Novel Haptic Interfaces and their Impact on Perception and Performance

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Abstract

This thesis explores novel haptic user interfaces for touchscreens, virtual and remote environments (VE and RE). All feedback modalities have been designed to study performance and perception while focusing on integrating an additional sensory channel - the sense of touch. Related work has shown that tactile stimuli can increase performance and usability when interacting with a touchscreen. It was also shown that perceptual aspects in virtual environments could be improved by haptic feedback. Motivated by previous findings, this thesis examines the versatility of haptic feedback approaches. For this purpose, five haptic interfaces from two application areas are presented. Research methods from prototyping and experimental design are discussed and applied. These methods are used to create and evaluate the interfaces; therefore, seven experiments have been performed.

All five prototypes use a unique feedback approach. While three haptic user interfaces designed for touchscreen interaction address the fingers, two interfaces developed for VE and RE target the feet. Within touchscreen interaction, an actuated touchscreen is presented, and study shows the limits and perceptibility of geometric shapes. The combination of elastic materials and a touchscreen is examined with the second interface. A psychophysical study has been conducted to highlight the potentials of the interface. The back of a smartphone is used for haptic feedback in the third prototype. Besides a psychophysical study, it is found that the touch accuracy could be increased. Interfaces presented in the second application area also highlight the versatility of haptic feedback. The sides of the feet are stimulated in the first prototype. They are used to provide proximity information of remote environments sensed by a telepresence robot. In a study, it was found that spatial awareness could be increased. Finally, the soles of the feet are stimulated. A designed foot platform that provides several feedback modalities shows that self-motion perception can be increased.

- to my father and my loved little family.

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List of Publications

The following publications have been accepted for publication as a direct or indirect result of the research during the time as a PhD student. In this thesis, especially [J1] and [C1-C4] are addressed. At the end of each reference is a link to the corresponding section in which parts of the publication can be found. I have designed and developed all of the five prototypes presented in this thesis. In those publications where I am not listed as the first author, I contributed an essential part to the idea, implementation, experimental design and writing part. Results and evaluations which were done collaborative have been evaluated and interpreted anew in the context of this thesis. The second part, further selected publications, aims to show that the research methods used in this thesis can be transferred to other fields.

Journals [J*] and Conferences [C*]:

[J1] **Jens Maiero**, David Eibich, Ernst Kruijff, André Hinkenjann, Wolfgang Stürzlinger, Hrvoje Benko, Gheorghita Ghinea, Back-of-Device Force Feedback Improves Touchscreen Interaction for Mobile Devices, *IEEE Transactions on Haptics, 2019* (refers to Section 4.4)

[C1] ***Jens Maiero**, Ernst Kruijff, André Hinkenjann, Gheorghita Ghinea,* ForceTab: Visuo-haptic Interaction with a Force-senstive Actuated Tablet, *IEEE International Conference on Multimedia and Expo (ICME), 2017*, [**Best Paper Award**] (refers to Section 4.2)

[C2] *Ernst Kruijff, Saugata Biswas, Christina Trepkowski, **Jens Maiero**, Gheorghita Ghinea, Wolfgang Stuerzlinger,* Multilayer Haptic Feedback for Pen-Based Tablet Interaction, *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI)* (refers to Section 4.3)

[C3] *Brennan Jones, **Jens Maiero**, Alireza Mogharrab, Ivan Abdo Aguliar, Ashu Adhikari, Bernhard Riecke, Ernst Kruijff, Carman Neustaedter, Robert W. Lindeman,* FeetBack: Augmenting Robotic Telepresence with Haptic Feedback on the Feet , *Proceedings of the 2020 International Conference on Multimodal Interaction (ICMI)* (refers to Section 5.2)

[C4] *Ernst Kruijff, Alexander Marquardt, Christina Trepkowski, Robert W. Lindeman, André Hinkenjann, **Jens Maiero***, Bernhard Riecke E., On Your Feet! Enhancing Vection in Leaning-Based Interfaces through Multisensory Stimuli, *Symposium on Spatial User Interfaces, 2016* (refers to Section 5.3)

Further selected publications:

[C5] ***Jens Maiero**, Ernst Kruijff, André Hinkenjann, Gheorghita Ghinea,* PICOZOOM: A Context Sensitive Multimodal Zooming Interface, *IEEE International Conference on Multimedia and Expo (ICME), 2015*

[J2] **Jens Maiero**, Ernst Kruijff, André Hinkenjann, Gheorghita Ghinea, Focus plus Context Techniques for Pico-Projection based Interaction, *IEEE Transactions on Multimedia, 2017*

[C6] *Alexander Wilberz, Dominik Leschtschow, Christina Trepkowski, **Jens Maiero**, Ernst Kruijff, Bernhard Riecke,* FaceHaptics: Robot Arm based Versatile Facial Haptics for Immersive Environments, *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI)*

[C7] *Anil Ufuk Batmaz, **Jens Maiero**, Bernhard Riecke, Ernst Kruijff, Carman Neustaedter, Wolfgang Stuerzlinger,* Telepresence Robot Navigation in Conference-Like Environments with Distance-Based Automatic Speed Control, *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* - in submission

[C8] *Alexander Marquardt, **Jens Maiero**, Ernst Kruijff, Christina Trepkowski, Andrea Schwandt, André Hinkenjann, Johannes Schoening, Wolfgang Stuerzlinger,* Tactile Hand Motion and Pose Guidance for 3D Interaction, *In Proceedings of the ACM Symposium on Virtual Reality Software and Technology, 2018*

[C9] *Christina Trepkowski, David Eibich, **Jens Maiero**, Alexander Marquardt, Ernst Kruijff, Steven Feiner,* The Effect of Narrow Field of View and Information Density on Visual Search Performance in Augmented Reality, *Proceedings of the IEEE conference on Virtual Reality (VR) 2019*

Chapter 1

Introduction

New technologies have grown immensely in recent decades. Most people use a smartphone for everyday things. Virtual environments allow users to immerse themselves in computer-generated worlds and meet with others. Telepresence systems allow users to attend remote events in person. Robots and artificial intelligence are other strong trends that reflect the impact of digitalisation. From a philosophical point of view, it can be said that computers and humans have become closer in recent years. Somehow, what used to be science fiction is now reality. However, what does the interaction between humans and computers actually look like? Will perception and performance be improved when multiple senses are used for interaction? This thesis presents five novel haptic user interfaces that show that engaging the sense of touch positively affects touchscreen interaction and perception in virtual and remote environments.

1.1 Context and Motivation

Looking briefly at the history of human-computer interaction (HCI) [Mye98], it can be seen that people have been searching for more effective ways of interacting with computers ever since the beginning of the computer era. The first computing operations were realized using punched card systems, and there was no human-computer interaction in the way that it is understood today. At that time, computers were used to perform specific tasks, sequentially, and only a few experts were able to operate them. With the first personal computers, such as the Apple 2 (1977) and the IBM PC (1981), a command-line was used to operate and interact with the operating system. Although the first research results on graphical user interfaces were already available at this time, they were not included in their systems. In December 1968, at the Stanford Research Institute in California, Doug Engelbart gave a legendary demonstration of how to control content on a computer monitor with a mouse [EE68]. However, it was still time before a graphical user interface (GUI) was available to a mass audience.

In the 1970s, graphical user interfaces were developed at the Californian Research Center Xerox PARC. However, for some reason, GUIs were not accepted by the market. In 1983, the Apple Lisa brought in first ideas of graphical user interfaces, and one year later, the Apple Macintosh was born. Two years later, Microsoft also presented the first version of Windows however, the graphical user interface's concept and implementation were not very user-friendly. The successor version, Windows 3.1; received more acceptance from users. However, the breakthrough came with Windows 95 and the introduction of the start button. Since then, human-computer interaction has continued to evolve, and rapid development has continued.

Mobile phones, later smartphones, have had a significant influence on HCI. The first mobile phones appeared in 1983 (Motorola DynaTAC 8000X), obviously without a touchscreen. The first smartphone (Apple iPhone) with a touchscreen, appeared in 2007, when Apple also introduced gesture-based interaction using touchscreens. Google presented the first Android smartphone about a year later. Multitouch gestures, such as pinch to zoom or rotate, are now indispensable. Early mobile phones had physical buttons to interact with. Display and interaction were physically decoupled. With the introduction of touchscreens, it became possible to combine display and interaction within a single device. However, feeling a button and sensing physical events has an impact on perceptual and performance aspects. That is why many researchers have been working on recreating precisely these lost properties as closely as possible. For example, vibration motors are used to enrich graphical user interface (GUI) elements with tactile feedback; even blind people can benefit. They are much more dependent on the haptic exploration. It seems that the combination of touchscreen interaction with haptic feedback has much potential.

However, haptic feedback can also be useful in other areas. When looking at the history of virtual reality (VR), it becomes clear that the rendering of physical properties, for instance, feeling textures, will enhance the experience. A milestone in VR history was the head-mounted display (HMD) by Ivan Sutherland in 1968. His stereoscopic display system made it possible to perceive three-dimensional environments visually. In the 1980s, it was realised that there was more to VR than just visual stimuli and other senses began to be included; for example, data gloves were explored. Since around 2010, starting with Oculus Rift, there was another VR hype. Alongside stereoscopic displays, HMDs were now available on the consumer market and affordable for everyone. While photorealistic three-dimensional environments can be rendered almost in real-time, the representation of physical properties, for example, not just seeing objects but also feeling them, is still an open issue in this domain.

Interaction, including haptic interaction and exploration, with a computer has been formalized over time; two models will be presented to demonstrate how interaction works. Interaction is a dynamic action that adapts inputs through a dialogue with feedback and provides corresponding results. In particular, haptic feedback aims at either changing a perceptual state or improving interaction performance. Norman's model [Nor13] focuses on the user's view, his interaction model consists of six stages per cycle. Each cycle begins with an execution part intended to achieve an established goal: (i) form the intention, (ii) specify the action sequence and (iii) execute the action. This is followed by an evaluation part: (i) perceive the system state, (ii) interpret the system state and (iii) evaluate the system state with respect to the goals. Norman introduced the terms gulf of execution and gulf of evaluation to provide an understanding of interface failures, while the *gulf of execution* refers to a misinterpretation of the functionalities provided by the system and how to use them, the *gulf of evaluation* is the difference between the physical state or feedback, and the state assumed by the user. It is important when designing haptic user interfaces to know and consider these possible failures. Abowd and Beale's model [DFAB04] is a universal version of Norman's interaction model which has four components: (i) user, (ii) input, (iii) system and (iv) output. Each component has its own language. An interaction cycle starts with the user's input; the input pursues a certain goal. In this context, a failure in the interface or in the interaction, is understood as a misinterpretation or mistranslation of the corresponding language.

The interaction models presented above are based on the fact that users can perceive and communicate with their world. A person's senses are used to interact with and in the real world; they help individuals communicate with other people and perform everyday tasks. Humans have five senses: sight, hearing, taste, smell and touch [Gol10]. In principle, the senses all function on a similar principle. Environmental stimuli such as light or odours are converted by the appropriate sense, into electrical neural signals that then reach the brain through the nervous system and are processed there [Gol10]. Each sensory organ has evolved its method of transforming an environmental stimulus. The eyes have rods and cones, while the ear converts vibrations through various stages, into nerve signals. The olfactory mucosa and the taste buds transmit smell and taste to the brain. The skin works differently, as it consists of thermoreceptors (hot and cold), nociceptors (pain) and mechanoreceptors (pressure), which convert the stimuli into nerve signals. Although the entire body has these receptors, some areas are more sensitive than others [DFAB04]. Kinaesthesia is a further, little known part of the sense of touch, which is the awareness of the body and limbs' position.

After this brief excursion into human physiology, we return to interaction with computers and look at the sensory channels most commonly used in HCI. The visual and auditory channels dominate in HCI [Sut03] which is in line with the discussion about the hierarchy of the senses, which has existed since Aristotle [Gru08]. However, when considering this order from a technological point of view, it should also be considered that visual and auditory sensations are more straightforward to synthesise than haptics. Of course, tactile feedback can easily be generated using vibration motors, but if looking at the simulation of real properties, haptic feedback becomes difficult. This is due to the fact that visual and auditory sensations are perceived by specialised organs, the eyes and ears. In contrast, a sensation of force can be perceived anywhere on the human body and is therefore directly related to physical contact [Gru08]. Another difference that makes haptic interaction fascinating is that it has a unique property compared to our other senses: interaction is bi-directional, for example, in manipulation tasks or when pressing a button. In both cases, input and output occur at the same location at our body [EOEC11].

Interacting with multiple senses leads to various concepts; to avoid confusion, four often used in this context will be introduced: multimedia, mulsemedia, multimodal and multisensory. The following explanations are inspired by [OSC+17]. The term multimedia is probably the first that has been established. Multimedia is a communication of information that uses more than one medium. It is rather a passive way of interaction and focuses on the system components. Whereas multimedia applications are mostly bi-sensorial in nature, mulsemedia applications are those that engage three (or more) of our senses [GTLG14]. In multimodal interaction, the focus is on modalities such as speech, gesture, touch or gaze. Multiple senses are not necessarily involved, in the definition by Oviatt et al. [OSC+17], it is assumed that the motor system is involved in the interaction. Multisensory interaction is a more general term and describes an interaction that is based on more than one sensory channel and is in comparison to multimedia more active. If we look at the haptic interfaces that have been developed in the context of this thesis, they can mainly be classified into two of the categories explained above, namely multisensory and multimodal.

When considering the potential of the sense of touch, the haptic sensation has many convincing aspects - haptic feedback can bring a wide range of improvements. This is why researching novel interfaces that address particular challenges is so important. For example, haptic perception can increase presence, which is especially important for virtual environments and for telepresence scenarios in remote environments to represent the whole rather than just a part. Furthermore, the sense of touch allows us to explore the world and objects. This is often referred to as active touch. Not just seeing objects on a touchscreen but also feeling them would be a huge step forward in HCI. Sensing geometry on a touchscreen would not only help blind people but could also create new interaction metaphors. It would be possible to interact with content and information without looking at the display (eyes-off). In this case, the eyes could be used for something different. Another point that makes haptic interaction so interesting is to feel and sense objects or people who are not in the same room. Haptic feedback could make it possible to feel textures of objects without owning them or interacting emotionally with close friends or acquaintances. Moreover, haptic feedback is essential when controlling robots in dangerous areas or during remote maintenance in order to take the right action. The sense of touch is incredibly versatile and offers a broad spectrum for interacting with a computer, so why not explore these possibilities further?

As already mentioned, the field of haptic exploration is extremely diverse, which is why we want to narrow the focus of this thesis to haptic feedback for hands and feet. Besides, we have chosen two application areas as the focus of this thesis. Both application areas (touchscreens and virtual/remote environments) were preferred because we see great potential in these areas. In the next section, the aims and objectives of the thesis are discussed and linked to the five prototypes implemented, which are presented later in the main chapters.

1.2 Aims and Objectives

In line with the above, the aim is to find the right balance, that combines already established interaction approaches and technologies with novel methods and interfaces, focusing on haptic interfaces. This means that we are looking for haptic feedback methods, concepts and technologies that can increase performance, enhance perception and improve user experience. We expect that applying these concepts will shift the focus more to the users, and novel haptic interfaces could be created. Exploring this subject also means that various aspects of several scientific areas are included and required. These scientific areas are outlined in Figure 1.1, which shows the three main research fields (human factors, technology and computer science) in the context of haptic interaction.

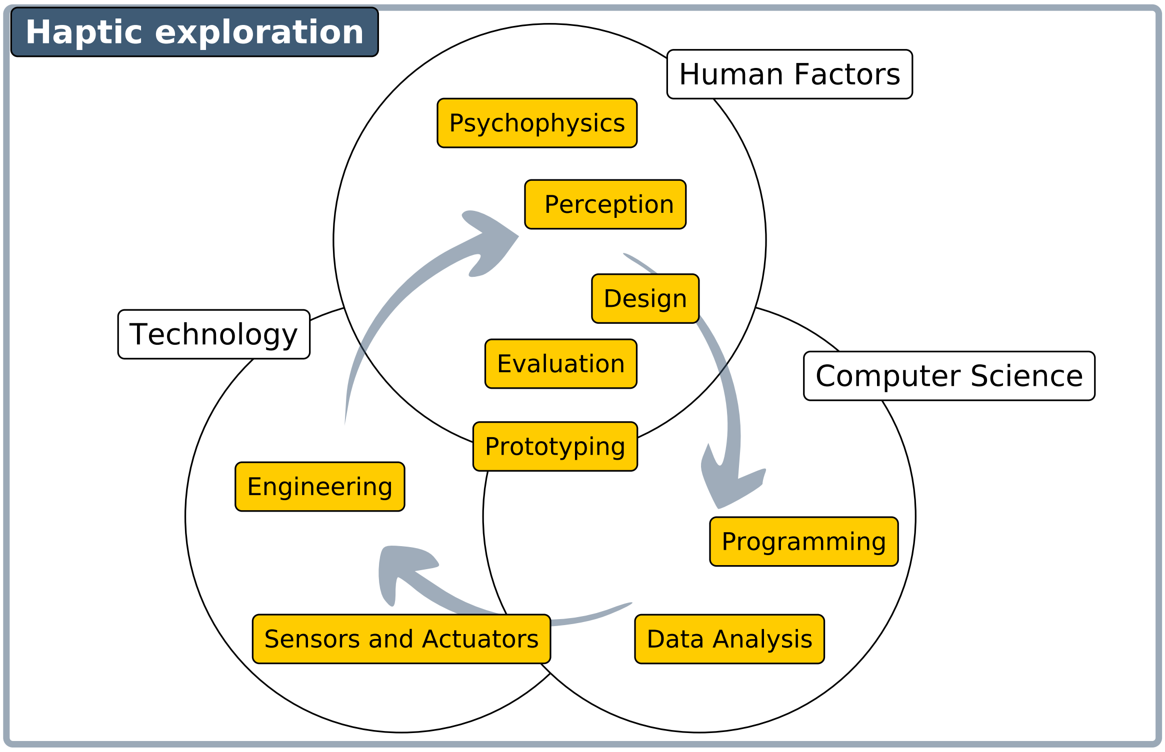

Figure 1.1: Classification of the individual areas that are important in this thesis. The three main areas important for researching haptic feedback are human factors, technology and computer science.

How the three research fields (see Figure 1.1) relate to Norman's interaction model [Nor13] to design haptic feedback is explained below. In the haptic feedback principle applied in this thesis (see grey circle in Figure 1.1):

Human: A user is at the beginning. A person wants to achieve a particular objective or experience something specific by interacting with a machine: an action that serves as an input for the system.

Computer science: The user's intention is passed on to the machine through sensors. Then, an algorithm calculates the output state, which is passed to an actuator using a micro-controller.

Technology: An actuator passed on the stimulus to the user. The user adjusts his/her input accordingly through the feedback - which in turn serves as new input.

Further disciplines can be found in Figure 1.1. They are just as important and are needed to achieve the objectives of the thesis. Therefore, besides the theoretical interaction model, creating prototypes, their design and evaluation are essential disciplines.

To explore a number of parameters, the two application areas were identified. Both areas will be referred to as *focus areas* in the following and will be presented in the two main chapters Chapter 4 and Chapter 5. The first focus area explores the combination of haptic feedback with touchscreens, as found in smartphones. For this purpose, three novel haptic interfaces are being developed whose feedback spectrum exceeds current research. Each of the three interfaces will follow a unique feedback approach. Hardware concepts will be developed and studied regarding perception, performance and user experience. Haptic feedback in this area focuses on the hands and fingers and attempts to solve common challenges or provide new opportunities.

The second focus area follows the same principle of providing haptic feedback to explore perception, performance and user experience. However, the focus in this case is more on unconventional metaphors - developing concepts and prototypes to show how haptic feedback to the feet can be applied in virtual and remote environments. Foot haptics has great potential; the feet can be used as a reference system for navigation. Moreover, foot-based feedback can enable hands-free interaction so that the users' hands can be used for other purposes.

Both aims and the five objectives are defined by the two focus areas and are reflected in the research questions that have synthesised from the literature review (see Section 2.3). The first three objectives belong to Chapter 4 while the last two are addressed in Chapter 5:

Aim 1: To develop novel haptic interfaces for touchscreens that provide a wide range of feedback stimuli to enhance perception and thus improve performance (see Chapter 4).

> **Objective 1:** Create a motion platform that actuates a rigid touchscreen to explore the limits of haptic perception of geometric shapes (see Section 4.2)
>
> **Objective 2:** Combine an elastic material with touchscreen interaction to create a novel haptic experience in mid-air (see Section 4.3).
>
> **Objective 3:** Implement a back-of-device approach for touchscreens, that allows to improve touch accuracy and hence improve occlusion issues (Section 4.4).

Aim 2: Implementing haptic interfaces for the feet to explore self-motion perception and spatial awareness in virtual and remote environments (see Chapter 5).

Objective 4: Build a haptic foot platform that maps spatial data of a remote environment sensed by a telepresence robot to increase spatial awareness (see Section 5.2)

Objective 5: Explore the effect of haptic feedback combinations to the feet on self-motion perception in virtual environments (see Section 5.3)

Based on these five objectives, several results have been achieved, including the design and development of five novel prototypes in each of the focus areas. New aspects of perception will be addressed in the course of evaluating these prototypes. Besides, it is intended to propose various application scenarios that are considered valuable.

1.3 Thesis outline

This thesis consists of six chapters, the bibliography and the appendix. The developed haptic prototype interfaces will be presented in the two main chapters together with the results and evaluations of seven empirical studies. There is also a detailed overview and analysis of the related work, the research methodology, a summary of the results in the conclusion chapter, and finally future work and research directions. Most of the work described in the main chapters has already been published (see List of publications). The structure of the thesis is as follows:

Chapter 1 - Introduction: summarizes the subject area, provides a historical overview and motivates research through the potential for involving further sensory modalities in the interaction, followed by the aims and objectives.

Chapter 2 - Literature Review: provides an summary of the state-of-the-art of all focus areas, resulting in the research questions.

Chapter 3 - Research Methodology: reflects quantitative and qualitative research philosophies and describes research methods that have been applied in this research. This includes e.g. methods originates psychophysic and prototyping as well as experimental design.

Chapter 4 - Haptic Interfaces for Touchscreens: presents three metaphors and prototypes that enable haptic feedback for touchscreens. Studies for evaluation focus on the perception and broadening of system-specific performance parameters.

Chapter 5 **- Foot Haptic Interfaces for Virtual and Remote Environments:** studies the potential of feet-based feedback in virtual environments and telepresence systems, mainly targeting the evaluation of the interfaces in terms of self-motion perception and spatial awareness.

Chapter 6 **- Conclusion:** discusses the findings of the main chapters, summarizes them, and lists all the contributions achieved. Finally, it provides ideas and recommendations for further research.

Chapter 2

Literature Review - Haptic User Interfaces

This chapter provides an overview of haptic user interfaces (HUI) and associated interaction methods and metaphors. It especially illustrates HUI's impact on performance and perception and highlights the need for additional research in our focus areas. Therefore, essential related work is introduced, discussed, presented, and synthesized into research questions.

The literature review starts with the fundamentals of haptic perception and the technical/mechanical principles for generating haptic feedback. This is followed by a literature review that looks into haptic interaction with touchscreens and explores foot-based haptic feedback and interfaces for virtual and remote environments. A final section highlights the thesis's main direction, derived from the literature review, followed by the research questions (see Section 2.3). The questions are the links to the two main chapters of this thesis. The underlying methodology for composing the literature review can be found in Chapter 3.

2.1 Fundamentals

Basic principles of haptic perception and the key technologies for creating HUIs are introduced in this section. Therefore, the first subsection looks at human physiology and explain the sense of touch, which is essential for haptic interaction. After that, the key technologies are presented; this includes the main actuation methods and how capacitive touchscreens work.

2.1.1 Sense of Touch

The sense of touch is probably the most versatile and definitely the largest sense organ of our body. It is distributed over the entire body, unlike the other senses, which are centralized around specific parts of our body [EOEC11]. Haptic perception is often neglected, but it is essential for survival - without the sense of touch, also called the somatosensory system, we would not feel any injuries and would not even be able to walk. Haptics refers to touch and it includes haptic interaction. Our haptic system uses sensory information that comes from mechanoreceptors and thermoreceptors in the skin and mechanoreceptors in muscles, tendons and joints [LK09]. The interpretation and processing of these information allows us, for instance, to interact with object, to use tools or to gesture. The somatosensory system consists of several perceptual channels, including [Gol10]:

1. cutaneous senses (skin), which are responsible for perceptions such as touch, pain and temperature that are normally produced by stimulation of the skin
2. proprioception, the ability to sense the position of the body and limbs
3. kinaesthesia, the ability to sense the movement of the body and limbs

The skin consists of two layers: the visible outer layer is called epidermis and mainly consists of dead skin cells. Below the epidermis is the dermis. These two layers are responsible for our haptic sensations; they contain four receptors that, for example, to perceive pressure, tension, force and vibration. The four receptors are called mechanoreceptors: The Merkel receptor and the Meissner corpuscle, are located close to the skin's surface, while the Ruffini cylinder and Pacinian corpuscle, are located deeper in the skin. Neural connections transmit the signals along the thalamus to the somatosensory cortex where they are processed. According to Goldstein, each of these four mechanoreceptors has a specific task, a particular response behaviour and an assigned frequency (see Figure 2.1) [Gol10]:

Merkel receptor is a disc-shaped receptor located close to the skin surface, it emits a continuous signal as long as the stimulus is on; the Merkel receptor perceives fine details and frequencies between 0.3-3 Hz.

Meissner corpuscle is a stacked receptor, which is also located near the skin surface. In comparison to Merkel receptors, it only fires when a stimulus is sensed and when it is removed. They perceive frequencies between 3-40 Hz and allow us to control tools with our hands

Ruffini cylinder consists of multi-branched nerve fibres located within a cylinder. They are located in the dermis, similar to the Merkel receptors they send a continuous signal. They sense the stretching of the skin and respond to stimuli of frequencies between 15-400 Hz.

Pacinian corpuscle is an onion-like receptor that surrounds a nerve fibre. The response behaviour is similar to that of Meissner receptors, they fire to on and off. The Pacinian corpuscle perceives vibrations and fine texture by finger movements; the perceived frequency is between 10-500 Hz.

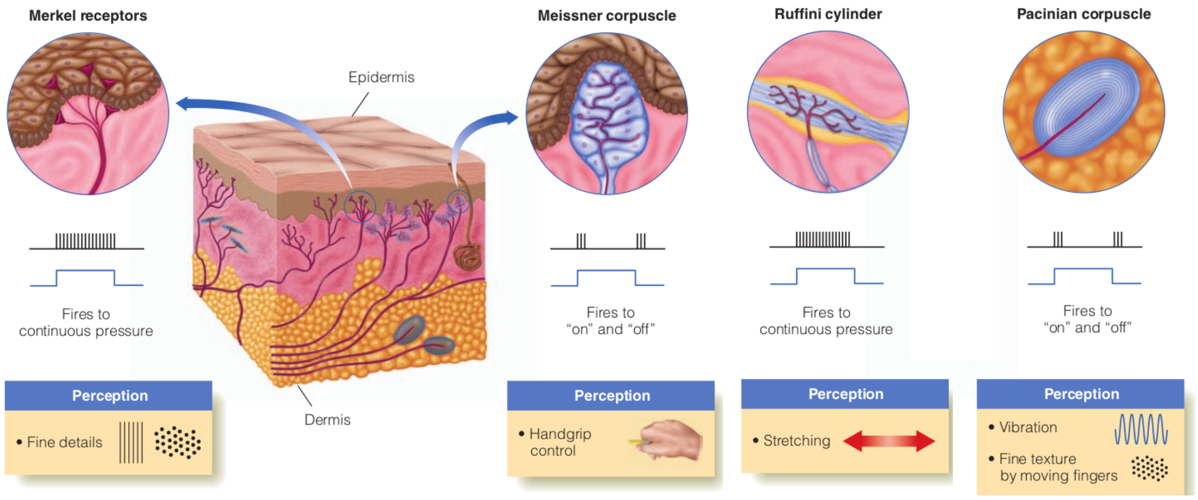

Figure 2.1: Characteristics of the four mechanoreceptors located in our skin [Gol10].

According to Goldstein et al. the sense of touch can be divided further: there is tactile perception, the perception of vibrations and surface structures and the perception of objects [Gol10]. While tactile feedback is perceived through the cutaneous system, i.e. the perception of surface textures and pressure sensations, force feedback is about the mechanical generation of information perceived by the human kinaesthetic system [EOEC11]. Vibrations such as those generated by vibration motors are referred to as tactile feedback and can perceived to a frequency up to 250 Hz.Not every part of the body reacts equally to haptic stimuli; the different distribution and density of the receptors is responsible for this. Considering our fingers, it can be seen that there are significantly more Merkel receptors in the fingertip than in the palm. This means that the resolution of tactile stimuli is higher at the fingertips than in the palm. The resolution can be measured in a similar way to an eye test, but in this case, two-point discrimination is used. This differs for each region of the body, on the calf or upper arm it is about 45mm, but less than 5mm on the fingers [Wei68]. Mentioned above, our skin can also perceive vibrations, responsible for this are the Pacinian corpuscle, which can react quickly to changes. The perception of textures can be divided into two types: spatial cues and temporal cues. Spatial cues are rather rough structures that can be recognized without active movements just by touching them with the fingertips (for example, Braille). Whereas temporal cues can perceive fine textures, hereby the surface is actively explored. In general, the sensory system perceives sensations such as touch, temperature, and fingers' position. Whereas the motor system enables us to explore objects, e.g. to grasp an object, and the cognitive system combines the information from the two previous systems, resulting in the perception of an object [Gol10].

Alongside the described perception capabilities through the mechanoreceptors, the sense of touch also offers the ability to sense a joint or limb's motion, this called kinaesthesia. Proprioception is often confused with kinaesthesia but refers to something different. While kinaesthesia focuses on movements, proprioception is about the position and orientation of limbs and the body. All of us know where in space our arms, hands or feet are located without actively verifying. Mainly responsible for the two perceptive abilities are so-called muscle spindles. They can perceive an stretching or contraction of the muscles [Gru08]. Another difference between those both is that proprioception is cognitive while kinaesthesia is more behavioural. For example, to walk we need to actively start the behaviour, whereas knowing where which limbs are is more passive.

Another aspect that should be considered is the time it takes for a stimulus to travel to the cortex. For example, in the case of hearing and seeing, the stimulus travels for a certain time outside the body, i.e. physically through space (i.e. 300 000 000 ms for vision vs. 330 ms for hearing), whereas in the case of the sense of touch, the stimulus is transported directly within the body, i.e. nerve system only. In addition, the position of the eyes and ears are at fixed parts of the body, while the skin is distributed over the whole body, which leads to different travel times of a stimulus. Assuming a typical transmission speed of 55 ms, will lead to a difference of about 30 ms between a stimulus perceived by either the toes or the nose [MW11]. Harrar et al. showed that a tactile stimulus have different latencies depending on the distance from the brain [HH05]. A more detailed explanation of their study is given in the following literature review. Despite the different travelling times of the stimuli, surprisingly the reaction times on the different senses are quite similar. According to Kosinski, the average reaction time on audio is 140 ms to 160 ms , which is faster than the reaction time of sight (180 ms to 200 ms) and touch (155 ms) [Kos10]. The average times can of course vary, this is due to the complexity of the overall system and therefore depends on various other factors such as the spatial separation between the components of the stimuli, the complexity of the stimuli, whether it is speech or not and also the semantic nature of the stimulus [MW11].

The physiology of the sense of touch was introduced in the previous paragraphs. It was shown that the sense of touch is versatile and can, at least through its perceptual prerequisites, support or even enrich the interaction with a computer. In the following, tactile stimuli, vibrations and the perception of movements, such as force feedback or spatial interaction, will be mentioned frequently; all of them are part of the somatosensory perception. This chapter helps to better understand the perception of haptic feedback and to evaluate its quality. In the main chapters, we will present five haptic user interfaces, these ranges from flexible stimuli (see Section 4.3) and force feedback (see Section 4.2). The presented prototypes also focus on different parts of the body, from finger (see Section 4.4) to foot sensations (see Chapter 5).

