodated on which floor. Having thus quickly and easily confirmed the location of NKK Int., he presses the button labeled "5th floor" and "NKK Int", and at the same time perceives a vibration from the control panel, which confirms his selection immediately. Mr. Rogers gives his appearance a final check in the elevator's mirror. When he leaves the elevator and enters Ms. Lion's office, the secretary asks him if he had any problem finding the way to NKK Int.'s office. "No problem at all", replies Mr. Rogers. At 10 am prompt, Mr. Rogers confidently starts to present his company's concept. Following a presentation and discussion lasting almost two hours, Ms. Lion expresses great interest in the proposed design, though she tells Mr. Rogers she would like to make a final decision only after she has talked with another two design offices.

Figure 54 shows an example of the interface of the building's elevator system, which gives an explicit overview of the companies and their locations in the building. The current floor is indicated by a red light installed to the left of the interface. The list of companies can be printed on a sheet of paper inserted behind a panel, which makes it easy and cheap to update the interface – if a company moves in or out the building, just take the paper list away and affix a new printed list. This removable interface eliminates mechanical buttons, making it easy to clean the surface and economical to update the content. But an absence of tactile response as confirmation can confuse users as to whether the input has actually triggered an action or not; consequently a common reaction is to press the touch surface repeatedly and hard till a response is received. To achieve greater energy efficiency, easier handling and quicker setup, a competitively priced touch solution and a dirt-insensitive resistive sensor can be considered for use in this touch panel. Small tactile actuators with, for example, an electric motor can be fixed behind the touch panel to convey tactile feedback. When a control indicating the location of one company in the interface is pressed, the system could offer a natural and intuitive effect simulating the pushing of a physical button, instead of just the feeling of pushing on a hard and static surface regardless of where the user presses. With tactile feedback, users recognize immediately that their input has been received, so that they need less forceful presses and fewer repeated inputs to make certain they have communicated with the touch interface. This reduces cognitive loading and makes selections quicker than with a conventional touchscreen. Meanwhile, tactile effects give users a greater feeling of familiarity in sensing controls and touch events.

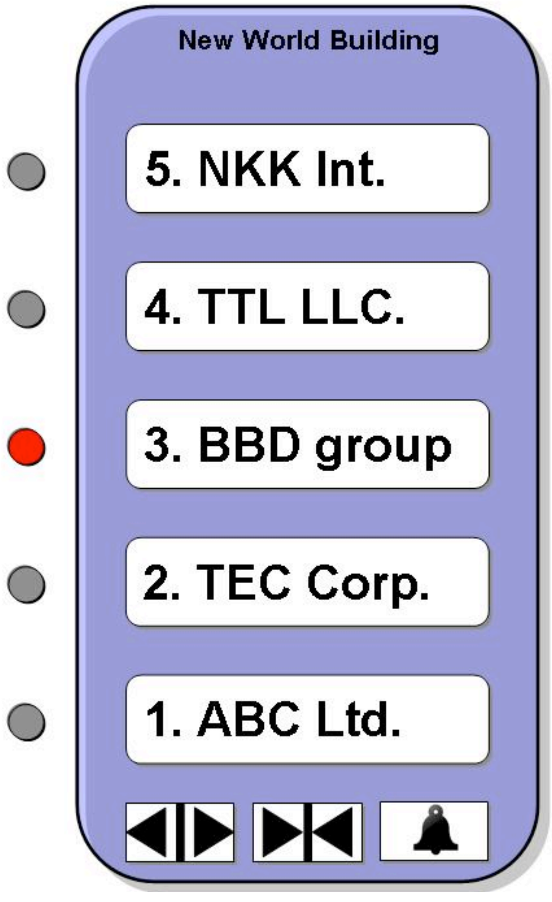


Figure 54: Example of a physically removable control surface in an elevator

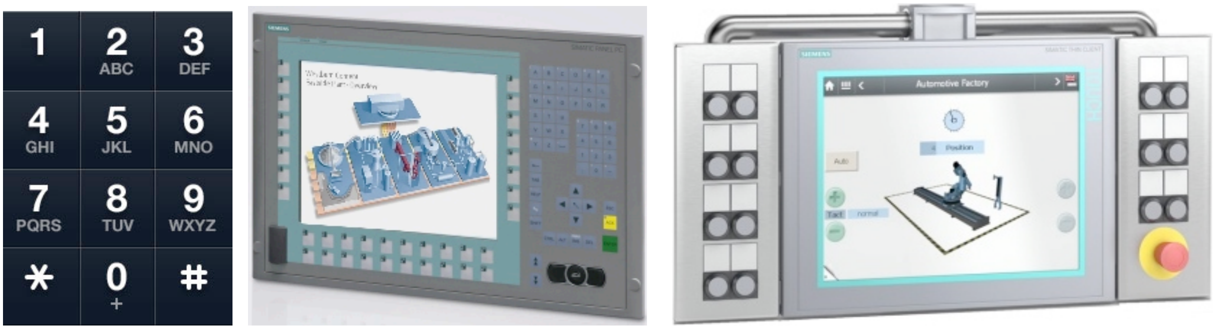
7.4.2 Example II: Touch control panel for industrial automation

Because of their dynamic interface, stable operation and reconfigurable controls, touchscreens are often used as control panels for industrial automation within environments where dirt, dust and fluids are prevalent. A touchscreen can provide an intuitive interface in which the options available can be clustered in a number of layers, and only the options relevant to the task in hand at the time are displayed. However, if there is a lack of multisensory feedback, especially tactile feedback, a touch-enabled control panel will have to rely heavily on visual feedback in an audio-visually distracting industrial working environment. Acoustic feedback can often be drowned out by the background noise of the environment. Thus, tactile feedback offers a useful way of exploiting a further sensory channel to help improve user confidence and working efficiency in a conventional touchscreen.

In harsh industrial environments, touchscreens needs to be resistant to scratches, breakage and accidental spillage, and have to withstand fluid splashes and aggressive cleaning; they must also be capable of being activated directly by a gloved hand, a stylus or a bare finger. Thus, resistive touch sensors and surface wave touch sensors are viable options for applications typical of industrial automation system. Such applications range from a low-priced entry-level solution with a 6-inch portable touchscreen display to cover basic requirements, to a powerful panel PC with a 19-inch touchscreen to meet high performance requirements. In these solutions, the touchscreen interface may constitute either part or all of the interactive display.

A sample scenario takes place in a beverages plant where Mr. Chambers works on an automated mineral juice bottling line. Bottles are collected from a stainless steel conveyor by a turret wheel, which carries them to a filling station for volumetric dosing and piston filling. The dosing volume is electronically controlled using flow meters, which Mr. Chambers has preset on the touchscreen-based control panel. He uses the same touchscreen to select the bottom-down filling option at the filling station. Once the bottles are filled, the turret wheel transports them to a capping station where each bottle has a cap placed on it ready to tighten. For the tightening station, Mr. Chambers selects screw-capping and multiple bottles from the options of screw-capping, press-capping, and single and multiple bottles. When tightening is complete, the turret wheel carries the capped bottles to an outlet conveyor for final packaging.

When operating a touch control panel in this kind of machine control applications, users have to make decisions and accomplish tasks depending on the information and notifications they received. This generally involves manipulating controls and operating functions on the user interface and entering characters into the system. A keyboard layout will need to be selected that is suitable with respect to input content (e.g. numerical or alphabetical input) and available screen space (e.g. a standard QWERTY layout is likely to occupy too much space on a small-size touchscreen). A full-size QWERTY keyboard may actually decrease character input efficiency on a touchscreen in a workshop, which is especially critical where mechanics who have to resort to single-tap input from among a large amount of characters suffer an increased cognitive load from using the control panel screen and lose concentration on what the machine is doing. In this case, a keyboard with less keys, such as twelve-key keypad, could be used to save screen space while still being intuitive to manipulate. As the means of entering characters on a touchscreen, a virtual screen keyboard (see Figure 55 (a)), a membrane key keyboard (see Figure 55 (b)) or physical buttons (see Figure 55 (c)) can be designed to be called up when required or to be permanently available on the interface. Soft keys or virtual keys - simulated keys displayed on-screen – often employ on touchscreens to graphically render physical UI controls such as buttons. These keys can easily be changed in size, style and appearance according to the type of interaction, the context of use and the available screen real estate. Physical keys can be also integrated into touchscreen systems for very frequently used or emergency function such as power on/off and alert.



(a) 12-key keypad (b) Touchscreen with integrated keypad (c) SIMATIC HMI PRO with extension units

Figure 55: Varying keyboards for character input and for control functions[7]

Tactile effects added into touchscreens will not be degraded by a harsh industrial environment. On the contrary, they provide the instantaneous confirmation of communication with process and machine control systems while alleviating the visual and auditory burden, and offer a more mechanical-like behavior to improve the usability of touch solutions for control panels. Tactile feedback on a touchscreen not only necessitates fewer repeated and less forceful taps in comparison with pressing a touchscreen with a hard and unresponsive surface, but also allow smaller on-screen controls at the same time as reducing reliance on visual feedback cues. However, it is also necessary to consider adapting the design of tactile effects to deliver suitable performance under conditions of ambient vibration in a workshop.

Usage-based design helps in envisioning tactile touchscreen-based UIs pragmatically and systematically. Based on use context and on available technology, tactile touchscreens used for primary tasks in the two applications described above can be developed by defining set of on-screen widgets for direct manipulation. A series of tasks are then accomplished by touching (with the feel of pressing and releasing) an area of a screen that is usually implemented with graphical UI controls. Sometimes mechanical buttons can be integrated into a touchscreen for certain special tasks such as numeric input or alarm management. Feedback as to what is happening on the user interface can be displayed on a status bar or by a new content conveyed through tactile cues such as vibration or impulse emission to reduce glance time. Matched tactile feedback can make a touchscreen system easy to learn, efficient to work with and pleasant to use. The selection of a suitable solution for a tactile touchscreen will also depend on how the user employs the system to accomplish tasks, in what working environment the tasks are executed, whether gloves are used, and how expensive the touchscreen solution can be. A touchscreen-based design incorpo-

[7] Resource: (b) + (c) from Siemens Intranet website (accessed on 2010-04-20)

rating tactile feedback needs to consider realistic use context and users' capabilities, as well as user behavior and experience as determined by analysis and modeling of well-specified tasks.

8 Haptically enhanced touchscreen used for a secondary task

The human being has the capacity to process multiple complex tasks at the same time. In order to investigate further the value of adding tactile properties to touchscreens, haptically enhanced widgets were tested on a touchscreen used within a multitasking use case, namely to perform a secondary task. In this setup, users had to direct full control of their attentional processes to a primary task, while performing a low-demand secondary task on a tactile touchscreen, as shown in Figure 56: A is the touchscreen with surface wave technology and B is a subject performing the primary task presented on laptop C. When users are engaged in the primary task, they cannot always be looking at the touchscreen. In some applications, users cannot always rely on audio cues for confirmation or guidance, especially if the environment is too noisy or requires silence.

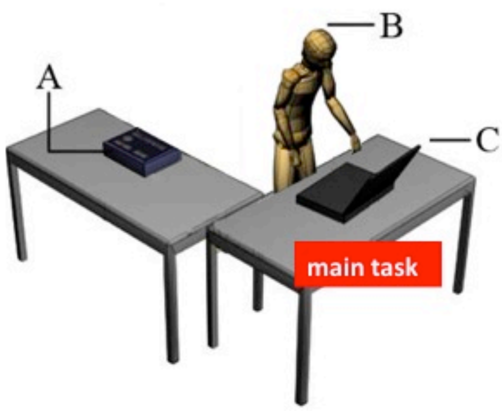


Figure 56: Experiment setup for touchscreen used for secondary task

8.1 Principle behind the design of the 3D touchscreen and its user interaction

A surface acoustic wave touchscreen [@22] was selected in this user test to provide ultimate optical performance and high resolution. Because piezo chips are used in this technology, this kind of touchscreen can recognize both the location of a user action and the force applied by the user in the vertical direction. The touchscreen was mounted on four bass shakers and a bread-board, as illustrated in Figures 26, 27 and 28 in the chapter 6.

8.1.1 Touchscreen-based 3D tactile sensing system

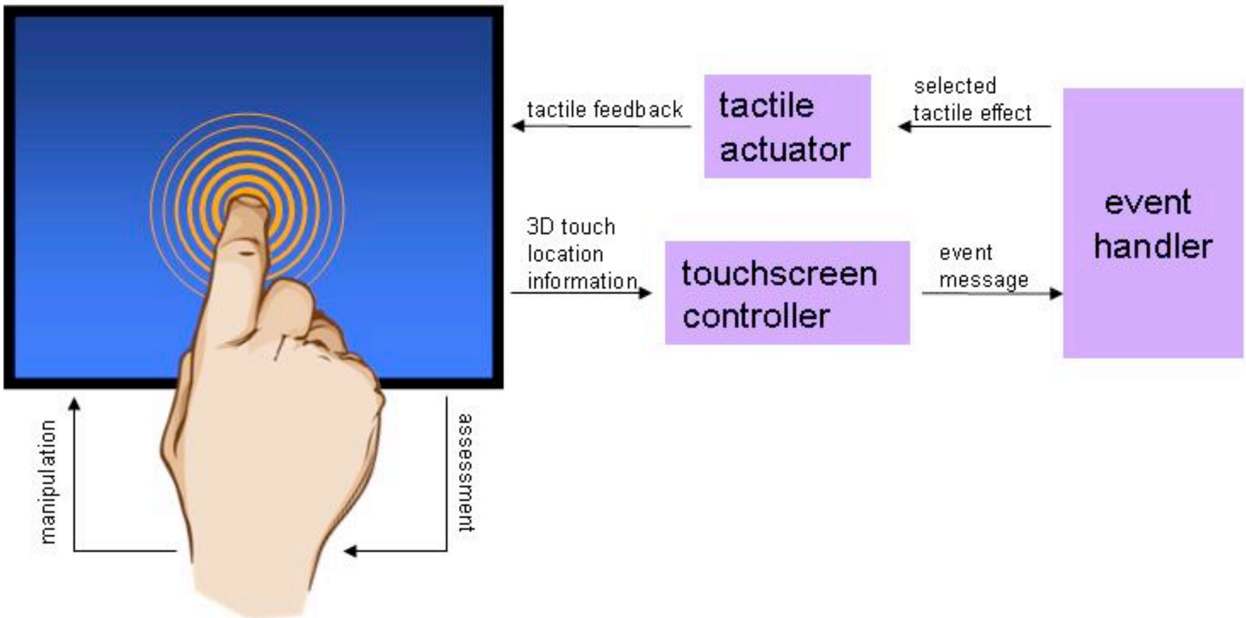


Figure 57: System architecture of touchscreen incorporating tactile feedback[8]

A 3D tactile sensing system can work with touchscreens or touch pads of different sizes. Nevertheless, its architecture generally consists of tactile actuators, a library of tactile events, control software, and a programmable interface for calling tactile feedback from the host application, as shown in Figure 57. Producing an effective tactile sensing system involves transducing tactile sensing data (information), processing the transduced tactile data (information) and providing feedback information to the user. In a touchscreen-based tactile sensing system, when the touchscreen is touched, the touchscreen controller calculates the precise location of the fingertip along the X and Y axes and the force along the Z axis. The tactile event is allowed to exert high-speed control over one or more actuators of varying size and form. The event handler triggers event messages (touched, untouched, moved, pushed and released) instructing the tactile actuator to play a pre-programmed tactile effect. The actuators placed behind touchscreen vibrate the touchscreen, conveying to the operator the perception of a button clicking.

8.1.2 Interaction design

Three types of interaction tasks are specified on such 3D tactile touchscreens with a view to accomplishing a set of goals via tactile feedback:

Identification of objects: The operator is able to identify objects and the non-objects area via tactile feedback.

Selection of a single object from a group of objects: The operator is able to identify objects and the non-objects area via tactile feedback.

[8] Based on the TouchSense System by Immersion Inc. [@46]

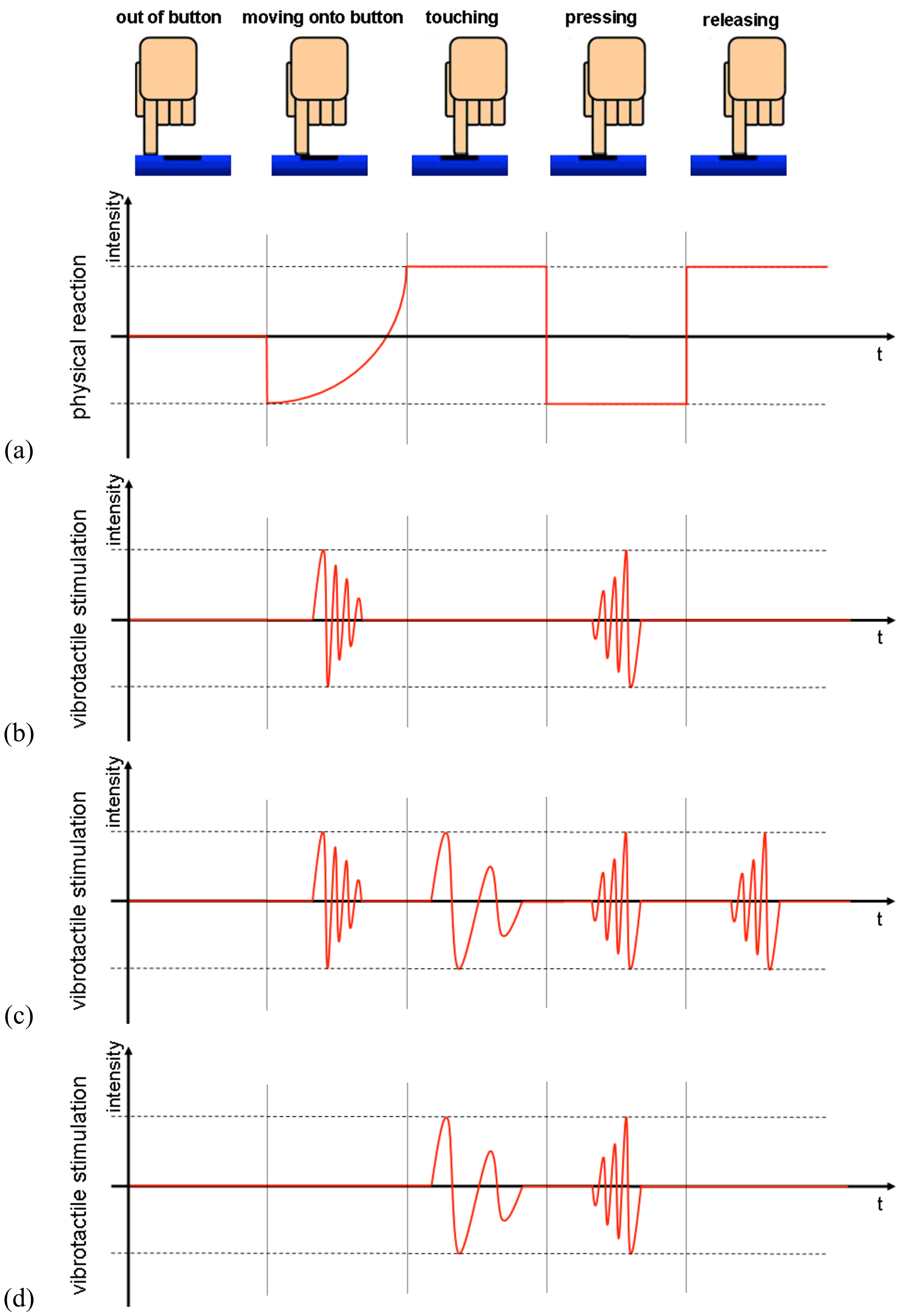
Manipulation of a selected object: The operator activates, repositions and reorients the selected object and gets a matched tactile response.

To enable these interaction tasks to be accomplished, a set of interaction techniques were developed to represent the performance of user actions: touching, moving, short-pressing, long-pressing, moving onto, moving off, releasing and rotating. These interaction techniques were applied in the following detailed tasks.

8.1.2.1 Button clicking

To recognize a tactile object, it is necessary to determine the location and orientation of the object's edges and surfaces. Accordingly, a number of interaction techniques were designed to characterize more mechanical-like behavior of a feel of button clicking. Considering the need for users in a distracting environment to feel their way to the required control before actuating it, the lift-off pointing strategy was employed as a basis for real-time feedback in this case study.

The findings in Chapter 6 show that an impulse when the finger moves onto a button gives the impression that an object has an edge in a 2D tactile touchscreen, and that the finger is entering the area of a button, no matter how far the buttons are from each other. In comparison to a 2D touchscreen, a 3D force-sensitive touchscreen provides additional tactile information in the vertical direction. Thus, tactile data was provided in three stages in a 3D touchscreen to enable users to determine the location of a button and manipulate it. Firstly, threshold-triggered tactile feedback was applied to facilitate detection of the button edge. Secondly, a constant vibration was provided to allow the surface area of the button to be tracked. In the third stage, pressure force and brief tactile feedback were combined to give the impression of the button clicking, the aim of this design being to simulate the feel of a real button clicking when pressed and released. There was no vibration when the finger was outside a button's touch area. When the finger moved onto a button, a short, high-amplitude vibration occurred. When the finger touched the surface of a button but without actually pressing it, a light, constant vibration occurred. This kind of haptic location information added to buttons can improve the memorability of button placement.


out of button
moving onto button
touching
pressing
releasing
physical reaction
intensity
t
(a)
vibrotactile stimulation
intensity
t
(b)
vibrotactile stimulation
intensity
t
(c)
vibrotactile stimulation
intensity
t
(d)

(e)
(f)

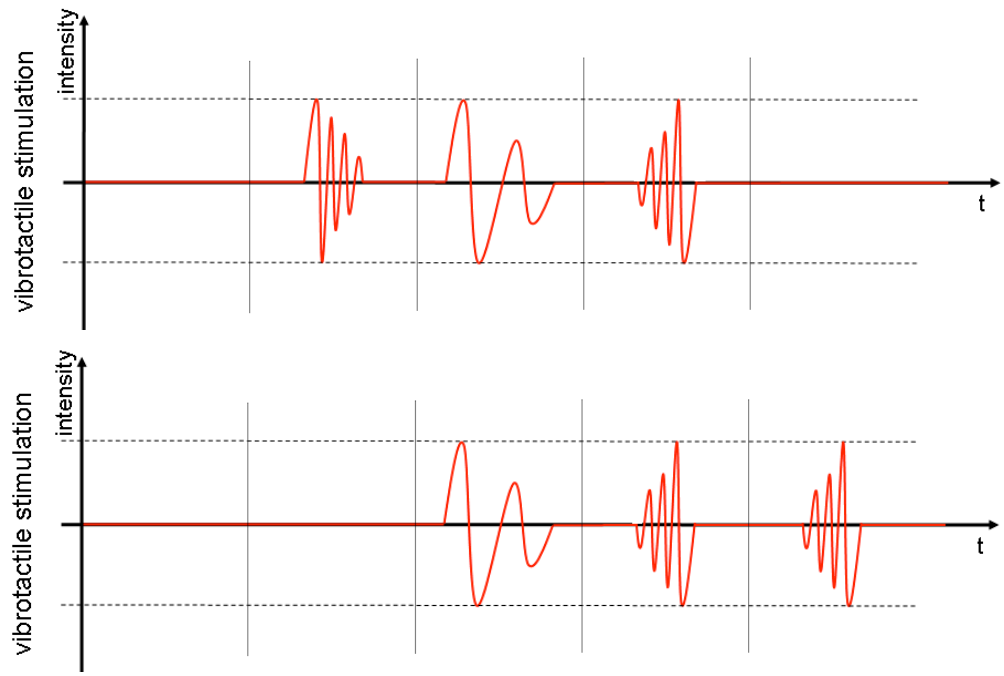


Figure 58: Tactile simulation of button events

Based on these results obtained by investigating haptically enhanced basic UI controls in Chapter 6, the tactile impulses which are clearly sensed were selected for this experiment. Therefore, the most sensitive impulses, namely those with a combination of a frequency of 58 Hz and a decreasing amplitude, were selected for recognizing the edge of a button. An increasing impulse as the second most sensitive tactile effects was used to differentiate from the decreasing impulse. Considering that the impulse duration when the finger moves onto or let go of the button has to be short but sensed clearly, the second most sensitive duration of 50 ms and not 150 ms was chosen to give the impression of the edge of a button. In addition, a constant vibration, a relatively strong signal, was used to simulate the button when the finger stays on it. Thus, four touch events were generated: 1) an impulse with a 58 Hz, 50 ms sine wave of decreasing amplitude was applied when the finger went onto the button, 2) a constant vibration with a 80 Hz, 200 ms sine wave of increasing amplitude was used as long as the finger stayed on the button, 3) an impulse with a 58 Hz, 50 ms sine wave of increasing amplitude was triggered by pressing the button, and 4) an impulse with a 58 Hz, 50 ms sine wave of increasing amplitude was delivered on release of the button. The stimulus duration of 50 ms was selected in view of the fact that the touch events occurring when the finger moves onto, lets go of and presses a button are very short actions. As shown in Figure 58, these four events were combined into five different interactions making up the clicking of a button. Therein, Figure 58 (a) describes a variation when pushing a mechanical button.

i) event 1) + event 3) (move onto ➔ press), see Figure 58 (b),

ii) event 1) + event 2) + event 3) + event 4) (move onto ➔ touch ➔ press ➔ release), see Figure 58 (c),

iii) event 2) + event 3) (touch ➔ press), see Figure 58 (d)

iv) event 1) + event 2) + event 3) (move onto ➔ touch ➔ press), see Figure 58 (e)and

v) event 2) + event 3) + event 4) (touch ➔ press ➔ release), see Figure 58 (f).

8.1.2.2 Zooming images

Tactile perception can be utilized to provide additional UI control functions by non-visual means. This makes it possible not only to reduce the size of UI controls but also to present more information on the display. In this way, a touchscreen can be used as a remote control to manipulate an image shown on a large display.

Press-hold (or *long-press*), the commonly used touch gesture for one-finger zooming, as a technique which provides self-explanatory and natural touch interaction, was used to zoom on-screen objects in this experiment. The tactile touchscreen system offered two different strategies for zooming an image to view it in more or less detail. 1) Firstly, when the finger pressed a button for more than 300 ms, the image on the other display was enlarged bidirectionally through three magnification levels of 125%, 150% and 200% of the original size. If the finger continued pressing the same button on the touchscreen, the resized image would be zoomed back out to an overview, either directly or through the magnification levels of 150% and 125% of the original size. The image could be stopped at any one of the intermediate sizes by lifting the finger off the button. The resized object presented in the zoomed image was modified so as to fit the relevant information into the current image size. 2) The second strategy allowed an image to be zoomed in continuously without going through distinct magnification levels, until the maximum of 200% of the original size was reached. If the finger continued pressing the same button on the touchscreen, the resized image would be zoomed back out to an overview, either directly or continuously without distinct magnification levels. The image could be stopped at any intermediate size by lifting the finger off the button.

8.1.2.3 Navigating objects

A navigation interaction technique was developed to process and control movement of the image shown on the large display. When the finger pressed a button on the touchscreen and moved, the object depicted on the large display moved a relative distance. In order to simplify the interactions, zooming and navigating could be integrated into one function: when the finger started to move from any part of the button toward one of its four corners, the image on the large display was zoomed in to show the corresponding quarter of the image. For instance, as shown in Figure 59, when the finger started moving from its current position toward the top right corner of the button control, while pressing and subsequently releasing the button, the top right quarter of the image was zoomed in and displayed in full on the large screen.

The zoom and navigation interactions could also be activated one after another. For instance, when the finger presses and moves but not out of a button, the resized image would be moved in the large display, followed by zooming an image. The zoom and navigation functions were designed to be combined in five different ways: 1) zooming in continuously and navigating, 2) zooming in and out continuously and navigating 3) zooming in through distinct magnification levels and navigating, 4) zooming in and out through distinct magnification levels and navigating, and 5) zooming in in four directions.

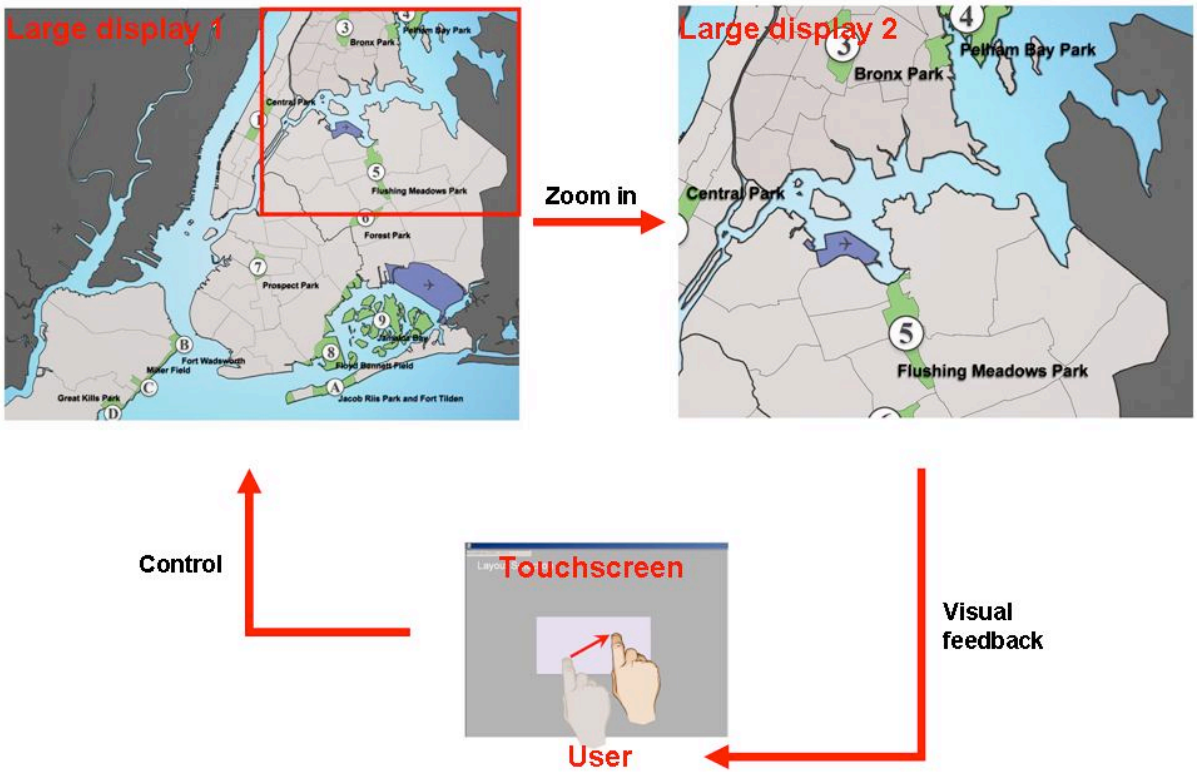


Figure 59: Zooming an image in through movement on the tactile touchscreen [@32]

8.2 UI layout and size

In this experiment, a low-fidelity prototype and interface sketches were produced to test the new UI functions of button press, image zoom and object navigation through pressure in the vertical direction on a tactile touchscreen. The size of UI controls depends on the size of the touchscreen display, the number of UI controls presented, and the relation among UI controls. Too small targets, for example, smaller than the fingertip, affect input efficiency. If the size of the targets is increased, the number of targets on the screen has to be reduced. In order to provide maximum functional information for some complicated applications used for a secondary task, the UI layout selected in the first part of this experiment has to comprise a large number of targets with a relatively small distance between them. Therefore, a group of twenty buttons were presented, each time one of five interactions of button click. Because of the small size of the touchscreen display, the onscreen buttons were limited to a size of 96 pixels, with an intervening space of 10 pixels, as illustrated in Figure 60. A displayed the name of the current button interaction in the control area B.