2.1.2 Actuators

In line with the previous narrative, this subsection will further explore haptic perception and interaction, in detail haptic feedback. Actuators can be considered as the motor system of a machine. The main technologies are introduce in this subsection. We present several systems which are based on different actuation methods. To illustrate the principle of actuating, key concepts are presented: ranging from servo motors to piezo actuators to electromagnetic motion. There are, of course, more approaches, but we would like to concentrate on the most common and applied solutions in our field.

In this thesis **servo motors** were used to create haptic feedback [JKT+16], [LGB+16], thus this paragraph deals with the basic principle of such motors. In contrast to a regular electric motor, a servo motor can provide a desired position at a desired speed. This high precision and efficiency control is often found in robotics and industrial production. However, it can also be used to provide haptic feedback. A servo motor consists of four main components: a control circuit, a regular motor, a gear assembly and a potentiometer (sensor for positional feedback). The servo is controlled either analogously or digitally [FL14]. For DC motors, the requested speed or position is achieved by the voltage applied.

In the implemented prototypes, all servos were controlled using pulse width modulation (PWM). This requires a pulse width voltage converter, which can convert varying pulse widths to a respective voltage and thus control the speed or position. A potentiometer measures the position, and in case that the current position deviates from the desired position, additional voltage is applied to adjust the motor's position. With this principle, electrical energy can be converted into motion energy, which stimulates the sense of touch.

Piezo actuators have not been used in the implemented prototypes in this thesis, however, they appear from time to time in related work [PM03], [LOM+11], so we would like to introduce the technology of piezoelectric actuators. Piezoelectric elementary cells change dimensions when an electric potential is applied. The most common piezo actuators consist of stacks of thin piezoceramic layers that expand when a voltage is applied. Depending on the shape of the piezo element, linear and rotational movement can be achieved. Piezo actuators can be controlled with pulse width modulation similar to servo motors. Looking at an excerpt of the comparison of the two prototypes by Jang et al., it can be seen that piezo actuators can achieve much higher accuracy at similar force while being quieter [JKT+16].

Another frequently used actuator is a **vibration motor**, which is used to create tactile feedback [GSK+20], [CBMB16]. In principle, there are two different types of vibration motors: eccentric rotating mass vibration motors (ERM) and linear resonant actuator (LRA) [PT19]. ERM is a standard DC motor with an off-centered mass attached to a shaft. When the motor is powered, the unbalanced mass creates a centric force. This force is what we perceive as vibrations. While an ERM operates based on a mechanical motor, an LRA moves a mass through an electrical signal. This signal activates an electromagnet that attracts the mass. When the electromagnet is deactivated, it is returned to its original position by a spring. This oscillating movement generates the vibration. Compared to an ERM, a LRA has a direction in which the vibration is emitted, i.e. it is a linear vibration. A key advantage of LRAs over ERMs, especially in terms of haptic feedback, is that they start and stop immediately, whereas ERMs have a certain start and stop phase - this is due to the DC motor. In both cases, vibrations can be described by two parameters: frequency and amplitude. Both parameters are dependent on each other. The frequency indicates how many oscillations (rotary or linear) per second the motor makes. The frequency influences the amplitude, i.e. the offset movement of the motor. Of course, this depends on the mass of the object to which the vibration motor is attached, which is why some manufacturers specify the amplitude of the motor for a 100g object [1].

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[1] https://www.precisionmicrodrives.com/vibration-motors/ (last accessed 19th April 2021)

Another technique for generating haptic feedback is using an **electromagnetic actuator**, also known as a solenoid. A solenoid valve can be used to cause a discrete impact or to realize a motor - we focus on a discrete impact [AS94]. A solenoid consists of a copper wire wound into a coil. By applying current to the coil, a magnetic field around the coil is created, forming a south and north pole - also called an electromagnet. To create a discrete impulse, an additional iron core is needed which is placed inside the coil. Whenever the electromagnet is activated, the iron core is moved in one direction, and an impact is created. The higher the voltage, the higher the impact. In this way a stimulus can be created similar to a small knock - we will use this approach later in Section 5.2.

There are other ways to create haptic feedback, for instance, **magnetorheological fluid**. This fluid reacts to magnetism and can change its viscosity. When no magnetism is present, the fluid is liquid; depending on the electromagnet's strength, the fluid changes its firmness from liquid to stiff. Typical reaction times are very fast, less than 2 ms. It can therefore also be used for tactile feedback [JKB10]. The properties of magnetism can also be used individually by using the properties of attraction and repulsion [ZDE16]. However, it should be kept in mind that the force is not linear to the distance. The smaller the distance between the magnets, the stronger the force becomes and is therefore difficult to control at low distances.

Finally, methods for changing friction properties of rigid surfaces are presented. This can be done using two techniques: a) **ultrasonic** and b) **electrovibrations**. With ultrasonic, the surface is brought into vibration, however, the frequencies are in the kHz range and are thus significantly higher as the described vibrations above and can therefore no longer be perceived as vibrations. The main principle of ultrasonic friction screens is that the vibrations alter the contact phase between the finger and the screen [WF95]. This can lead to a slippery or sticky feeling. Electrovibration, in contrast, generates an electrostatic field which influences friction properties [KIP13]. The vibrations and resulting electrostatic fields lead to similar perceptual phenomena as with utlrasonic.

In summary, it can be said that haptic feedback can be generated based on a variety of actuators. Pneumatic and hydraulic actuators have not been considered in this summary, as they are not used frequently in the context of this research. Furthermore, it is difficult to compare the presented actuators in detail, as they often evoke different haptic sensations, which are used in different applications. Parameters such as response time, form factor, weight, power consumption and force should be carefully considered before selecting an actuator. Table 2.1 assigns the different actuators to related work and reflects on further parameters.

2.1.3 Touchscreen Technology

A main theme of this thesis's research is to explore the combination of haptic feedback with touchscreens. It is therefore essential to introduce base technologies of how to sense touch events on a screen. The most well-known techniques are based on a resistive film or on a capacitive mesh to sense a touch event. Further methods, such as touch panels rely on optical sensors or panels based on electromagnetic induction. However, in this subsection, we focus on capacitive touchscreens. These have become established for smartphones and some of the prototypes developed use capacitive screens, for instance, to improve touch accuracy (see Section 4.4).

There are two capacitive methods for determining a finger's position on a touchscreen: surface capacitive and projected capacitive. Both methods are based on a similar principle: Sensors are used to detect small changes in the electrical current generated by touching the screen, which changes electrostatic capacity. Surface capacitive technology is mainly used for large screens and has a limited resolution. A transparent electrode film in the display is necessary to determine the location of an event. Whenever a finger touches this film, the capacitance changes and four electrodes placed at the corners can determine the finger's position. With this technology, it is challenging to calculate more than one touchpoint.

On the other hand, projective capacitive screens can be found in smaller screens such as smartphones [BO10]. This method achieve high-precision multi-touch functionality and high response speed. Similar to surface capacitive technology, electrodes are also used in this case, more precisely transparent electrodes. These electrodes are attached to the four corners, but in a special pattern, a grid, so that far more electrodes can be used. They are additionally divided into x-y layers. An IC chip is used to read the capacitance of the individual electrodes. If a finger is detected, the intensity of the neighbouring electrodes is interpolated to determine the position of the finger. Depending on the configuration and number of electrodes, the resolution can vary, for instance, Kumar et al. presented a deep learning approach that achieves an error offset of 2.35 mm [KMRL19]. In their approach a Synaptics ClearPad 3350 with a 15x27 grid was used.

In this overview, the fundamentals have been presented, on which we will continue to build later. In the following, related work will be presented that specifically deals with haptic interaction in the context of this work, starting with the combination of touchscreens with haptic feedback.

Table 2.1: Structured overview about the main related work in the context of this thesis, categorised in actuating technology, feedback type, research focus, body part and application.

Reference	Actuator	Feedback type	Research focus	Body part	Application
[JKB10]	Electromagnets	tactile	GUI	finger	Desktop
[WRSS16]	Electrovibration	tactile	GUI/information	finger/hand	Pen-interaction
[CBMB16]	Vibration motor (LRA)	tactile	hand writing	finger/hand	Pen-interaction
[PM03]	Piezoelectric	tactile	GUI/gestures	finger	Touchscreen
[LMBS07]	Piezoelectric	tactile	GUI/gestures	finger/hand	Touchscreen
[YK08]	Piezoelectric	tactile	texture/materials	finger	Pin-display
[PBKW18]	Piezoelectric	tactile	Blind interaction/spatial	finger	Braille display
[PH20]	Piezoelectric	tactile	Multitouch	finger	Touchscreen
[RGOB15]	Pneumatic	tactile	Blind interaction	finger	Braille display
[BCML15]	Servo motor	tactile	Blind interaction	finger	Braille display
[AS94]	Solenoid	tactile	Find targets	finger	Mouse
[TMM+12]	Sound	tactile	Walking experience	feet	Desktop
[CSL+13]	Ultrasound	tactile	GUI/information	hand/finger	Mid-air
[BCB07]	Vibration motor (ERM)	tactile	Keyboard typing	finger	Touchscreen
[KLS09]	Vibration motor (ERM)	tactile	GUI/text	finger/hand	Pen-interaction
[NNTS12]	Vibration motor (ERM)	tactile	Presence/immersion	feet	VR
[VBV+12]	Vibration motor (ERM)	tactile	Information	feet	Blind navigation
[TBS13]	Vibration motor (ERM)	tactile	Realism	feet	VR
[CCKB15]	Vibration motor (ERM)	tactile	Eyes-free	finger	Touchscreen
[GSK+20]	Vibration motor (ERM)	tactile	Keyboard typing	finger/wrist	VR
[VTBC20]	Vibration motor (ERM)	tactile	Information	feet	Haptic discrimination
[GMPT13]	Vortex rings	tactile	Entertainment	body	Mid-air
[SGB+18]	Magnetic fluid	force feedback	Ground firmness	feet	VR
[IYN01]	Motor	force feedback	Ground properties	feet	VR
[JS19]	Motor (falcon)	force feedback	Manipulation	hand	Desktop
[KIP13]	Servo motor	force feedback	3d features	finger	Touchscreen
[SPB14]	Servo motor	force feedback	3d features/information	finger	VR
[WTC+20]	Solenoid valve (air)	force feedback	Ground firmness/Medical	feet	VR
[FLO+13]	Motorized potentiometer	tactile/force	Dynamic Affordances	hand	Pin-display
[NFM+19]	Motorized potentiometer	tactile/force	Dynamic Affordances	hand	Pin-display
[JKT+16]	Piezoelectric/Servo motor	tactile/force	Dynamic Affordances	finger	Touchscreen
[MNY+09]	Servo motor	tactile/force	Textures/heights	finger	Mouse
[BHSO16]	Servo motor	tactile/force	3d shape rendering	finger	VR
[SHS16]	Spandex	elastic	Information	finger	Projection
[BPIH10]	Electrovibration	friction	GUI/information	finger	Touchscreen
[KIP13]	Electrovibration	friction	3d features	finger	Touchscreen
[LOM+11]	Piezoelectric	friction	GUI/gestures	finger	Touchscreen
[RVGG17]	Piezoelectric	friction	Texture/object	finger	Touchscreen
[SJM13]	Sheet of Paper	spatial	Information	hand/arm	Projection
[SBC+16]	Bend input	deformation	Proprioceptive feedback	hand/arm	Touchscreen
[PGG+12]	Spandex	deformation	Depressing and stretching	hand/arm	Projection

2.2 Research on Haptics

2.2.1 Touchscreen Interaction

Combining haptic interaction with touchscreens is the first focus area. An overview of related work is given in Table 2.1. It shows the variety of different actuator technologies, the research interests and the associated applications. The table highlights the regions of the body that is stimulated by each interface. Furthermore, it introduces various research related to this thesis, which will be introduced and discussed in the following sections. Nevertheless, some approaches do not relate directly to haptic user interfaces but are also important for this thesis.

Haptic feedback and haptic interfaces can be divided into two main categories [Gru08] (see Section 2.1.1). Firstly, there is tactile feedback, a perception that deals with actively touching surfaces and feeling textures. In contrast to tactile feedback, there is force feedback. Force feedback can be perceived by the human kinesthetic system [EOEC11]. In both, the stimuli are mostly produced by movable mechanisms based on actuators, such as motors (see Section 2.1.2). This section starts with a more general part that deals with tactile and haptic prototypes. It is followed by a detailed review of different categories, ranging from pen-based approaches to tangible interfaces and more specific concepts such as flexible materials and back-of-device interaction.

Tactile feedback stimulates the upper skin layers to reproduce surface properties or to differentiate one state from another - it is the system response to touch. Tactile cues can be generated using a variety of different technologies, a representative being vibration motors [BHSO16], linear resonant actuators [GSK+20] and electrovibration [WRSS16]. They are often employed to reduce visual or auditory attention, enabling eyes-off interaction, as they operate in a separate perceptual channel. Vibrotactile cues have been shown to improve task performance [BCB07]. However, tactile cues can not only increase interaction performance. The feedback stimuli seem to be excellent for pressing a key during a typing task [GSK+20]. Some studies also demonstrated task performance improvements under cognitive load [LMBS07]. Vibrotactile cues have also been used to simulate various surfaces [RVGG17], friction characteristics [LOM+11], and rims associated with surface textures [KIP13]. Furthermore, an increase in vibration feedback has been shown to increase perceived softness [VDH14]. Adding audio cues to tactile or haptic feedback has been studied, by looking into which modality works best for widgets [HCBK09] or shapes [CV17]. From a technical point of view, localised feedback on a rigid screen is hard to achieve. However, recent research on localised tactile feedback in the context of multitouch seems to be promising [PH20].

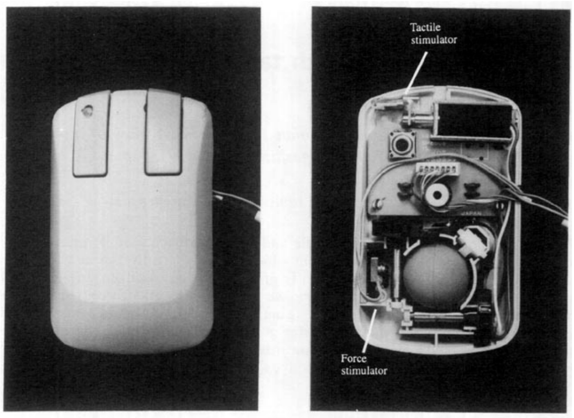

Figure 2.2: Inside and outside view of the haptic mouse prototype of Akamatsu [AS94].

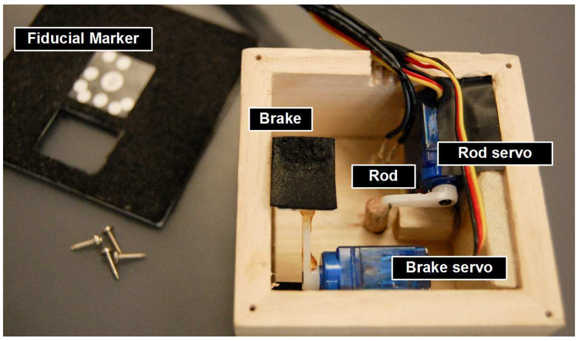

Figure 2.3: Haptic Tabeltop Puck presented by [MNY+09].

Rod-like systems have shown promising results for lower finger forces. Akamatsu and Sato developed a mouse-like interface supporting tactile and force feedback [AS94]. For this purpose, a mouse was augmented by solenoids. Tactile stimuli were produced through a pulsing solenoid under the fingertip resting on the mouse button. Force feedback was generated through an embedded solenoid that increases and decreases friction between a mouse and a table (see Figure 2.2). However, to do this, interaction with the prototype has to be performed on a unique magnetic surface. Haptic sensation was combined with visual content. Akamatsu and Sato showed that tactile and force feedback can reduce response time and select targets more efficiently [AS94].

Marquardt et al. enhanced the approach of Akamatsu and Sato [MNY+09]. They replaced the solenoids by servo motors (see Figure 2.3). Changing the friction was done by a brake like mechanism using a servo motor pushing a rubber plate against the table. A pressure sensor embedded on top allows Marquardt et al. to position the pin depending on the applied pressure. This prototype enables a set of application scenarios using, on the one hand, different heights as feedback and on the other hand, two pressure modes as input. This state-based interaction shows that both texture and height information can be perceived by a user [MNY+09]. A further difference between Akamatsu and Marquardt was the representation of the visual information. In Akamatsu's approach, visual information was perceived through a screen, in which Marquardt's prototype users directly interacted on the visual content through a projection. Both HUIs presented have shown that haptic feedback on the finger either through a servo motor or a solenoid can increase the interaction performance and perception of information.

Many tactile approaches have looked at how to facilitate access to digital information for blind people. Brayda et al. presented another mouse-like device with tactile feedback to assist visually impaired people to improve spatial understanding and mobility skills [BCML15]. Russomanno et al. looked into tactile display technology to improve accessibility for visually impaired people. In their approach, the Braille pins were operated by pneumatic actuators and fluid logics actuation [RGOB15]. Prescher et al. developed a larger tactile display allowing blind people to read Braille and perceive graphical content. The proposed display allows spatial relationships to be perceived [PBKW18].

Combining temperatures with a 6x5 pin tactile matrix integrated into a mouse interface to create more realistic features was proposed by Yang and Know. A Peltier element was used for displaying thermal [YK08]. They investigated whether the perception and reproduction of textures and material properties is possible. Comparing the introduced approaches, diversity of the technology becomes clear: While Akamatsu and Sato realized their actuation with magnets, Marquardt's system relied on servo motors, and Yang and Kwon's prototype is based on the piezoelectric effect.

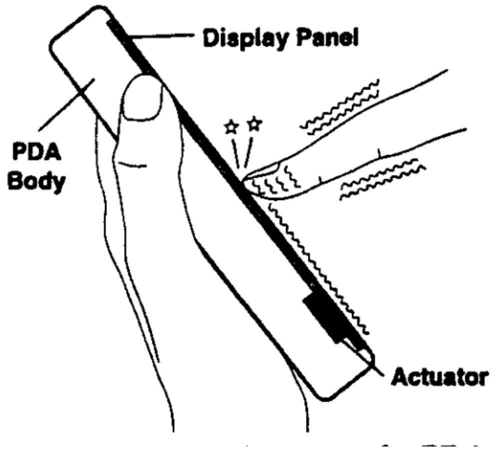

Figure 2.4: First tactile feedback introduced by Fukumoto and Sugimura [FS01].

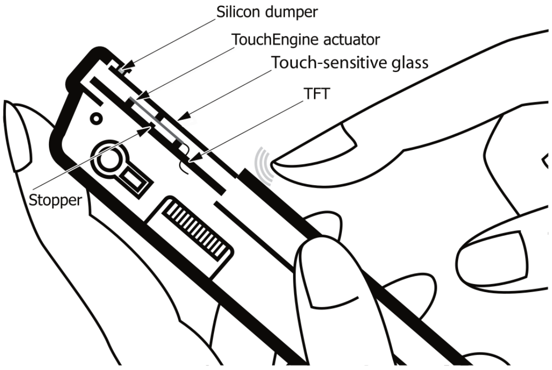

Figure 2.5: The improved version of Poupyrev and Maruyama using piezo electric actuation [PM03].

In all systems presented so far, display and interaction were physically decoupled. With the introduction of touchscreens, it became possible to combine display and interaction within a single device. Interacting directly with a display has many advantages, as can be seen in the following sections. Nevertheless, haptic actuators cannot be installed in the same way as in uncoupled systems; for example, they can be too bulky or occlude content of the display. Fukumoto and Sugimura studied mobile touchscreen interaction with a tactile feedback [FS01]. Their system, Active Click, was the first published tactile interface for mobile touchscreens (see Figure 2.4). The approach is similar to today's smartphones; a vibration motor was mounted directly under the touchscreen. Poupyrev and Maruyama enhanced this approach by replacing the vibration motor with a piezoelectric actuation (see Figure 2.5). They added a soft silicon damper between the touchscreen and the frame to exclude the frame to vibrate [PM03].

Enhancing touchscreen interaction using tactile cues have been explored by Brewster et al. [BCB07] and Hoggan et al. [HKLB08]. Aspects related to latency and perception of tactile buttons were discussed by Kaaresoja et al. [KBL14]. To gain a more detailed understanding of tactile cues in relation to perception and mobile touchscreen technology, the approaches are considered in detail.

While the contributions from Fukumoto and Sugimura as well as from Poupyrev and Maruyama focused on the idea, the system and its hardware, Brewster et al. showed that tactile feedback could significantly improve typing performance for mobile touchscreens [BCB07]. In a study conducted by Brewster et al., subjects were asked to rewrite a text as fast and as accurately as possible. They performed the study two times, once under laboratory conditions and once seated in a train to show that the approach is also valid in real-world environments. In both scenarios, typing with tactile feedback achieved better results. Brewster et al. assumed that the results were achieved by increased awareness through tactile feedback [BCB07]. Additionally, Brewster et al. showed that tactile feedback was significant for mental demand, performance and annoyance using NASA TLX.

Another important aspect associated with the introduction of touchscreen technology on mobile devices and the resulting disappearance of physical buttons was that two essential characteristics are lost - users can no longer feel and hear clicking a real key [HKLB08]. This lack of feedback leads to a different perception of the familiar physical buttons and a more limited usability. While Brewster et al. showed that tactile cues could increase performance in terms of completion time, Hoggan et al. looked into a further issue. They explored how the interaction of tactile, visual and auditory feedback could be used to generate different button styles [HKLB08]. It was found that there is a relation between visual perception and tactile stimuli.

In contrast to Hoggan et al., Kaaresoja et al. were interested in how timing and latency of tactile, audio and visual feedback affect perceived quality [KBL14]. Kaaresoja et al. performed several perception studies, to do so, they varied latency between 0 and 300 ms.

With these timings, feedback (tactile, audio and visual) of a touch event was delayed. To ensure low latency and reliability, a dedicated virtual button simulator was used during the study. As a result, Kaaresoja et al. recommended that tactile feedback latency should be between 5 and 50ms, audio feedback latency between 20 and 70ms, and visual feedback latency between 30 and 85ms [KBL14].

When dealing with touchscreen interaction at present, terms such as pinch-to-zoom or two-finger scrolling have become indispensable - multi-touch gestures are common concept. Therefore, it is not surprising that the combination or enhancement of multi-touch gestures with tactile feedback is also being researched [PH20]. Pantera and Hudin focused on localised tactile feedback in the context of multi-touch interaction. They use the Inverse Filter Method with a grid of 11 piezo actuators to create localised tactile feedback. Their current research concentrates on a calibration and interpolation step and system evaluation. Pantera and Hudin's work again indicates that tactile feedback can improve performance and perception when interacting with a smartphone.

Besides localised feedback [PH20], the interplay between visual and tactile feedback was studied by Harrar and Harris. For this purpose, they explored the simultaneous perception of visual and tactile stimuli [HH05]. Visual information from the immediate environment is perceived independently of location related to the speed of light. Consequently, the reaction time to visual content (light) is constant. In contrast, Harrar and Harris showed that tactile stimuli applied to different body parts result in different reaction times. They found that reaction times to touches varied proportionally with distance from the brain [HH05].

Methods for evaluating the influence of tactile perception using touchscreens are another interesting aspect studied by Alsuradi et al. Whereas currently used methods are based on subjective feedback, [APPE20] has started to evaluate tactile feedback on a touchscreen through EEG. First results seem to be promising. Alsuradi et al. have shown that tactile feedback on a touchscreen can be detected differently in different areas in our brain. Knowing this could help to design haptic feedback more efficient for touchscreens. In a first study, they considered building a haptic model capable of objectively determining and quantitatively assessing the subject's haptic experience.

The usage of friction to provide tactile feedback can also be found in literature [LOM+11]. For instance, a friction screen can create the illusion of force, shape and texture on a fingertip when interacting with widgets (see Figure 2.6). While the generation of previous tactile stimuli is based on a physically moving touchscreen, friction forces are based on an electrovibration effect, ultrasonic or high-frequency vibrations generated, for instance, through piezoelectric actuators. TeslaTouch by Bau et al. was the first prototype that

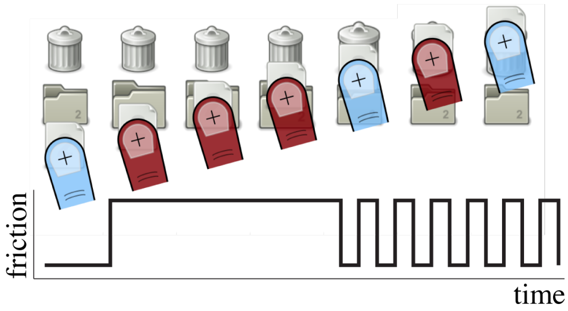

Figure 2.6: Frictional Widgets used for tactile feedback in a file manager [LOM+11].

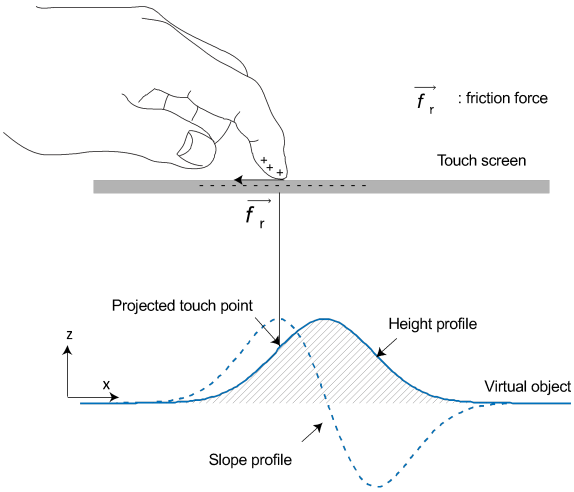

Figure 2.7: Using electrovibration to provide friction between the finger and the touchscreen [KIP13].

uses electrovibration to control the friction between a touch surface and the user's finger [BPIH10]. With the assumption that lateral forces mainly trigger a perception of a physical bump on a sliding finger (see Figure 2.7), Kim et al. explored the rendering of geometrical features [KIP13].

Previous paragraphs have shown how vibration and friction can provide haptic feedback; the next paragraphs focus on force feedback. In comparison to tactile feedback, it is still largely unexplored in the context of touchscreens. Some exceptions: TouchMover shows how a 1D transformation can create a haptic sensation using an actuated stereoscopic display (see Figure 2.8). The system consists of a large screen mounted on a robotic arm [SPB14]. The movements are perpendicular to the screen and dependent on user interaction. As the screen moves, the stereo convergence plane is adjusted according to the user's position. They proposed a 3D physical simulation with force feedback, in which objects displayed on the screen can have, for instance, different force resistance. TouchMover also allows exploring a 3D contour of ridged bodies. It haptically renders object's contour according to the users' 2D finger position [SPB14]. A third application scenario proposed by Sinclair et al., was a volume viewer, in which the user can explore and annotate the different layers by pressing on the screen. In this scenario, the screen moves depending on the location of the layer. Finally, Sinclair et al. showed the integration of GUI elements into the system by implementing buttons with different activation resistance.

Other scientists have studied actuated touchscreens, Kim et al. for example, explored a horizontally mounted touchscreen setup, using a tablet mounted onto a small motion

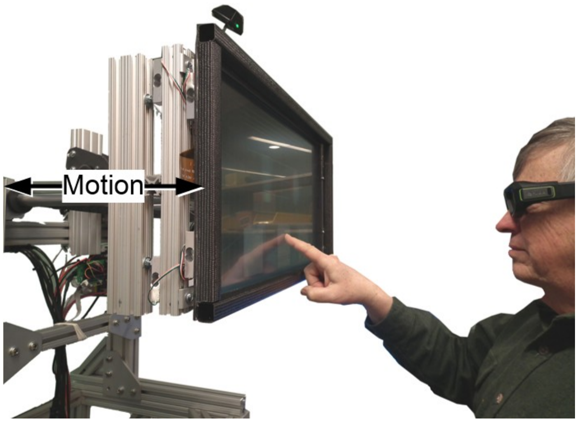

Figure 2.8: TouchMover a stereoscopic actuated touchscreen with integrate forcing enabling physical simulation [SPB13].

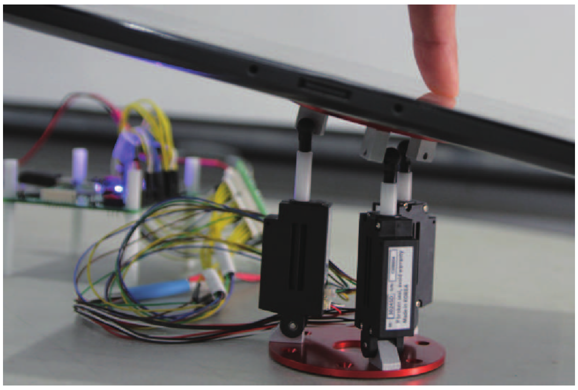

Figure 2.9: A horizontally mounted tablet for haptic interaction with virtual geometries [KHSK14].

platform [KHSK14]. Instead of focusing on user perception, Kim et al. concentrated on the actuation and how to control the screen (see Figure 2.9). Hausberger et al. have also studied actuated touchscreens. With their prototype, they are investigating how haptic feedback can help blind people. They found that additional tactile feedback can help in detecting different sizes of shapes. In their study, they presented the same shape in four different sizes to the user. The task was to find the right size. The detection rate was significantly higher with the support of tactile feedback than without [HTE+17].

Actuated touchscreens combined with haptic multi-touch gestures were Nagamatsu et al. investigated [NNTA14]. They used a so-called Stewart platform for actuation (supporting 6DoF). Servo motors were used to operate the platform. Visual content was projected using a projector mounted directly underneath the system. A multi-push approach consisting of two interaction steps was the key contribution of their work. Starting with placing the first finger on the tablet, results in a linear movement downwards. Then, when the second finger hits the screen, the projection screen rotates around the first finger without changing its position, so that both fingers receive independent feedback within on ridged object.

It has been shown how to combine force feedback with a tablet-sized and even larger touchscreen. However, the combination of force feedback with smaller screens, such as those found in smartphones, is mostly unexplored. One reason is that tactile feedback can be generated with comparatively small physical components to stimulate upper layers of the skin. However, when stimulating the human kinesthetic system, more force is required. Consequently, physical components need to be bigger and therefore more challenging to integrate into a mobile system.

Figure 2.10: Second version of the Haptic Edge prototype with 40 pins (2.5mm in pitch), showing a notification example [JKT+16].

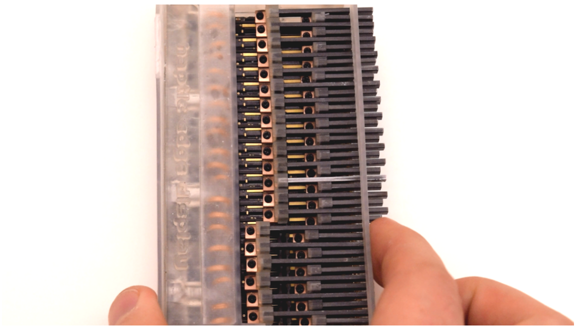

Figure 2.11: Actuation of the tactile pixels at the side of a smartphone is depicted in this figure [JKT+16].

A few researchers have looked into actuation at the side of mobile devices. The Haptic Edge Display consists of a linear array of tactile pixels at the side of a smartphone [JKT+16]. They introduced two prototype implementations of their Haptic Edge Display, a set of application scenarios, including UI control, tactile display and notifications (see Figure 2.10). Servo motors actuated the first version of the Haptic Edge Display while a piezoelectric actuator was used in the second version (see Figure 2.11). A relatively high number of pins and the limited space for the actuators result in a low output force of the pins. In a psychophysical study, Jang et al. determined the JND of their system. Users were able to perceive a difference of 0.15mm with the Haptic Edge Display.