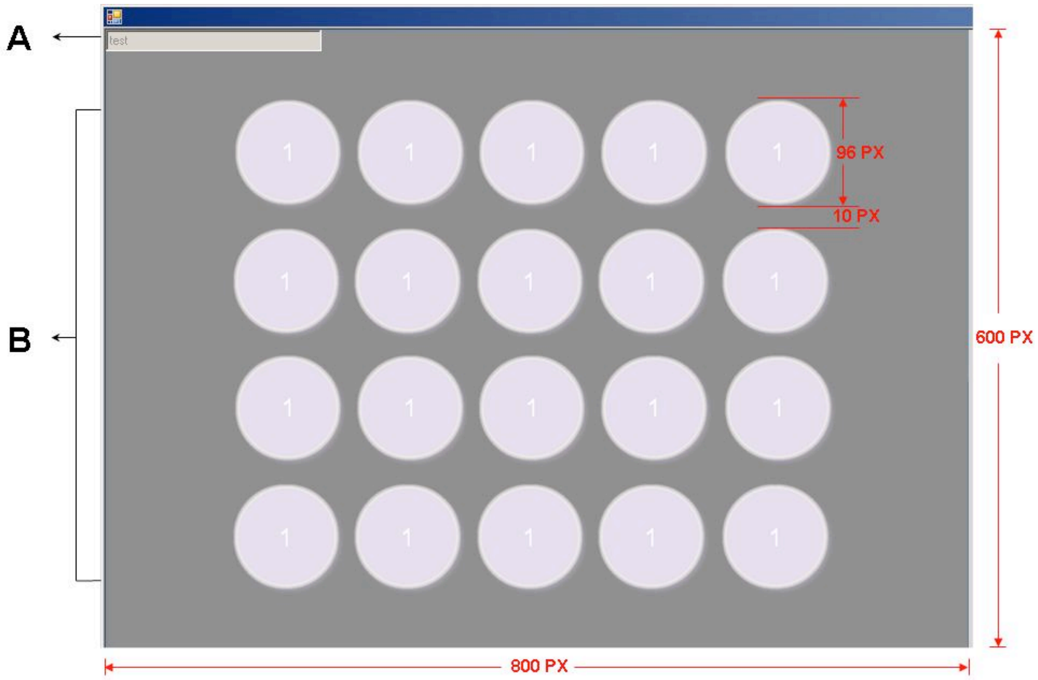


Figure 60: Layout of a group of buttons

Other UI functions like zoom and navigation through a touchscreen-based control panel operating with force were designed as shown in Figure 61. The name of the current function was displayed in the text box A, when the finger zoomed and navigated in the control area B. The large onscreen button was 355x179 pixels in size.

Four buttons were presented in the "Layout Selection". They were 355x179 pixels in size and had spaces of 24 pixels between them, as shown in Figure 62.

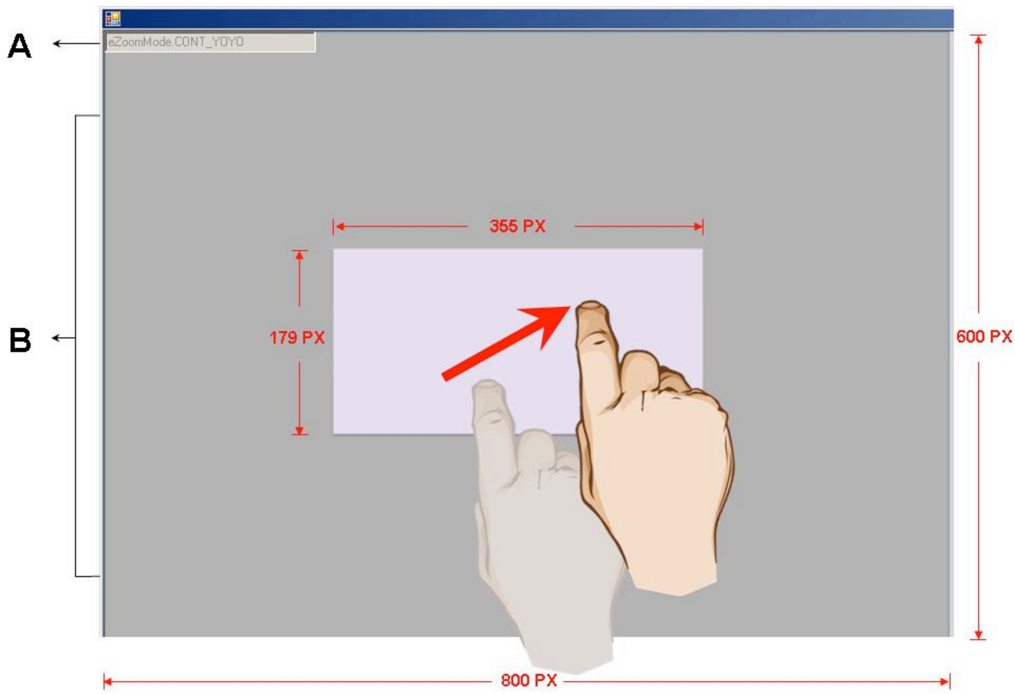


Figure 61: A large button for the UI functions of zoom and navigation

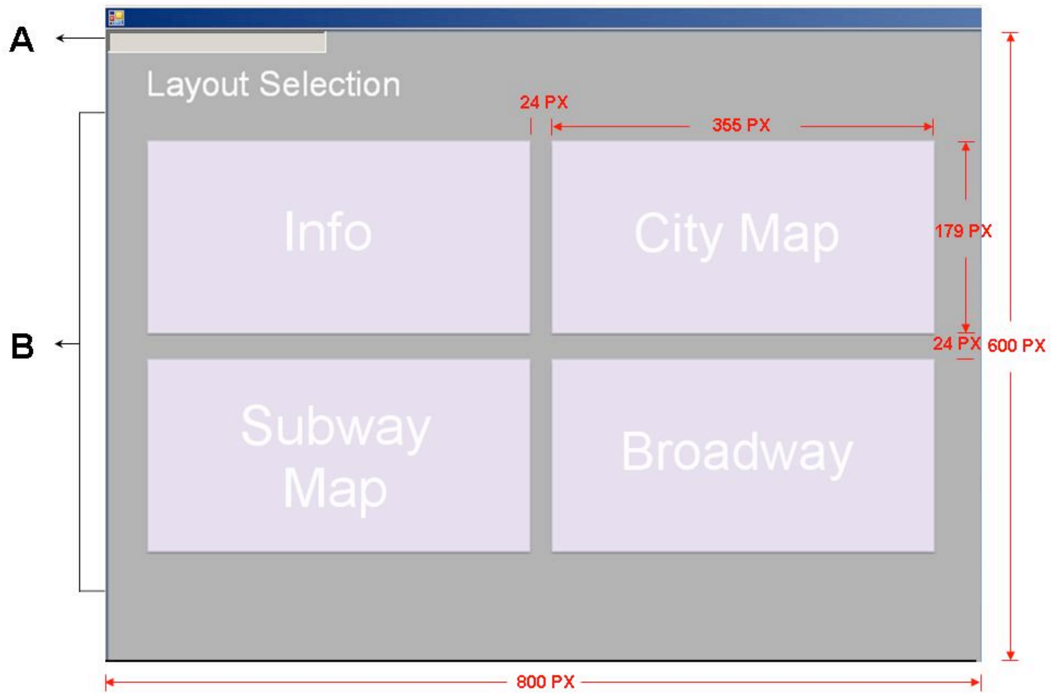


Figure 62: User interface of the layout selection

8.3 Experiment setup

A surface acoustic wave touch panel was taped firmly to an 8.4'' TFT LCD module [@28] in 800x600 pixels resolution, which was mounted on four bass shakers [@10] using copper bars and threaded rods. The hardware setup is equipped as same as it is shown in Figure 26. With two piezo chips, the surface acoustic wave touch panel can calculates the precise location of the fingertip along X and Y axes and the force along Z axis.

Because a screen with a 90-degree-inclination avoids parallax and a touchscreen mounted in a horizontal direction offers lowest perceived fatigue, as described in the section 2.3, the touch events and screen viewing were arranged in two different parts – an 8.4 inch tactile touchscreen and a 56 inch display, as shown in Figure 63. A laptop used for the primary task in this experiment displayed the questionnaire. Followed the questions displayed on the laptop, participants operated the tactile touchscreen measuring force. The 56 inch display was projected on a large screen.

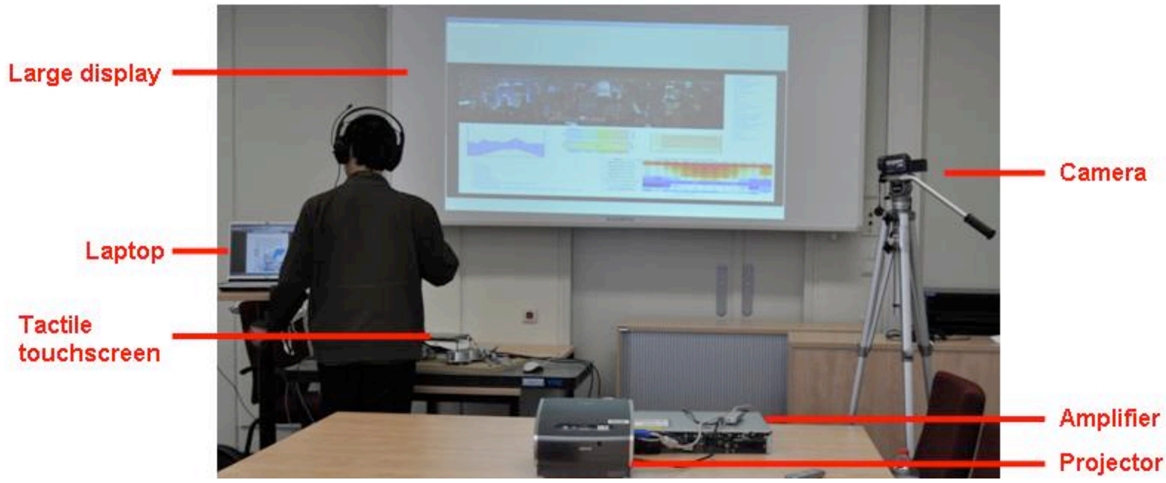


Figure 63: Experiment setup for secondary task

8.4 Research method

8.4.1 Participants

Twelve subjects, six women and six men, aged between 25 and 59 years (mean = 37), participated in this experiment. The subjects were consultants at Siemens AG in Munich and researchers at LMU Munich. All subjects were right handed, with no known hand disorders. They used their right hands for this experiment.

8.4.2 Experiment procedure

During the experiment, participants were asked to wear a headset emitting constant noise so that they could not hear but only feel the vibrations generated by the bass shakers. Because the touchscreen with the surface wave technology we selected can recognize location and pressure when the user touches the touch panel, which wouldn't be constricted in the lighting condition and in employing a conductive material, the participants were asked to operate the touch panel with gloves. In the first part of the experiment, participants rated each time one group of stimuli with which they subjectively easily associate with the haptic behavior of a button click on a scale from "very difficult to associate" to "very easy to associate". The group of the stimuli was displayed randomly on the screen. Following the evaluation of five groups of stimuli, participants were asked which group of stimuli was the best suitable for the haptic behavior of a button click.

Following that, five different combinations of zoom and navigation were tested using a large button. Each time, participants rated one interaction displayed randomly on the screen as to whether the "zooming and navigating" function would be adequate to manipulate the large image. When they had finished the evaluation of these five combinations of zoom and navigation, participants were asked to select the best zooming and navigating function.

The last experiment simulated a stressful work environment and utilized a tactile touchscreen to complete some secondary tasks. Participants were asked to concentrate on the narrative stories displayed on the laptop. The tactile touchscreen was used as a remote control to zoom and navigate images shown on a large display, which had to be done to find out the solutions to questions posed in the stories displayed on the laptop.

8.5 Subjective evaluations

The statistical analysis used for comparing five techniques of simulating the feel of physical switch buttons with 3D touch information, as shown in Figure 64, was a standard two-factor ANOVA without replication, based on the critical values of the F distribution, where alpha = 0.05. The ANOVA indicates that there are significant differences between five different techniques ($F = 4.499 > F(11, 44) = 2.014$, $p = 0.00015 < 0.05$). The switch button, which had an impulse when the finger moved onto the button, constant vibration as long as the finger stayed on the button, and an impulse when the finger pressed the button, scored the highest preference rating as a means of simulating the feel of a physical switch button.

For the assessment of the zoom and navigation function, the statistical analysis used was a standard two-factor ANOVA without replication, based on the critical values of the F distribution, where alpha = 0.05. The ANOVA indicates that there are significant differences between five different zoom techniques ($F = 3.083 > F(11, 44) = 2.014$, $p = 0.004 < 0.05$), as shown in Figure 65, and between five different navigation techniques ($F = 3.586 > F(11, 44) = 2.014$, $p = 0.001 < 0.05$), as shown in Figure 66. These results indicate that zooming in and out continuously, while being able to navigate the whole screen, is the most natural interaction for zooming and navigating an image.

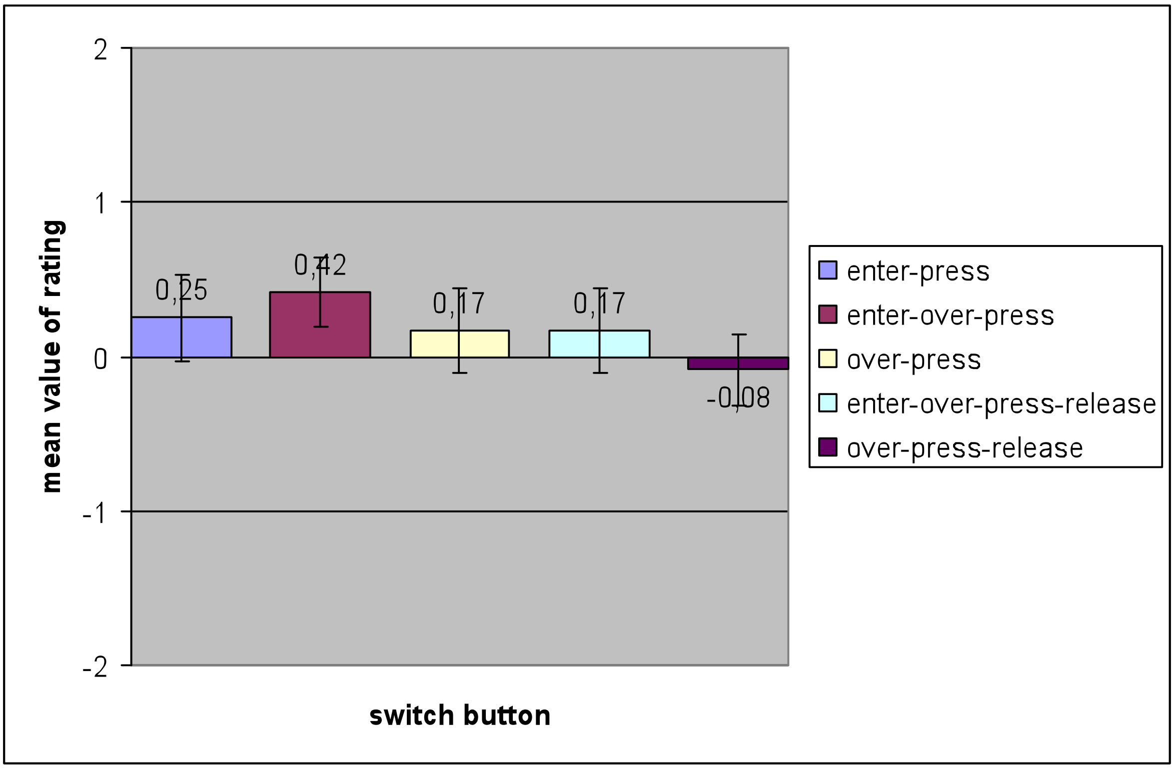


Figure 64: Comparing five techniques for simulating the feel of physical switch buttons with 3D touch information (with standard deviation)

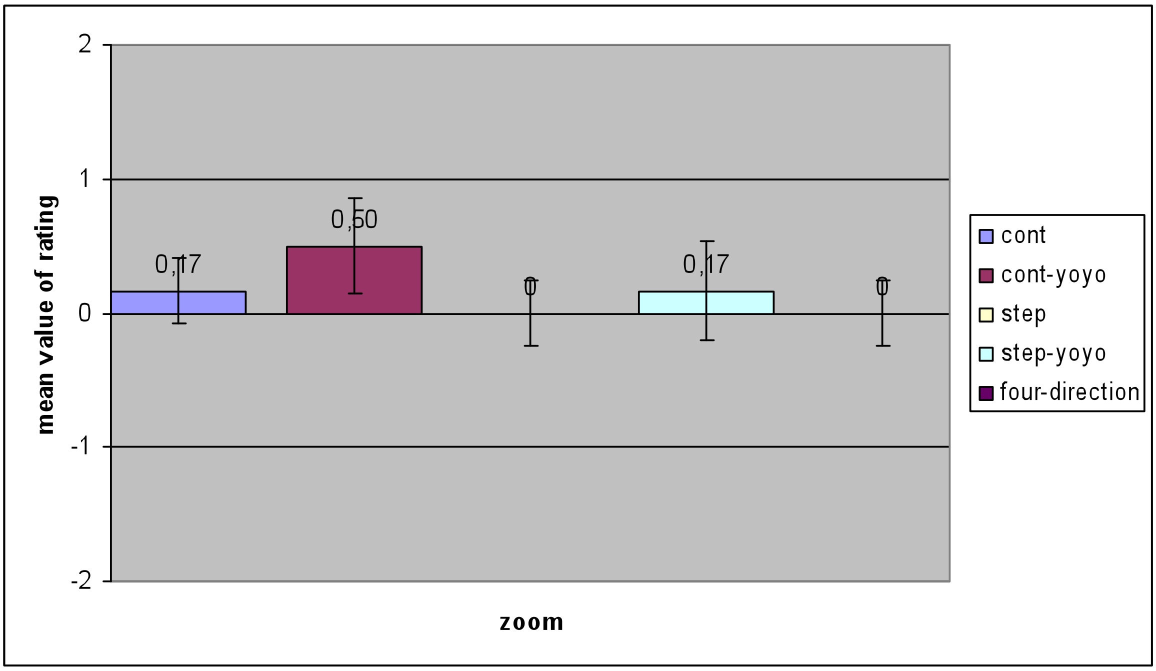


Figure 65: Comparing five zoom techniques with 3D touch information (with standard deviation)

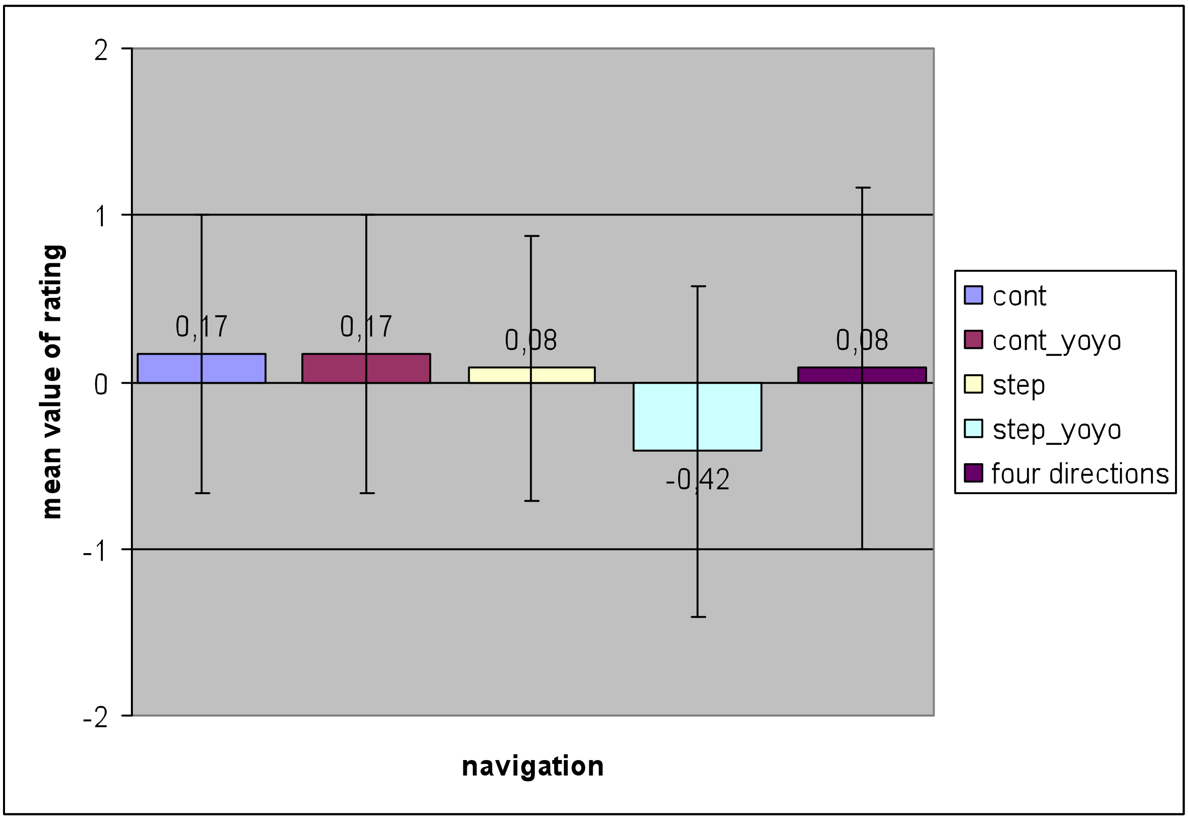


Figure 66: Comparing five navigation techniques with 3D touch information (with standard deviation)

Regarding the operating time needed to complete the group of eight tasks (see Figure 67), a t-test shows that there is no statistically significant difference between a touchscreen with tactile feedback and one without tactile feedback ($p = 0.229 > 0.05$). Nonetheless, there is a tendency for users to need less operating time to perform a secondary task with a tactile touchscreen.

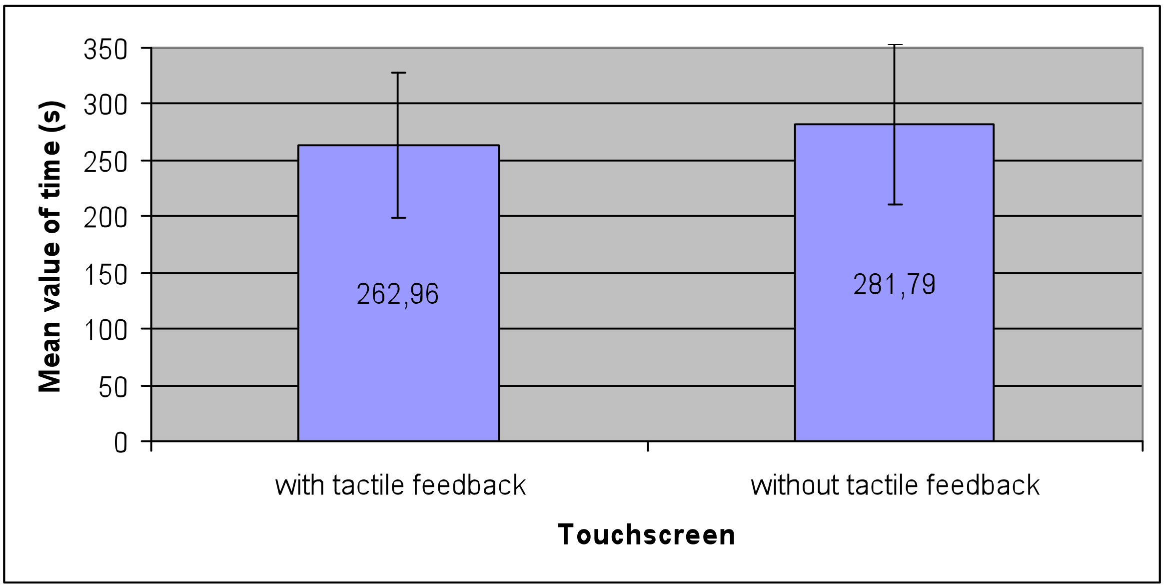


Figure 67: Time needed to complete a group of eight tasks (with standard deviation)

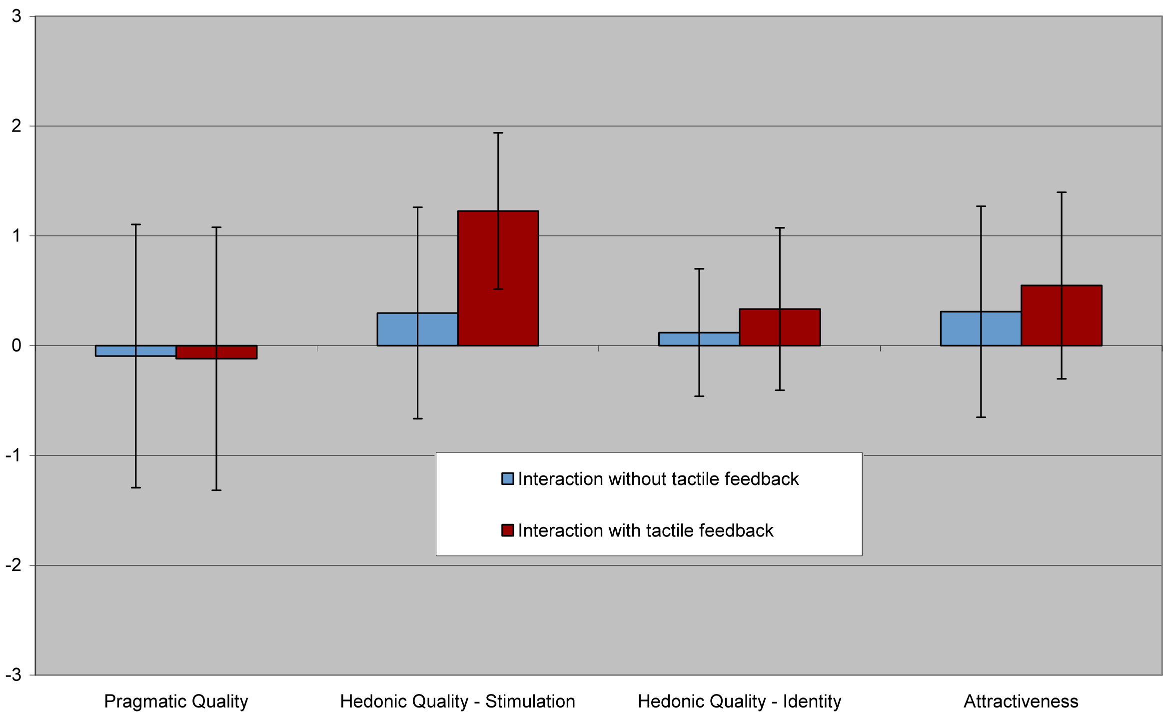


Figure 68: Subjective perception of secondary-task touchscreens with and without tactile feedback, judged against the four criteria Pragmatic Quality, Hedonic Quality-Stimulation, Hedonic Quality-Identity and Attractiveness