In this subsection, different approaches, technologies and challenges of haptic feedback combined with touchscreens have been presented. While some research focused on increasing typing performance [BCB07], others looked into the psychophysical evaluation of their interface [JKT+16]. In the following subsection, we will continue to focus on interaction with touchscreens, but this time with a pen.

2.2.2 Pen Prototypes

Haptic and tactile cues have also been explored in pen interaction on screens [CBMB16], [LDL+04], [WRSS16], including those that provide non-controllable, sideways elastic feedback [HK08]. Pen-based interaction on a screen is directly related to touchscreen interaction. In Section 4.3, a prototype is presented that combines pen interaction with haptic feedback on a screen.

Similar to the previous subsection, where it was shown that haptic could increase performance, it is also possible to use pen-based tactile cues to improve user performance, especially for smaller targets [POM04]. General pen interaction with touchscreens [CST15], or artistic and writing applications [CBMB16], [FPG17] and education [LWLS11] have also been explored. These systems often provide feedback similar to haptic mice [AS94] or pens for spatial interaction [CK17]. In general, haptic feedback is often unfamiliar. It may not be perceived as useful by users during the initial learning phase [LMBS07], which is not only true for pen-based interaction. Finally, there are some hand-held (joystick-scale) devices that provide texture [BHSO16] and variable compliant haptic feedback [TR18], but these are not designed for on-screen interaction.

Tactile pen interaction has been shown to improve task performance on touchscreens. Poupyrev et al., for example, have introduced a tactile pen to improve the user experience when interacting on a touchscreen. In detail, the purposed tactile pen allows feeling displayed content, such as GUI elements or other data [POM04]. Apart from the pen's implementation, the main result was that the performance in a drawing task could be significantly increased. At the same time, Lee et al. have presented Haptic Pen a similar system [LDL$^+$04]. While both explored the interaction with GUI elements, both interaction devices differ in generating the stimuli. Poupyrev et al. used a piezoelectric actuation, and Lee et al. used a solenoid to generate tactile stimuli.

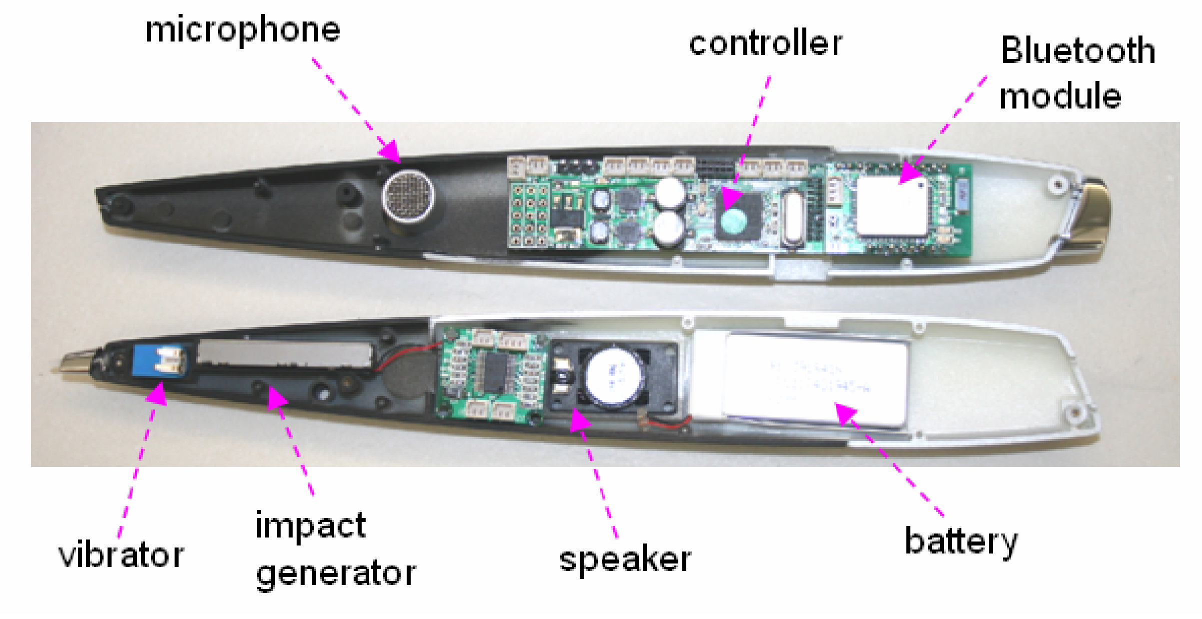

Figure 2.12: Hardware prototype showing all built-in components of the haptic pen introduced by Kyung et al. [KLS09]

The usage of active haptic (pen) interfaces for simulation of different GUI elements is hardly studied. Kyung et al., for instance, proposed a haptic pen for touchscreen interaction. It can provide vibration, an impact and sound. To ensure an interactive wireless system, a built-in battery and a Bluetooth module were integrated. As depicted in Figure 2.12 tactile cues are generated using a typical vibrations motor. However, in comparison to Lee et al. [LDL+04] the impact is created by a linear vibration instead of a solenoid. With their designed feedback metaphors, they explored the performance when interacting with GUI elements. Kyung et al. found an interesting correlation between completion time and haptic feedback. In all three GUI tasks (button clicking, icon/file manipulation and text handling), users could solve the task faster with haptic feedback than without. Kyung et al. stated that the impact generator has an advantage of controllability compared to vibrations [KLS09].

Wang et al. introduced the EV-Pen. A pen that uses similar technology as introduced by TeslaTouch [BPIH10]. The key contributions of the EV-Pen are precise interaction and a pen-on-paper feeling [WRSS16]. Findings of the conducted studies, precisely a steering task and a tracing task, showed that users have higher precision with the EV-Pen than the other pen interfaces. Wang et al. argue that the higher accuracy of the EV-Pen is that the resistance occurs directly at the pen's tip and not inside the pen. As the vibration takes place inside the pen, smooth movements are complicated because vibrations hinder a precise control of the pen [WRSS16].

Another pen-based approach that generates haptic feedback is FlexStylus [FPG17]. Fellion et al. have developed a flexible pen; all deformations of the pen are detected by a bending sensor and used as input modality. Various interaction metaphors have been implemented, which are based on rotational and lateral deformations. Compared to the interfaces already presented, Fellion et al.'s approach does not use an active actuator, but rather an individual, flexible material.

As mentioned earlier, there is a strong interest in improving handwriting applications. Compared to writing on a paper, traditional handwriting on touchscreens does not offer the physical characteristics known from real experience. As a result, it leads to less acceptance. Cho et al. introduced RealPen, a with a linear actuator to provide a realistic writing sensation (see Figure 2.13). RealPen can create real tactile sensations. A sensing approach of a real pen on paper writing is used to recreate auditory-tactile feedback for different pen-tips. In a study, Cho et al. were able to show that RealPen could improve paper writing realism compared to other pen interfaces.

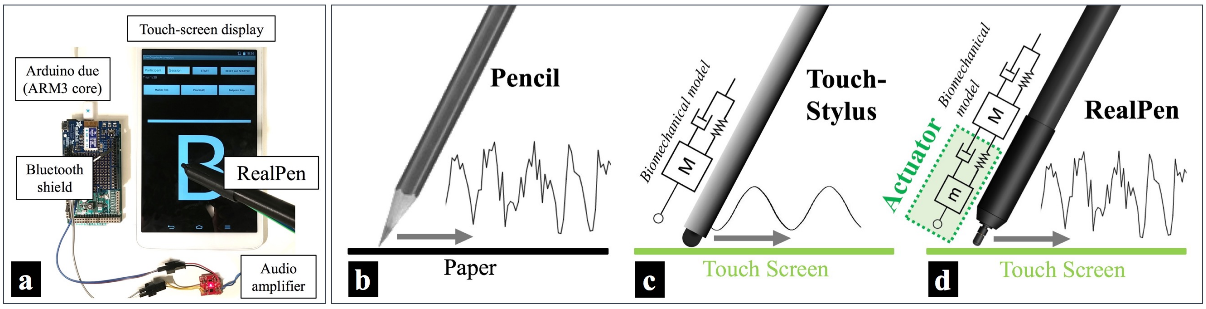

Figure 2.13: RealPen, a pen enhanced with a linear resonant actuator to recreate paper-like surface characteristics for more realistic writing sensations [CBMB16].

To summarize, most important pen interfaces providing haptic feedback were covered in this section [CBMB16], [WRSS16]. In most cases, the pens were equipped with additional sensors and actuators to generate tactile sensations [KLS09]. An important aspect of pen interaction seems to replicate real-world pen properties as closely as possible [CBMB16]. Back-of-device interaction is another modality of interacting with touchscreens. For this reason, the next section will focus on such interfaces.

2.2.3 Back-of-Device Interaction

Figure 2.14: Three main style to hold a smartphone. 95% of all users preferred to use the thumb for interaction, only 2% of the observed users preferred using the index finger [GDT+12].

Interaction with mobile devices can be performed using different modalities. In recent years, speech has become popular as an input modality for smartphones. However, most users interact with a smartphone using touch. Gold et al. observed that the two main styles of interacting with a smartphone are either typing with one or two thumbs (see Figure 2.14). Only 2% preferred using the leading hand's index finger while holding the device with the other hand [GDT+12]. Additional studies have shown that 95% of all participants tend to use the thumb as touch input. Generally, the front touchscreen is used for interaction. But what about the back? In Section 4.4, a prototype will be presented that enables haptic feedback on the back of a smartphone. Therefore this subsection discusses Back-of-Device (BoD) interaction.

Integrating the back opens up new opportunities to interact with mobile touchscreens and devices. For example, interaction is no longer limited to the thumbs or fingers on the front screen. It allows the use of more fingers simultaneously [WLF+06]. Currently, the fingers on the back are mainly used to stabilize the grip. However, when using the back for interaction screen content will not be occluded by the fingers [CDVB17] and allows, therefore a more precise input and better visibility. BoD interaction can also be used to enter private information such as authentication data like a pattern, a code or a fingerprint [DvZN+13] since other people cannot easily observe the back.

Touchscreen interaction suffers from limitations as the fingers can easily occlude screen content. To overcome this limitation, Wigdor et al. presented a mobile system called LucidTouch. Further prototypes have also addressed occlusion aspects, for instance, "under the table" interaction, looked into semantic associations [WLF+06], the HybridTouch system [SH06] explored the manipulation on the front, and the back of a personal digital assistant (PDA), or the Behind Touch system [HMT03] studied text input at the back. The performance of dual touch input was explored by Iwabuchi et al., who introduces LimpiDual, a transparent display system with two touchscreens, one at the front and one at the back [IKN08]. Apart from the primary goal of avoiding finger occlusion of screen content, Iwabuchi et al. proposed a set of application scenarios, including the manipulation of layer information and 3D objects.

Besides occlusion issues, researchers have looked into further aspects of BoD interaction, including gestural interaction [WSR14], [XHW13] and the influence of finger agility. Therefore, Le et al. looked into the development and design of BoD prototypes and applications and how to ensure reachability of all interaction elements, a stable grip and ergonomic comfort. Le et al. explored fingers' range and estimated comfortable areas per finger for one-handed smartphone interaction on the back-of-device [LMBH18]. A motion capturing system was utilized to record finger motions on the back of a smartphone. Results showed an effect of hand sizes and grip. They additionally displayed comfortably reachable areas for all finger. Shimon et al. explored back-of-the-device gestures. In their work, they have introduced a mapping of known touchscreen gestures to the back of a device (see Figure 2.15). The conducted user study results showed that users often mimicked gestures that they already knew from the front screen [SMSJ+15].

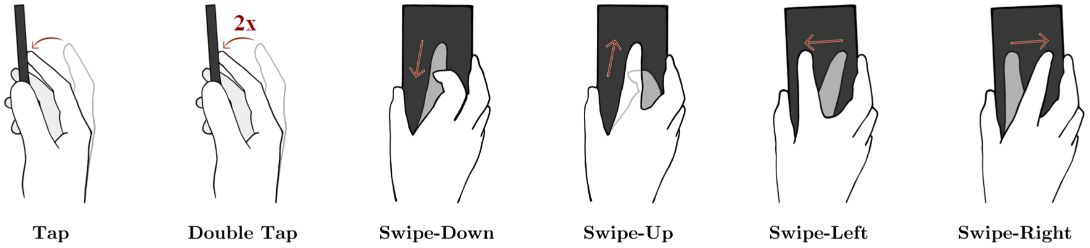

Figure 2.15: An example of an one-handed mapping of common gestures to the back-of-the-device by [SMSJ+15].

Wobbrock et al. explored hand postures in front and back interaction scenarios. Therefore three performance studies were conducted [WMA08]. All studies were performed: one and two-handed using either the index finger or the thumbs. Wobbrock's assumption that the thumb is well suited for interaction on the front turned out to be wrong, as Wobbrock et al. found that the index finger works well on the front and back of the device.

Gold et al. came to a different conclusion, they found, that most users prefer to use the thumbs [GDT+12]. Nevertheless, this is an excellent example of how interaction metaphors can change in a short term of time. It seems that it is no longer feasible to interact with the index finger on the front screen using one hand as proposed by Wobbrock et al. Interaction metaphors also evolve with the technology build-in modern devices, such as displays and sensors. Comparing the postures introduced by Wobbrock et al. it becomes evident that interacting with a smartphone has progressed.

Besides postures, combining text input with back-of-device interaction was researched by Schoenleben and Oulasvirta [SO13]. They compared typing performance on a conventional physical keyboard with their BoD folded keyboard approach and found that works very well with the Dvorak standard keyboard. The typing speed on a standard keyboard (QWERTY) layout was poor in comparison. According to Schoenleben und Oulasvirta this is due to QWERTY requires longer finger movement paths and flexion than when using a Dvorak standard keyboard (DKS) layout.

BoD interaction also supports creating smaller interactive display devices, which was discussed by Baudisch and Chu [BC09]. They found that BoD touch input is not affected by display size. In contrast, front-screen touch input was affected by display size; a smaller display size significantly reduced touch precision. This highlights that BoD interaction improves performance in several ways, from touch precision to 3D manipulation to error reduction.

Authentication with a fingerprint scanner on the rear is a conventional method and already built in many smartphones available on the market[2]. In this respect, De Luca et al. proposed a system where users draw shapes on the back-of-the-device to unlock the device [DvZN+13]. Their main focus was to avoid spying on touchscreen interaction (authentication patters) while maintaining usability and performance, which was proven by a user study.

Up to here, this subsection has shown that BoD interaction mainly refers to an input modality, i.e. the user controls the smartphone so that the communication channel passes from a human to a computer. Feedback, e.g. output and especially haptic feedback, on the backside was rarely found in literature, even though it is suitable.

Nevertheless, a few representatives also use the back as the output channel. Corsten et al.'s approach, HaptiCase, explored eyes-free absolute touch using tactile landmarks on the back [CCKB15]. They studied how exactly proprioceptive pinching of fingers and thumbs can be supported using tactile feedback on the back. In detail, they looked into indirect tapping on a visible mirrored screen. Users had to select specific regions on a distant screen using a touchscreen eyes-off with their thumbs, supported by tactile grids on the back. Different configurations of the tactile grids were analysed. Corsten et al. observed that pinch accuracy also depends on the finger position, e.g. the pinch accuracy in the middle of the smartphone is more accurate than at the border. Complementary non-visual interaction had explored previously, e.g. [WYLS13], showing the potential of using such methods for the in-the-pocket operation of a smartphone for visually impaired people [KJWL09].

Most of the BoD research relates to improving performance parameters, like increasing touch accuracy or visibility. In contrast, Feelsleeve looks at how to increase the reading experience and how to make it more exciting and memorable for children [YILK15]. Feelsleeve uses a kind of gloves attached to the back of a tablet. Vibration motors are integrated to support the displayed story with tactile stimuli. Yannier et al. conducted a user study with 44 participants and showed that haptic sensations while reading have the potential to improve children's experience and make it more memorable.

A detailed description of the state-of-the-art of BoD methods and interfaces were presented in this section. It was shown that BoD methods are mainly used as input modality [SO13], [DvZN+13]. In addition, it was also highlighted that BoD interaction has great potential to overcome certain challenges, such as eyes-free navigation [WRSS16] and interacting with small objects [BC09]. Most approaches looked into performance [SO13], [CCKB15]

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[2] Manufactures, like Samsung and Huawei, have built-in fingerprint scanners on the back of the device.

issues while only a few addressed perceptional aspects [YILK15]. The next section is slightly more detached from touchscreen interaction, but it will present work that is also important in the context of this thesis.

2.2.4 Tangible and Shape-Shifting User Interfaces

Tangible and Shape-shifting User Interfaces address haptic sensations by using physical properties, and, according to Rassmussen et al., they have three functional goals [RPPH12]: they can communicate information over their shapes, they can offer possibilities for actions, which is also known as dynamic affordance, and they can provide haptic feedback. Especially the latter makes this kind of interfaces interesting for this thesis. Before discussing relevant research in this area, a brief description of two concepts is provided: 1) Tangible User Interfaces (TUI) use physical objects to represent and manipulate digital data [SH09]. 2) Shape-shifting interface (SSI) use a physical change of shape as input or output [RPPH12]. Both concepts include physical objects, either focusing on manipulating data or changing the shape to interact with digital data.

Ishii and Ulmen published an initial idea of Tangible User Interfaces, and defined the properties of TUIs as follows: it should augment the real world by coupling digital information to everyday objects and environments [IU97]. Fishkin, in contrast, introduced a taxonomy in which TUIs can be classified based on their embodiment: full, nearby, environmental and distant [Fis04]. Two further areas in the field of TUIs that have become increasingly popular in the last years are wearable and mobile textile interfaces [SKBH18] and pin-based display systems [NFM+19], [FLO+13]. Holmquist et al. looked at TUI's future trends and consider that they will develop in two directions: 1) in the material domain, Human Material Interaction (HMI) and 2) in the Mixed Reality domain, Extended Reality (XR) [HZB+19].

Magnetorheological (MR) fluid provides a way to generate tactile and force feedback using a shape-shifting approach. Jansen et al. introduced MudPad. They showed how to use the properties of MR, low reaction time, for example, to create a haptic overlay for a touchscreen [JKB10]. Jansen et al. discuss some limitations of the idea, one of which is that MR fluid can only be used with top projections as MR fluid is opaque. Moreover, the use of a capacitive touchscreen in combination with MR fluid is not applicable as iron particles interfere the capacitive sensing [JKB10]. Finally, the resolution of the system is discussed, it depends primarily on the size and number of the magnets. Jansen et al. used a resolution of 12x7 matrix using 2cm in diameter magnets.

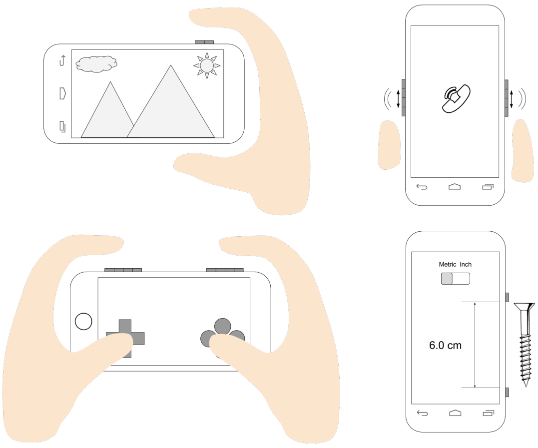


Figure 2.16: A reconfigureable tactile shape-changing interface by Strasnick et al. exploring dynamic affordances for mobile device applications [SYT+17].

Figure 2.17: A textile tactile display, allows active and passive adjustable feedback using a 7x7 matrix [BPM09].

Before looking at the work of Strasnick et al., a brief explanation of what dynamic affordances is offered. The term affordance came from the perceptual psychology [Gib80] and was later associated with the usability of objects [Nor13]. Affordance means that a well-designed object/product allows the user to know what to do with the object/product without overthinking, just being intuitive. The object has explained itself to the users by its shape, for example. Dynamic affordance means that an object can change its shape, which affects how a user wants to use it [RPPH12].

Strasnick et al. investigated reconfigurable tactile elements to change the affordance for physical dynamic in and output [SYT+17]. For the actuation of the dynamic elements, Strasnick et al. focus on magnetic actuation. They introduced two different prototypes that can change affordance. Both can dynamically place haptic feedback elements at the side of a smartphone, similar to the Haptic Edge Display [JKT+16]. Strasnick et al. introduce four applications for their interface (see Figure 2.16), ranging from configurable physical buttons, haptic notifications, gaming controller to interactive callipers to measure the external world are explored [SYT+17].

A further representative is BubbleWrap [BPM09], a haptic display prototype (see Figure 2.17). Similar to Strasnick et al., Bau et al. used a magnetic approach for actuation. They combined a permanent magnet, a coil and a flexible wrapping material allowing a dynamic expanding and contracting of the coil depending on the current flow. BubbleWrap arranges the developed actuators in a 7x7 matrix. Each pin can expand up to a maximum

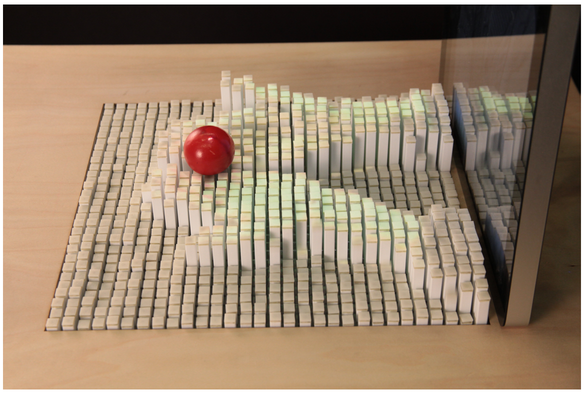


Figure 2.18: Pin-based force feedback display inFORM, showing interaction with a ball. [FLO+13].

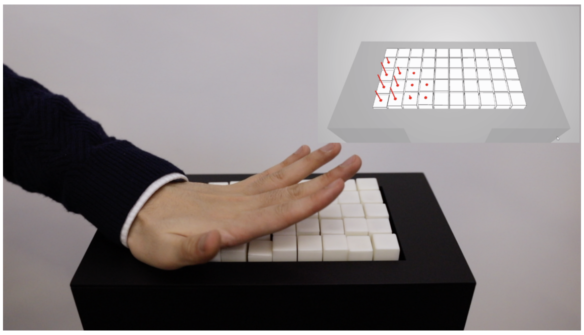


Figure 2.19: InFORCE an extentsion of the inFORM display, each pin moves induvidually based on the applied force [NFM+19].

of 10 millimetres. BubbleWrap provides active and passive haptic feedback. A conducted user study showed that users could quickly and reliably discriminate among three levels of firmness [BPM09].

Pin-based display systems generally consist of pins arranged in a matrix. The pins can have different profiles, from square to circular. The resolution can be specified similarly to a conventional display, in which the resolution is the number of pixels in width and height direction. However, resolution and element density are lower. Another difference between visual displays and pin-based display systems is that the pins are movable, similar to a 3D nail board. In this way, arbitrary shapes can be dynamically generated. Follmer et al. proposed inFORM, a pin-based display system, which consists of 30×30 motorized white polystyrene pins, squared with a side-length of about 3 mm (see Figure 2.18). A nylon rod inside a plastic housing connects the pins to a motorized slide potentiometer, enabling bi-directional force [FLO+13]. Compared to other systems, the pins move relatively slowly, for instance, in Follmer et al.ś system, the pins reach a speed of about 1 m/s. To add colour to the white pins, a projector-camera unit was used. The interface opens up a set of novel application scenarios reaching from simple button or handle interfaces up to a painting tool or to actuate other devices [FLO+13]. Nakagaki et al. extended this approach to achieve better haptic quality by introducing individual force feedback for each pin (see Figure 2.19) so that users can feel material stiffness through pressing the pins [NFM+19].

Follmer et al. introduced Jamming Interfaces, that rely on malleable media. According to Follmer et al., jamming techniques can change the shape state. For instance, a user deforms an object, and the object maintains the deformation - this state is called jammed.

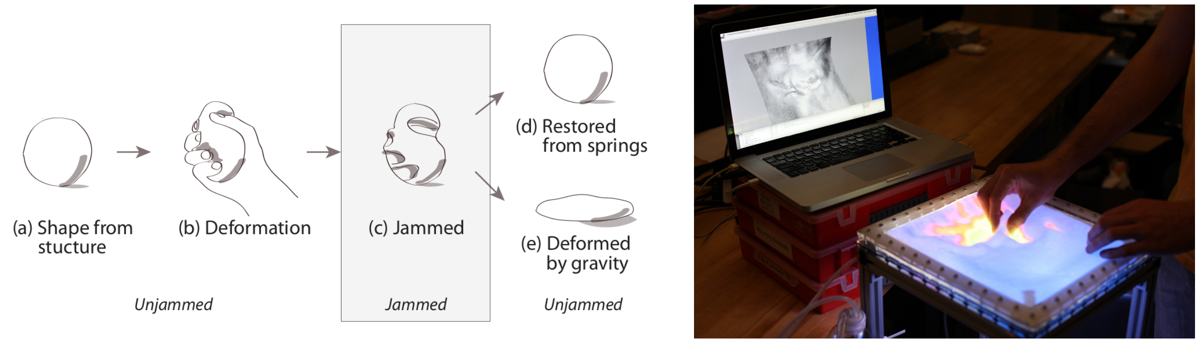


Figure 2.20: Jamming interfaces: the technique behind jamming (left); tunable stiffness for deformable interfaces on tabletops (right) [FLO+12].

Unjammed returns the shape to an initial state which is either influenced by gravity or mechanically caused [FLO+12]. Follmer et al. proposed a hydraulic and a pneumatic system, while the hydraulic approach allows an optical sensing of the surface, the pneumatic approach is not able to sense the surface due to the used material. Using this jamming technique, Follmer et al. present a sculpting application, a tabletop lens and a mobile interface approach (see Figure 2.20). The mobile approach differs in the sensing technique, while previously a visual approach has been used, namely a structured light approach, the mobile version of which uses a capacitive membrane to capture the deformed surface. Using capacitive sensing allows in the proposed implementation a resolution of 9x9 and was mounted on the back of a tablet for interaction.

A variety of different prototypes and approaches have been presented in this subsection. Many of the interfaces presented served as a source of ideas [NFM+19], [SYT+17]. In the following, flexible and elastic interaction techniques as well as techniques for providing haptic feedback in mid-air are presented.

2.2.5 Flexible and Mid-air User Interfaces

In contrast to flexible interfaces, which use material properties, mid-air interaction targets the space around or above a device to provide haptic feedback. In Section 4.3, a prototype is presented that combines both properties. It shows how haptic feedback above a touchscreen, i.e. in mid-air, can be provided using an elastic material. Therefore, related work in this area will be discussed in the following paragraphs.

The usage of elastic surfaces relates to organic user interfaces [HV08]. Researchers studied general interaction metaphors with deformable materials [LKJ+10] the use of electromagnets [JKB10] or bendable materials, including paper(-like) [GSV08], [SJM13]

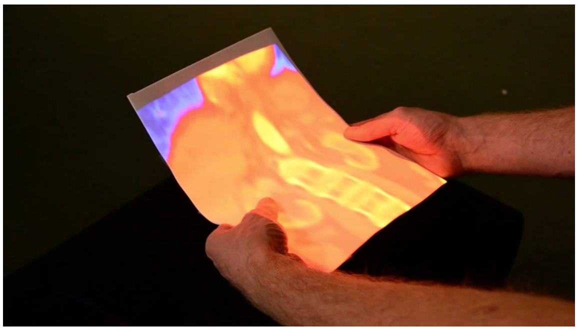


Figure 2.21: Steimle et al. introduced an approach that combines a mobile projection system with a deformation of a plain white sheet of paper to interact with [SJM13].

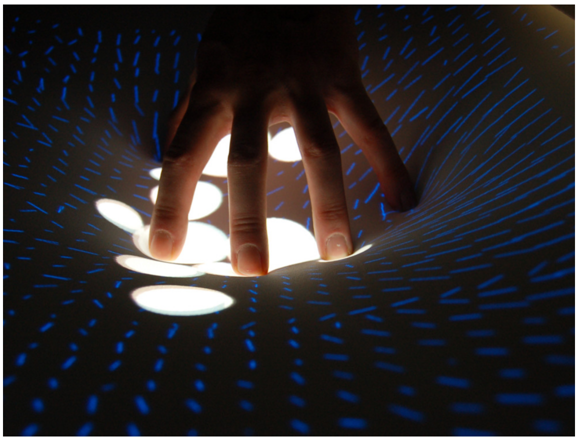


Figure 2.22: Depthtouch: a Microsoft Kinect is used to detected deformations of an elastic material to visualize informations according to the deformations [PGG+12].

or silicon(-like) materials [HGL14], and simulating variable compliance on rigid screens [Kil10].

Various paper-based interfaces like a tracked paper [HVA+05] used as display or a flexible input device for foldable interaction [GSV08] are one of the predecessors of Flexpad [SJM13]. Steimle et al. uses spatial metaphors to represent, for instance, layers of a volume (see Figure 2.21). Gallant et al. described their interface as foldable user interfaces (FUI) and foldable input device (FID). Both recognized the manifold possibilities of interaction with just a sheet of paper, reaching from squeezing, and corner bending, and folding, to flipping.

In recent years, the use of new display technologies has also become increasingly widespread. For example, flexible and deformable displays are being developed - with no need for projections [SBC+16], [GZBV16]. Most mobile, flexible displays consists of so-called flexible organic light-emitting diodes (FOLED). FOLED displays are a extension of an OLED display. All OLEDs are mounted on a flexible material. An advantage of FOLED displays compared to projection-based systems is that there is no need to track the displays to rectify the visualization. However, tracked data can be used to sense user interaction. Otherwise, additional sensors are required to detect any bending of the device to handle user input.

Elastic variable compliant surfaces have also been explored. Accordingly, Peschke et al. proposed a flexible tabletop using a back-projection (see Figure 2.22). Their DepthTouch system consists of a highly elastic material (spandex, elastane) [PGG+12]. While the interface can be deformed, it also provides feedback based on the natural properties of the surface, where pressure and tension can result in a more natural interaction. An exploratory application scenario in which virtual spheres roll into the created valleys shows validity of the prototype. FlexiWall introduced by Müller et al. looked into the exploration of layered data using flexible displays. Müller et al. concentrated on multi-layer image data that were displayed according to the depth of the deformation [MKG+14]. A further aspect of the proposed flexible projection surface is that the material can also be pinched and pulled out.

Sahoo et al. proposed a further elastic screen which can provide self-actuated deformations and tactile feedback. The screen, called TableHop, consists of a 3x3 grid of transparent electrodes used for vibration and deformations (up to ± 5 mm) and a back-projection. It measured 30x40 cm [SHS16]. In contrast to [PGG+12] and [MKG+14], Sahoo et al. evaluated their prototype. This includes a tracked polystyrene bead and a mounted high-speed camera to measure the amplitude and the frequency of the deformation/vibration. For all of the three prototypes above, no details were given of the perceived resolution or shapes that can be felt.

In the introduced interfaces, deformations were not always well-controllable [PGG+12]. Other kinds of materials, including sand and fluids, have been studied, but are also challenging to control [FLO+12]. Jamming [FLO+12] and tabletop [SHS16] interfaces could provide flexible and even shape-shifting properties, for usage in mobile devices [FLO+12]. Follmer et al. illustrate the potential of haptic feedback through controllable stiffness. Similar feedback has been explored in mechanical actuation for hand-held squeezing [GCHP10] and mouse-like interfaces [MNY+09], as well as medical skin simulation [KTC+12]. Furthermore, multiple bendable screens that provide "flexible" feedback have been presented [SBC+16].