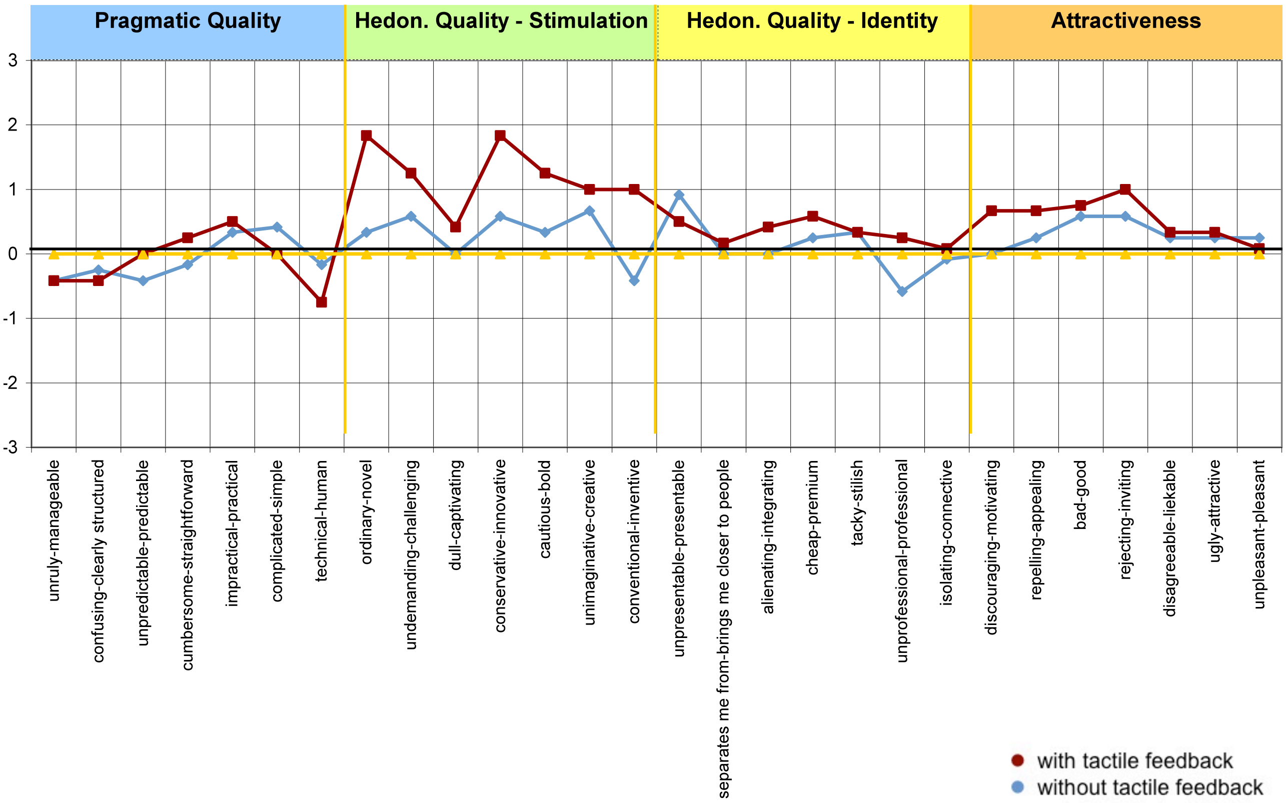


Figure 69: 28 criteria of comparing secondary-task touchscreens with and without tactile feedback

Furthermore, participants were asked to compare the secondary-task touchscreens with and without tactile feedback by rating them against the four criteria of **Pragmatic Quality**, **Hedonic Quality - Stimulation**, **Hedonic Quality – Identity** and **Attractiveness,** which comprise 28 items serving as semantic differentials, as shown in Figure 68 and Figure 69. Although the force-sensitive effect in the vertical direction increases the complexity of operating a touchscreen, its pragmatic and hedonic qualities indicate that a 3D tactile touchscreen is pleasurable to users, thus heightening their preference for using this kind of interface.

8.6 An application involving a tactile touchscreen used for a secondary task in healthcare

The above use scenario in which a touchscreen is used for a secondary task can translate to the way the user has to concentrate in a typical practical application in healthcare, namely when clinicians are engrossed in their primary task of arriving at a diagnosis or administering treatment using medical instruments, while operating a touchscreen to control ancillary equipment.

To easily understand the context in which such a healthcare application occurs, consider the following scenario involving cardiac surgery performed in an operating room. A coronary angioplasty procedure (repair of a blood vessel in or near the heart) is to be done using a combination of special-purpose angiography and surgical treatment. The imaging equipment is installed in the operating room.

Mr. Miller, a 50-year-old, is a patient with atheromatous plaque (see Figure 70), whose coronary artery has become blocked, putting him at risk of a heart attack. His cardiologist, Dr. White, decides to treat his condition by performing a PCI (Percutaneous Coronary Intervention), or more specifically a PTCA (Percutaneous Transluminal Coronary Angioplasty) in which, after the initial angioplasty, a tiny wire-mesh tube called a stent is inserted through the skin into the treated artery to keep it open.

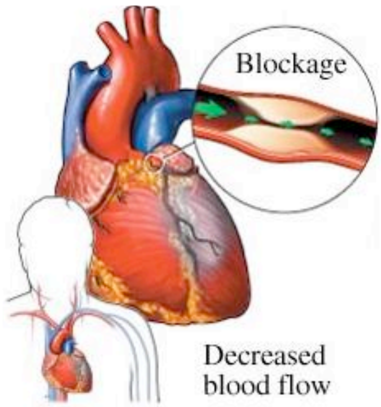


Figure 70: A patient with atheromatous plaque [@11]

Monday 9am, Dr. White and his team carry out the coronary angioplasty procedure for Mr. Miller. The procedure is illustrated diagrammatically in Figure 71. Dr. White makes a small incision in the main artery in the patient's numbed arm, through which he inserts a guide wire into the blood vessel, followed by a balloon-tipped catheter. Mr. Miller is awake during the procedure. Dr. White manipulated the control panel of the cardiac imaging system to see obstructed vessels, the guidewire and the catheter, which are displayed on a monitor in a live fluoroscopic image (a reference X-ray image produced using a contrast dye). Using this live angiogram, Dr. White follows the progress of the balloon catheter along the blood vessels leading to Mr. Miller's heart, and carefully guides the catheter up into Mr. Miller's coronary artery. The guide wire is moved into and through the blockage, after which the balloon-tipped catheter is pushed over the guide wire into the blockage. The tiny balloon on the end of the catheter is inflated inside the narrowed blood vessel, compressing the plaque that is causing the blockage. The balloon thus widens the blood vessel and lets more blood flow through the artery. After widening the vessel, Dr. White inserts a stent wrapped around a catheter into the treated passage. The balloon inside the stent is then inflated, causing the stent to expand against the wall of the artery. Dr. White zooms the images on the monitor to improve stent visibility, as shown in Figure 72. While the stent now stays permanently in the treated passage to support the artery walls and keep the vessel open, the balloon is deflated and pulled out of the artery. ECG (electrocardiogram), blood pressure and inflation time are documented and displayed on the large display. Concluding the procedure, Dr. White retracts and removes the catheter, and a tight bandage is put over the opening in the artery to stop any bleeding from blood vessel and help it heal.

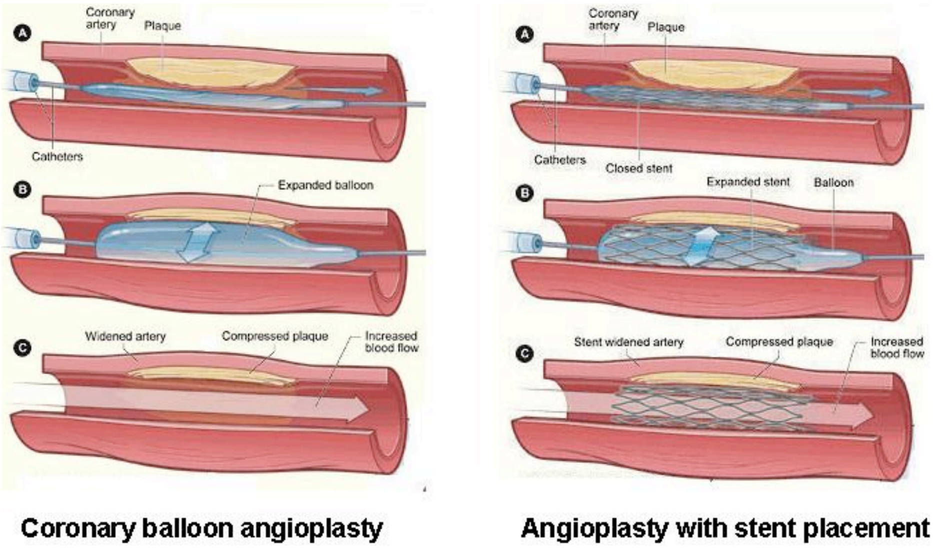


Figure 71: Coronary angioplasty [@7] [@19]

The procedure is completed in around forty-five minutes. Mr. Miller stays in the hospital for one day, keeping the wound where the catheter was inserted dry for 24 hours. As follow-up medication, he is given a clopidogrel bisulfate drug, which makes blood thinner and stops it from forming clots in the arteries and stent.

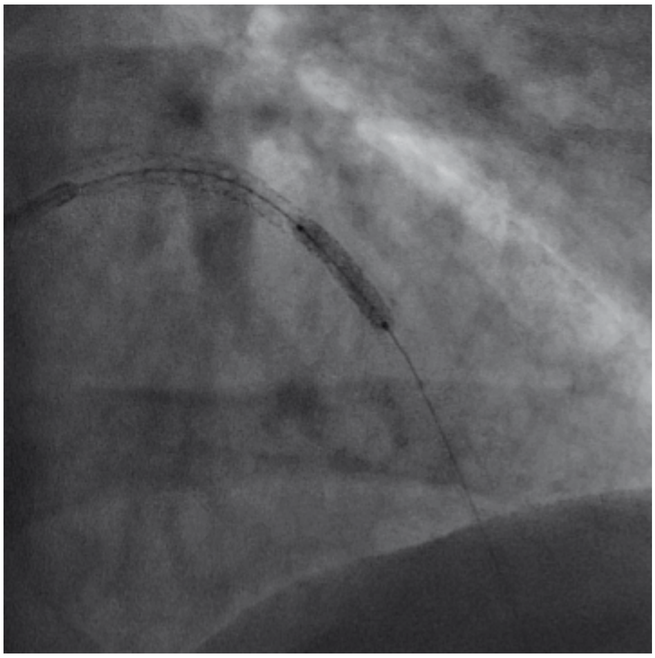


Figure 72: Cardiac imaging with stent visualization

During this angioplasty procedure, the real-time fluoroscopy that is displayed on a monitor is a vital guide to the cardiologist in visualizing the obstructed vessel and following the path of the balloon catheter and subsequently the stent, particularly at difficult points where vessels branch.

The cardiologist will also record these scenes to document the procedure for legal reasons, and to allow a "before/after" quality control when the operation is finished. Generally such cardiac imaging systems are controlled using physical controls such as joysticks or touch panels. While performing the angioplasty procedure, the cardiologist needs to concentrate intensely on the patient and the treatment being administered, which makes it hard to pay too much attention to these physical controls. A good physical control therefore supports the cardiologist by not demanding full attention to its manipulation, thereby reducing the likelihood of mistakes. Touchscreen interfaces offer designers and users flexibility in that they can be customized for each special application. However, if there is a lack of tactile feedback – as is the case with most touchscreens – this is liable to cause other sensory channels to be overloaded. With this in mind, tactile feedback was added to a touchscreen-based control panel in this case study in order to afford better performance and usability.

8.6.1 An angiocardiography system with touchscreen

As an example, the Siemens Artis zeego multi-axis system for cardiology is designed with a tableside touchscreen-based control panel used to remotely the complete workplace and a large display, as shown in Figure 73. A wireless footswitch allows a number of simple tasks to be accomplished without stumbling over cables. The system uses *syngo*® workplace[9], which produces 3D images for angiographic applications. This system provides a single integrated user interface for imaging and waveform applications and enables fast switching between different applications by direct manipulation of the touchscreen-based controls. During treatment, the cardiologist stays around one meter far away from the large display.

The remote control panel consists of four modules: a table control module, a stand control module, a collimator control and a touchscreen console. The touchscreen console provides complete *syngo* functionality with *syngo* icons in a new ergonomically redesigned color GUI. The user interface matches with multi-layer tab cards for preparation, examination, post-processing, quantification and multi-modality viewing such as CT, MR and US.

8.6.1.1 System challenge

Today's operating rooms are spacious, easy to clean, well-lit - typically with overhead surgical lights - and have viewing screens, monitors and manipulating controls. The design of a tactile touchscreen for healthcare applications is based on the working environment in which the system is to be deployed.

Sterile environment

The whole system is required to operate under completely sterile conditions in the exam room. Therefore, a seamless sheet of plastic film is used to isolate the system from bacteria. This means

[9] *Syngo*® workplace [@39] based operation concept provides intuitive graphical user interface for medical imaging and recording system that enables efficient postprocessing of images from various modalities such as AX (angiography / X-ray), CT (computer tomography), MR (magnet resonate) and US (ultrasound).

that the remote control panel as an input device cannot be directly touched, which limits the choice of suitable touchscreen technologies and UI controls.

Figure 73: Siemens Artis zeego multi-axis system

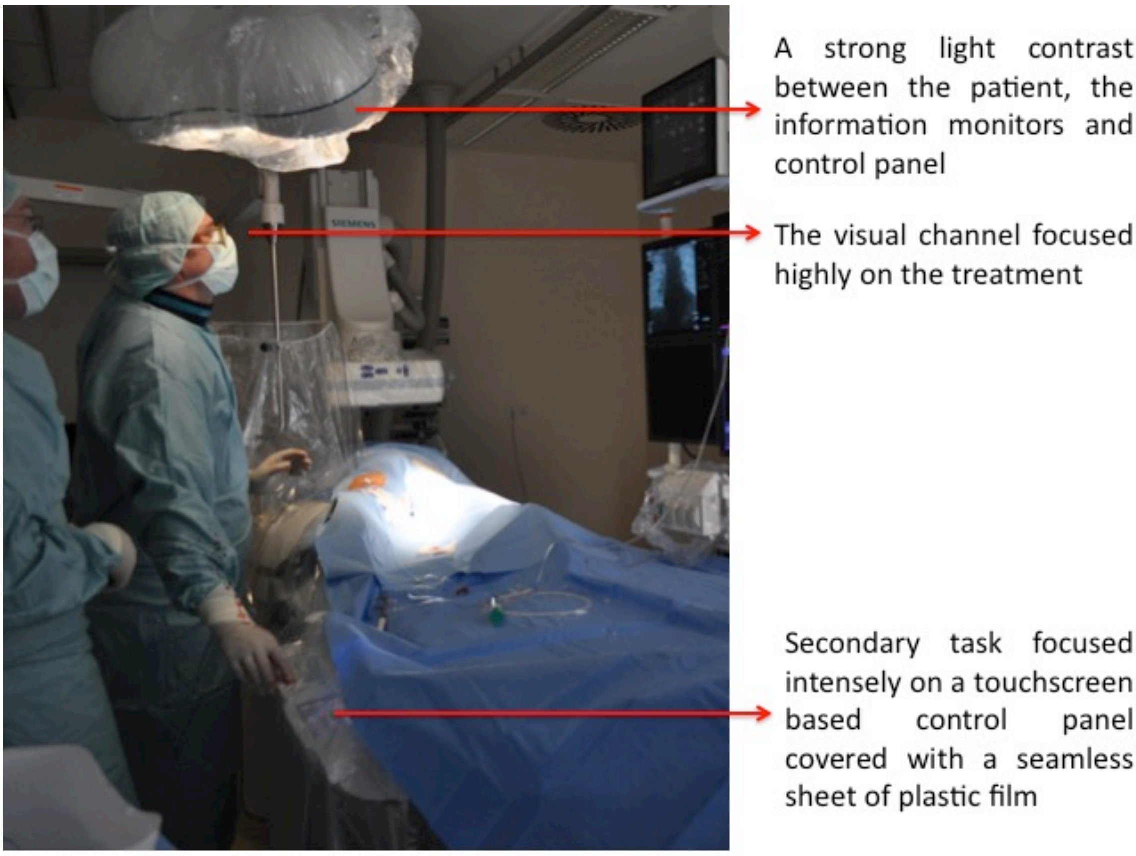


Figure 74: Working environment in Operating room

Secondary work

Cardiologists have to devote their full concentration to the patient and the treatment while they are working with the Artis zeego system. Any interruption of the cardiologist's visual channel due to other tasks or a complex manipulation on the remote control panel can cause them to be distracted from focusing on their main activity. Therefore, it is not acceptable to confront clinicians with a large number of tasks for which they have to manipulate the GUI; by the same token, the UI system requires a clear structure and a consistent information display.