Beside interaction with flexible materials to provide haptic feedback, the interaction space above displays, the "hover space", has also been explored by many researchers. Medusa, for example, is a Microsoft Surface augmented with 138 low-cost proximity sensors to sense the user's hand, arm and body [AGWF11]. This prototype introduces a novel sensing technique which enables novel pre-input metaphors and visual feedback on detected presence. For instance, by detecting the interacting arm (left/right), different functionalities can be assigned per arm (see Figure 2.23). Sahdev et al. explored the same problem. They describe a capacitive sensor approach that can distinguish between the hands of a single or two users [SFJ+17].

Similar to Annett et al., recent research on two-handed interaction with touchscreens explored the non-dominate hand's anticipation to assign functionalities to the users' hands

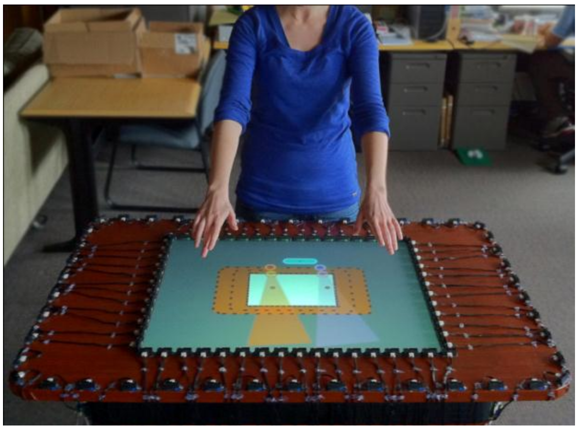


Figure 2.23: Medusa: a tabletop that can sense three levels of a users to support spatial interaction around the device [AGWF11].

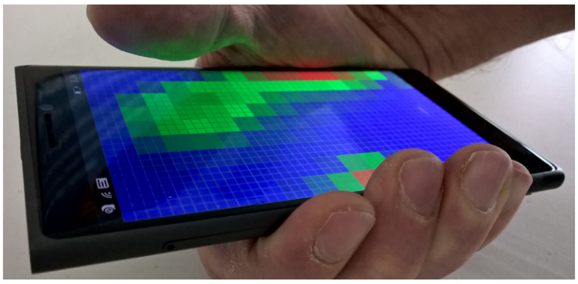


Figure 2.24: A highly sensitive capacitive touchscreen enables finger sensing above and around a smartphone [HBH+16].

dynamically [WFK+19]. Besides the recognition of arm and hands for mid-air interaction, gestures were also investigated. Cheung et al. presented a set of interaction guides on how to adapt and expand common interaction metaphors like mouse interaction into the above the display space. Their research includes considerations about proximity range, feedback location for the hover space and interaction techniques for hover devices [CHSD12].

Mid-air gestures for smartphones have also been developed [HBH+16]. The motivation was to extend the constrained vocabulary of 2D touch interaction to a third dimension, the hover space, in order to facilitate continuous 3D interaction with a 2D touchscreen (see Figure 2.24. A highly sensitive self-capacitive touchscreen enables looking into the design space of pre-touch interaction, including anticipation plus system feedback. The system can assign different touch functionalities according to hover trajectory tracking. The hover space, in combination with the 2D touchscreen, can additionally be used for combined gesture detection [HBH+16]. Mid-air interaction techniques are not only being explored for smartphones, but can even be found in stereoscopic applications, e.g. for manipulation tasks [LAB+15]. According to Lubos et al., recent sensing technologies such as Leap Motion and Microsoft Kinect support the evolution of mid-air and above-the-display interaction.

Previously mentioned mid-air interaction research focused on the design of metaphors in hover space and on sensor technologies. Methods for haptic feedback in non-contact situations, i.e. in the air, have not yet been discussed. Nonetheless, several techniques provide haptic feedback in mid-air, ranging from ultrasound to systems based on magnetic

Figure 2.25: UltraHaptics: a prototype which renders haptic feedback using ultrasound above a screen [CSL+13].

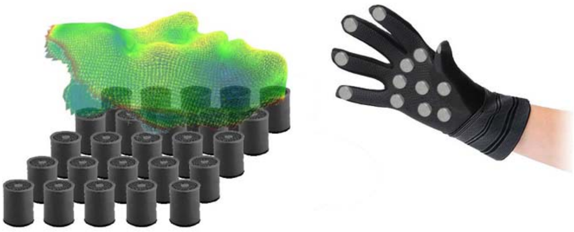


Figure 2.26: Exemplary representation of a magnetic-field based prototype, including a glove with magnetic elements and an array of electromagnets [ZDE16].

fields. In the following, selected haptic feedback technologies in mid-air are presented and discussed.

Carter et al. introduced a haptic feedback using ultrasound [CSL+13]. Their system, called UltraHaptics, uses a 2D array of ultrasound transducers to create tactile focus points in hover space. A leap motion tracks the user's hand and a screen that consists of a front projection and an acoustically transparent material. The acoustically transparent material allows to focus the ultrasound directly on the users' hands. In the system, multiple tactile focal points could be generated that reach their maximum intensity at a distance of 20cm [CSL+13]. For example, GUI elements can be enhanced with tactile stimuli without touching the display. An application scenario of UltraHaptics is depicted in Figure 2.25.

In contrast to ultrasound-based systems, Gupta et al. proposed a prototype that uses so-called air vortex rings[GMPT13]. Their system was not explicitly designed for interaction in the hover space. It focused on non-contact haptic feedback. However, this also enables interaction above a system, i.e. a display. In their research, they introduced a prototype air vortex generator and its physical and perceptional resolution. In an experiment, Gupta et al. showed that the physical resolution ranges from 10 cm to 250 cm with an accuracy from 5 cm to 10 cm. Eight body locations were chosen to estimate the perceptual resolution. After each stimulus (condition), users were asked which region was stimulated - resulting in a resolution from under 10 cm in diameter at each location.

A further method to provide haptic feedback in mid-air includes magnetic fields (see Figure 2.26). The approach is similar for all magnetic field methods. Typically, a magnetic object, such as a magnetic ring [MS05], is attached to the user's hand. For the display an array of electromagnets is used, the intensity of each single magnet being controlled by varying voltage. Within this mechanism, the magnet attached to the user can either be pushed off and pulled in, to create force event (haptic feedback) above the display. In related work, Zhang et al. introduced an advanced system that enables magnetic force feedback rendering in the air. The system can render three levels of resistance, reaching from very firm and firm to soft in an interaction area from 0cm up to 5.2cm above the display [ZDE16].

When comparing the above non-contact display systems, the feedback ranges varies. While air-based systems can stimulate up to 250 cm, using ultrasound works in an up to 20 cm interaction area. The introduced magnetic field-based approach can provide feedback within a range of 5.2 cm. Besides intensity, different approaches have been used to determine the resolution of the prototypes. Whereas Carter et al. conducted a differentiation study in which users had to distinguish two neighbouring stimuli, Gupta et al. gave the resolution with a mean targeting error.

The aforementioned feedback mechanisms are based on contactless technologies. Instead, Gupta et al. investigated different mid-air feedback metaphors in typing tasks. Unlike their predecessors, Gupta uses vibrating elements that are attached to specific regions of the hand, such as the fingertip or wrist [GSK+20].

Besides the feedback ranges, resolution also varies. For instance, the system introduced by Carter et al. achieved a resolution of 2cm and the prototype proposed by Gupta et al. a resolution of 10cm. Zhang did not provide more detailed information about the resolution except for the use of a 15x15 array of magnetic elements. Since resulting resolutions were measured at different distances and different methods, it is challenging to compare them. However, the introduced research shows that hover space, haptic feedback is possible. The combination with visual information is rather rare in this field [ZDE16], some approaches use front or top projection [CSL+13], however, they suffer from occlusions.

In summary, while interaction with elastic and flexible materials focused mainly on hands [PGG+12], [SJM13], mid-air techniques are no longer specifically tied to the hands, rather can affect the whole body [GMPT13]. This is intended as a transition to the second focus, the next three sections will therefore present haptic interfaces that stimulate the feet, also known as foot haptics.

2.2.6 Virtual Reality

In previous subsections, the focus was on haptic interfaces that mainly focused on providing feedback to the hands. As mentioned in Chapter 1, the main chapters not only deal with the augmentation of touchscreens, but also introduce haptic interfaces for virtual environments and remote environments. We see great potential in stimulating the feet with haptic feedback, firstly because the feet are not used in most applications in these areas and are therefore "free", and secondly because the feet are also stimulated in normal life, for example when walking. With haptic feedback to the feet, a more realistic feeling could be evoked. In Chapter 5, two research prototypes will be presented that looked into performance aspects, as well as on how to increase spatial awareness and self-motion perception. Therefore, in the next three sections, haptic feedback to the feet in the particular fields will be reviewed and related research will be presented.

As already stated in the Fundamentals (see Section 2.1), mechanoreceptors are not equally distributed across the entire body, which of course also applies to the feet. Since there are comparatively many mechanoreceptors in the feet, but still fewer than in the hands, they still offer a good opportunity for haptic feedback. In order to show which locations of the sole are appropriate for tactile stimuli, different frequencies of vibration at different locations were tested [GG11]. In an enhanced study, Jammes et al. showed that the sensitivity of vibrations on the soles decreases with age. In this case, vibration detection threshold was determined at varying frequencies. The main result was that older people (53-67 years) could detect higher frequencies ($> 150\,\mathrm{Hz}$) less well compared to younger participants (20-34 years) [JGF+16].

When looking specifically at virtual reality research, it can be seen that a research goal of virtual reality is to make experiences as realistic as possible. In order to achieve this and make VR as authentic as possible, it is worth considering the feet, as they are also part of our perceptual system. For this reason, related work that explores foot haptics in VR presented below. Foot haptics can be used to elicit ground texture cues, partly also in combination with audio [NNTS12], [PFC+10]. The perception in virtual environments with tactile foot stimulation was subjectively more realistic than without haptics [NNTS12]. For this reason, in Chapter 5 two novel haptic interfaces will be introduced that provide a wider range of feedback.

Furthermore, plantar cutaneous vibration feedback (the stimulation of the foot sole) can be sufficient to elicit a walking experience [TBS13]. In this respect, Turchet et al. proposed a system controlled by a micro-controller, and studied how walking experience in virtual environments can be increased using foot simulation (see Figure 2.27). They performed a

Figure 2.27: The back of the shoe interface shows two vibrations motors and a force resistance sensor [TBS13].

set of studies with the result that haptic feedback can increase the realism of walking in non-interactive (seated) and interactive (walked) virtual environments. In both scenarios, they used the same interface. A pair of sandals extended with four vibration motors were used as interface (two in front (toes) and two behind (heel)). Two additional force resistance sensors were embedded per shoe to detect the steps (again at the front and the back). Three different soil conditions were tested: snow, sand and forest ground [TBS13]. Subjects participating in the experiment felt that the haptic stimulation on the sole worked best for the snow scenario.

A further approach to enhance walking experience was proposed by Terziman et al., who used visual and vibration patterns. A low-frequency loudspeaker was used instead of vibration motors [TBS13] to create vibrations patterns. The patterns simulate either one or two ground contacts. One ground contact corresponds to a heel strike, and two contacts reflects a heel strike and then a toe strike, similar to natural walking [TMM+12]. It was found that users preferred one contact point, and that more complex stimuli are perceived as less natural. Users also prefer simulating the contact point with the ground more than the texture of the soil. In general, Terziman et al. showed that multisensory feedback does increase walking sensation. A further, more recent approach is RealWalk, the proposed interface consists of a pair of actuated shoes. The interface is designed to designed to create realistic sensations of ground surface deformation through MR fluid [SGB+18]. It can create a variety of ground material deformation in VR, such as snow, mud, and dry sand by modulating the viscosity of the MR fluid in the shoe sole. Compared to the prototypes based on vibrations, RealWalk is able to render not the texture but the surface firmness haptically.

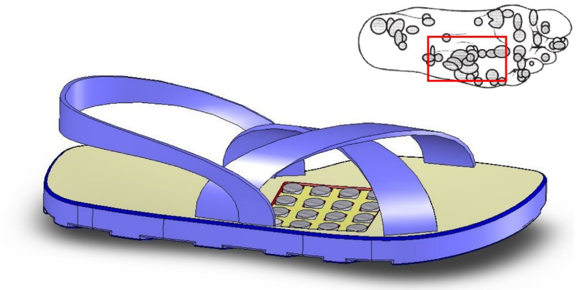


Figure 2.28: Foot-based navigation interface with a regular grid with 16 vibration motors and the distribution of mechanoreceptors at the sole of the foot [VBV+12].

Similar to Terziman et al. Feng et al. look into the influence of a multisensory design space to enhance the walking experience in virtual environments. They introduced a set of multisensory feedback, including wind, vibration and audio. They showed that foot stimulation could help maintain spatial orientation, and it can increase user experience. Furthermore, non-directional tactile cues (e.g., floor vibrations) have been shown to provide some self-motion perception [FDL16]. Auditory feedback, footstep sounds have also been used to elicit self-motion sensations [FDL16], as the frequency of steps provides some information about how fast the user is moving.

Recent research follows the same line, Wang et al's interface reproduces both roughly sloping terrain and subtle sensations when stepping on small objects or uneven surfaces [WTC+20]. With their interface, Wang et al. pursue two goals. Firstly, they want to make the walking experience as realistic as possible, and secondly, they want their system to provide a training environment for people suffering from Parinkson's disease. Similar to the Gaitmaster [IYN01], which will be presented later, the SmartShoe can map inclinations up to 10°. This is done through a set of chambers, each chamber is controlled by a solenoid valve. For example, a left inclination can be achieved by closing all valves on the left side and opening those on the right side. In this way, the air in the left chambers is maintained while it flows out of the right chambers. In their application they use a treadmill interface to walk realistically in place. In a study Wang et al. looked at spatiotemporal gait properties and kinematics which are important for training in this area.

Some studies specifically looked into navigational cues, for instance, "turn right", by deploying a regular dense grid of 16 vibrations motors under the mid-foot [VBV+12]. All vibration motors support a frequency between 10 and 55Hz. The metatarsus (inner foot sole) was chosen to provide feedback because of the high density of mechanoreceptors Figure 2.28. Accordingly, Velazquez et al. conducted three user studies to demonstrate that foot-based stimulation is suitable for navigation. Users have to detect directional cues, shapes and patterns. Both blind and sighted people took part in the study. Results showed that there are signals that distinguishable and therefore, suitable for navigation. In particular, results additionally suggest that blind people can perceive tactile cues on the sole of their feet better than sighted people [VBV+12].

Vibrations have also been used for providing collision feedback [BB10a]. In contrast to previously mentioned feet-based interfaces which were included into a shoe or a sandal, Blom and Beckhaus integrated haptic feedback directly into the floor. The "sound floor" consists of bass-reflex speakers that are directly mounted to the floor surface of an L-shape display system. Audio and haptic feedback were studied - each in a rumble and a thump mode. The conditions: no feedback, automatic stopping and visual feedback were taken into account. In a questionnaire, users specified the fastest, most realistic, and the condition that best representing solid walls. According to them, floor thump is considered to be the most practical method, and also the method for representing the most solid walls. No feedback and automatic stopping were subjectively perceived as the fastest methods. However, objective data showed that this was only the case for one user [BB10a].

It was shown that foot-based tactile feedback can be improve navigation and collision in VR, Vyas et al. showed that tactile feedback on the toes enables more complex information to be transmitted. Instead of taking a single actuator and not encoding the information temporally, [VTBC20] used multiple actuators to create a spatial display. Hands would be a good target of their spatial display, however, they are often occupied by other tasks, therefore Vyas et al. decided to concentrate on the toes. But the differentiation of stimuli on the fingers is not comparable to that on the toes. Tactile stimuli can be distinguished better on the fingers than on the toes. Using a special encoding that incorporates neighbouring toes in a temporal sequence, they showed in a study that encoded tactile rendering can significantly increase performance [VAB+20]. The presented toe interface has shown how sensitive and what abilities the feet, especially the toes, have to perceive information.

Closely related to foot stimulation is gait. Therefore the following paragraphs briefly discusses the gait. The physical aspect of locomotion can be defined by gait, the bipedal (forward) propulsion caused by the human limbs, which is affected by, for example, velocity and ground surface [FN10].

Gait is comprised of the different stride phases, in which the legs are moved, and the feet hit the ground. Stride phases differ in both frequency and length, depending on how fast the person moves. They include the stance phase (where a foot touches the ground) and swing phase (where the leg is moved and the foot is airborne); combined, they form one gait cycle. Thereby, ground contact of the foot is defined by a roll-off process of the human foot, affected by different force (pressure) phases underneath the foot sole. Furthermore, the amount of ground contact per roll-off (step) differs with velocity. Foot strike can differ between different people, as for example runners commonly have either heel or mid-foot strike [SF11].

Feedback for both physically moving and non-moving people has been approached from various directions. Not only the feet themselves but also the legs have been stimulated, for example through two motion platforms [IYN01]. The GaitMaster is specially designed for uneven terrain; two platforms on which the user stands can simulate the ascent and descent of stairs. In a more advanced version, the GaitMaster also allows omnidirectional movements. This was achieved by using a turntable as base.

In summary, it was shown that foot haptics were mainly explored to simulate ground textures [NNTS12] and walking-like cues [TMM+12]. In most cases, these cues were provided by vibrations attached to a shoe [TBS13] or surface [FDL16]. Specifically for the sole of the foot, it was shown that it is sometimes better to give less stimuli than too much [TMM+12]. Foot sensations have great potential because, on the one hand, the distance between two stimuli to be distinguished is small [Wei68] and thus more sensitive than many other parts of the body, and on the other hand, despite these capabilities, they are simply not included in interaction in most settings. In addition to tactile interfaces, interfaces related to gait were also presented [IYN01]. Gait is controlled by our kinaesthesia and proprioception, which are also part of our sense of touch. The following section synthesises necessary research on remote environments and how to br presence and interact in a remote location with the help of a robot. Finally, the context to haptics is established.

2.2.7 Remote Environments

Overall, robotic telepresence helps people to communicate over distances, it allows users to control and navigate a system to interact in a remote environment, and it usually contains a video conferencing system. As this thesis explores a combination of telepresence robots and haptic feedback to the feet, the state of the art of in this area will be discussed in the following. In Section 5.2, a haptic user interface is introduced, this interface supports users steering a remote robot by providing proximity and collision feedback to the feet.

Telepresence robots have been studied in a variety of settings, including academic conferences [NVPH16], [RN17], offices [RTM12], schools [NO17], and health care settings [KKL14]. Across these settings, researchers have found strong benefits, mostly stemming

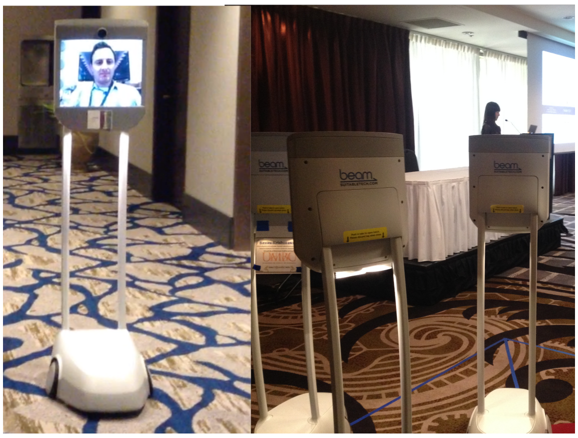


Figure 2.29: A conference scenario showing the remote robot beam (left) attending a talk [NVPH16].

Figure 2.30: The difference between control your telerobot, and being telepresent through a tablet controlled by a third person [YJNS18].

from the ability to be mobile in the remote environment with a form of "physical body" [NVPH16] (see Figure 2.29).

Digital mobility has supported people attending meetings and maintaining informal awareness in the workplace [RTM12], attending social gatherings and mingling with others [NVPH16], [RN17], engaging in small group activities such as workshops [RN17], supporting long-distance relationships [YJNS18] (see Figure 2.30), establishing friendships and participating in learning activities [NO17].

In all described situations, the user has a view into the remote space and can easily change that view by moving the telepresence robot. Control over what is seen is in the hands of the remote user. This contrasts with other video conferencing setups (e.g. Skype) where the view is typically in the hands of the local user [JWB$^+$15].

There are still some challenges. For example, it can be hard to understand the body language of the operator of the telepresence robot [NVPH16]. Many telepresence robots do not have hands or arms so they cannot easily touch objects or interact in the physical world [NO17]. Privacy challenges stem from being in two environments at the same time [NVPH16], [NO17]. Telepresence robots also create challenges in understanding how one is presented in the remote environment, including how one looks and sounds [PST$^+$11], [TH13], as well as where one is spatially located [NVPH16]. This makes it challenging to manoeuvre telepresence robots while performing other tasks like talking [NVPH16], [RMT+14], [TH13].

It can also be hard to know where one is in a building, especially if it is a new space for the user [NVPH16]. In crowded spaces, it is difficult to avoid obstacles or people with a telepresence robot [RN17]. Researchers have investigated a variety of means to increase the amount of feedback that users have when interacting through a telepresence robot. This includes wider fields of view [JRMT15] [JP02] and audio feedback to know how one sounds in the remote space [JP02]. Yet there remains a design gap in providing telepresence robot users with means to help them receive feedback and improve their spatial awareness of obstacles while moving through a space.

The combination of haptic feedback with a robot is quite advanced in the fields of humanoids [AFHW+18] and also in human-robot interaction [Oka18]. However, when looking in particular at haptic feedback to support the control of a robot in a remote environment, it becomes apparent that it is mainly in the area of assembly tasks and less often in the area of awareness. Hannaford et al., for example, showed in a very comprehensive study that in different manipulation tasks the performance could be improved with additional feedback [HWMZ91]. The tasks included peg-in-hole insertion, electrical connectors, Velcro attach-detach, and a twist-lock multipin connector, all involving high-precision control of the robot.

Haptic feedback to enhance navigation is much less widespread. Hacinecipoglu et al. investigated how haptic feedback affects performance in obstacle avoidance scenarios [HKK13]. In a study in which an unmanned vehicle had to be steered through a course with a set of obstacles, they were able to show that the participants completed the course faster and with fewer collisions with haptic feedback. Nevertheless, it should be mentioned that the course was simple and a conventional gaming steering wheel was used for the haptic feedback. Using the NASA TLX, Hacinecipoglu et al. also found that the mental demand is lower with haptic feedback. Level of frustration and effort also perform better with haptic feedback. A similar result was shown by Ju and Son. [JS19] also looked at the impact of haptic feedback on obstacle avoidance. Instead of a steering wheel, a commercially available haptic device was used. However, even the somewhat unusual or unknown navigation technique does not seem to have a negative impact on performance.

Another approach using a commercial interface to enhance navigation performance was presented by Lee et al. [LKSP04]. Although the authors' placed their research in the telepresence domain, it consisted of an unmanned vehicle and no social or other interaction other than navigation was described. However, an interesting aspect compared to the predecessors was implemented and explored. Whereas the others focused mainly on collisions, Le et al. have also included the environment in the feedback spectrum. However, an interesting aspect compared to the predecessors was implemented and explored. Whereas the others focused mainly on collisions, Le et al. have also included the environment in the feedback spectrum. The results reflect the trend described above and Le et al. showed that the number of collisions can be reduced by haptic feedback.

2.2.8 Navigation Cues

Navigation is one of the key tasks performed in real, virtual and remote environments, it encompasses both physical and psychological aspects. It is necessary to interact in both: virtual realities and telepresence scenarios. Since navigation is often enriched with haptic feedback in order to optimise it, different approaches are presented below. These range from light vibrations [VBV+12] to interfaces based on kinesthesia, for example walking in place [BKLP05] or leaning [GPI+15]. Navigation means how to move from one place to another in an environment. In principle, there are three different navigation tasks: exploration, search and manoeuvring. Each of the tasks pursues a different goal, while exploration focuses on exploring the environment to gain knowledge. In the search task, a specific location is targeted, and the shorter the path and the time, the better. Manoeuvring also involves heading for a specific location, but the focus here is on avoiding possible obstacles. Short, precise movements are important to complete the task well.

Physical navigation interfaces have been studied widely and can increase the overall usability and user experience of the system [BKLP05], [RBM+10], enhance spatial perception and orientation important for a wide range of tasks [BKLP05], and reduce motion sickness [BBG08]. Most of the factors mentioned above also affect virtual environments as well as controlling a remote robot. In both cases, orientation in space and spatial perception are essential. In the following, we look more closely at related studies on leaning-based navigation interfaces, as well as feedback to support navigation.

Leaning-based interfaces are often used for travelling and navigating in virtual environments like games or virtual environments. Some prototypes utilize a Wii balance board, and its pressure sensors, to perform navigation tasks in virtual environments [VSBH10]. Through the shifting of weight users are able to navigate in a 3D world. Other types of leaning interfaces use the body position determined by an optical sensor [GPI+15] or a spring mechanism to navigate through a environment [MPL11]. Even unusual locomotion metaphors, such as surf-like metaphors, were examined using a Wii Balance Board [JL12].

Leaning interfaces to some degree resemble other interfaces that keep the user physically at one location while walking, these include metaphors such as walking in place (WIP) interfaces [TDS99], natural motion interfaces such as those supported by treadmills [DCC97], or navigation systems for seated users. An overview of many techniques can be found in [BKLP05], while a focused overview of how, in particular feet can be used for interaction purposes is described in [VSA$^+$15].

Another aspect that is important for navigation is the so-called self-motion perception. Embodied self-motion illusions (e.g. vection) have been studied and can be induced in stationary observers by moving visual flow fields, moving spatialized sounds, and biomechanical cues from walking on circular (but not linear) treadmills [RFR09]. Visually-induced vection can be enhanced by adding simulated camera motions that mimic jitter [BKAP11] or head bobbing, the vertical and horizontal oscillatory motion of the head during natural walking [BB10b], which can be communicated as a purely visual cue [TMM$^+$13], as well as through physical movement of the user [ISK$^+$14].

Some studies showed that minimal provision of vestibular cues can enhance self-motion [SF11], as do footstep sounds [TMM$^+$12], wind [FDL16], and tactile patterns associated with walking [RSP13] or leaning in sideways directions [KMT$^+$15], all of which showed positive effects. Likewise, body pitch could also affect self-motion [BVB10]. Studies on actively tilting the body have shown that while horizontal (sideways left-right) vection was not affected by body tilt, vertical (a.k.a. elevator) vection was reduced for upright posture and increased to the level of horizontal vection as body tilt increased [NS98]. In contrast, static leaning has also been shown to affect self-motion for seated users positively [KRTK15].

The usage of vibration to provide cues related to navigation other than self-motion has also been studied. Directional information through vibrations has been explored through foot-based [VBV$^+$12] and body-worn devices. For the latter, it has been shown that directional cues can be successfully provided by stimulating a specific side of the body [LSMM$^+$05]. It has also been used to convey collisions [BB10a], or even to avoid collisions during navigation [AB11]. Collision avoidance also relates to the breed of interfaces that have been developed to indicate proximity, which has been studied for general 3D selection tasks to indicate how near the user is to a target [ABKS18], [MKT$^+$18], but also has found specific application in navigation systems. For example, SpiderSense [MHL$^+$13] uses vibration motors distributed over the body to support navigation for the visually impaired. This kind of feedback is similar to a distance-to-obstacle feedback approach to communicate distances to surrounding objects [HOAH15] and wheelchair operation using a glove-based interface [UCP08].

Many different navigation methods have been presented in this section. They range from slight navigation cues based on vibrations [MHL$^+$13] to leaning-based interfaces

[GPI+15]. Some navigation techniques were presented to increase self-motion perception [KRTK15], while others focused on more efficient navigation [MKT+18]. In the next section, a summary of related work is presented that leads to the two research questions of this thesis.

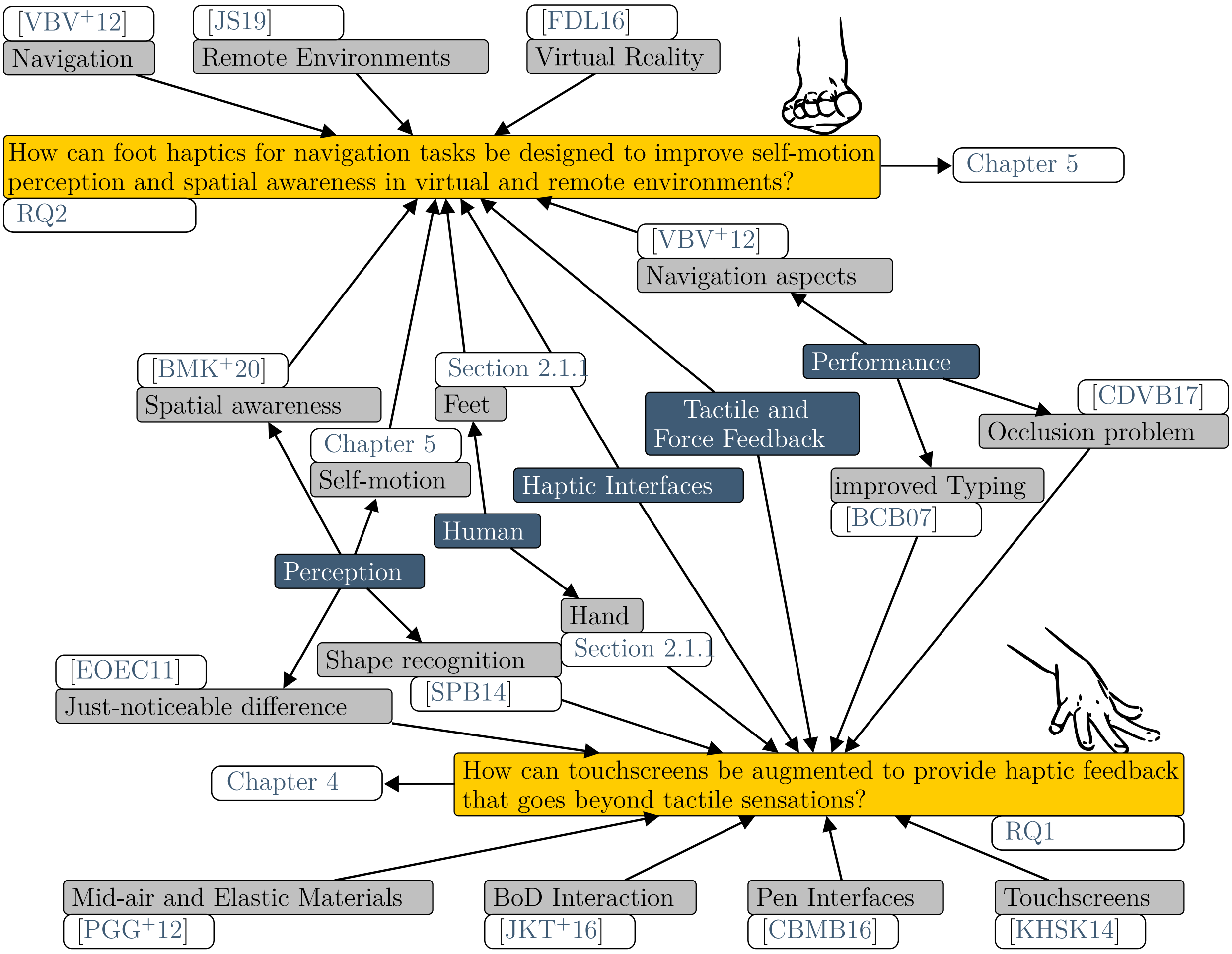


Figure 2.31: A summary schematic representation of the dependencies and intersections between the two research areas. The diagram also shows the dependencies of related work and subject areas on the research questions. The references represent a representative of each subject area or refer to a specific section or chapter.

2.3 Summary and Research Questions

In the previous sections, related work have been introduced, discussed, organized in sections in order to present corresponding research. An overview of haptic interfaces from both focus areas is given at the beginning of this chapter (see Table 2.1). The table shows related work and categorises them into five groups:

1. **Actuator** (the key technology responsible for providing the haptic feedback)
2. **Feedback type** (sensation triggered by the feedback)
3. The **focus** of each research
4. The part of the **body** that is stimulated
5. Classification into **application** areas

These five groups appear directly or indirectly in many of the related work presented so far. For example, looking at the sectioning into body regions, it can be seen that the first sections of this chapter are more focused on haptic feedback for the hands and fingers, while the last three sections address the feet and present haptic interfaces from this area. When looking at the application areas, it becomes apparent that the hand or finger's stimulation focuses on touchscreen interaction, while haptic foot interfaces mainly refer to virtual reality and remote environments.

A schematic overview of the main dependencies and intersections is given in Figure 2.31. It highlights three main aspects. Firstly, the graph shows the connections, intersections and dependencies of the related work presented. Secondly, it shows which related work or areas have an influence on finding the research questions and thus a need for further research. Finally, the link from the research questions to the corresponding chapters is provided. Looking at the intersection (see Table 2.1, highlighted in blue), it becomes clear that the humans, their perception, various aspects of performance and tactile and force feedback are are part of this thesis, which can also be summarised under the overarching concept of haptic interfaces and interaction [EOEC11].

Both summaries, Table 2.1 and Figure 2.31, are a starting point and the base for the following two subsections. These will lead to the research questions and highlight the need for further research that has been dealt in this thesis.

2.3.1 Haptic Feedback for Touchscreens

The first focus area addresses the challenge of pairing haptic feedback with touchscreens. Three open challenges have been identified and highlighted, which are then brought together and linked in a single research question. The three challenges all explore ways in which haptic feedback can enrich touchscreens. More specifically:

RQ1.1: What are the limitations of force feedback provided through a rigid screen?

RQ1.2: How can elastic materials be combined with touchscreen interaction?

RQ1.3: How could a small mobile touchscreen be equipped with haptic feedback?

All three sub-questions of the described challenges are taken up and dealt with again in Chapter 4.

In Section 2.2.1, it was shown that two modalities of haptic feedback can be found in combination with touchscreens, namely tactile [FS01] and force feedback [HTE+17]. Furthermore, it was described that both types of feedback can be generated using different technologies (see Section 2.1.2), which in turn has an influence on the type and manner of feedback. Finally, we have shown that tactile cues, combined with mobile touchscreens, are well researched [GSK+20]. Various systems and prototypes have been presented that can provide tactile feedback, ranging from simple vibrations [BCB07] to friction screens [KIP13]. Tactile feedback was used, for example, to improve the perception of GUI elements [KBL14] or to improve performance [BCB07], e.g. to minimise the error rate when writing on a virtual keyboard. Force feedback, in contrast, combined with mobile devices, such as smartphones, has been rather rare researched and still has further potential.

Actuated display systems such as the vertically mounted display prototype of [SPB13] and the horizontally mounted tablet proposed by [KHSK14] have shown that their systems can make contours and shapes tangible. However, not all limitations have been explored, in particular, Sinclair et al. used a stereoscopic system and their screen was mounted vertically. In addition, TouchMover only supported 1DoF. In the study conducted, the perception of different geometric shapes was investigated, but the users were able to see the screen, which provides additional visual cues and can potentially support haptic perception. Furthermore, the users were directly informed of their result after an exploration, which in turn can lead to a faster learning effect [GS05]. In contrast, Kim et al. focused strongly on haptic rendering techniques, such as the control of the screen, without considering perceptual limitations [KHSK14]. Although Kim et al's system is similar to the one in presented Section 4.2, they differed in the evaluation and implementation of the system. Any complex shape can be represented using such a system, apart from a few physical limitations. The question that should be in focus, however, is what information can be processed with an actuated screen through our haptic perception. To some extent, Hausberger et al. have addressed this question and found that the size of a geometric shape can be better detected when tactile feedback is added to the screen actuation [HTE+17]. Also the work of Nagamatsu et al. which deals with multi-touch in the context of actuated touchscreens could benefit from more detailed information [NNTA14]. In general, the existing literature does not explore the resolution which can be provided by an actuated screen. We want to investigate this in Section 4.2 by showing the implementation of our interface, determining the horizontal and vertical resolution, and also looking at the limitations of such a systems.

We also discussed flexible and mid-air interaction (see Section 2.2.5), and it turned out that there is still much potential for further research in this area [HBH+16]. We consider the combination of pen-based interaction [WRSS16] with elastic and mid-air interaction [PGG+12] to be promising, we will introduce at multi-layer interaction with a touchscreen in Section 4.3. Therefore, we propose a flexible surface that combines tension feedback with vibration as well as rigid feedback to improve pen-based interaction with touchscreens. In summary, the interaction with pens on touchscreens is manifold [CBMB16], [LDL+04], [WRSS16]. Both active and passive pens were presented, and different technologies were used for actuation. The field of applications ranges from the simulation of realistic pens [WRSS16], e.g. friction, to other interaction metaphors [BPIH10], e.g. supporting the selection of objects. It is undisputed that interaction with elastic surfaces opens up new design spaces [PGG+12]. Similar to pen interaction there are passive [MKG+14] and active systems [SHS16]. Neither the interaction with a pen combined with an elastic material nor the combination between elastic materials and a touchscreen has been sufficiently researched, as was shown in Section 2.2.5. Our approach introduced in Section 4.3 opens a new kind of multilayer interaction space, extending previous above-the-table multilayer approaches [SAL06] by adding the exploration of haptic properties in the spatial flexible haptic layer. In contrast to both non-contact-based and mechanically linked systems, our system extends hover space approaches through contact-based variable compliant haptic feedback. We principally divide above-the-display space into virtual (without contact) and physical (with contact) space. Hover space generally explores virtual objects in a virtual space [ZDE16], whereas our work looks at virtual objects in a physical space.

So far, the focus was on touchscreen interaction, without considering the portability of the screen. Since the components needed for tactile feedback are very small and require low power, it is not challenging to provide mobile or handheld touchscreens with tactile feedback [PH20]. As already mentioned, there are some force feedback and pin-based approaches [NFM+19], [SPB13] , but all of them are not portable. The literature review has shown that haptic feedback is usually used in prototypes to represent the real world's physical properties [RVGG17], like buttons [HKLB08], or make these properties tangible to the user. Less publicised, however, there are approaches that use haptic feedback to improve performance [BCB07], e.g. to enable blind people access to digital content [PBKW18].

The design problem that it is difficult to place larger components, like actuators, on the front of the screen, as they would obscure the view and interfere with the interaction with a touchscreen. In this thesis, the back of a smartphone became a feasible solution for placing force feedback. There is another advantage when the back is included: interaction on the back of a device can improve visibility on a touchscreen [CDVB17]. The fingers that are usually used to hold a smartphone can now be used for interaction [BC09]. BoD interfaces can create entirely new or transfer already familiar metaphors for interaction with a smartphone [SMSJ+15]. At the moment nearly all prototypes are based on dedicated hardware and highly specialized on particular applications [JKT+16]. A fingerprint scanner on the back for authentication is a technology that has prevailed with several manufacturers and accepted by the users. BoD interaction is mostly used as an input method, i.e. to control the behaviour of an application [HMT03]. Feedback is primarily visual through an integrated LCD or a visual projection. Rarely do researchers deal with haptic feedback on the back-of-the-device. However, Yannier et al. have shown that the reading experience can be increased with haptic feedback, which suggests that there is still potential [YILK15]. Another issue that has had a considerable impact on the acceptance of BoD interaction are ergonomic aspects, for example, the accessibility of interaction elements without taking an uncomfortable posture by maintaining a stable grip can considerably affect the usability [CDVB17].

A number of TUIs and SSIs have been introduced (see Section 2.2.4). While traditional TUIs use the natural physical properties of objects to manipulate data, newer interfaces usually include additional technologies. Although the interfaces presented are not directly related to touchscreens, they fit very well into the context of this work. For example, pin-based interfaces [NFM+19] were presented, which can also be found in a modified form in Section 4.4. In addition, deformable interfaces [FLO+12] and interfaces that change their state [SYT+17] were dealt with, which partly served as sources of ideas for the research in this thesis.

In general, haptic feedback for mobile devices has not been researched in depth in the existing literature. Summarising the previous sections, it is clear that the combination of haptic feedback and touchscreen interfaces has the potential for further research, which led to the first research question addressed in Chapter 4:

> **RQ1:** How can touchscreens be augmented to provide haptic feedback that goes beyond tactile sensations?

2.3.2 Haptic Feedback for Virtual and Remote Environments

While the first section explored the combination of touchscreen interaction with haptic feedback and thus concentrated on the hands and fingers, the second section will switch focus on the feet. In detail, haptic feedback to the feet in virtual and remote environments is explored. Figure 2.31 gives an overview and puts this area in the context of the thesis. Furthermore, it shows the dependencies to the first area as well as direct aspects and domains that are important. Haptic interface design and the haptic feedback principle are further aspects that connects both areas.

Similar to the previous summary, open challenges will first be identified and highlighted, and then brought together and linked into a single research question. The main challenges explore ways in which haptic feedback can enrich virtual and remote environments. In particular:

RQ2.1: How can foot haptics support users awareness when interacting in remote environments?

RQ2.2: What influence do foot haptic cues combinations have on self-motion perception in VE?

In Section 2.2.6 it was shown, that haptic foot stimulation pursues different goals. On the one hand, foot-based feedback is used in virtual environments to increase immersion [TBS13] - to make virtual environments more realistic [BB10a] [WTC+20]. On the other hand, tactile stimuli on the sole of the foot are also used for navigational cues [BB10a], shape recognition [VBV+12], and rendering surface texture and firmness [NNTS12] [SGB+18]. Interfaces based on weight shifting or leaning can also improve self-motion perception [KRTK15]. Different prototypes were also presented that simulated the feet with haptic stimuli [TBS13], [VTBC20]. In general, however, the literature did not show how the combination of leaning-based interfaces and foot haptics behaves. In addition, it is therefore interesting to study, how the combination of different feedback types perform, as they have achieved positive results individually. In Section 5.3, we introduce a new foot-stimulating approach that increases self-motion perception in virtual environments.

However, we do not only want to deal with foot-based feedback/stimulation in the context of VE , we further want to explore foot haptics in combination with telepresence robots [NVPH16]. With regard to the implementation of haptic feedback, both areas (VR and RE) are very similar. In both cases, the user is immersed in a remote world. With the only difference that once it is synthetically generated and the other is real. The telepresence robots can be seen as virtual avatars and are used today in many different ways, as discussed in Section 2.2.7. Nonetheless, there are still open challenges, such as how to control the remote robot in dense environments and how to improve the spatial perception of the remote environment. These challenges are discussed in Section 5.2.

The usage of haptic feedback to enhance robotic telepresence systems has mostly been to support manipulation tasks in teleoperation to improve accuracy and awareness [HWMZ91]. Using haptic feedback to support navigation is far less common. Some examples provide haptic cues for collision avoidance to improve situational awareness [HKK13], [JS19]. However, all studies used hand-operated devices instead of providing feedback to the feet, which can provide an additional sensory channel that is mainly unused in current telepresence robots despite being the body part that might naturally bump into things. Proxemics, the notion of proximity, has also found some interest in robotics, albeit foremost in relation to social aspects [VJ17]. Only a few studies have focused on the effects of haptics on navigation performance, including [LKSP04] that explored driving a mobile robot (non-telepresence). Results showed improved performance and presence. However, systems were studied in environments that were neither complex nor dynamic. Using haptic feedback to improving self-motion has been probed before, especially in Virtual Reality systems. Embodied self-motion illusions (e.g., vection) have been studied for quite some time [RSP13] and can be realized with a variety of methods, including visual cues [BB10b], sound cues like moving sound sources [RVSP09].

Nonetheless, all these systems do not have the granularity of feedback - that is, providing directional proximity and collision feedback - afforded through the system introduced later (see Chapter 5). Overall, we do not see explorations in the related work of how haptic feedback systems can be designed to aid telepresence robot driving, especially when systems are designed for the feet. Furthermore, we do not see related work on how people would experience such systems, which is the focus of our work. The above sections have shown that there are still open questions, in this thesis the following research question will be addressed:

> **RQ2:** How can foot haptics for navigation tasks be designed to improve self-motion perception and spatial awareness in virtual and remote environments?

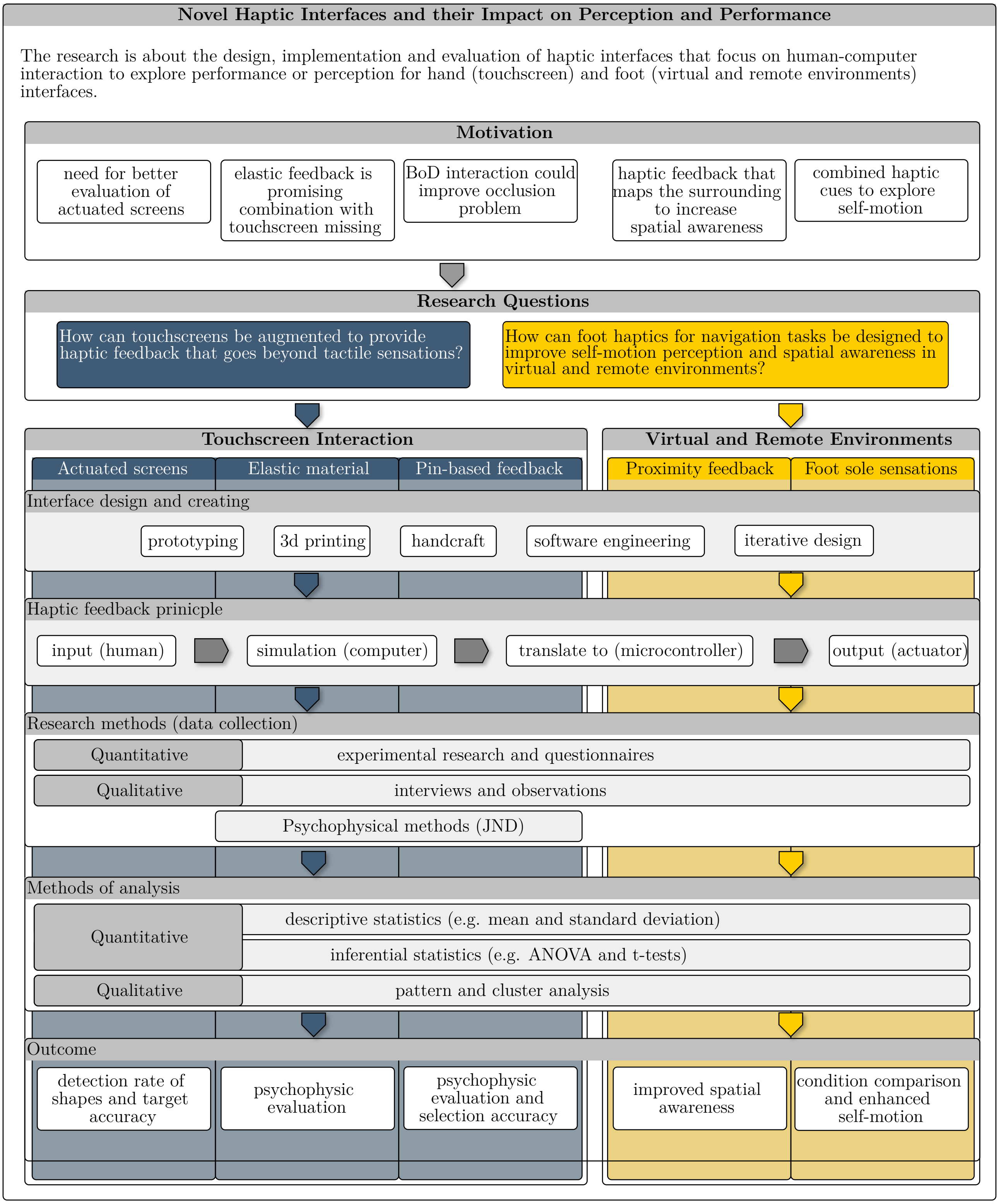
Chapter 3

Research Methodology

3.1 Introduction

There are several ways in which humans can interact with computers, similar to the interaction between humans, whose interaction involves both our sensory perception and the motor control of our effectors. Humans have five senses: sight, hearing, touch, taste and smell, and according to Dix et al., sight, hearing, and touch are currently crucial for human-computer interaction [DFAB04]. Taste and smell are not so widespread and mostly used in research at the moment. Just like humans, computers also need an input and an output channel in order to communicate.

Sensors and actuators are essential in this context, as they can, to a certain extent, substitute our senses and effectors. Later, a mapping between human (functionality) and machine (sensor or actuator) is presented (see Table 3.2). Both are necessary to provide haptic feedback: a sensor is responsible for recording the haptic stimuli that the user applies to an object and sends these force readings to a computer (input). It converts this information into a form that can be perceived by the user through an actuator (output) [EOEC11].



The research is about the design, implementation and evaluation of haptic interfaces that focus on human-computer interaction to explore performance or perception for hand (touchscreen) and foot (virtual and remote environments) interfaces.

How can touchscreens be augmented to provide haptic feedback that goes beyond tactile sensations?

How can foot haptics for navigation tasks be designed to improve self-motion perception and spatial awareness in virtual and remote environments?

Figure 3.1: An overarching diagram of all research studies conducted. It highlights the common research methods and analyses as well as the outcomes.

In line with previous work in this area, the methodology is adapted to do multimodal and multisensory research, focusing on haptic interaction. Consequently, both the human being and the interface are at the centre of this research. An overview of the methods used and the interplay of the studies conducted can be found in Figure 3.1. The diagram includes the motivation and the identified research questions (see Section 2.3 and Figure 2.31). It depicts the two main research areas, and their associated sub-areas are highlighted. Furthermore, the methods used for prototyping, evaluation and analysis are presented. Finally, a brief outline of the outcomes is given. The diagram shows the connections in this chapter but also beyond this chapter and links the different parts of this thesis. For a more detailed view of the methods used, a procedure and design diagram is presented below before each study.

The following provides a summary of the literature review, a definition of HCI and two philosophies on what research is and how to perform research, especially in our field. Subsequently, research methods are discussed to illustrate the diversity of research in the area of haptic interaction. The chapter deals with creating haptic interfaces and methods for performing user studies, including collecting data, sampling, evaluation, and ethical aspects.

The Literature Review and the resulting research questions (see Section 2.3) have led to a more precise classification of the subject area. Thus, the focus is on the design, the implementation and the evaluation of hardware interfaces to provide haptic feedback. The thesis looks into both human perception issues and interface design. That implies that following models, techniques and procedures will be applied to find answers to the research questions.

To improve the understanding of the methodology, first of all, we would like to refer to a definition of HCI and show that HCI research draws on many different disciplines, including computer science, sociology, communication, psychology, human factors, industrial engineering and design [LFH17]. This makes research in this field undoubtedly exciting, but also more complicated since in most cases no "standard protocol" can be applied. When considering the number of disciplines, it is also common that research methods are mixed and modified for the use in HCI [LFH17].

One of the first definitions of human-computer interaction highlights this diversity. Accordingly, Hewett et al. define human-computer interaction, in the ACM SIGCHI curricula as follows [HBC+92]:

> *Human-computer interaction is a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them.*

On the one hand, the definition lists different technical disciplines, such as implementation (e.g. Computer Science/Engineering) and evaluation (e.g. Statistical Data Analysis), and on the other hand it includes the human being (e.g. Physiology) and further subject areas. In considering haptic perception, for example, many disciplines such as neurophysiology, psychology and psychophysics come together [EOEC11].

In the following, two fundamental research approaches are briefly introduced to get an understanding of the selected methods. Then the several research methods that used in the thesis are presented and linked to the respective sections.

3.2 Quantitative vs Qualitative Research

The quantitative approach is inspired by the philosophy of positivism, which is based on the assumption that everything around us is real and that this reality can be described logically. Within this approach, an order exists, which means that a specific description can define everything. It is a rational and objective approach compared to a qualitative approach which is instead a more subjective approach. New knowledge develops from existing knowledge [LFH17], meaning that the research conducted in a quantitative approach is based on a deductive principle, where one concludes from the general to the specific.

Quantitative study designs are specific, well structured, have been tested for validity and reliability [Kum10]. They are explicitly defined and, therefore, systematically designed. This, in turn, means that gathered data typically also have a specific structure. Results are obtained by evaluating the data. In a quantitative approach, questions such as how something is or how it relates to each other are mainly asked.

According to Rogers et al., a quantitative approach can be used to answer specific research questions [RSP11]. For this purposes, mainly questionnaires are used, but other methods can, of course, be used for gathering data, e.g. log files recorded during an experiment, or user activity can be recorded. A quantitative approach uses statistical methods for validation. Validation is often done employing a significance test, in which collected data are examined for individual properties and/or correlations between properties, such as error rate, speed and distance. Findings can be presented with charts or figures.

In contrast to a quantitative approach, which uses objective methods deductively to answer specific questions, qualitative methods are based on subjective data and conclusions are drawn inductively. Similar to the quantitative approach, a philosophy can also be assigned to the qualitative approach, namely interpretivism. Similar to positivism, there is a real world, but it cannot be explained in the same way for everyone. Everyone experiences the world individually through his/her perceptions which are influenced by their preconceptions, beliefs and values [Wal11]. In this philosophical approach, humans are part of the world, so they are not neutral.

A qualitative study design usually is not well structured or follows a logical process such as quantitative study design do. It is, therefore, difficult to plan an experiment. A qualitative study design is less specific and precise, and does not has the same structural depth as quantitative study design [Kum10]. Since research results originate from the subjects' own opinions, questionnaires may be a wrong way to conduct research within a qualitative approach. Since there is no special protocol and subjects participate interactively in the study, a pre-designed questionnaire cannot dynamically deal with potential new aspects. Therefore, this approach mainly works with interviews, which, of course, must also be well prepared. This allows the subjects to be addressed individually in order to find out their opinions and preferences on a specific or broad topic.

Unlike quantitative approaches that use statistical tests for validation, a qualitative approach does not have a clear, straightforward validation, and the process of analysis is often more complicated. The focus here is not on numerical measurements, but on the evaluation of observations, videos, interviews or studies texts, and therefore the understanding of complex situations [LFH17]. What makes it even more complicated is that the statements of for example two test persons contradict each other, and since the truth is not known either, the comments have to be interpreted and discussed to find a feasible solution to the problem.

In summary, it was shown that doing human-computer interaction research is very diverse since many different factors influence this domain. Therefore, it is challenging to decide using either a quantitative or qualitative approach. Consequently, it makes no sense to strictly separate the two methods but rather connect them through a continuum. Partly mixing these two philosophies becomes visible in this work (see Figure 3.1). However, our research philosophy is based more on a quantitative approach. Nonetheless, especially at the start of creating new prototypes, qualitative methods, like discussions and interviews, are often crucial as pointers. An overview of the main characteristics of quantitative and qualitative approaches is illustrated in Table 3.1. In the following, we will further discuss on the methods used in this thesis.

	Quantitative	Qualitative
Philosophy	positivism	interpretivism
Approach	objective	subjective
Reasoning	deductive	inductive
Sampling	random	purposive
Data	structured	individual
Records	numerical	verbal
Evaluation	statistic	interpretive

Table 3.1: The table shows the main characteristics and differences between a quantitative and a qualitative approach.

3.3 Haptics Exploration

There are many methods and procedures for researching haptic user interfaces. To find the right research direction, it is essential first to understand what contributions can be expected and then work towards those contributions. Wobbrock and Kientz present seven potential contributions, ranging from empirical, artefact, methodological, theoretical, dataset, survey to opinion contributions [WI16]. When considering the number of contributions published in HCI, it can be seen that empirical contributions dominate, followed by artefact contributions. Since the contributions that have been made belong to these two categories, both will be briefly explained. An empirical contribution is the analysis of qualitative and quantitative data collected, for example, through an experiment or a survey. An artefact contribution is a contribution that introduces, for example, a new interface or a new toolkit. The combination of an artefact followed by an empirical contribution reflects the contributions achieved within this thesis. According to Lazar et al. this combination is also known as HCI system research or HCI interaction techniques [LFH17].

However, how can one achieve these contributions? Shneiderman et al. describe ways detailing how to gain findings or contributions [SPC$^+$16]. The most frequently used methods to collect HCI data are observations, field studies, surveys, usability studies, interviews, focus groups, and controlled experiments [SPC$^+$16]. Each of these options has its strengths and weaknesses. For instance, observations can be extremely time-consuming and complex to analyse [LFH17] (for more detail see Section 3.7). A general scientific research approach (see Figure 3.2) can also assist in gaining contributions. This cycle reflects standard scientific methods, but they can, of course, be transferred to researching haptic interfaces. Observation and the resulting idea and design of a new hardware prototype is the starting point of each cycle in this thesis. An evaluation follows them: an empirical study, to collect and analyse data.

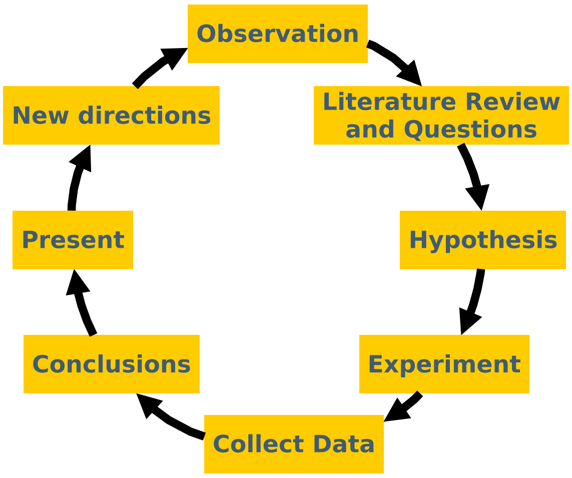


Figure 3.2: A standard iterative cycle of scientific methods, inspired by [Nor13], [Wal11]

As introduced in the fundamentals, the sense of touch is different from the other senses. When, for example, researching visual feedback, the focus is usually on algorithms for generating image content rather than on prototypes [Gol10]. However, it is currently common in haptics research to develop prototypes [EOEC11], due to the versatility of the sense of touch. An essential method for developing haptic interfaces is **pilot testing**. This method supports more efficient planning and helps determine the parameters for the experiment to be conducted [Gru08]. In many cases, it is sufficient to conduct the pilot study with a very small sample in order to collect initial results and feedback [LFH17]. This will help to iteratively improve the feedback and its design. The method of conducting pilot studies can often be found in related work [WRSS16], [HNW+14], [MKT+18]. In this thesis, pilot studies were performed on all prototypes in order to make haptic feedback as appropriate as possible. A good example of pilot studies can be seen in the design of the haptic back-of-device feedback for smartphones. The Figure 4.21 from Section 4.4 depicts early prototypes optimized through pilot test.

Adopting a quantitative approach and aiming to quantify haptic perception, there are methods that can measure haptic perception [JT13]. Methods that are often used to quantify the properties of haptic feedback come from psychophysiology. Psychophysiology is a field of research that deals with measuring physical changes in response to mental states [CW11]. A question that often arises with haptic interfaces is what can be represented with a particular interface or how accurately changes can be perceived through our sense of touch. The main method to determine the perception threshold is the **just-noticeable difference** (JND). It measures how much we need to change the stimulus along a certain dimension before people even notice the change. A table of sensory resolutions of tactile and haptic stimuli can be found in [JT13]. There are classical methods, such as the method of the constant stimuli [Ges97], and adaptive methods, such as the staircase method [JT13]. A crucial difference between the two methods is that when using the method of constant stimuli, all values have to be set in advance. In contrast, using an adaptive method, the stimuli presented depend on the user's responses. Both methods were used in our experiments to quantify haptic perception (see Section 4.3.2 and Section 4.4.2).

In this context, two concepts will be discussed more closely. Firstly, there is the Weber's Law. It states that the ratio of the perception threshold to the stimulus intensity is constant. The constant of $\Delta I/I$ is called the Weber fraction. Secondly, there is the psychometric curve. It describes the relationship between a person's responses or perception and the physical stimulus. In other words, it represents the probability of detecting a stimulus correctly along the vertical axis and the intensity of the stimuli on the horizontal axis. It is the basis to determine the JND [JT13]. As an example, the psychometric curves obtained from the experiment in Section 4.4 can be shown (see Figure 3.3). Obtained data of all individual participants were fitted using Weibull function. Each plot shows the stimulus level on the x-axis and the percentage of correct stimuli detected on the y-axis. The blue dots show the probability that a particular stimulus was detected.

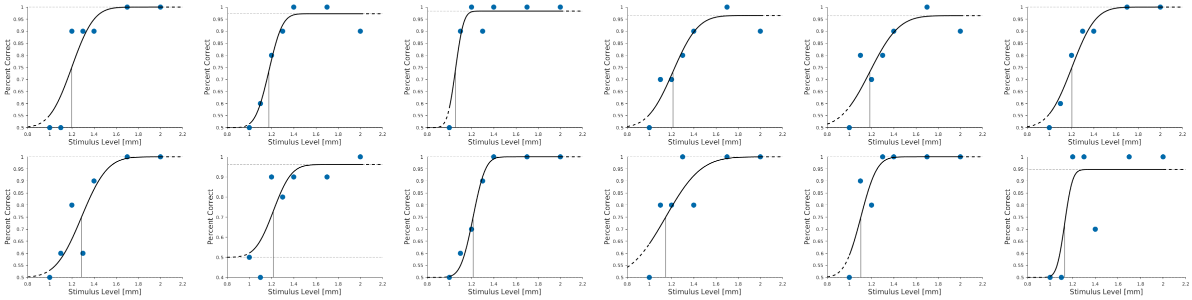


Figure 3.3: Psychometric curves obtained from the experiment in Section 4.4

Other methods that can be used to quantify haptic feedback are the active palpation and **detection of shapes** or geometries [SPB13] and surface textures [SGB$^+$18]. When recognising shapes, different geometric shapes are rendered haptically and the users have to identify the shapes, usually without visual feedback. The detection likelihood can be represented by a matrix [SPB13], [HTE$^+$17], as can also be seen in Section 4.2. Explicitly controlling variables to limit the parameter space of a experimental design is a common used method. A example of limiting the parameter space is to follow a path or marker

[GPI+15], [RF12]. With this method, the user is asked to follow a certain object or marker. It can be used, for example, to control the velocity. This method, for instance, was used in Section 4.2 and Section 5.3, among others. In both cases, this was done to better compare the haptic sensation.

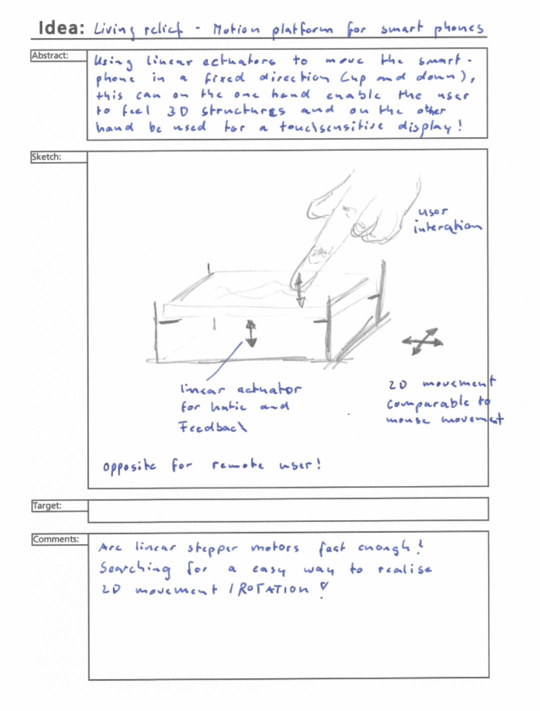
In the following, further research methods are discussed, including developing the prototypes that will be introduced in the main chapters, and methods for performing user studies/experiments are discussed, including designing, performing, and evaluating those.