Cost estimation

User-centered design can dramatically affect the cost of developing new interactive systems. When opting for a touchscreen technology, it is necessary to understand the requirements of clinicians and their work environment in order to produce adequate touchscreen-based interactive systems more cheaply and efficiently.

Lighting

During a treatment, the overhead surgical lights highlight the patient over the operating table. Consequently there is a strong light contrast between the patient on the one hand, and information monitors and control panel. This would place heavily burdens on visual attention on a user interface.

8.6.1.2 Functionality meets design

The working environment and system feature of a healthcare application can involve some specific aspects that need to be taken into consideration.

Tactile feedback device

A substantial amount of visual attention becomes a significant drawback when a cardiologist concentrates on the operation, especially in an environment that is only moderately brightly lit to allow X-ray images to be taken. On the basis of the compact size, low cost and low power requirements, tactile feedback technology is worth adding to a touchscreen-based control panel as a potentially much more affordable means of accessing to data visualizations via the sense of touch and reducing visual burden on clinicians in the OP room. Tactile feedback could provide confirmation to clinicians whether the correct actions are about to be or have been performed, so that clinicians do not need to take their eyes off their prime point of high concentration.

Haptic enabled user interface

The viewing distance between cardiologist and table-sized control panel in an exam room means that the widgets on information displays have to be large enough to read. The widgets on the touchscreen need to be designed large enough to avoid input mistakes. However, because of the small size of the touchscreen control panel, it limits the size and number of on-screen UI controls. Haptic feedback is used to help clinicians follow the outline of a UI control and manipulate some interaction without additional visual distraction. The system should response clinicians' input immediately by providing tactile feedback acknowledging the input is received in order to promote speed performance and reduce user frustration. Tactile information presented to clinicians should be readily unambiguous and understood. Haptic interaction design should be accurate and intuitive and avoid causing user fatigue. In addition, considering the working conditions in an OP room, designing touch events on a touchscreen needs to avoid working with both hands.

Touchscreen option

This size of touchscreen determines the size of the UI controls, their arrangement onscreen and the interaction design of the GUI. The resolution of the touchscreen has to be high enough to let the onscreen UI controls be easily recognized. Because a plastic film and a glove separate the touchscreen from the human hand, a capacitive touchscreen activated by a conductive object cannot be considered for this application. And because an OP room is light-sensitive, a touchscreen using infrared technology is not recommended either. A touchscreen using resistive or surface wave technology suits this medical application environment.

8.6.2 Interviews of cardiologists[10]

In order to find out whether the findings in sections 8.5 regarding the use of a tactile touchscreen for a secondary task are in principle transferable to the typical practical application in which a cardiologist treats a patient by inserting a catheter, four cardiologists were interviewed about the concept for adding tactile properties to touchscreens in their stressful use scenario.

Participants

The participants in the interview are four male invasive cardiologists, aged between 37 and 44 (means = 40.75), who have work experience from 5 to 12 years. One cardiologist had been working three years and four hours every week with the table-sized touchscreen in a Siemens Angio system. One cardiologist had been working only three times and one hour every week with the table-sized touchscreen in a Siemens Angio system. The other two had no experience with such system.

Prototype

A prototype created served as a tool for cardiologists to experience the functions of a tactile touchscreen. As a remote control panel, the touchscreen needs to be of a size that will save space. This prototype used an 8.4 inch touchscreen (800 x 600 pixels resolution, with a color depth of 16 bit), which is small enough to allow the operator to get close to the patient. Although the resistive sensor engages only at a perceptible level of force threshold, a resistive touchscreen can be reliably operated in the context of tasks where e.g. clinicians have to wear gloves to work with this system. However, because of the poor clarity of the light transmitted through the resistive touchscreen, a touchscreen using the surface wave technology was selected for this study.

[10] I would like to thank the surgeons of the Department of Cardiology, Campus Innenstadt, Munich University Clinic for allowing me the opportunity to attend their angioplasty procedures, and for participating in the interviews and giving their feedback to my doctoral project in the area of medical applications.

This selected touchscreen using surface wave technology can be activated with touch force of less than 85 grams. A lift-off strategy is preferred because it allows for slight adjustment of the touch by miss-touched.

The prototype for the large imaging display used a full-color projected images on a wall at 56 inch (3830 x 2160 pixels) [@40] to view multiple inputs simultaneously that provides the integrated imaging sources in one projected display and direct control at tableside and allow to change the layout according to the workflow step.

In the prototype of the interview, the user interface of medical diagnostics was designed to consist of a tab card and forty buttons, as shown in Figure 75[11]. They have the same size as the buttons in Figure 60. Three groups of buttons were tested by the cardiologists. Each group has the same stimulus in the buttons and the tabs. The three stimuli, which scored the highest preference ratings, as a means of synthesizing a physical button (see section 8.5), were applied in the interview: 1) an impulse of a 58 Hz, 50 ms sine wave of decreasing amplitude was applied when the finger went onto the button, 2) a constant vibration of a 80 Hz, 200 ms sine wave of increasing amplitude was used as long as the finger stayed on the button, 3) an impulse of a 58 Hz, 50 ms sine wave of increasing amplitude was designed by pressing the button.

An interface sketch was produced to experience the new functions such as zoom and navigation on a tactile touchscreen for a clinician, as shown in Figure 76. The left button used the interaction of zooming in and out seamlessly, while being able to navigate the whole screen, which met the highest rate of preference in section 8.5. Considering that movement into four directions could integrate the functions of zoom and navigation into one interaction, this technique was arranged in the right button, as illustrate in Figure 77.

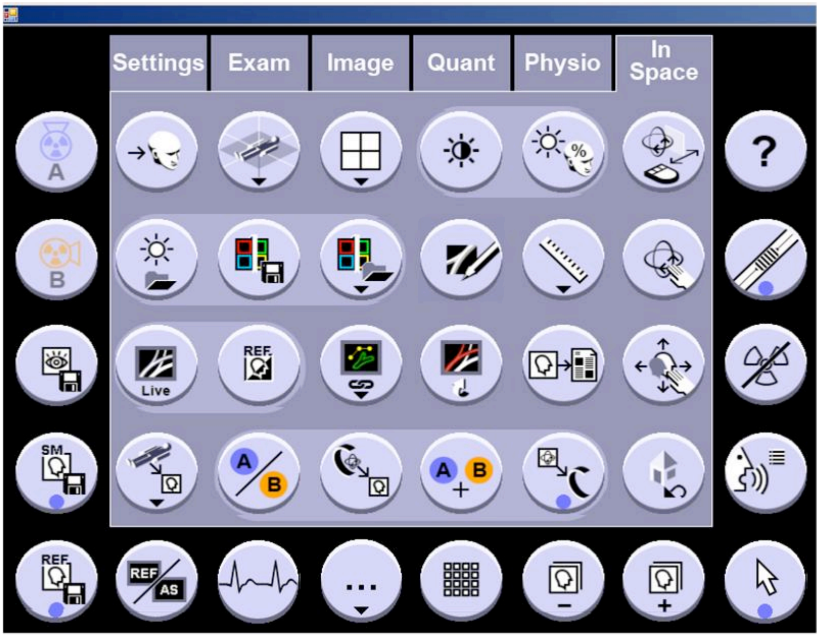


Figure 75: User Interface for intuitive tableside operation in a tactile touchscreen

[11] This prototype is based on the interface of the Siemens Artis zeego multi-axis system.

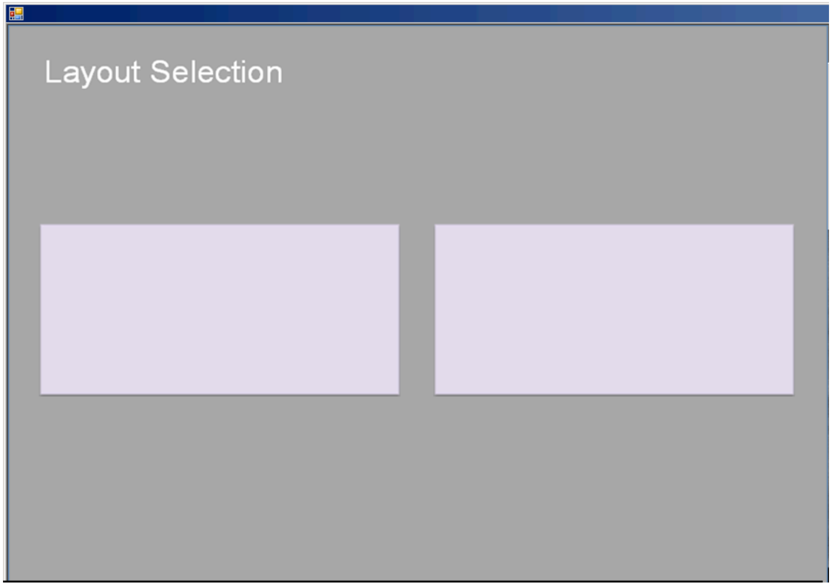


Figure 76: Window-widescreen display of Layout Selection

Figure 77: Zooming in the selected image in a large display

Interview procedure

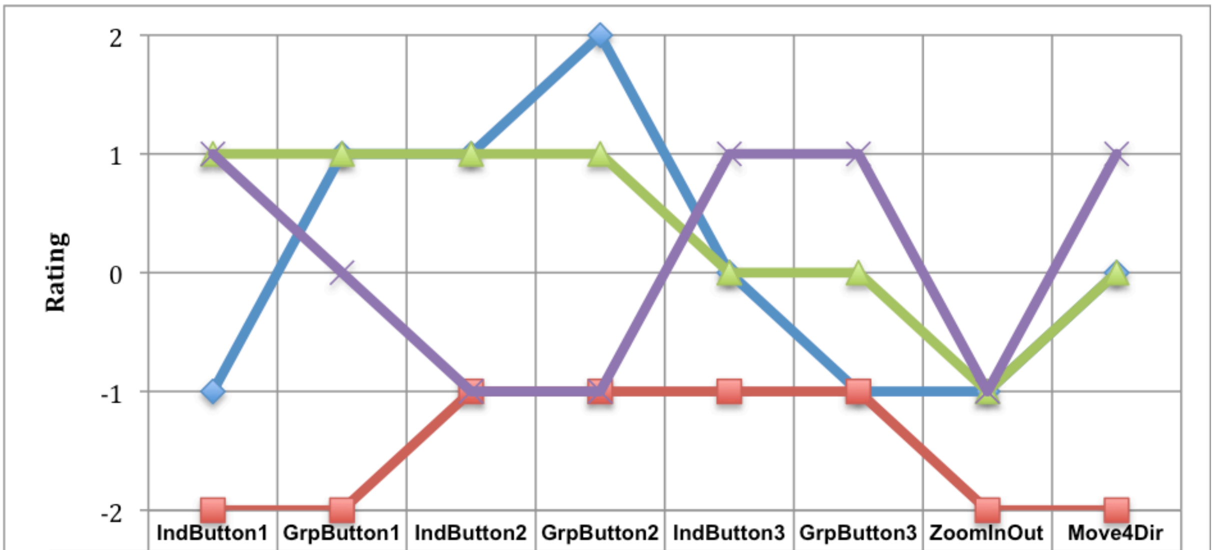
The prototype simulated a stressful work environment and utilized a tactile touchscreen to complete some secondary tasks. The cardiologists were asked for wearing a headset emitting constant noise so that they could not hear but only feel the vibrations generated by the bass shakers and wearing a pair of gloves as they were working in OP room. Each time, they were asked whether the selected stimulus can be easily associated with a physical switch button on a scale from "very difficult to associate" to "very easy to associate", when they moved their fingers into a button and pressed it. Following that, they were asked to move fingers along the rows and columns to evaluate whether the location of buttons were easily recognized with the touch events. Meanwhile, the favorite interaction of a button was asked to select by completing testing the three groups of button interactions.

Subsequently, the cardiologists were asked to rate the two "zooming and navigating" functions and select their favorite one.

In conclusion of the interview, they were asked to give the overall impression of tactile pushing buttons, the “zooming and navigating” function on a tactile touchscreen and a tactile touchscreen as a device for use in their daily work. Then, they were asked for listing three aspects mostly liked to use this system and listing three aspects desirable to improve.

Results

A five-point rating scale was used to evaluate the quality of the stimuli, as shown in Figure 78. For each task, the cardiologists had around five minutes to test the tactile effect.



	IndButton1	GrpButton1	IndButton2	GrpButton2	IndButton3	GrpButton3	ZoomInOut	Move4Dir
P1	-1	1	1	2	0	-1	-1	0
P2	-2	-2	-1	-1	-1	-1	-2	-2
P3	1	1	1	1	0	0	-1	0
P4	1	0	-1	-1	1	1	-1	1

Figure 78: Rating of switch buttons and “zooming & navigating” function

Table 8 summarizes the overall feedback obtained in the concluding interview regarding the tactile touchscreen as a device, the button pushing function, and “zooming and navigating” as a tactile touchscreen function for use in everyday work.

The results of the interviews indicate that in the stressful use scenario of cardiac treatment, tactile feedback would be beneficial in a touchscreen used in a distracting and multitasking work environment. In some functions, for example zoom and navigation, incorporating tactile feedback can simplify operation. In these cases, tactile feedback provides confirmation to users that the correct actions are about to be or have been performed, so that cardiologists could quickly return their focus to the prime point of high concentration; on the other hand, they would not risk missing acoustic feedback among the aural distractions of the OP room.

User	Comments			Recommendations
	Tactile touch screen	Button pushing	Zooming & navigating	
1.	Generally helpful	Like the feel of the press	Will be good in combination with multitouch	Needs to be personalized; number of buttons should be limited
2.	Easy to learn, comfortable to use	Practical enhancement; buttons are big enough.	Practical enhancement	Vibrations need to be stronger to enable operation with gloved hand
3.	Training required	Needs getting used to	Zooming makes the work easier	Combine with visual feedback (e.g. color change)
4.	Training required	Not practical	Good function design, but tactile feedback response time is too fast	Good for a distracting and multitasking work environment; more angioplasty functions need to be tested

Table 8: User comments and recommendations

As the cardiologists reported in the interviews, they would like to use the tableside control panel to control the whole cath lab system, paritcularly to support them in controlling images displayed on the large display and in analyzing angiographic films. Accordingly, due attention needs to be paid to the selection – based on human haptic sensation – of the proper stimulation technique and hardware setup for their applications. This in turn has a fundamental impact on designing suitable tactile effects for interactions such as pushing buttons, zooming displays and navigating images as investigated in this study. It should be borne in mind here that cardiologists wear pairs of gloves during their operations. Therefore, some touchscreen technologies (e.g. capacitive solutions) are not suitable for this use case: the intensity of tactile effects should be strong enough to make them easy to perceive. If there are too many functions and tactile effects on a touchscreen, this could confuse the cardiologists and make operation of the tactile touchscreen complicated. One suggestion was to develop a multimodal system to add visual or auditory feedback to the tactile touchscreen to provide more natural interaction. Consistent use of visual design and tactile information, presented in similar ways across different displays, could enable cardiologists to better integrate tasks involving size, shape and position judgment across GUIs (graphical user interfaces) and HUIs (haptic user interfaces) and make the necessary connections between them. Thus, they would not need to pay excessive attention to the result of any action that took place on the touchscreen. In fact, tactile interactions and functions are cost-effective and response-fast to set up for the purpose of verifying ideas, without having to put too much effort into making the prototype.

In summary, this chapter investigates a tactile touchscreen featuring three-dimensional tactile sensing for the purpose of performing a secondary task, with a view to optimizing the user experience in relation to more complex interaction tasks. In comparison to 2D interaction on a tactile touchscreen, a touchscreen user interface simulating physical controls in a 3D world makes interaction design more complex. The control techniques commonly used on touchscreens (e.g. pressing buttons, zooming and navigating images), which are investigated in the first part of this dissertation in connection with force-reflecting input on the Z axis, are used as a source of guidance in selecting a suitable interaction design for a touchscreen application. Based on the results of investigating control elements on a 3D tactile touchscreen, an interface for a cardiology application is implemented as an example of a haptically enhanced touchscreen used for a secondary task. Findings gained from interviews with four cardiologists show that this novel interaction concept, used on a touchscreen-based control table by a user preoccupied with a surgical operation, is able to reduce the cognitive load on visual attention.

9 Summary and future work

A touchscreen system supplying tactile feedback needs to achieve two capabilities: 1) dynamic information display and 2) touch sensitivity. This study investigates touchscreens incorporating tactile feedback, with the aim of developing an interaction concept achieving these two capabilities and making on-screen UI controls behave more like their mechanical counterparts, in such a way as to maximize the usability of tactile effects in touchscreens.

9.1 Synopsis of the study

As a first step toward developing an interaction concept and choosing suitable design solutions for tactile touchscreens, this study starts by making a technology-oriented analysis of hardware and software requirements to help identify potential new activity designs determining how on-screen UI controls are to be manipulated. Chapter 2 gives an overview of current technical features of touchscreens for purposes of interaction design. A number of studies have discovered that, in terms of performance, touchscreen interfaces face the challenge of providing joy of use and improving user experience. A key factor affecting the difference in their performance as compared with mechanical interfaces is the lack of tactile feedback in conventional touchscreen solutions.

As an alternative to the graphical touchscreens in common use today, and to acoustic solutions which are influenced strongly by the working environment, attempts have been made to add haptic sensation to conventional touchscreen solutions, as discussed in Chapter 4. There has been plenty of research confirming that graphical touchscreens could draw additional benefit from exploiting the nature of human tactile sensation in laboratory and commercial applications. Based on current research into the haptic sensing system as described in Chapter 3 and the current studies on haptic touchscreens analyzed in Chapter 4, an interaction concept for a touchscreen-based user interface taking advantage of tactile feedback is developed, with a view to matching the user's level of skill in different kinds of interaction.

In regard to effective exploitation of tactile feedback in touchscreens, the mechanical equipment used to build such tactile touchscreens becomes a critical factor affecting the perception of tactile effects. As reported in Chapter 5, the first part of this study provides quantitative research into the effects of mechanical vibrations in three different directions: vertical, left-right horizontal and forward-backward horizontal. The results show that vertical vibration along the Z axis can be identified more clearly than the left-right and forward-back horizontal directions of motion. It is also evident that perception of the differences between the vibration directions is easier than recognition of the exact direction. Guided by these findings, further work on the mechanical arrangement of tactile touchscreens focuses on vertical vibration, thereby making maximum use of tactile feedback in touchscreens.

Chapter 6 pursues the goal of designing haptically enhanced UI controls for such touchscreens, the approach being to combine the individual effects of varying tactile parameters such as frequency, amplitude and duration, with the aim of effectively simulating the mechanical properties of the equivalent physical controls. The experiments conducted survey these parameters of vibrotactile stimuli in relation to the semantics of pushing a button, toggling between two states of a checkbox or a switch button, moving sliders and rotating knobs. By examining one vibrotactile parameter while ignoring the others, it emerges that a stimulus of 150 ms, a stimulus with a brief intense final impulse or a stimulus of decreasing amplitude can bring about an enhancement in synthesizing the click feeling of a pushbutton. As to sliders and knobs, an amplitude change conveys the natural feel of either moving a slider or rotating a knob. Regarding perception of two-state checkboxes and switch buttons, if the tactile feedbacks designed for the two states are not significantly distinct, the states will be difficult to tell apart.

As far as the arrangement of UI controls on tactile touchscreens is concerned, it is necessary to investigate the effect of distance between UI controls in order to know how to place them on the touchscreen interface to enable accurate selection. Three concepts are surveyed in an interface incorporating sets of buttons placed very close together and with large spaces between them. The means used to simulate the edges of mechanical buttons are an impulse when the finger moves onto the button, an impulse when the finger moves onto the button followed by an impulse when the finger lets go of it, and constant vibration as long as the finger stays on the button. The findings reveal that an impulse delivered when the finger moves onto the button achieves the best usability results for perception of buttons placed very close together, and constant vibration as long as the finger stays on the button is best for buttons with a large space between them. This finding can be used to guide the arrangement of varying UI controls on a tactile touchscreen.

The investigations into the perception of vibration directions in Chapter 5 and the design of haptically enhanced UI controls in Chapter 6 then serve as basic knowledge informing the development of prototype applications using various touchscreen technologies for both primary and secondary tasks.

A highly reliable tactile touchscreen system helps users work efficiently while making fewer mistakes, and leaves them feeling subjectively pleased by their experience in using it. Accordingly, error rates and operation times revealed through usability testing determine how well the system meets users' practical needs. In Chapter 7, on the basis of use context and available technology, two applications are implemented which provide a set of UI controls on a resistive touchscreen for performing a primary task. The results indicate that, in the performance of a primary task, there are significantly less errors made with a tactile touchscreen than with a conventional touchscreen without tactile feedback. In a realistic use context such as manipulating a touch interface in an elevator or controlling the touch panel of an industrial automation system, feedback as to what is happening on the touchscreen can be given by a new status conveyed through tactile sensation such as vibration or impulse emission, which reduces glance time.

In Chapter 8, a 3D tactile sensing system is developed by taking a tactile touchscreen receiving X/Y coordinated input delivered by surface acoustic wave technology and adding force-reflecting interaction on the Z axis through the use of piezo chips. To investigate interaction design on such a tactile touchscreen, three interaction tasks are specified with a view to completing a set of goals via tactile cues – identification of objects, selection of a single object from a group of objects and manipulation of a selected object. Based on the results obtained from investigating haptically enhanced basic UI controls in Chapter 6, four touch events are generated by combining varying frequency, amplitude and duration values as described in section 8.1.2. These four events are combined into five different interactions, comprising clicking a button and zooming and navigating objects on an interface designed for a secondary task, the purpose of which is to monitor primary tasks. By comparing five techniques for simulating the click feeling of a mechanical button with 3D touch information, it is found that the best usability result is achieved by the button that delivers an impulse when the finger moves onto the button, constant vibration as long as the finger stays on the button, and an impulse when the finger presses the button. The findings made further indicate that zooming in and out continuously while simultaneously navigating the whole screen is a more natural way of zooming and navigating an image. However, investigation of these interaction tasks with a 3D tactile touchscreen and a conventional touchscreen without tactile feedback – despite the increase in spatial information conveyed by tactile sensation and the interaction complexity involved in manipulating the onscreen UI controls – reveals that there are no statistically significant differences in task performance speed using touchscreens with and without tactile feedback. Nonetheless, there is general tendency for users to need less operation time with a tactile touchscreen. Based on the findings made, an interface for an angioplasty procedure is then implemented as an example of an application for a secondary task. The results of four interviews indicate that tactile feedback could be beneficially used in a touchscreen with a view to reducing the cognitive load on visual attention. Cardiologists would no longer run the risk of missing acoustic feedback confirming touch events on acoustic touchscreens among the aural distractions of the operating room.

9.2 Research contribution and future work

The objective of this study is to devise and build usable tactile touchscreens by optimizing the mechanical arrangement of hardware components and by simulating the semantic characteristics of physical UI controls, as a contribution to the scenario-based design of tactile touchscreens for both primary and secondary tasks where visual attention is heavily burdened and acoustic sensory channel is overloaded.

Mechanical arrangement of a tactile feedback device

The findings made in this study reveal that incorporating vertical vibration into a touchscreen enhances the performance of haptic tasks, by making maximum use of tactile cues to the human sensory system. This will be particularly helpful to designers packaging a set of touch events into a single UI control – tactile effects have to be so intuitive as to provide clear and immediate feedback, in order to enable highly efficient interaction between the user and the touchscreen system.

Taking a tactile touchscreen receiving X/Y coordinated input delivered by surface acoustic wave technology as a basis, a 3D tactile sensing system is designed by adding force-reflecting interaction on the Z axis through the use of piezo chips. This touchscreen concept increases the complexity of designing interaction tasks, but expands the design opportunities, enabling sleek designs simulating mechanically operated objects on the touchscreen.

The findings made regarding the mechanical arrangement of a tactile touchscreen will contribute to future research by providing guidance and offering new perspectives for the design of tactile touchscreens, with the aim of effectively simulating mechanical objects using the critical features of the sense of touch.

Semantic features of tactile widgets

Commonly used UI controls can have various touch events assigned to them, such as *moving onto*, *moving off*, *pressing*, *rotating* and *sliding*. The multiple factors of a vibrotactile stimulus that impact on the quality of the simulation of mechanical controls include duration, amplitude and frequency.

*Duration***.** The results of testing various combinations of vibrotactile parameters for basic tactile widgets in this study indicate that 150 ms is the best duration with which to convey the sense of a button click. A short duration of less than 50 ms could be so brief as to be ignored by users, whereas a duration of more than 150 ms prolongs the tactile effects to such an extent that the finger may leave the touchscreen while the stimulus is still occurring. It makes sense for future research to look into the duration range that is best suited to enabling perception of a tactile event.

*Amplitude***.** Both a stimulus with a final impulse and a stimulus of decreasing amplitude increase sensitivity toward tactile events. This finding can assist the design of tactile effects by guiding selection of a tactile stimulus suitable for making touch events noticeable.

Frequency. In accordance with past studies, the experimental results on vibrotactile spatial acuities reported here show that the sensitivity of the human skin gradually increases up to a frequency of around 50 Hz, but decreases over 50 Hz. In view of the limitation of the frequency range to 15–80 Hz in this study, it will be of interest to future work to look further into higher frequencies, for instance the maximum sensitivity level of 250 Hz.

This research into vibrotactile parameters underlies further investigation into touch events with a view to simulating the mechanical operation of physical UI controls.

Pressing. Due to the differing sensitivity of the tactile channels of different users, it is impossible that a given stimulus with a specific combination of various vibrotactile parameters can produce the best sensitivity to a simulated click feeling in every user. Future work with a large group of samples is required to establish the optimum range within which different vibrotactile parameters can be combined to synthesize a pressing event on a tactile touchscreen, and to determine whether two substantially different vibrotactile feedbacks can be easily distinguished as indicating a toggle between two states in checkboxes and switch buttons.

Sliding and rotating. Both dragging a slider and rotating a knob are actions embracing a set of continuous values along one single axis. Three sets of values are designed in this study as a basis for investigating interaction along one axis (see 6.4.3). The results show that a stimulus of continuously increasing and decreasing amplitude meets with the highest preference among users as a means of simulating the feel of sliding and rotating actions in a distracting work environment. By comparison, step-by-step incrementation of the amplitude level, while can create a range of detent sensations, does not convey the feel of a continuous state change – in fact this may even confuse users, especially when rotating a control on a glass-like surface. This kind of design feature is therefore not recommended as a means of simulating the feel of dragging a slider or rotating a knob.

Moving onto and moving off. Three interaction techniques are applied in this study to simulate physical interaction with the edges of a widget when the finger moves across an on-screen target (see 6.4.4). However, the spatial arrangement of the widgets has a direct impact on the selection of a suitable interaction technique. This study compares these three kinds of simulation techniques in layouts comprising small and large spaces between targets. The findings made indicate that when targets are very close together, only an impulse delivered when the finger moves onto a target provides a clear signal that the current target has changed, whereas with a large space between targets users need constant vibration as long as the finger stays on the target. An interaction technique that delivers an impulse when the finger moves onto the target, followed by an impulse when the finger lets go, meets with low preference both for targets positioned very close together and for those placed further apart from each other. The reason for this is likely to be cognitive load caused by quickly analyzing two similar stimuli and integrating them into the related interactions. This could also be a basic consideration for designing two highly distinct stimuli to discriminate two states of a checkbox and a switch button.

The greater the number of interaction tasks that need to be integrated into one tactile widget, the greater the design challenge. A comparison of five interaction techniques for simulating the feel of physical switch buttons with 3D touch information (see 8.1.2) shows that the best usability result is achieved by a switch button that delivers an impulse when the finger moves onto it, constant vibration as long as the finger stays on it, and an impulse when the finger presses the button. This mode of interaction featuring three of four touch events (moving onto, staying on, pressing and releasing) further reveals that tactile vibration tends to be ignored if it is not short, precise, intense and fast enough.

Some complex tasks on a tactile touchscreen can be simplified by integrating multiple interactions. A comparison of interaction techniques using 3D touch information to provide controls for zooming and navigating an image (see 8.1.2) shows that zooming through distinct magnification levels and zooming in on the four corners demands incremental visual attention. The technique of zooming in and out continuously while being able to navigate the whole screen provides the most natural tactile interaction and reduces the visual burden involved in operating a touch panel used for a secondary task; it is thus recommended for the purpose of resizing and navigating an image. For complex interaction tasks, the results indicate that the better design is one that simplifies the touch events and makes the interaction more clearly perceptible to the tactile sense.

This investigation into the semantic features of tactile events in single- and multi-target situations will be beneficial in guiding the simulation of mechanical UI controls and also the arrangement of tactile widgets on touchscreens.

Haptically enabled touchscreens as an enhancement to user experience in distracting environments

Selection of the proper tactile widgets and touch events depends on user requirements, task features, system capabilities, and the application environment. For example, choosing one item by scrolling through a list saves input space but increases the need for visual feedback, even if tactile cues are provided. A high demand on visual attention is a significant drawback, especially in a poorly lit or stressful environment. Also, acoustic feedback can be drowned out by the background noise of the work environment. By contrast, tactile feedback provides a direct, private and bidirectional channel, enabling a touchscreen-based control panel to be used particularly effectively in noisy and low-visibility situations. Interaction design for tactile touchscreens depends on the task in hand and the user's mental model of the system, which are analyzed in this study in relation to primary and secondary tasks. The size and content of an application influences the way in which tactile widgets are arranged on a touchscreen and the choice of suitable tactile effects for them. Tactile touchscreens that are limited in size can easily become cluttered with tactile information. This can increase the complexity involved in operating the on-screen tactile widgets.