3.4 Prototyping Haptic Interfaces

It can be asked whether a prototype is a right approach to explore haptic interaction. Would it not be enough to do a questionnaire or a survey? The answer is yes and no - to get specific trends or opinions (qualitative) - a survey is sufficient. However, if someone wants to explore an aspect more closely, it is essential to develop a prototype. Especially for haptic or spatial interfaces, as introduced in the main chapters, it is essential to try things out [OSC+17]. Practical experiences are often necessary to draw conclusions, especially when it comes to the sense of touch. As five prototypes were created, prototyping methods as used in this work are presented below.

Initially, it must be clarified how the haptic interface should look like and how it should behave. Therefore a physical and conceptual model must be created, while the conceptual model includes functionality and behaviour [RSP11], the physical model, the prototype, looks into the appearance, the materials and the physical constraints. In this thesis, methods ranging from virtual and real prototyping, rapid prototyping, vertical and horizontal prototyping, low fidelity prototyping and high fidelity prototyping were used to create haptic user interfaces. Usually, however, it starts with a pen and a sheet of paper on which the first sketches are made. For a deeper understanding of these techniques, they are discussed in the following subsections.

According to Buxton, a sketch can help: to think more creatively about ideas, to instantly generate a lot of ideas (quality does not matter), to record ideas, to share them with others and to have fun while designing and sketching [Bux07]. In addition, sketching does not require many tools; for instance, a paper and pen are portable, cheap and always on. It is difficult to draw a clear line between sketching and prototyping. In some cases, it merges into each other or in other cases sketches can be the first stage of a prototype [RSP11], [Nor13]. Of course, digital sketches can also be created, the principle remains the same, but with the digital counterpart templates can be created, components can be



Idea: Living relief - Motion platform for smart phones

Abstract: Using linear actuators to move the smartphone in a fixed direction (up and down), this can on the one hand enable the user to feel 3D structures and on the other hand be used for a touchsensitive display!

Sketch:

Target:

Comments: Are linear stepper motors fast enough?
Searching for a easy way to realise 2D movement / ROTATION ?

Figure 3.4: A sample sketch using the developed template. The sketch was continued and contributed to this thesis.

reused and deleting a component is easier. A disadvantage of digital sketches is that users take longer to sketch an idea, as users try to create a high-fidelity screenshot instead of merely sketching an idea.

To further simplify sketching, a sketching template was developed as part of this thesis. This template contains five categories:

- a heading (the *idea*)
- a brief summary (*abstract*)
- a drawing area (*sketch*)
- the problem you're trying to fix (*target*)
- and *comments.*

The template aims to record ideas quickly and with the template it is easier to collect ideas. It is not necessary to fill in all points; it is just a framing. Figure 3.4 shows four of the many sketches that were made during the time of the thesis.

Similar to sketches, prototypes can be created either digitally or physically. Digital prototyping is known as virtual prototyping. An excellent example of virtual prototyping is design evaluation. Designers evaluate products that have not yet been built [Sut03]. Meanwhile, there is an increasing number of computer-aided design (CAD) tools that allow a simple engineering and additionally support photorealistic rendering[1]. The latter enables visual design evaluation based on a virtual prototype.

A further advantage of virtual prototypes is that a digital model is available. In combination with a 3D printer, a physical twin can be created quickly. 3D printing is increasingly being used in research to create new user interfaces [HZB+19], [OOH+19], [GZBV16]. Some user interfaces developed in this research are based on virtual prototypes and then being printed in 3D. Figure 3.5 shows, for example (from left to right) a virtual prototype of a haptic module for smartphones, the corresponding photorealistic representation and the physical 3D model. More details about this research prototype can be found in Section 4.4.

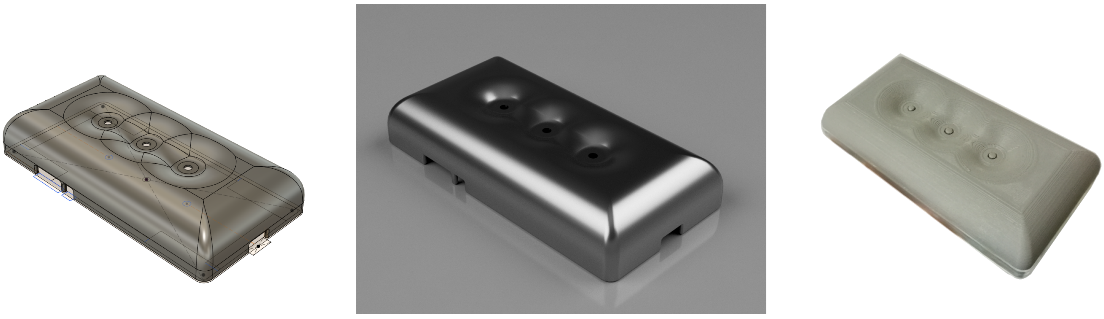


Figure 3.5: An example of a virtual prototyping process from left to right: a virtual prototype, a photorealistic rendering and a 3D printed physical representation.

Rapid prototyping is a further technology that allows to create haptic interfaces quickly and is often used in combination with manufacturing. It includes all technologies that can be associated with nowadays common 3D printing techniques. The main representatives are, among others: stereolithography, selective laser sintering, solid ground curing and, as mentioned, 3D printing [MRS15]. Similar to virtual prototyping, the geometry data must be available digitally. For this purpose, computer-aided X programs are used. Rapid prototyping is also used in the design and development of novel user interfaces; for example, the interface of [BHSO16] presented in Chapter 4. All prototypes were developed using rapid prototyping technologies. However, 3D printing can not only produce housings, it can also produce mechanisms up to a certain complexity, which will be seen later (see Figure 4.23).

Finally, there are low-fidelity and high-fidelity prototypes [LFH17] - both have their advantages. At the beginning of a development where the direction is not yet 100 per cent given, it is necessary to react quickly to new requirements. Therefore the prototypes must be built quickly and easily (low-fidelity). In contrast, in a final stage of the development,

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[1] Autodesk Fusion 360 https://www.autodesk.com/products/fusion-360/ (last accessed 19th April 2021)

meaning before the prototype is complete and ready to be used for studies, it must have a higher quality and functionality (high-fidelity). This type of low-fidelity prototypes were often created to explore certain aspects, whether ergonomically or to answer the question: "how does it feel?"

It can be emphasized that prototyping is suitable for exploratory and agile development of haptic user interfaces. Most of the mentioned methods can also be found in many publications referenced in Chapter 2, directly or indirectly. Of course, prototypes can also be created with other methods, but the ones presented here are probably the most prominent. Engineering and prototyping is a part of the outlined research process. Researchers have to try and iterate to create a physical user interface, especially when developing haptic interfaces [OSC+17], and this is exactly what prototyping is appropriate for. The prototypes developed can be found in the main chapters. The combination of haptic feedback with touchscreen interaction is presented in Section 4.2, Section 4.3 and Section 4.4. Foot haptics prototypes that could increase presence and spatial awareness can be found in Section 5.2 and Section 5.3.

The following will discuss tools, materials and equipment used to build and design haptic interfaces. Since most developed user interfaces consist of several components, an overview of individual components and how to prototype them is given. The five main components are sensors, actuators, housings, one or more mechanisms and a control unit.

Sensors and actuators are as important to a physical user interface as our senses and motor system are to humans. With these components, interfaces can interact with the environment and with humans, Table 3.2 gives an overview of sensors and actuators. The table shows a wide range of sensors and actuators, the parameters to be influenced and their focus. For example, a touch sensor (type) can track the position (parameter) a finger of a user (focus). Alternatively, a projector (type) can change the appearance (parameter) of the environment (focus). Especially for haptic interfaces, actuators are necessary [EOEC11].

A control unit is required to control a sensor or an actuator. Therefore, several microcontroller platforms are suitable for prototyping user interfaces, for instance Phidgets[2], Adafruit[3] and Arduino[4]. According to [OSC+17] the open-source platform Arduino is the most impactful platform in the context of user interfaces. However, the main difference between them is that Adafruit and Phidgets are proprietary products and offer additional hardware such as sensors and actuators. All three prototyping environments mentioned

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[2] https://www.phidgets.com/ (last accessed 19th April 2021)

[3] https://www.adafruit.com/ (last accessed 19th April 2021)

[4] https://www.arduino.cc/ (last accessed 19th April 2021)

Type	Parameter	Focus
Sensors		
Distance	Distance, proximity	user, object
RFID	Existence, proximity	user, object
Touch / force	pressure, force, position	user
Vibration	Surface vibration, displacement	user, object, environment
IR reflection	Light, interruption	objects
Spatial (IMU)	Movement, orientation	user, object
Bend	Flex angle / flex radius	user, object
Magnetic	Magnetic strength	object
Load	Weight	object
Loudness	Decibel	user, object, environment
Light	Lux	object, environment
Temperature	Celsius/Fahrenheit	user, object, environment
Humidity	Humidity	object
Soil moisture	Humidity, conductivity	object
Steam	Humidity, rain	object, environment
Alcohol	Alcohol (fumes)	object, environment
Gas	Gas, vacuum, pressure	object, environment
Camera image	pixels, objects, contours, light	
Actuators		
Servos	Displacement, rotation	user, object
Motors	Displacement, rotation	user, object
Linear servo	Displacement	user, object
Muscle wire / contraction	Contraction	user, object
Vibration	Vibration	user, object
Heat	Temperature	user, object, environment
Wind	Air flow	user, object, environment
Smoke, smell	Air particles	user, object, environment
Light	Illumination	user, object, environment
Sound	Sound	user, object, environment
Fluidity/taste	Taste	user
Visual/projection	Appearance	user, object, environment

Table 3.2: This table shows common sensors and actuators. In the first column the type of sensor/actuator is shown. The second column describes the parameters that can be mapped to the sensor/actuator. And the last column shows potential focus of the sensor/actuator. Cells highlighted in yellow are important for this thesis.

above also appear in the research discussed in Chapter 2. For example, the Haptic Edge Display by Jang et al. uses components of Adafruit [JKT+16]. In contrast, the research of Deber et al. Hammer Time, uses an Arduino as the control unit [DAJ+16]. Phidgets components are, for instance, include TouchMover by [SPB13]. As shown in the two main chapters, the interfaces developed were also implemented using at least one of these components.

In this thesis, housings and moulds have been manufactured in different ways. For example, for a low-fidelity user interface, modelling clay was used to see how it is felt in hand or to explore further form factors. Methods such as rapid prototyping, including 3D printing, was used to create high-quality prototypes. However, it is also worth going to dollar stores or hardware stores. One can find beautiful materials for prototyping, or it may just be useful for finding an idea [Bux07].

Finally, it could be necessary to include a mechanism into a user interface. According to [Tsa00], a mechanism is a device that transforms motion and torque from one or more links to the others. In other words, whenever a motion has to be redirected, a mechanism exists. The methodology of designing a mechanism can be compared to that of an interface design [Tsa00]. Besides, there are already components that contain a mechanism, for example, a linear actuator. A modified scotch-yoke mechanism providing haptic feedback was developed in this work, which turns a rotational movement into a linear movement (see Section 4.4).

In summary, this section showed how and with which resources a new interface could be built. At the beginning, methods for prototyping were described. These methods range from simple sketching with paper and pencil to the creation of high-quality prototypes. Sensors and actuators are required to create interfaces that can interact with humans. Sensors and actuators differ and must be adapted to the particular sense channel. Table 3.2 gives an overview of the variety of sensors and actuators.

3.5 Experimental Design

Whenever a haptic interface has been built, it must be evaluated in order to show quality, limitations and potentials. This is usually done by conducting a user study. Therefore, in the following, an overview of the design, implementation and evaluation of user studies is given. All studies that have been conducted in this thesis have applied theses methods. In general, a user study aims to collect data for later analysis to answer specific questions, the research question(s) [FH03]. However, before a study can be conducted, it first must be designed. The following paragraphs discuss the methods for conducting user studies.

In order to create an experimental design, certain framework conditions must already have been identified. For example, literature research and the resulting research questions have to be formulated. The research question(s) is/are then used to determine the parameters to be evaluated, to which the user study must be adapted. In most cases, the research question clearly defines which parameters have to be examined [FH03]. In theory, there is always a cause and an effect. This is known as a dependent (effect) and independent (cause) variable. How does the effect change when the cause is changed?

How these parameters are related can be illustrated using the example of the following question (see Section 4.4): How does the haptic feedback on the back of the device affect touch accuracy on the front screen? In this case, the dependent variable is the touch accuracy (cause). We would like to know how touch accuracy performs with varying haptic feedback. Consequently, the independent variable is haptic feedback (effect). Thus, the dependent variable determines the outcome of an experiment. In general, a way of manipulating the independent variable is complicated. There is no standardized approach as to how and to what extent the variable must be changed to achieve a proper result [FH03], [LFH17]. This usually depends on each experiment individually. In this case it helps to perform a pilot study to determine potential values in advance.

A factorial design is an experimental description that contains more than one independent variable. The number of conditions in a factorial design is determined by the total number and the levels of independent variables [LFH17]. Levels indicate how and how often a variable is changed.

For example, studying the typing performance on different keyboard layouts - in this case, the keyboard layout would be the independent variable, and the layouts used in the study (e.g. QWERTY, DVORAK) represent the number of levels. The influence of one-handed and two-handed typing should additionally be studied. The independent variable number of hands also has two levels. Therefore the factorial design is: 2x2. In other words, the factorial design provides the total number of conditions [LFH17].

Another aspect when planning experiments is how to divide the subjects into groups. In human-computer interaction, there are two standard group designs: a within-group design and a between-group design. A within-group design means that all subjects have to participate in all conditions. There is only one group. In contrast, a between-group design means that there are as many groups as conditions. Each group is allowed to complete only one condition [LFH17]. Consequently, a between-group design has more participants than a within-group design. Consequently, in a within-group design participants have to study more conditions than in a between-group design.

Finally, there is a design that is a combination of the two mentioned above. It is called a split-plot design. With a split-plot design, conditions can be combined. This allows creating fewer groups than conditions. Looking at previous typing example, a within-group design would require one group, a between-group design would require 4 groups and a split-group design could require 2 groups. One group is studying both hand conditions on a QWERTY layout, and another group is studying both hand conditions on the DVORAK layout.

Comparing the two approaches, it becomes apparent that from a statistical perspective, between-group is a clearer concept, since each user contributes to only one condition, so there is no learning effect. Besides, parameters such as fatigue and frustration can be better controlled [LFH17]. However, there are limitations of between-group design, the two main disadvantages are of which being: firstly, the performance of several groups with disjoint participants are more difficult to compare; secondly, a comparatively large number of participants is required, which means that the study will take much more time. In a within-group design, individual differences are effectively isolated, as each participant is tested for all conditions. However, there are also disadvantages in using this method. Users might become fatigued and a learning effect have a negative impact on the results [LFH17]. As the split-plot design is a combination of the two mentioned designs, the advantages and disadvantages are to be transferred proportionately to the design.

In exploratory studies with a focus on discovering new trends and initial results, HCI prefers a within-group design [LFH17]. For a more detailed study, all three presented groups are appropriate designs. According to Caine, who has analysed all CHI[5] papers regarding their group design, Caine reported that 17 within-group, 26 between-group and 25 split-plot design were published in 2014 [Cai16]. Of course, Caine's analysis cannot be generalised, however, it shows some interesting findings.

A further factor we have considered when designing our experiments was the order in which studies are conducted. If all participants complete the study in the same order, results can become biased. The influence of the conditions on each other can bias the results. For example, if condition A always follows condition B, events A and B cannot be considered independent. A and B are dependent. Therefore, it is important to provide the conditions in either random order or a counterbalanced order [FH03]. Latin Square,

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[5] Top tier conference in the field of HCI: ACM CHI Conference on Human Factors in Computing Systems https://sigchi.org/conferences/conference-history/chi/ (last accessed 19th April 2021)

for example, is a counterbalanced approach. An extension of Latin Square considers the number of successive conditions, the so-called balanced Latin Square.

To conclude, this subsection has shown which factors have to be taken into account when planning an experiment. These factors were also considered and applied in the experiments performed in this thesis. Of course, everyday factors have also to be considered, e.g. should one stand or sit during the study? Does it make a difference? Or are there other factors that can influence the results, e.g. is the user dazzled and does this influence the study? Additionally, it should be already defined at this stage if and which questionnaires have to be used. Furthermore, it should be clear whether interviews will be conducted after/before/during the study. The studies conducted in the main chapters applied a within-group design. With the knowledge that for some studies, a between-group design might have produced more generalisable results. However, since the experiments conducted were more exploratory in nature, it is sufficient for evaluating the implemented haptic prototypes. This guarantees a proper experimental design to aim the three goals of the research: reliability, validity and importance [FH03].

3.6 Sampling

Before proceeding with more detailed methods for collecting data and statistical data analysis, the population and sample size should be discussed. When conducting experiments, the term population refers to a group of humans for whom the analysis results are valid and can be generalized. The choice of the population can influence the results [CW11]. However, in most cases, the whole population is not able to participate in an experiment. Therefore certain people are selected from the group, either randomly or determined. The number of selected persons determines the sample size.

Skills fluctuate throughout life, the attention span is shorter in childhood, and other skills such as reading and writing still need to be learned. Moreover, abilities also decrease again, for example, the sensory capabilities of older people decrease. According to Lazar et al., most computer applications are designed for people between 20 and 50. This age group also seems to be the target group for our studies [LFH17]. This means that in our case, the population and the resulting sample group should also be in this age range, in which case the very young or the elderly would bias the results.

There are different methods for determining a population, including random sampling, voluntary sampling, all of which have their advantages and disadvantages. Of course, the approach (quantitative or qualitative) also influences the sampling procedure. Whereas quantitative methods tend to be based on random sampling, qualitative methods tend to use non-random sampling techniques [Kum10].

A specific method of determining samples is called convenience sampling. Convenience sampling is a common practice in human-computer interaction [BACM11]. The advantages of convenience sampling are that the population consists, for example, of all university members and the samples/persons can be collected fast and without much effort using, i.e. a mailing list. The disadvantages are obvious, this sampling technique can lead to bias; for example, if only students, locals or university employees are selected [BACM11]. Caine examined the convenience sampling technique and concluded that it is a method used at ACM CHI. However, the student population cannot be considered as representative for the whole western society [Cai16].

In most of the studies performed in this thesis, convenience sampling was used. Participants were invited using a university mailing list, word to mouth or could register online to participate at a particular experiment. In addition to the studies by Caine and Bernstein et al., it should be mentioned that our studies were voluntary, and the results could have been slightly different if we had paid the participants [SC18]. Nonetheless, there are studies, such as the research of perception thresholds, where it is challenging to bias them, as these depend entirely on a person's sensations. In contrast to perception studies, there are performance studies, and these depend more on motivation and further parameters that can be influenced unconsciously or consciously by the user [LFH17].

In addition to the group of people, the size of the sample should be considered. Various techniques can be used to determine the sample size, these depend, similar to the sampling methods, on the individual approach. In quantitative studies, for example, power analysis is often used, it is an a priori approach to determine the sample size [FH03]. Caine examined not only the group design but also the sampling size of CHI 2014, she has shown that the sampling size ranged from 1-916,000, and the most common number of participants was 12 [Cai16].

Studies presented in this thesis have mostly been performed at our university (Bonn-Rhine-Sieg University of Applied Sciences), and two studies (see Section 5.2) have been conducted at our partner university (Simon Fraser University, Canada) where the population was also determined using a convenience sampling technique.

3.7 Collecting data

Data collection is one purpose of an experiment. An experiment typically follows the design and is part of the evaluation. Data can be collected in several ways: through questionnaires, interviews, focus groups, observation or by collecting performance data. In order to collect data, a study must fulfil several requirements. This section discusses both the data collection methods and the requirements that are important when conducting a study.

Questionnaires The responses to the questionnaires can be given in several ways: either as free text or using a specific scale. The former makes an analysis more complicated because the answers must be interpreted; the latter allows a statistical evaluation. In the field of human-machine interaction, the so-called Likert scale is often used [LFH17]. When using a Likert scale, quantitative data are collected, for example, users give a rating similar to a 5-star rating, which is a common practice on the Internet. In this way, ordinal data are gathered. There are further scales like the Thurstone scale (interval data) or the Guttman scale (ratio data), which were not used in this thesis, because both scales are more difficult for the user to understand and also more challenging to construct.

Gathering data through questionnaires is, besides other methods, considered as a standard in the evaluation of haptic investigations [Gru08]. In HCI questionnaires are often used to query subjective data, preferences or task load [BLC+12], [WRS17], [HS88]. In the case of Boring et al. and Wang et al., subjects had to complete the questionnaire after the actual experiment. Studies presented in this thesis also include questionnaires, which were usually asked after an experiment to obtain subjective data about user experience and self-perceived performance.

Especially when using a Likert scale, there are some details to be considered. First of all, the number of options available to choose from; if an odd number is chosen, there is the possibility of being neutral. In contrast, if an even number is chosen, the user is forced to choose, for example, positive or negative. The presentation of the scale can additionally influence the results, there are categorical scales (strongly agree, agree, neutral, disagree, strongly disagree) or numerical scales (from 1, 2, 3...7) [Kum10]. Attention should also be given to cultural aspects and effects of order [CW11].

When designing questionnaires, it is essential how questions are formulated because unclear formulation can lead to confusion [EOEC11] or can influence the subjects [LFH17]. Moreover, according to El-Saddik, the problem using a questionnaire is that subjects may misunderstand the implication of the question or may not wish to report feeling or emotions.

Nowadays, there are simple tools that allow to create a questionnaire and put it online. This has the advantage that users can fill in the questionnaire themselves. This can be achieved with a reliable and specialized tool, e.g. SoSci Survey[6]. These tools further allow us to reach many people with few resources [RSP11].

Questionnaires can either be designed individually or standardized questionnaires can be used. As already mentioned, when creating a questionnaire, it is essential to ensure that the phrasing is clear to avoid misunderstandings. However, there are standardized questionnaires, for example, the System Usability Scale (SUS) is a reliable tool for measuring usability; it consists of ten questions [Bro96]. Another standard questionnaire is the Nasa TLX [HS88], which can be used to determine a task load index. It indicates how challenging the present task is for the user. The use of standardized questionnaires has advantages: results can be compared, and thus a benchmark about the researched system can be given, and they have been used several times before, so the questions have been reviewed quite often. In this thesis, we used both - we created our questionnaires that asked for specific properties, but we also used the two standard questionnaires above to evaluate our interfaces.

Interviews A further method of collecting data is to conduct interviews. Interviews are normally used to collect qualitative data. Advantages and disadvantages described in Section 3.2 are also valid in this case. Interviews are an excellent technique to obtain in-depth knowledge about a specific topic. It is possible to obtain information that might have been lost with a questionnaire, and it is a method to get individual feedback. However, interviews are hard work and can take a lot of time [RSP11]. Apart from that, it is challenging to manage potentially unbounded discussions. Compared to the evaluation of quantitative data, e.g. from questionnaires, the evaluation is more demanding and complex. Identifying important aspects is challenging.

According to Lazar, direct feedback from subjects is a key element in human-computer interaction research [LFH17]. Therefore, interviews were used in initial explorations and after performed user studies. Interviews were mainly done unstructured to get individual feedback. Gathered information and comments were used to enhance the design of new prototypes or to improve the usability of the system and device, respectively. However, interviews were used noticeably less often than questionnaires.

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[6] https://www.soscisurvey.de/ (last accessed 19th April 2021)

Focus groups In contrast to interviews, which are usually conducted one-to-one, focus groups are a method of sharing and discussing a particular topic with a group of stakeholders. Again, it is complex to evaluate individual responses. A further disadvantage of focus groups is that there is always the possibility of having one or more dominant characters in a group and that other participants may not be as engaged as they would like or can be. An advantage of this method is that it brings together different groups or opinions. Focus groups promote contact between users and developers or researchers [RSP11]. Within this thesis, focus groups have been rarely used. It may have been used unconsciously in group sessions or discussions, but no data was consciously collected in focus groups.

Observation Similar to focus groups, this technique was used rarely. The subjects were, of course, observed during the experiments and pilot studies, and of course, results of the observations contributed to the respective systems. However, observation was slightly unstructured. In general, monitoring users collects qualitative data and has its origin in ethnographic studies. Caine examined the distribution of data collection methods at ACM CHI 2014 and showed that the observation method was used comparatively as often as interviews [Cai16].

Experiments In Section 3.5, three group designs of experiments were presented. This paragraph shows how experiments can be used, for example, to collect performance data. By performance data, we mean data to which a metric can be applied in order to ensure comparability. In our research area, these are, e.g. accuracy, error and time to completion [RSP11]. This means that during the experiment, we record data that we can later statistically analyse, i.e. the data are quantitative.

It should be mentioned in this context that experiments can also be combined with other methods, described above. For example, in almost all experiments presented in Chapter 4 and Chapter 5 both performance data and questionnaires have been used. With this methodology, both objective and subjective data about the experiment can be collected. Also, numerous related research presented in Chapter 2 make use of exactly this methodology. For instance, a combination of one or more experiments with a questionnaire is used in the evaluation of haptic user interfaces [KLS09], [LOM⁺11] as well as in the evaluation of other advanced user interfaces [NKW11].

There are several methods for conducting user studies. However, especially when evaluating physical devices, a usability test becomes important [LFH17]. According to Lazar:

> *Often, in usability testing, we're not researching the user, we're researching the interface. We're trying to figure out how to make a specific interface better.*

This quote from Lazar describes the situation quite well. Of course, there are pure human-centred usability studies, for example, when evaluating graphical user interfaces. Nonetheless, when researching physical prototypes, other questions arise, e.g. how can the prototype be improved to perform a specific task? Or how can the prototype be optimized for the used sensory channel? This can be applied to the understanding of interface failures introduced by Norman in Chapter 1 [Nor13], both the gulf of execution and of evaluation must be considered.

Caine shows that the assignment of an experiment to a particular category can often be ambiguous [Cai16]. According to the categories of Caine, an experiment includes within-, between-group and split-plot designs. Therefore, in this thesis, usability studies and experiments have been conducted.

3.8 Evaluating

After designing a new interface, creating a prototype and collecting the data through an experiment or a usability study, the evaluation procedure can begin. Evaluation is an essential issue for haptic devices, as it determines contribution, quality and novelty to a certain degree. As mainly quantitative data have been collected in all experiments conducted, the focus of this subsection is on the analysis of quantitative data. However, it also describes the methods used to evaluate qualitative data as well as psychophysical methods.

In order to identify a particular trend in quantitative data, basic statistical methods can be used. These include, for example, mean, median, mode, standard deviation, standard error of the mean and percentiles. This analysis is known as **descriptive statistics** [CW11]. As soon as conclusions are to be drawn, further methods have to be applied. Such methods are summarized under the term **inferential statistics** and allow to generalize results and test hypotheses. The main idea of these methods is to test research hypotheses [FH03]. Usually, hypotheses are specified through the research question(s) [LFH17]

Which method or statistical test can be used depends on some parameters. Consideration must be given to whether the samples are dependent or independent, the scale of the data, whether there is an underlying distribution or not and finally, whether correlations or tendencies are in focus. Since a within-group design was applied in all the studies conducted, there is a dependency within the individual studies. If a between-group design had been used, the groups would be independent, and a different test would have to be chosen [FH03]. There are three main scales of data: nominal, ordinal and interval scales. Nominal data have no order, ordinal data have an order, but the inter-distances between subsequent items are not equal. Interval data have an order and an equal inter-distances. The data collected in the studies are, in most cases, interval scaled [CW11]. For example, in Section 4.2 and Section 4.4, distances to a certain point were collected to estimate the error deviations.

A standard approach used in statistical testing is the introduction of a null hypothesis. The null hypothesis assumes that there has been no effect. In the next step, the probability of the null hypothesis is determined. If the probability is high, no effect has occurred, and the hypothesis is true. However, if the probability is low, the hypothesis that no effect was present is false, and it has to be rejected. This probability is referred to as p-value. There are several statistical methods to test hypotheses. Popular parametric tests are the analysis of variance (ANOVA) or the t-test [CW11]. ANOVA with repeated measurements has to be used when comparing more than two groups or items. In contrast, the t-test is used to compare pairs. Nonetheless, before testing for the null hypothesis, all data must be checked for normal distribution, as this influences the method to be used and is, therefore, a precondition. A popular test to check for the normal distribution is the Shapiro–Wilk test. Most standard statistical tools, such as R or Python, provide the necessary functions for this purpose. These two tools were used for the analysis in this thesis. If the data are not normally distributed, it is still possible to find a central tendency, i.e. a significant difference. The counterpart to the t-test for interval-scaled dependent data that are not normally distributed is the non-parametric Wilcoxon Signed Rank Test [FH03]. In both cases, parametric and non-parametric tests, it is common practice to speak of a statistically significant effect when the probability is less than 5%, in other words, $p < 0.05$ [FH03].

The previous paragraphs have dealt with the analysis and evaluation of quantitative data. The statistical methods presented were primarily used in all conducted studies. Nevertheless, qualitative data was also used, although relatively rarely. The qualitative analysis aims to transform the unstructured data found recorded from interviews and other sources into a detailed description [LFH17]. It is essential to consider the problem and context. In this thesis, the following methods were often used for data collected through pilot testing (see Section 4.2) or for the analysis of multimedia content (see Section 5.2). Qualitative analysis is an iterative process. The most important aspect is first to identify the key direction or aspects in the data. To get an overall picture, the identified items need to be compared with each other, which can help to find potential effects of different groups. Several methods can be found in [LFH17]. As mentioned above, it naturally takes less effort to analyses quantitative data, as there is usually a strict procedure and special tools for this. In contrast to the qualitative data analysis, it is obvious that the analysis requires more time and effort.

3.9 Validity and Reliability

All aspects discussed previously in this chapter influence the validity and reliability of research. The basic idea behind validity and reliability can best be explained using a figure (see Figure 3.6), for visualization a target is used [Bab15]. In the first case, the target is always hit at a similar position, which means that all answers are consistent, but have an error. If we now refer to the quality of research, it can be said that the research is reliable, but not valid. Looking at the second case, here, the target is hit everywhere with a similar distribution. The centre of the data is located in the centre of the target, i.e. a small amount gives the correct answer. Moreover, if you look at all the data points, the overall quantity of data is valid, but individual samples are not. This example shows that we have valid data, but it is not reliable. In the third case, both validity and reliability do not apply. The target is not hit with sufficient accuracy. There is a high degree of variability in the data, and the answers consistently miss the target. The fourth case now seems clear: the shooter has high accuracy, she/he hits the target with great accuracy.

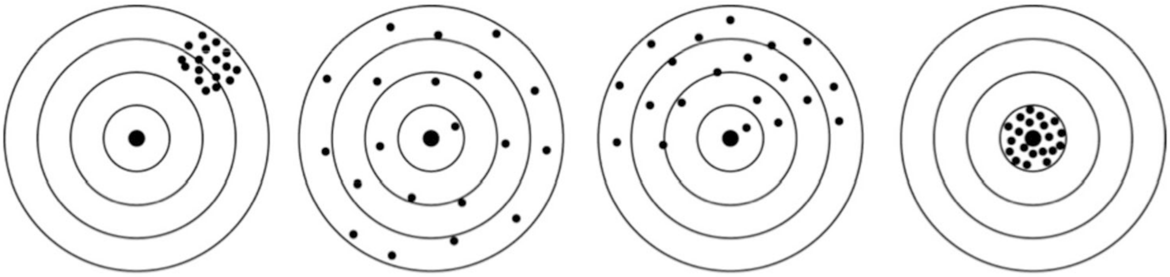


Figure 3.6: A metaphor showing the four cases to illustrate validity and reliability, adapted from [Bab15].

For the conducted studies that explore how the implemented interfaces affect the addressed issue, many factors have an influence, as already mentioned. In the first place, the designed and implemented prototype has to fulfil its purpose, Sutcliffe refers to this as requirements validation [Sut03]. In other words, if the feedback is ambiguous or not tangible or distinguishable, it will not be easy to fulfil the purpose, and of course, validity and reliability will suffer. Potential ambiguities can be improved through iterative design and pilot testing, which was also a standard method for the creating the haptic interfaces introduced in this thesis. Back to the metaphor from the beginning, when a shooter gets a bow with which it is impossible to hit the target consistently, his/her result will not be valid or reliable.