As an example of a primary task, this study implements a use case in which users switch between a media player control and a room light control in a distracting environment. Users are concerned with the results of manipulating tactile widgets as perceived in the form of immediate system responses, but they don't want to have to concentrate on visual confirmations in the user interface. Further application scenarios discussed involve interaction with a touch interface for an elevator system in an office building and a touch control panel for an industrial automation system. Building technology devices usually employ cost-effective, operationally stable and energy-efficient instruments for simple applications. A touch control panel for an industrial automation system, operating within the constraints of a harsh industrial environment, has to be resistant to scratches and accidental spillage, and withstand fluid splashes. The tactile touchscreens employed for both applications have to be capable of being activated by a bare finger, a stylus or even a gloved hand. For the above purposes, the inexpensive and robust resistive touchscreen can be the right choice for both applications as a basis for adding tactile feedback. At the same time, users expect interaction tasks to be few in number and easy to control, e.g. pressing an on-screen radio button to select one item from a list of five. In an application using a relatively small display, tactile feedback can provide direct confirmation that a small target has been successfully pressed, obviating the need for excessive visual attention to the action performed.

Touchscreen-based tactile interfaces have applications in many areas including computer-assisted surgery. Chapter 8 describes how an application is designed for a secondary task involved in an angioplasty procedure. In this application, a touchscreen-based control panel enables remote control of the workplace equipment. However, a large number of functions displayed graphically on a touchscreen-based control panel, where have to concentrate on a relatively small interface, can obviously cause heightened visual attention to the touchscreen and thus distraction from the primary task. In this situation, adding tactile feedback into the touchscreen-based control interface should be a potentially affordable means of accessing visualized data via the sense of touch, thereby decreasing the need for excessive visual attention to the result of any action taking place on the touchscreen used for the secondary task. For some practical applications like the completely sterile conditions prevailing in the light-sensitive operating room - a seamless sheet of plastic film is used to isolate the system from bacteria. This means that any touchscreen selected requires a high resolution, but must not be light-sensitive or conductivity-activated. Thus, a touchscreen based on a surface wave or resistive solution can be reliably operated in medical or similar application environments. On the other hand, the intensity of tactile events should be strong enough to make them easy to sense even for a gloved hand. Moreover, this kind of system increases the need to select a pointing strategy in which the touch events constitute natural actions. A take-off strategy is preferred for this application, because it allows for slight adjustment of the touch in the event of an initial mistouch.

Meanwhile, experiments comparing tactile touchscreens and conventional touchscreens without tactile feedback show that tactile feedback has a quantifiable effect on speeding up touch recognition, decreasing error rates and improving touch confidence in distracting circumstances, both for a primary and for a secondary task. Tactile cues can convey a significant quantity of information on mechanical properties in the physical world, not just simple notifications. Human tactile reaction is instantaneous, so receiving information in this way helps reduce operation time and error rates, thereby lessening distraction and enhancing user satisfaction – a beneficial application of the tactile sense which leverages the features of mechanical controls. As well as reducing complexity and stress in using touchscreens, this also enables more controllable and comfortable use of touchscreen real estate. It is suggested that the number of functions and tactile effects on a touchscreen should be reduced in order to make operation of the tactile touchscreen easy to understand and interpret. In addition, incorporating tactile feedback along with audio-visual feedback could provide added value to using a touchscreen.

Moreover, this study indicates that integrating human tactile sensation into software-controlled widgets and control functions can produce control panels that offer fully reconfigurable, flexible interface settings and are economic in terms of system scale. When designing tactile events for primary and secondary tasks, the capabilities of the selected tactile touchscreen have to match the requirements of the particular application.

This study lays the groundwork for further investigation into the following aspects of tactile feedback in touchscreens:

Environment-dependence. The work environment dictates the selection of touchscreen technology and impacts on the design of tactile events in a tactile feedback interface. An approach to specifying a solution of a tactile touchscreen should understand how users do why they do in which environment they do.

User-centered design. A tactile touchscreen, as an interactive application interface, needs to be designed for users rather than around the technology. The results of this study indicate that it is worth further investigating the tactile widgets to find out which of their range of tactile parameters (duration, amplitude etc.) are most strongly sensed, the aim of this being to allow users to leverage the distinctive sensitivity of their individual tactile channels by customizing the strength and intensity of the predefined tactile effects. For instance, based on the results obtained in Chapter 6, there is scope in future work for further investigation into whether a stimulus of a duration of 150 ms combined with an amplitude of decreasing effect and a brief intense final impulse can induce the best perception of a mechanical pushbutton.

Context-sensitivity. Tactile cues should assist in navigating and operating a system as users would naturally expect for the tasks concerned. Based on the findings in Chapter 5, it would be profitable to investigate how the sensation of directional perception is influenced by the other tactile parameters, for example, when the amplitude alone is increased, decreased or modulated. Future work should furthermore test the ability of the hand to identify and distinguish whether the direction of vibration is horizontal along the X or Y axis or vertical along the Z axis, and whether this ability plays a role in interpreting tactile cues.

Fast response. An immediate tactile response enables users to get prompt confirmation to speed up touch recognition, improve touch confidence, and thus reduce hand-eye coordination errors in the performance of interactive tasks on a touchscreen. In a distracting working environment, a tactile touchscreen should provide a reasonable duration with a view to giving the user enough time to react to the tactile effect or to sense the impulse naturally, for instance when receiving a physical detent. For these purposes, the findings made in Chapter 6 and Chapter 8 will guide simulation of the sensation of pressing the basic physical UI controls on a 2D and even a 3D touchscreen.

Precise control. Tactile events should allow precise control and discrimination of actions, particularly when completing a number of complex tasks on a touch interface, or operating some UI controls that have two or more states. As to checkboxes, in general the selected and unselected states of a checkbox can be described as two kinds of button clicks. If the tactile feedbacks for two states of a checkbox have no significant distinction in vibrotactile duration, amplitude or frequency, this will increase cognitive load, making two states of a checkbox hard to discriminate. Thus, future work needs to be done with a large group of samples to investigate whether two discernibly distinct tactile feedback indicators could be used to discriminate state changes in checkboxes and switch buttons, especially when used in a 3D touchscreen with force reflection on the Z axis.

Consistent Feedback. Tactile feedback must provide coherent responses, not only to promote intuitive understanding of objects but also to allow identification of the same tactile widgets in the same locations across the entire interface (e.g. when clicking an "OK" or "Cancel" button used throughout the application). The object of this is to reduce the cognitive loading.

This study seeks to enhance the effectiveness of the touchscreen by properly exploiting its fundamental intrinsic characteristic: the tactile modality addressing the human haptic communication channel. If this modality is fully utilized, it can avoid the visual sense becoming overloaded or the auditory sensory channel being distracted. Accordingly, the purpose of the study is to investigate, by means of user tests, exactly how the human tactile perceptual channel responds to the mechanics of the touchscreen, and how this insight can help determine what haptic signals are best mapped to what mechanical controls. As a basic consideration regarding the interplay between the haptic, visual and auditory channels, the scenario-based design of the experiments conducted with both a 2D and a force-reflecting 3D tactile touchscreen reveals that there is a need to develop separate interaction concepts for primary and secondary tasks. Beyond this, the discussions elaborated and the findings made in the study lay the foundations for further essential research into specific aspects of touchscreen user interface evolution: the design and arrangement of hardware components for tactile touchscreens; the development of strategies for the simulation of particular mechanical controls; and the conceptual design of tactile touchscreen interfaces based on usage scenarios.

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Appendix

Appendix 1: Questionnaire on subjective perception of touchscreens with and without tactile feedback in terms of their pragmatic and hedonic qualities. (© AttrakDiff 2.0)

Please provide your impressions of the product you have tested by check marking your impression on the scale between the terms offered in each line.

Please checkmark...

	1	2	3	4	5	6	7	
human	☐	☐	☐	☐	☐	☐	☐	technical
isolating	☐	☐	☐	☐	☐	☐	☐	connective
pleasant	☐	☐	☐	☐	☐	☐	☐	unpleasant
inventive	☐	☐	☐	☐	☐	☐	☐	conventional
simple	☐	☐	☐	☐	☐	☐	☐	complicated
professional	☐	☐	☐	☐	☐	☐	☐	unprofessional
ugly	☐	☐	☐	☐	☐	☐	☐	attractive
practical	☐	☐	☐	☐	☐	☐	☐	impractical
likeable	☐	☐	☐	☐	☐	☐	☐	disagreeable
cumbersome	☐	☐	☐	☐	☐	☐	☐	straightforward
stylish	☐	☐	☐	☐	☐	☐	☐	tacky
predictable	☐	☐	☐	☐	☐	☐	☐	unpredictable
cheap	☐	☐	☐	☐	☐	☐	☐	premium
alienating	☐	☐	☐	☐	☐	☐	☐	integrating
brings me closer to people	☐	☐	☐	☐	☐	☐	☐	separates me from people
unpresentable	☐	☐	☐	☐	☐	☐	☐	presentable
rejecting	☐	☐	☐	☐	☐	☐	☐	inviting
unimaginative	☐	☐	☐	☐	☐	☐	☐	creative
good	☐	☐	☐	☐	☐	☐	☐	bad
confusing	☐	☐	☐	☐	☐	☐	☐	clearly structured
repelling	☐	☐	☐	☐	☐	☐	☐	appealing
bold	☐	☐	☐	☐	☐	☐	☐	cautious
innovative	☐	☐	☐	☐	☐	☐	☐	conservative

dull	☐	☐	☐	☐	☐	☐	☐	captivating
undemanding	☐	☐	☐	☐	☐	☐	☐	challenging
motivating	☐	☐	☐	☐	☐	☐	☐	discouraging
novel	☐	☐	☐	☐	☐	☐	☐	ordinary
unruly	☐	☐	☐	☐	☐	☐	☐	manageable

Appendix 2: Activities assigned as part of primary tasks.

Block 1.	Select Stereo Mode Turn Power on Play a song
Block 2.	Turn the volume to the maximum Stop the song Select the next song
Block 3.	Turn the volume to mimimum Pause the song Select the Light Control Mode
Block 4.	Turn on all lights Turn off bathroom light Change living room light to maximum
Block 5.	Select Stereo Mode Turn Power on Play a song
Block 6.	Turn the volum to the maximum Stop the song Select the next song
Block 7.	Turn the volume to minimum Pause the song Select the Light Control Mode
Block 8.	Turn on all lights Turn off bathroom light Change living room light to maximum
Block 9.	Select Stereo mode Turn Power On Play a song
Block 10.	Turn the volume to the maximum Stop the song Select the next song
Block 11.	Turn the volume to minimum Pause the song Select the Light Control Mode
Block 12.	Turn on all lights Turn off bathroom light Change living room light to maximum

Appendix 3: Questionnaire for usability interview on tactile touchscreen for operating table.

1. Demographic data

1.1 Profile

1. Gender: ☐ female ☐ male
2. Age: ______

1.2 Occupation

3. What is your area of expertise?

______

4. What position do you currently hold at your hospital?

______

5. How long have you been working in your area of expertise?

☐ less than 6 months ☐ 2-5 years
☐ 6-12 months ☐ 5-10 years
☐ 1-2 years ☐ more than 10 years

6. Education:

______

7. Additional qualifications:

______

1.3 Experience with touchscreen

8. How long have you been working with a touchscreen?

______

9. Do you have experience with a tactile touchscreen?

______

1.4 Experience with Siemens Angio and/or Card Systems

10. How long have you been working with the Artis system?

______ years

11. How many hours per week do you work with the system?

    _____ hours/week

12. What are your three main tasks when working with Artis? Please list the three most frequent ones.

    1.

    2.

    3.

13. For which functions do you use the tableside control panel with a touchscreen? Please list the three most frequent ones.

    1.

    2.

    2.

14. What are the problems you encounter when you work with the tableside remote touchscreen? Please list the three most frequent ones.

    1.

    2.

    3.

2. Task

2.0 Switch button

2.0.1 Individual button: Does this group of buttons give you feedback that you can easily associate with a physical switch button? Please rate this group on a scale from "very difficult to associate" (--) to "very easy to associate" (++).

	--	-	+/-	+	++	
Very difficult to associate	☐	☐	☐	☐	☐	*Very easy to associate*

Reason:

Button group: Please move your finger along the rows and columns. Rate the buttons by how well you could feel the feedback of this group, on a scale from "very bad" to "very good".

	--	-	+/-	+	++	
Very bad	☐	☐	☐	☐	☐	*Very good*

Reason:

2.0.2 Individual button: Does this group of buttons give you feedback that you can easily associate with a physical switch button? Please rate this group on a scale from "very difficult to associate" (--) to "very easy to associate" (++).

	--	-	+/-	+	++	
Very difficult to associate	☐	☐	☐	☐	☐	*Very easy to associate*

Reason:

Button group: Please move your finger along the rows and columns. Rate the buttons by how well you could feel the feedback of this group, on a scale from "very bad" to "very good".

	--	-	+/-	+	++	
Very bad	☐	☐	☐	☐	☐	*Very good*

Reason:

2.0.3 Individual button: Does this group of buttons give you feedback that you can easily associate with a physical switch button? Please rate this group on a scale from "very difficult to associate" (--) to "very easy to associate" (++).

	--	-	+/-	+	++	
Very difficult to associate	☐	☐	☐	☐	☐	*Very easy to associate*

Reason:

Button group: Please move your finger along the rows and columns. Rate the buttons by how well you could feel the feedback of this group, on a scale from "very bad" (--) to "very good" (++).

	--	-	+/-	+	++	
Very bad	☐	☐	☐	☐	☐	*Very good*

Reason:

General Feedback: Which group of buttons do you prefer to use? Why? What kind of feedback would you like to push a button?

2.1 Zooming & Navigating

Please rate the following two "zooming & navigating" functions on the touchscreen.

2.1.1 How would you rate this "zooming & navigating" function on a scale from "very bad" (- -) to "very good" (++)?

	--	-	+/-	+	++	
Very bad	☐	☐	☐	☐	☐	*Very good*

Reason:

2.1.2 How would you rate this "zooming & navigating" function on a scale from "very bad" (- -) to "very good" (++)?

	--	-	+/-	+	++	
Very bad	☐	☐	☐	☐	☐	*Very good*

Reason:

General Feedback: Which "zooming & navigating" function do you prefer to use? Why? What kind of "zooming & navigating" function would you like to manipulate an image?

3. Closing interview

What is your overall impression of a tactile touchscreen as a device for use in your daily work?

What is your overall impression of pushing buttons on a tactile touchscreen?

What is your overall impression of the "zooming and navigating" function on a tactile touchscreen?

What aspects did you like the most?

Please list the "top three" aspects.

1. _____
2. _____
3. _____

What aspects need improvement?

Please list the three most important aspects.

1. _____
2. _____
3. _____

What function / interaction do you wish to have on a touch panel?

Do you have any other comments?

Do you have any further questions you'd like to ask us?

Thank you very much!