As described in Section 3.5, the experimental design has an impact on validity and reliability [FH03]. Perhaps the most prominent factor in a design that affects validity and reliability is the order of the conditions. If the chosen approach of the order of conditions is not described, different results may be obtained when the experiment is repeated. In the experiments presented in the three main chapters, either a counterbalanced or randomized approach was used. Another essential aspect to consider when designing an experiment, especially in our field of research, is the length of the experiment. Since most of the studies, we conducted involved cognitive as well as physical tasks; therefore, care must be taken that the participants are not fatigued [FH03]. This can lead to biased results. Further aspects of experimental design that can improve the quality of research are listed in Section 3.5.

Sampling and the associated population has a fundamental influence on the validity of the research. The research is only valid in the selected population. To evaluate the proposed haptic user interfaces, we have chosen a population from the university environment, as shown later. Further parameters that can influence the validity of research are according to Kumar [Kum10]: the method of data collection can be inaccurate (see Section 3.7), or the statistical data analysis (see Section 3.8) and subsequent conclusions can be incorrect.

In summary, the results obtained with our methodology are internally valid once all the methods have been performed correctly, and the requirements have been met. Examples that have to be considered or possible sources of error are described above. The key to achieving a high internal validity depends on the experimental design [FH03]. However, we cannot guarantee external validity; nonetheless, in the studies, that have bee conducted, we have used some methods that can improve external validity. Pilot studies have always been performed to find out initial trends that have been confirmed in the main experiments. Moreover, the pretest were used to adjust the levels of the conditions to ensure feasible experiments. Likewise, our questionnaires have also been pretest, to ensure that they are clear, unambiguous, and unbiased [LFH17].

Furthermore, we tried to improve the external validity with our sampling method. Therefore, we chose an age span of the participants between 20-50 years, as we intend to generalize our results for this group of persons. Moreover, in many of the studies that have been conducted, we have focused on haptic interfaces. Still, in doing so, we have always tried to create a level of independence from the interface so that it could be easily replaced. This, in turn, improves external validity in respect of different devices.

3.10 Ethics

Our studies are mainly concerned with haptic interaction. However, since we have conducted experiments with users, we have to address ethical aspects as well. All studies were conducted in the field of HCI, there was no risk of injury or harm to the participants. In addition, ethical approval for the study was obtained from the Ethics Department of the Brunel University. There are different ethical categories, and the type of studies we conducted were considered by the Ethics Committee to be classified in the low-risk category.

We respected the dignity of the participants at all times - before, during and after the studies. This implied that users were informed about the study in detail. We also informed the participants prior to the study that they could quit the study at any time without consequences. Participation in each study was voluntary, and no money was paid for participation.

Before the study, users were informed about the above points in a consent. After the study, a debriefing took place. It was specifically reiterated that if concerns arise after the study, participants could contact a representative to discuss their concerns.

In summary, this chapter has given an overview of the research methods used in this research. A methodology was presented, which has been applied to research and develop our haptic interfaces: Chapter 4 and Chapter 5. It was also shown which methods were used to develop new prototypes and how to perform user studies. Finally, the variety of data collection methods and their analysis was presented.

Chapter 4

Haptic Interfaces for Touchscreens

4.1 Introduction

The augmentation of mobile touchscreens to explore the versatile of haptic feedback is examined in this chapter. Therefore, we present three prototypes, all of which provide haptic feedback using an individual approach. While most of the smaller touchscreens already support tactile feedback generated by small vibration motors [FS01], we want to present further potentials for haptic feedback. These include perceptual issues, but also performance and, to a certain extent, user experience in using these interfaces.

Specifically, this chapter is dedicated to the first research question. All three prototypes will highlight the versatility of haptic feedback and introduce novel interfaces. Each interface will address a sub-questions that will contribute in answering RQ1 defined in Section 2.3:

> **How can touchscreens be augmented to provide haptic feedback that goes beyond tactile sensations?**

In Section 2.3.1, it was shown that there are still many possibilities to develop haptic feedback for touchscreens. However, all smartphones are almost all equipped with tactile feedback, so haptic feedback is actually available. However, RQ1 aims to explore further perspectives and explore novel questions. Besides adding haptic feedback the focus in this chapter is on touchscreen interaction. In the last decade, touchscreen interfaces have become popular, enabling a wide variety of applications through established interaction styles. These interaction styles afford finger or pen-based interaction with a multitude of graphical user interface (GUI) elements. Often, interaction is aided by audio and simple vibrotactile cues, which has been shown to improve interaction [KSL+13]. While apt for many applications, interest is also growing to explore other directions, including haptic feedback. However, in particular, the combination of haptics and touchscreen interaction has not been widely studied and is still challenging. For example, sensing the shape of an underlying geometry like a button is still hard to implement.

The structure of this chapter is as follows. Firstly, the three prototypes are introduced and connected to a sub-question. Then, each prototype is considered individually, which means that in each section we present: the implementation, the procedure of the particular experiments, the results and potential application scenarios. Finally, the results are then discussed, and in a summary section, all prototypes are considered from an overarching perspective.

This chapter aims to design and evaluate novel haptic interfaces for touchscreens (Aim 1). Therefore, our objectives are coupled to the sub-questions in order to pursue three clearly different approaches. Using the first prototype seeks *to establish the limitations of force feedback provided through an actuated rigid screen* (RQ1.1). On the one hand, enhancing touchscreen interfaces with non-visual cues has been shown to improve performance [BCB07]. On the other hand, similar actuated haptic interfaces focus on realising and developing an actuated screen interface [KHSK14], but only barely show the limitations or possibilities of perception [HTE+17]. TouchMover, a large actuated stereoscopic display, explores the perception of shapes but it misses the connection to a small horizontal touchscreens [SPB14]. ForceTab, our prototype based on a force-sensitive motion-platform enhanced interface to improve multi-modal interaction based on haptic (force feedback) instead of tactile feedback is introduced in Section 4.2. Extending mobile touchscreens with force-sensitive haptic feedback can enhance performance interacting with GUIs and improve the perception of visual information. In this respect, a user study was performed to determine the haptic perception of different 3D shapes and the perception of different heights. Furthermore, two application scenarios are proposed to explore our proposed haptic user interface.

While ForceTab actuated the entire touchscreen, our second prototype focuses on the interaction above a display and how an elastic material can be used for this purpose. By doing this, a novel haptic feedback sensation is designed *that explores the combination of elastic material and haptic feedback* (RQ1.2). Motivated by the interaction with elastic materials [PGG+12] and the interaction above a display [HBH+16], FleXurface was implemented. Furthermore, it includes a novel approach to provide haptic interaction with a pen. The prototype provides a multilayer interaction approach that enables state transitions between spatially above-screen and 2D on-screen feedback layers (see Section 4.3). Our approach supports the exploration of haptic features that are hard to simulate using rigid 2D screens. We accomplish this by adding a haptic layer above the screen that can be actuated and interacted with (pressed on) while the user interacts with on-screen content using pen input. The haptic layer provides variable firmness and contour feedback, while its membrane functionality affords additional tactile cues like texture feedback. Through a user studies, we look at how users can use the layer in haptic exploration tasks, showing that users can discriminate well between different firmness levels.

Both introduced prototypes explore haptic feedback of tab-sized screens, however, they can hardly be considered as mobile systems. Within our third prototype we aim to extend the variety of approaches and show *how force or pin-based feedback can be combined with a small mobile touchscreen* (RQ1.3). Therefore, we want to introduce a further prototype. HapticPhone is a back-of-the-device haptic feedback approach for smartphones (see Section 4.4). Since touchscreen interaction suffers from occlusion problems as fingers can cover small targets [CDVB17], this makes interacting with small targets challenging. To improve touchscreen interaction accuracy and consequently the selection of small or hidden objects we developed HapticPhone. The proposed approach combines force feedback from the back to enhance touch input on the front screen. The interface consists of three actuated pins at the back of a smartphone. A psychophysical study shows the differentiability of haptic events, which were used in a second study to improve touch accuracy.

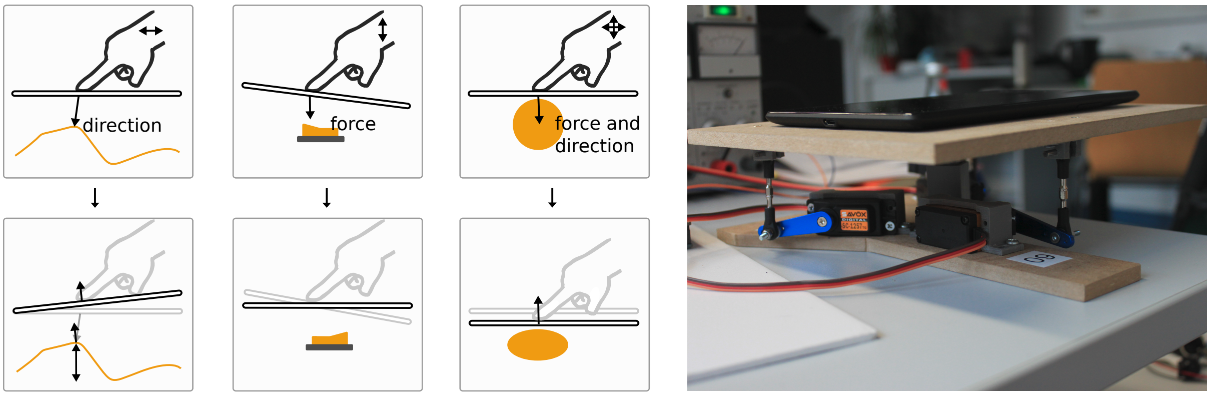


Figure 4.1: Potential scenarios feasible with ForceTab, reaching from simple touch input and force input to up a combination of both (left). A photo of one of the first versions of the presented tablet (right).

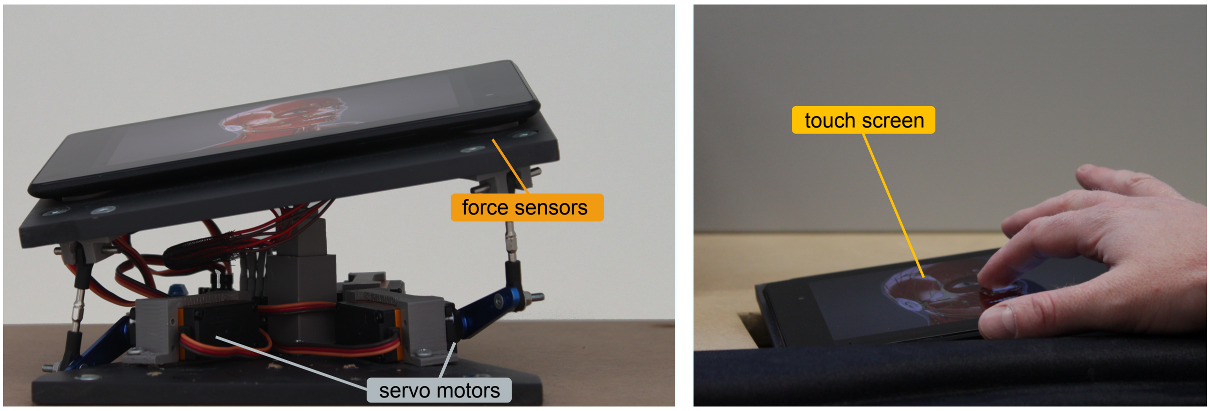


Figure 4.2: Shows the hardware prototype: the force actuated touchscreen lowered into a table (right). The platform is driven using 3 high speed servos and 4 force resistance sensors mounted underneath the tablet (left)

4.2 Haptic Feedback through an Actuated Touchscreen

ForceTab is the first prototype that explores the versatility of haptic cues in touchscreen interaction (see Figure 4.1). The interface deploys a motion-platform enhanced tablet interface that has been extended with pressure sensors to sense finger pressure (see Figure 4.2). While related systems without pressure sensing exist, an in-depth analysis of actuated tablet interaction techniques, with and without pressure support, is lacking. We present and validate a refined set of feedback mechanisms tailored to such systems.

In contrast to previously mentioned 1DoF movements [SPB14], our approach also supports inclination, according to the position and the underlying geometry. Since most available touchscreens are capacitive, capturing finger pressure without additional sensors is challenging or even impossible [HL13]. ForceTab presents the potential of visuo-haptic devices by exploring the detection rate of different, static and dynamic, 3D geometries. To do so, we introduce a velocity guided detection approach, to determine a relationship between velocity, shapes and detection. Through a set of user studies, we report on both the low-level potential and limitations of the feedback methods to elicit shapes. The studies were mainly conducted to answer the Research Question 1 raised in Section 2.3.1. We are interested in the resolution of perceived shapes and how exactly an individual peak can be identified. In Section 4.2.3, it is additionally shown how visuo-haptic feedback can be deployed through two application scenarios.

4.2.1 Implementation

This subsection provides an overview of the hard- and software components that have been used setting up ForceTab. However, beforehand, Figure 4.3 illustrates how the interaction concept is designed: there is a sensor unit, which is responsible for user inputs, and an actuation unit, which controls specific feedback. Additionally, all associated components and relationships are depicted in Figure 4.3.

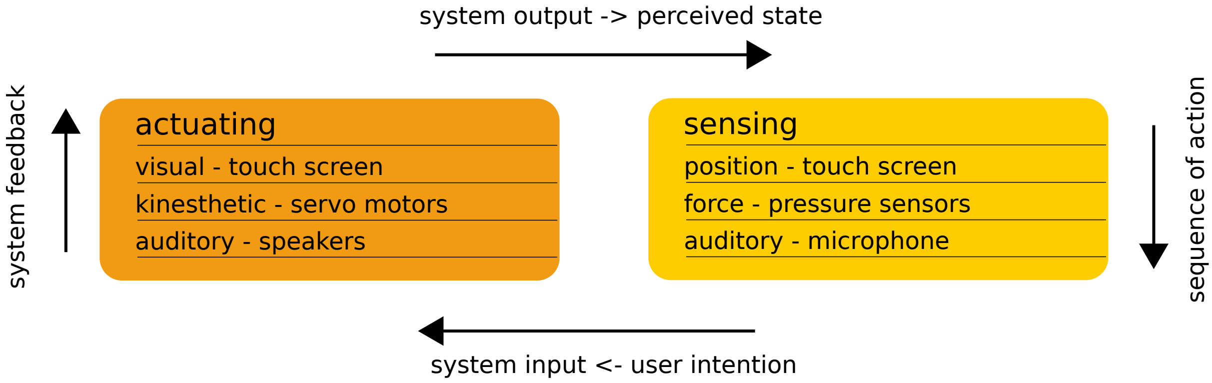


Figure 4.3: The interactions principle: from user intention through system feedback to a state perceived by the user, inspired by the seven stages of action from Norman [Nor13].

Hardware

ForceTab comprises of a motion-platform driven by three high-speed digital servos (Savox SC-1257) and four force resistance sensors (Interlink 402). This provides a 3DoF and a low latency feedback system combined with a touch-sensitive display for user interaction. It enables constrained haptic feedback with screen content and supports 3D touch events. The servo motors are arranged in an equilateral triangle with a side length of 150 mm and connected to the platform using ball heads. They are operated at 6 V using an external power supply, affording movement of 60° in 0.07 s, enabling the platform at high speed (average system response is 75 ms).

The platform is made of medium-density fibreboard and measures 200 mm in length and 170mm. Four Force-Resistance Sensors (FSR) are used to sense force and touch sensitivity at each corner on the top of the fibreboard. Each FSR can detect applied forces in the range of 100g-10kg. ForceTab uses an Android tablet (Asus Nexus 7), with a 7 inch touchscreen, as primary display device. All low level introduced hardware components (servo motors and FSR) are connected to a micro-controller (Arduino Uno), that controls the servo motors and receives force events. The system is driven by a conventional desktop computer running a Linux system (Debian). Our prototype is designed in a way that with minor modifications, any Android smartphone or tablet can be used with the platform. Therefore we have developed a dynamic holder for the platform, which can easily be printed in 3D.

Software

A desktop computer (manager) handles time-consuming tasks and the communication between our touchscreen and the micro-controller. It receives touch events over Wi-Fi (from the tablet) and forces events over USB (from the micro-controller). To adjust the servo motors, signals (pulse-width modulation) are sent back to the micro-controller. A ray-based approach estimates the position of the platform. More precisely, a ray is cast into a 3D scene at the location of the finger using a virtual orthographic camera model. This 3D scene can be seen as representative for the 2D scene display on the touchscreen. If there is an intersection between ray and geometry, the position and the normal at the intersection can be calculated.

In a final step, we map the estimated normal to our platform. The position of each servo is determined using forward kinematics. Inclination mapping of the platform is a culling process, meaning that angles which are larger or smaller will be mapped either to the maximum or minimum inclination. ForceTab can map heights up to 32 mm and an inclination up to 14°, according to the fingers position and the underlying geometry. To simplify height computation, all scenes are pre-processed by scaling them to a specific height. This height corresponds to the height constraints of the platform.

Force input is computed using a distance-weighted function to linearly interpolate over all four force sensors. To calibrate the force sensors, all force values are requested whenever there is no touch event and thus no motion event, so that these values are considered as a new initial point. Normalizing the values within a logarithmic scale enables us to precisely capture pressure events.

Our implementation supports a velocity guided mechanism to enforce users to interact within a pre-defined velocity range. To do this, users were asked to follow a animated visual disc with their fingers. This mechanism increases the controllability of the experiment and, as introduced in Section 3.3, the levels of the condition can be specified more precisely. Thus, disruptive factors can be excluded and the data is less noisy. The system can adjust the velocity of an object on both touchscreen and desktop screen. This is realized using a one to one mapping from the touchscreen to the main screen. Through the described configuration of hardware and implementation, ForceTab is able to support 3DoF haptic interaction, namely movement in upwards and downwards (height) as well as roll and pitch (gradient). In the following user study, we focus on how this feedback can be employed.

4.2.2 Experiment - Low Level Perception

This study was designed to show the possibilities as well as the limitations of the implemented haptic interface (see overview in Figure 4.4). It falls into the category of a lower-level exploratory perception study. For this purpose, three different characteristics are investigated: combination of resistance levels (pressure sensitivity) and force feedback, the perception of geometric shapes and the differentiation of heights. The aim is to determine a perceptual resolution of geometric shapes. What can users be perceived with this haptic feedback approach? In the following it will be referred to as force, horizontal and vertical resolution.

The force study has been conducted to test five hypotheses:

H1: Haptic feedback will help users to differentiate three resistance levels.

While for the horizontal resolution study it was assumed that the geometric shapes are perceivable and it was hypothesized that:

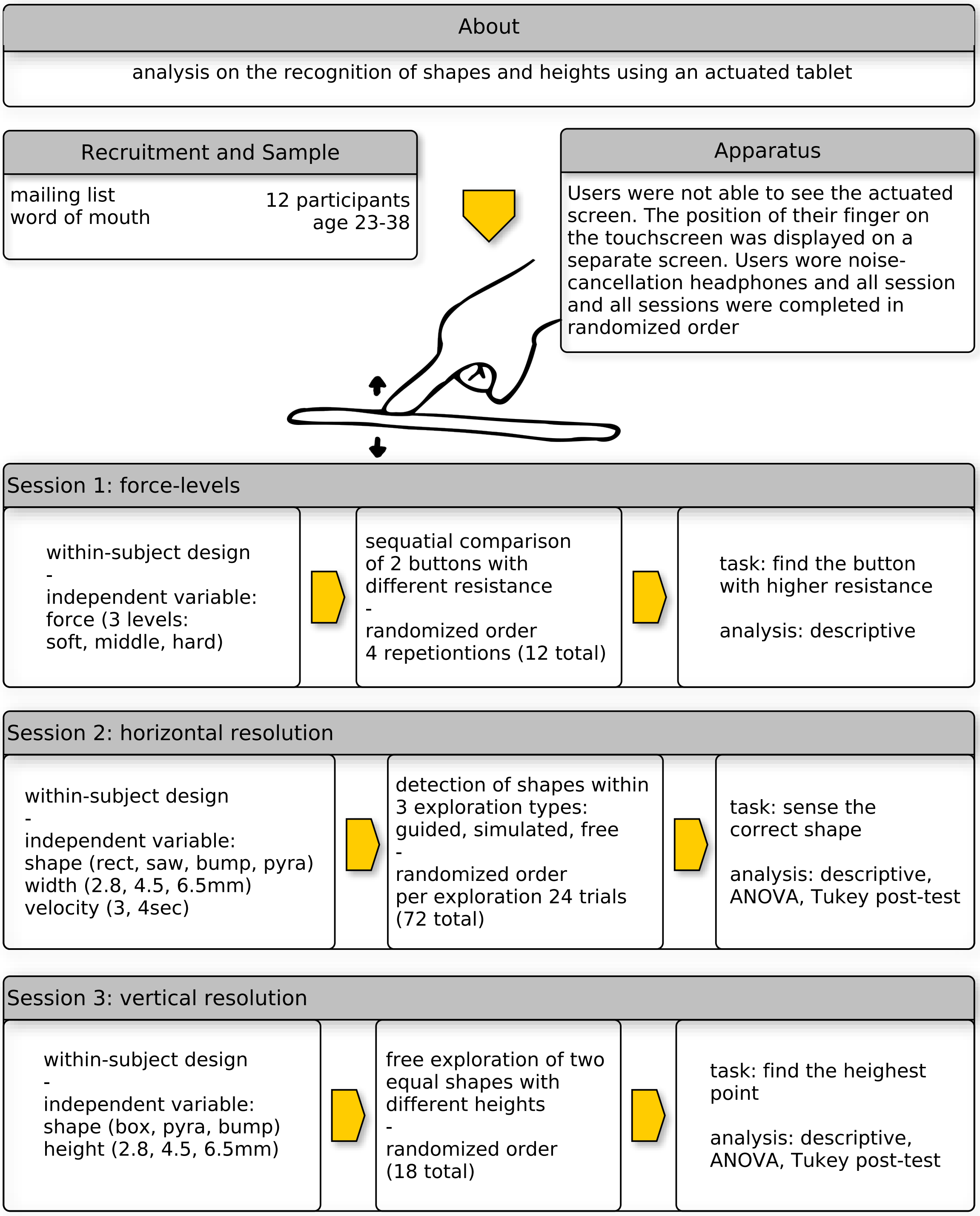
H2: Geometric shapes can be best perceived with free exploration.

H3: Larger shapes (a) and slower movements (b) help to perceive the geometric shapes better.

Finally, the following hypotheses will help to explore the vertical resolution of the haptic interface:

H4 Smaller differences in height will be more difficult to perceive.

H5 The tip of a pyramid can be better localized than that of a Gaussian shape.



About

analysis on the recognition of shapes and heights using an actuated tablet

Recruitment and Sample

mailing list
word of mouth

12 participants
age 23-38

Apparatus

Users were not able to see the actuated screen. The position of their finger on the touchscreen was displayed on a separate screen. Users wore noise-cancellation headphones and all session and all sessions were completed in randomized order

Session 1: force-levels

within-subject design
-
independent variable:
force (3 levels:
soft, middle, hard)

sequatial comparison
of 2 buttons with
different resistance
-
randomized order
4 repetiontions (12 total)

task: find the button
with higher resistance

analysis: descriptive

Session 2: horizontal resolution

within-subject design
-
independent variable:
shape (rect, saw, bump, pyra)
width (2.8, 4.5, 6.5mm)
velocity (3, 4sec)

detection of shapes within
3 exploration types:
guided, simulated, free
-
randomized order
per exploration 24 trials
(72 total)

task: sense the
correct shape

analysis: descriptive,
ANOVA, Tukey post-test

Session 3: vertical resolution

within-subject design
-
independent variable:
shape (box, pyra, bump)
height (2.8, 4.5, 6.5mm)

free exploration of two
equal shapes with
different heights
-
randomized order
(18 total)

task: find the heighest
point

analysis: descriptive,
ANOVA, Tukey post-test

Figure 4.4: A schematic overview of the study conducted. The diagram shows the three sessions for determining force, horizontal and vertical resolution.

Participants

This user study was performed as a within-subjects study in which 12 participants took part (age 23-38, 3 female, 9 male). All participants took part in the study voluntarily. No funds were paid for participation. Furthermore, all participants were informed prior to the experiment that they can stop the study at any time without consequences.

Apparatus

Participants were seated and wore noise cancellation headphones, to block sound patterns from the servos that could provide unwanted cues. In order to exclude visual cues a wooden panel was placed between the tablet and the user, so users could not see the interaction device actuation (eyes-off). ForceTab was integrated into a table so that the display was at the same height as the table surface (see Figure 4.2). The users were asked to rest their palm onto an ergonomic wrist pad. Using this pose, users would receive feedback primarily over the finger. This avoided potential bias when the hand would need to be held in mid-air, where feedback would be partly perceived over the wrist-arm lever system too.

So that users knew where their finger was on the tablet (which was not visible to the users), the position of the finger - the touch event - was mapped on a separate (desktop) screen visible to the user. A circle was used to indicate the finger position. In order to validate the detection rate, users were prompted to select the perceived shape or force value displayed on the desktop monitor after each condition.

We conducted a pilot study to reduce the number of conditions and thus exclude any influence on fatigue on the results. In the pilot study we investigated whether it makes a difference if perceived shapes are convex or concave. Six users validated the potential of rectangular concave and convex shapes. As a result, both shapes had a similar error and detection rate: Users detected concave shapes with 85% accuracy versus convex shapes with 82%. So convexity or concavity does not seem to be a difference in the detection rate. Subsequently in the main study we concentrated on the only one convex shapes. In the following, the term resolution refers to the detail (size and shape) of a single convex shape that can be perceived by the user.

Design and Procedure

Force In the first part of the study, users were asked to differentiate between two squares, each square representing a resistance level. As already mentioned, there were three levels: sensitive, middle, hard. The three levels were found to be differentiable through a pilot study. When a user exceeded the resistance criterion, a mechanism was triggered; the touchscreen moved 10 mm downwards and back to the starting position within 750 ms. The idea behind this study is to find out how well the participants can distinguish between the levels. Each participant completed 12 trials in a randomized order. To estimate the three pressure levels, we asked participants to press two squares (randomly paired levels) sequentially. To avoid possible cues, the study was conducted eyes-off. Therefore, finger position and the two squares were shown on a separate screen. A 2AFC response paradigm was used, which means there was always a unique solution, and users were asked to select the square with higher resistance.

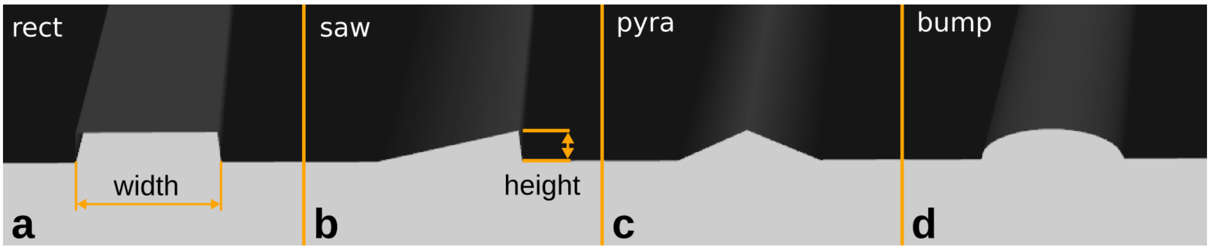


Figure 4.5: Depicts the 4 patterns used for estimation horizontal resolution (a) rectangular (rect), (b) saw, (c) triangular (pyra) and (d) semi-ellipse (bump) shape).

Horizontal resolution The second part of the study focused on the perceived level of detail in the horizontal direction, and employed a 3 x 4 x 3 x 2 factorial design. It deployed the factorial combination of 3 exploration types (guided finger movement, simulated patterns and free exploration), 4 shapes (see Figure 4.5), 3 widths (35px $\hat{=}$ 2.8mm, 57.5 $\hat{=}$ 4.5mm, 80px $\hat{=}$ 6.5mm) and 2 velocities (3 sec and 4 sec per trial). To avoid a constant change between the configurations we have decided to group all trials according to the exploration types. Thus, each participant completed 3 x 24 trials in randomized order. We specifically chose these geometric shapes because they represent a wide spectrum. In this way, symmetrical, asymmetrical, rectangular and round shapes could be tested, while keeping the number of shapes and the length of the study manageable to avoid fatigue.

Within **guided** finger movement, users were asked to follow a straight line from left to right with a specified velocity. This velocity was visualized on the separate screen using a circle. Users were asked to follow the circle, and their finger was displayed as a second circle to provide a reference frame. In the middle of the guided path, the shapes with the described parameters appeared.

Instead of moving the finger over the touchscreen, in the **simulated** mode the feedback passes underneath the fingertip (like a wave), while the finger is held at the same position. To activate the system the user has to move her/his finger onto a predefined rectangle at the centre of the screen. The rectangle changed colour to indicate the user that a shape would appear.

Finally, since the previous exploration types were based on a specific velocity a third type was added. Within this exploration type the users were asked to **freely** explore the shapes for 5 seconds. After each condition users had to select the perceived pattern. For this purpose all patterns were displayed on the separate screen and users could select the perceived one.

Vertical resolution The last session of the low level perception study looked at the estimation of the perceived vertical resolution, and employed a 4 x 3 factorial design, using the factors: 4 elevations (varying between 3mm, 5mm, 7mm, 9mm) and 3 shapes (diameter/side length 35mm, a box shape, a pyramid shape and a bump (Gaussian) shape). No equal heights were allowed, ensuring that there was always a unique solution. Each user completed 18 trials in randomized order. In contrast to our prior study we enabled inclination, as we wanted to investigate whether this had an influence on finding the tip of a pyramid or a Gaussian shape.

Users were asked to find the highest point on the tablet. Again, a circular shape on the second screen indicated the finger position on the tablet while no additional information was displayed. In each trial, two elevations with different heights but same shape were mapped on the tablet with a random position but no overlaps - equal heights were not allowed. When the user has found a maximum, he/she can submit the position of the finger by pressing the space bar the distance to each maximum local and global was recorded. After that, similar to the previous study, users are invited to select the shape on the screen.

Results

Force All users could differentiate between all three levels correctly, which means that the detection rate of the three force levels was 100%. Hypothesis (H1) can be considered true. The 12 users always chose the correct square. This also reflects the consistency of our system. This further enables the system to response discrete to each level, for instance, a button with three states. Looking further, ForceTab is also able to map continuous force input to height, for example, navigating through a hierarchy using three velocities.

	rect	saw	bump	pyra
rect	81%	11%	0%	8%
saw	7%	80%	4%	11%
bump	9%	9%	35%	44%
pyra	3%	0%	61%	35%

Table 4.1: Detection rate and error rate of the 4 shapes. Orange cells depict the detection rate of the considered shape, additionally each column depicts the falsely detected shapes. The table indicates the confound of pyra and bump shapes.

Horizonal resolution Table 4.1 shows the overall detection rate over all trials and indicates that rectangular (rect) and saw shapes were detected very well (81% and 80%). However, semi-ellipse (bump) and triangular (pyra) shapes were detected poorly (35% and 35%). This is due to users tending to confuse semi-ellipse and triangular shapes. It was therefore not correct to assume that all shapes are perceptible.

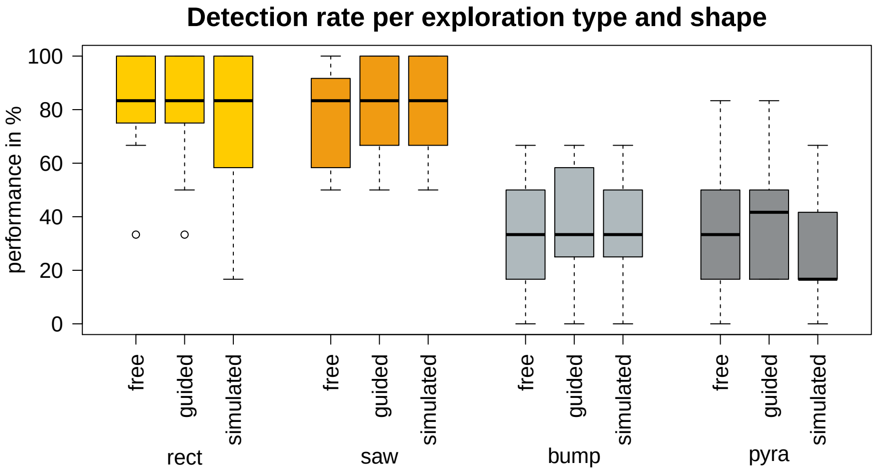


Figure 4.6: Overall detection rate of the three exploration types (free, guided and simulated). The graph shows the difference in detection rate including both velocities. The shapes that were confused have been marked in grey.

Figure 4.6 illustrates the confusion of pyra and bump-like shapes in a further way. The figure contrasts the relationship between exploration types and the four shapes in terms of detection rate. To clarify the difference between the shapes, an ANOVA was performed, which highlighted that a significant difference indeed exists ($F(3, 140) = 56.66, p < 0.001$).

Post hoc analyses were done with Tukey's HSD test and showed that there is a difference between all pairs except rect-saw and bump-pyra. Since the confusion of bump and pyra shapes affects the influence of the exploration types, they were left out of our analysis. Hypothesis H2, the users can perceive geometric shapes better when they have the opportunity to explore them freely must be rejected. A significance analysis showed that the way of exploring does not influence the detection rate.

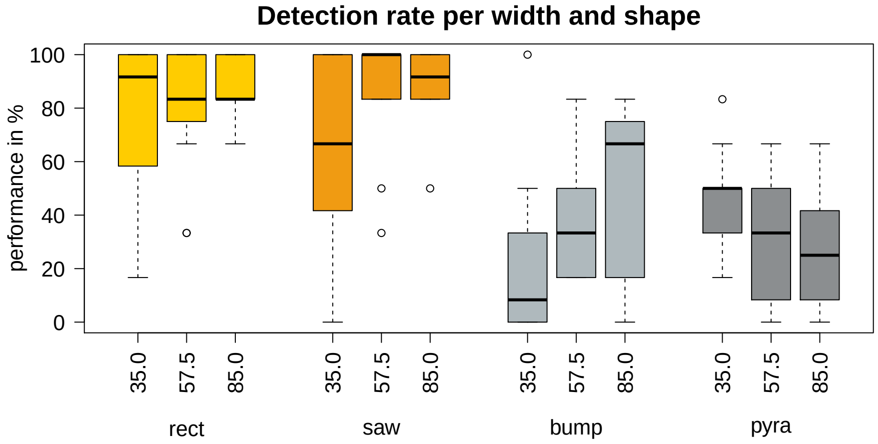


Figure 4.7: Box plots showing the detection rate per width (35px, 57.5px, 80px) for each shape and overall interaction metaphors.

Furthermore, the width of the shapes was examined. Figure 4.7 compares the detection rate of the different shapes at the three widths. Since bump and pyra shapes would again bias the results here, they have been omitted in the analysis of the width. For the analysis, all the same widths of rect and saw shapes were combined. So we only investigate the impact of the width, independent of the shape, on the detection rate. ANOVA showed a significant difference between the three widths ($F(2, 69) = 3.3, p < 0.05$). A post-hoc analysis using the Tukey HSD indicates that there is a significant difference between 35px and 85px (p<0.05). Part a of the third hypothesis (H3) can therefore be accepted, the size of the geometric shape has an influence on the detection rate; the larger the shape, the better it can be detected.

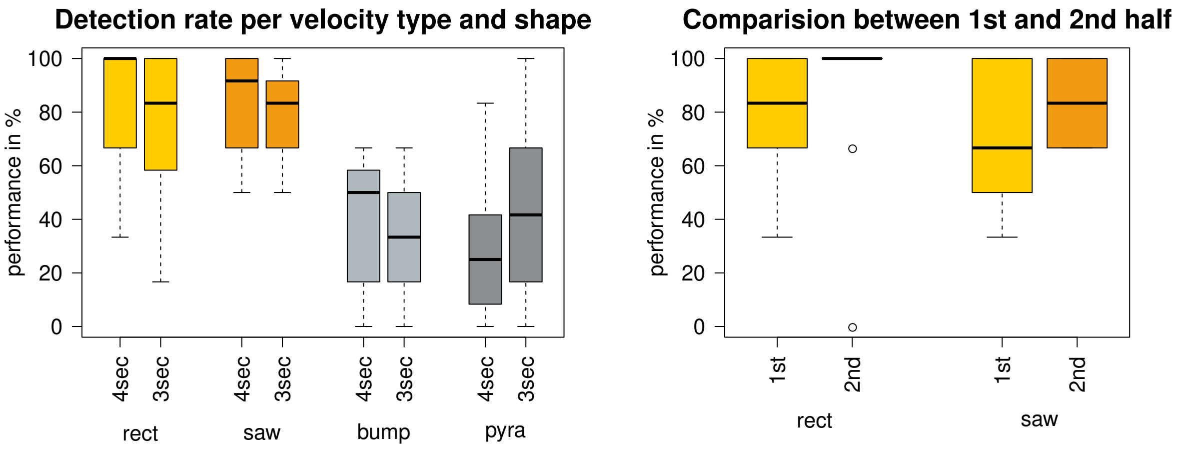


Figure 4.8: Detection rate at different velocities (left) and the learning rate comparing first and second half of the free exploration method.

The results show that the faster, the less accurate the users were - as expected. Although the detection rate at the faster velocities was on average 12% worse, a significance analysis could not detect any statistical differences (see Figure 4.8, left). Thus, it can be concluded that a trend has been identified, but to fully accept part b of H3 further research is needed.

In addition, there is a learning effect, as users detected rect and saw shapes in the second free exploration with a 12 % higher accuracy compared to the first free exploration (see Figure 4.8, right). Due to the confused recognition of bump and pyra shapes the performance and learning effect analysis is not indicative. It only shows that within the given interaction metaphors and velocity users can differentiate between 3 different shapes.

The study of perceived horizontal resolution showed several important outcomes. Firstly, the impact of the shapes' properties, like form, are an essential issue when estimating the perceived detail and especially designing applications for ForceTab and similar devices. Distinct properties, such as strong discontinuity, can be accurately recognized by almost all users. Participants reported they are able to observe particular properties in the shapes, whereas similar shapes with no unique features are hard to distinguish.

Secondly, there is a correlation between velocity and width, showing that shapes with a width smaller than 57.5px ($\hat{=}$ 4.5mm) are not feasible for finger interaction. To increase the detection rate we would recommend an even larger width (80px $\hat{=}$ 6.5mm).

Lastly, as users habitually interact with touchscreens in a visual guided way - meaning that visual elements are the main factor controlling finger position and velocity - users have to adapt to the novel interaction properties. This means that when adding haptic cues to touchscreens users should be motivated to adapt finger velocity to the underlying geometry (fine shapes require slow movements and coarse shapes allow faster movements). A finger velocity of around 0.025 $\frac{m}{s}$ evidenced good results for the proposed scenarios.

Vertical resolution Users were able to find the global maximum with an accuracy of 87%, which indicates that even small differences could be perceived by the users. Looking closer to the relative differences in heights (2mm, 4mm and 6mm), on average users were able to find the global maximum with an accuracy of 78%, 90% and 90% for each height, respectively. Smaller differences in height are therefore more difficult to perceive (H4).

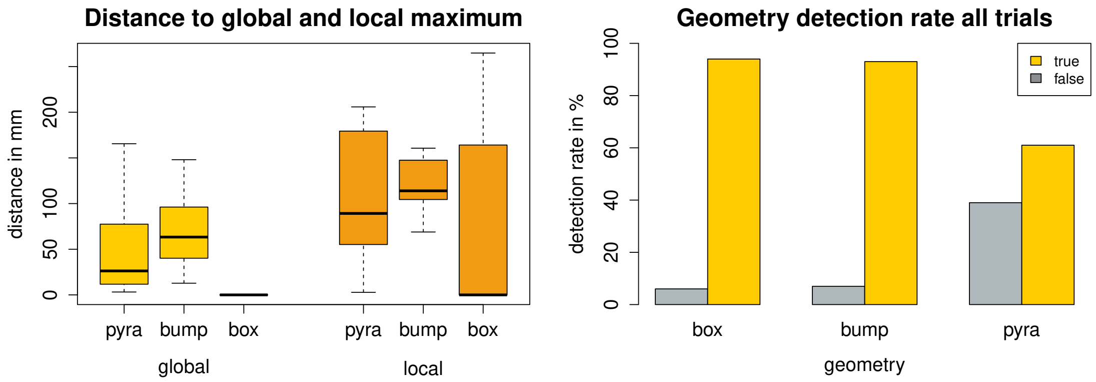


Figure 4.9: Distance to the global and local maximum for each shape (left). Detection rate of the global maximum shape is depicted in the bar plot (right).

Boxes were either found or not, but for pyramids and bumps we can clearly determine the distance to the maximum. Figure 4.9 depicts this distance to the global and local maximum grouped by the three shapes. Figure 4.9 on the left shows that the global maximum was found with a lower error. A significance analysis shows that the global maximum was found significantly more accurate ($F(1, 214) = 11.4, p < 0.001$). The median distance to the global maximum for pyramid shapes was 2mm and for bump shapes 4.8mm. The maximum of the pyramidal shape was felt significantly more accurately than bump-like shapes ($F(1, 214), p < 0.01$). H5 is true, the tip of a pyramid can be localized more precisely than that of a Gaussian shape. We assume that this has to do with the sharp tip of the pyramid compared to the blurred top of the Gaussian shape. Furthermore, Figure 4.9 shows the detection rate of the three shapes, which was high for most but not all shapes (box 94%, bump 93% and pyramid 61%).

4.2.3 Application Scenarios

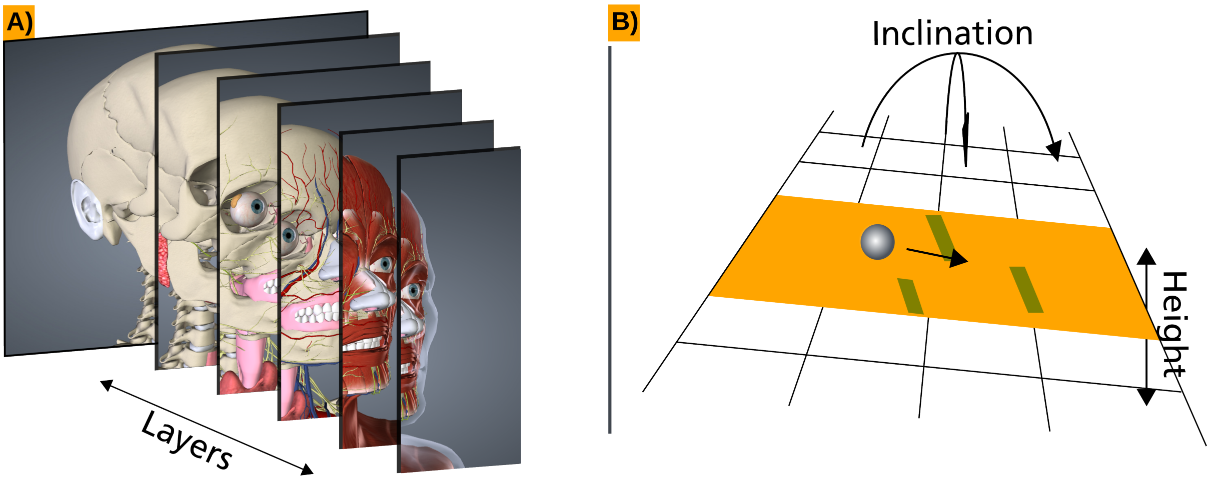


Figure 4.10: Depicts two possible application scenarios. A layered image stack of a anatomy data set (left) and a physical plane with gravity (right).

Lastly, we combined pressure, position and visual feedback within two different application scenarios (see Figure 4.10). In the **level of detail viewer** scenario, we visualized a layered image stack of an anatomy data set. This dataset was chosen because we believe that our interface is well suited for educational use because visual content is combined with physical movements. Users would be able to better memorise learning content, which of course needs to be proved. Furthermore, we chose this dataset because the different levels are very clear in this dataset. The position/height of the tablet indicated the different layers. From the muscles, over veins to the skeleton, all levels were accessible through different finger pressure. In addition to the vertical layers, each layer could also be accessed individually for additional layer information. As such, the system employed 2 dimensions of information, one in vertical direction (layered data) and the other around the pitch axis (additional information). In the **physical interaction plane** scenario the tablet acted like a physical plane. Based on the angle of inclination, the elements displayed on the tablet moved to the deepest point of the plane, based on the friction and gravity parameter of each object. Small obstacles were integrated to show collision detection. We designed two interaction metaphors to access either different levels of detail (first scenario) or to manipulate the physical plane (second scenario). A force-based metaphor (finger pressure) and a position based metaphor (finger position) was implemented to control the touchscreens position.

Users explored each scenario for at least 90 seconds. Thereafter, the users were asked to answer a set of questions (7 point Likert scale, ranging strongly disagree (-3) to strongly agree (3), see Questionnaire 1). Users rated state based feedback well in both the layered image viewer $M = 2.6/SD = 1.2$) and physical plane ($M = 1.8/SD = 0.7$). In addition, the novel force based metaphors ($M = 2.8/SD = 1.4$) gained almost the same result as position based metaphors ($M = 2.7/SD = 1.6$). The overall satisfaction with the system was rated with ($M = 2.2/SD = 1.1$).

4.2.4 Discussion

The results show that the proposed interface is able to generate different heights/elevations and resistance levels that can be perceived well by the users. To answer RQ1 (stated in Section 2.3.1) we conducted a user study with three different sessions to determine force, horizontal and vertical resolution. As expected, users have more difficulties differentiating between smaller differences than with larger ones. We have additionally shown that confusion can occur with smaller shapes, especially if they are similar. Moreover, we have examined four shapes with different widths, for unique shapes we found that if the shape has a width larger than 4.5mm users were able to perceive them robust within our device.

As the top of pyramid shapes was detected more precisely than the top of bump shapes, we expected that the detection rate of pyramid shapes should be equally or even higher compared than the other two shapes: we thought a user might draw conclusions from the shapes top, which was actually not the case. However, finding the top of pyramids was underlined by feeling a peak at the maximum. Pyramids were often perceived as bumps (34%) but not the other way round (4%). However, in general users commented that inclination of the actuated platform helped to detect the shapes.

With regard to the sub-question (What are the limitations of force feedback provided through a rigid screen?), it can be concluded that complex geometric shapes cannot be represented, as the discrimination of simple geometric shapes has partially failed. Which is in accordance with previous system [SPB13]. Looking at the detection of shapes, haptic feedback could conceivably support visual feedback. In contrast, to locate different locations of the touchscreen, the proposed approach is well suited. Users could find the maximum well regardless of the geometric shape. In this case, pure haptic feedback is sufficient. In combination with the presented resistance levels, the proposed approach would be ideal for the use of realistic buttons.

4.2.5 Conclusion

Within this section we looked into the pressure levels, as well as vertical and horizontal resolution users can perceive while using our actuated platform. This understanding is crucial to design and develop real applications scenarios. Interacting with mobile actuated displays is new to almost all users. In our results, we identified system constraints as depicted by the boundaries of the system feedback, while also highlighting user's perceptual capabilities in frame of the provided feedback range. While not necessary for many GUI element interactions, as a next step it would still be beneficial to perform a just-noticeable difference experiment to further study finer-grained feedback levels.

We presented results of feasible mappings that need to be adjusted to particular applications. Our results create an understanding of the possibility and limitations of comparable platforms such as presented by Kim et al. [KHSK14]. The system by Sinclair et al. [SPB14] showed a better detection rate in 1-DOF, but in comparison to our study, users were able to see the visual display device which strongly supports the identification of shapes.

Another novel aspect is the introduced force-sensing method. An actuated force-sensitive visuo-haptic platform can enable a set of novel application scenarios and interaction metaphors, which we partly explored in the application section. For instance, in education ForceTab can enhance knowledge transfer: data can become "tangible" to support users to understand relations and conditions better. Based on users' feedback, we will extend ForceTab to a broader range of multimodal feedback, in particular vibrotactile and audio feedback. Both can help to further enhance perceptual issues of mapped geometry. For example, tactile and audio cues might enhance the perception of edges and borders, which is an issue of the current system. Since we analysed perceived resolution and proposed two scenarios of state based interaction, in the future we would like to focus on the third feasible interaction component: continuous tracking of force and position to explore additional object properties, like stiffness and surface texture.

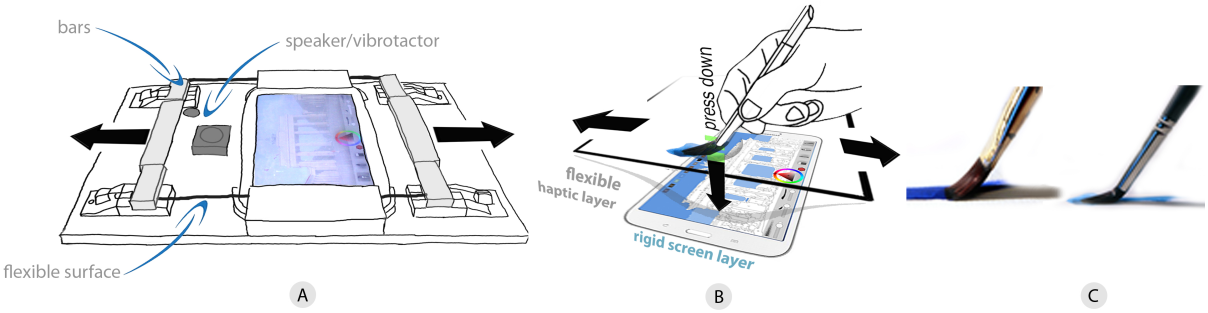


Figure 4.11: Our multilayer system consists of a stretchable flexible surface above a tablet display. (A) The bars (light grey) stretch the flexible surface to change its haptic properties, which can be further augmented through vibration (dark grey: speaker, vibration motor). (B) The user can press down on the flexible surface to explore the haptic properties. (C) This enables the simulation of, e.g., different brushes and paper surfaces.

4.3 Elastic Feedback above a Touchscreen

In our daily lives we frequently explore different kinds of haptic properties. In the previous subsection (see Section 4.2) we investigated how such properties could be reproduced and perceived by a user through a rigid screen. The limitations and benefits in using a rigid screen have been clearly shown.

Research in this area includes considering several properties that can be perceived through our sense of touch, including kinaesthetic and tactile cues such as texture, firmness, temperature, weight, enclosure and contours [LK09]. While interacting in the real world, we experience haptic features that are constrained by a surface. However, we also explore features more spatially. For example, we pass our fingers over the contour of an object or experience the spring force of a flexible tool (e.g. a brush) (see Figure 4.11).

In general, haptic rendering can be very useful for certain applications (see Section 2.2.1), e.g. for medical training [KPP13]. Tactile cues can improve performance, e.g. typing on a touchscreen [BCB07], improving expressiveness [BSLM01], accuracy of perception and ambiguity [LGH+03]. It is obvious that not all haptic properties can be easily rendered on a rigid tablet screen. Therefore, in the following subsection, a novel user interface will be presented, which shows the versatile of haptic feedback on touchscreens by introducing an elastic multilayer approach.

4.3.1 Implementation

To investigate further aspects of versatility of haptic feedback and thus explore RQ1 we have developed our second prototype: a novel multilayer interaction approach for pen-based tablet interaction have been designed, developed and explored. It offers a haptic layer to support the exploration of haptic features and direct manipulation of visual screen content. The interface consists of a transparent stretched elastic material attached above a tablet screen. Due to the gap between the flexible surface and the tablet, the system augments pen interaction with the rigid tablet screen into the interaction space above the display itself. We change the stiffness of the layer by stretching it, which can be sensed through pen interaction. We use membrane properties of the haptic layer to relay vibrations, also in cohesion with audio cues. The motivation for adding audio-tactile cues is twofold. Firstly, previous work has shown high relevance of vibro- and audio-tactile cues for improving performance [BCB07], [LMBS07], [VDH14]. Secondly, some haptic exploration tasks can depend on audio-tactile information (e.g., texture).

Through the gap between the flexible layer and the touchscreen, the pen can be pushed down to the screen. The interfaces allows spatial exploration of the trackable space above the 2D display and at the same time enable haptic feedback to the pen. Users can easily switch between the two layers as the haptic layer, under low tension, can touch the rigid screen with sufficient pen pressure. The transition between flexible and rigid states is an important feature of our approach: e.g. such transitions are often used by engineers, designers and architects while using devices, tools and systems, see a discussion of state changes (and shape-changing UIs) [FLO+12].

The proposed multi-layer interface supports the research of material and spatial haptic properties in flexible as well as in rigid space. It is able to simulate firmness and shape contours by using spatial and flexible properties. It is also able to render texture properties (roughness) using the mounted membrane. In this way, FleXurface can generate tactile feedback, as the surface moves slightly when vibrated. Furthermore, the elastic layer can create smooth feedback that can be associated with soft tools. Finally, the rigid tablet screen can be used for direct manipulation, while it can limit pen movement to a 2D layer. As a result, it is possible to recreate a real event, e.g. the pressing of a soft or spring button before the actual activation, i.e., state transitions between flexible and rigid states (see Figure 4.12). To obtain this functionality, we seamlessly blend between the dynamic force haptics above the screen (which simulates pushing down the spring-loaded button) and the rigid layer that constrains the downward movement to select (click) the button. Such dynamic force buttons can create different types of buttons with different functionalities. For example, a delete button may require more force to operate, so that the user is warned and it becomes more difficult to activate it accidentally.

System

The main idea of the interface is to provide a further approach on how to design haptic feedback. The prototype is based on a transparent, flexible material with variable tension over a touchscreen. By stretching the elastic material, it is possible to achieve different levels of tension, which is useful, for example, to simulate firmness. The touchscreen is used for visual feedback, i.e. displaying information. In contrast to the elastic feedback layer above the screen, the rigid display can be considered as a second feedback layer, which provides rigid feedback. The management of dynamic tension of the elastic material and the mounting of the different components, such as the servos was realized with 3D printed parts. The housing is built from medium density fibreboard. The software is based on Unity3D, and a client-server system controls the interface. The server (tablet) sends its current touch event via WLAN to the client (laptop). The laptop handles all computations for controlling the motors, it is therefore responsible for the haptic rendering. Thus all actuators (servo and vibration motors) are controlled by the client using a micro-controller (Arduino Mega).

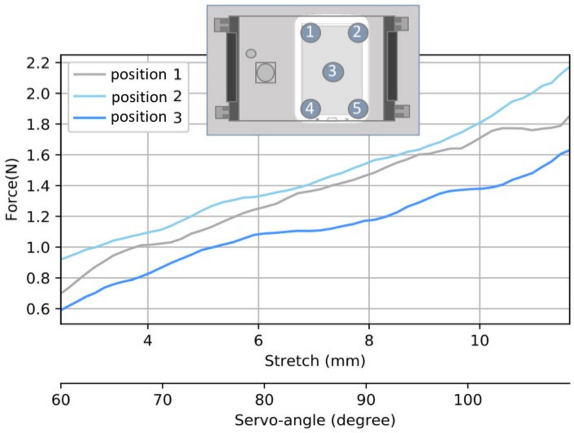


Figure 4.12: Stress-strain curves at 3 measured positions (1,2,3). Due to symmetry, positions 1 and 4, and 2 and 5 produce about the same results.

Display

A Samsung Galaxy Tab 8 tablet, with an 8” touchscreen was used as the main display. It natively supports interaction through a pen, as well as through direct finger input. The pen’s 2D location on the screen can be tracked even if the pen-tip stays within a range of about 12 mm above the display. As the S-pen is pressure sensitive, the interface is able measure the relative pressure placed on the tip of the pen for interaction purposes. Pressure sensing is reliable at all tension levels: Calibration measurements were collected at 6 mm penetration depth under all tension levels. (see Figure 4.12). For example, the interface is able to trigger a button feedback reliable at the same penetration depth under all tension conditions, which is important for repeatability.

Elastic haptic layer

A fully-transparent 0.8 mm silicone sheet was used to provide haptic feedback (Silex Superclear 40). It is glass-clear so that the content displayed on the tablet screen is fully visible. The flexible material is mounted between two 3D printed bars, which are able to stretch and release the material above the screen. Directly onto the flexible material, a bendable ultra-thin plastic layer was placed. This second ultra thin layer was necessary because the interaction between pen and elastic material caused too much friction, which led to undesired effects during the interaction, for example sliding with the pen over the surface was difficult. The second transparent layer is mounted on the sides using a thin highly flexible material (neoprene), which allows the plastic layer to deform along with the main elastic layer (see Figure 4.13).

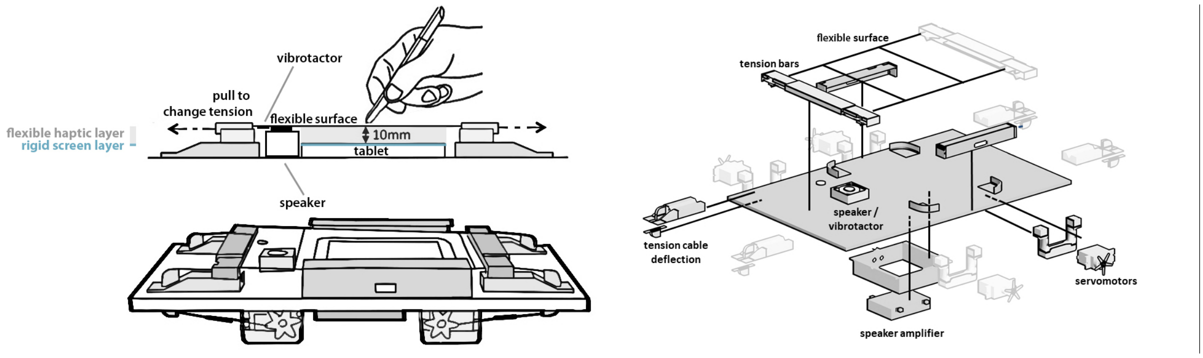


Figure 4.13: (Left) Schematic side view of the system, showing the pulling mechanism to change the variable compliant tension, (Right) exploded diagram of all the system components. Light grey objects with reduced contrast (to improve image clarity) are further instances of the main "highlighted" functional components.

The material protrudes about 2 cm beyond the edge of the display, thus avoiding the appearance of wrinkles. During our experiments no such disturbing wrinkles were observed. The distance between the flexible surface and the touchscreen is 10 mm. In all studies, users looked at the screen almost perpendicularly, limiting any parallax effects that might be caused by the space between elastic layer and screen. There were no disturbing visual effects observed. While parallax can be a problem when interacting with oblique viewing angles, we can also emphasize that parallax effects are implicitly attenuated when the user pushes the pen down towards the rigid display surface to manipulate the screen content directly.

Each of the two 3D-printed bars that stretch and release the elastic haptic layer are connected to two servos using 0.5 mm nylon cables. These servos were mounted below the surface on which the touchscreen is located. The cables are tightened between the bars and the digital servos with adjustable spanners. This allows the system to be dynamically readjusted. The bars were operated with digital servos (Align DS655). An external power supply was used to provide the operating power of 6 V.

All servos have a theoretical motion speed from 60° in 0.05 s at 6 V, but under load speed is likely to decrease. The servos are controlled synchronously, i.e. one single control signal is transmitted to all four servos. This results in a symmetrical tension in the direction of the bars. This tension/stretch can be defined by the servo angle. The surface can be stretched up to 12 mm (at 130°), in comparison to the neutral position where the flexible surface is flat (at around 2 mm stretch, 65°). This results in a system stretch range between 2 mm and 12 mm.

Within the interface, the flexible haptic layer can in general be used in two modes: static or dynamic. In static mode the servos build up a surface tension before the pen reaches the surface and maintain this tension regardless of user actions. In contrast, the dynamic tension is changed by user events. In this case, two events can generally cause tension changes: pressure events (e.g. pressing a button) or sliding events (e.g. exploring an element). Note that an increase in tension on the flexible surface actually moves the pen upwards, away from the display, as the pen is pushed upwards (see Figure 4.14).

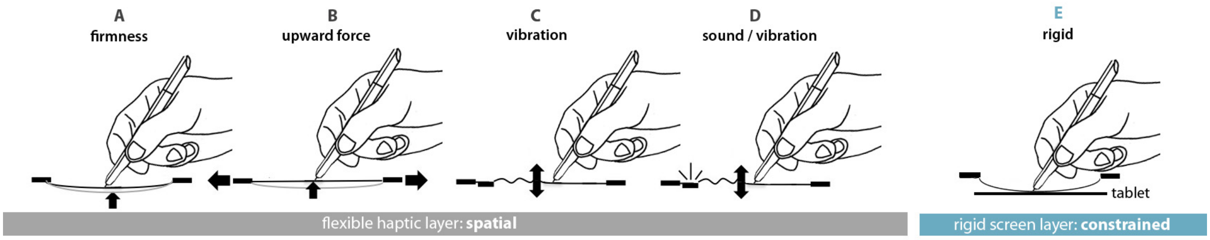


Figure 4.14: Feedback types afforded by our system based on different forms of actuation and the flexible or rigid state of the system. From left to right: firmness, upward force, vibration and sound (including vibration), and rigid.

Membrane properties

A further characteristic of flexible materials is that they serve as a membrane: Transmitted vibrations can be easily felt when the pen touches the vibrating material, as the surface is under sufficiently high tension. To explore the potential of vibrations, a small loudspeaker and a vibration motor were attached to the flexible haptic layer next to the tablet (see Figure 4.13). The fixed membrane centre of the loudspeaker is connected to the flexible surface using a rubber ring on the loudspeaker membrane. In this way, it is not only possible to reproduce audio, but the flexible surface also functions as an extended speaker membrane and offers the possibility of displaying tactile cues in accordance with the audio feedback that can be perceived through the pen. The speaker is driven by a tiny 3 W mini amplifier mounted underneath the bottom plate and connected to the tablet line-out. Obviously, audio from that loudspeaker can normally be heard, but not if the users wear headphones. For tactile feedback independent of audio, a Precision Microdrives 12 mm/3 mm pancake vibration motor (from 0-1.4 g (amplitude) and 0-300 Hz (frequency)) was fixed onto the flexible material.

Calibration

A calibration is required to determine the characteristics of the flexible layer. This includes several components that have to be considered. First of all, the relationship between servo motor and tension in Newton must be determined. For this purpose a pressure distribution of the transparent elastic layer has been computed. Therefore a pressure sensor (Interlink 402) with a small disk similar to the pen-tip diameter in a mechanical contraption was mounted above the tablet. The contraption allows to adjust the depth of the sensor, for calibration this was exactly 6 mm depth. During the generation of the stress-strain curve, symmetry properties were used. Therefore, 3 locations (1, 2 and 3 - see Figure 4.12) had to be measured. The three stress-strain curves of the three locations are also depicted in Figure 4.12. It can be seen that each of the three measuring points has a slightly different curve. We measured pressure at the full tension range of the flexible material and calculated both the stress-strain curves and pressure accordingly.

Since the pen also has a pressure-sensitive tip, the next step is to calibrate the pen. To do this, we mounted the S-pen in the mechanical contraption and measured the pen-tip pressure again under the full tension range, at the middle position (number 3) at 6mm protrusion depth. The pen-tip was also matched with a force profile using the aforementioned method. With these calibration steps it is possible to determine which force is applied to the pen as well as how deep the pen has penetrated the flexible material at all tension levels. Furthermore it is possible to convert the servo positions to the applied force by using the stress-strain curves. Position 3 was used as main feedback area in our user studies. To avoid mis-calibration or bias, the top plastic layer was fixed during both calibration and studies.

4.3.2 Experiment - Perception Study

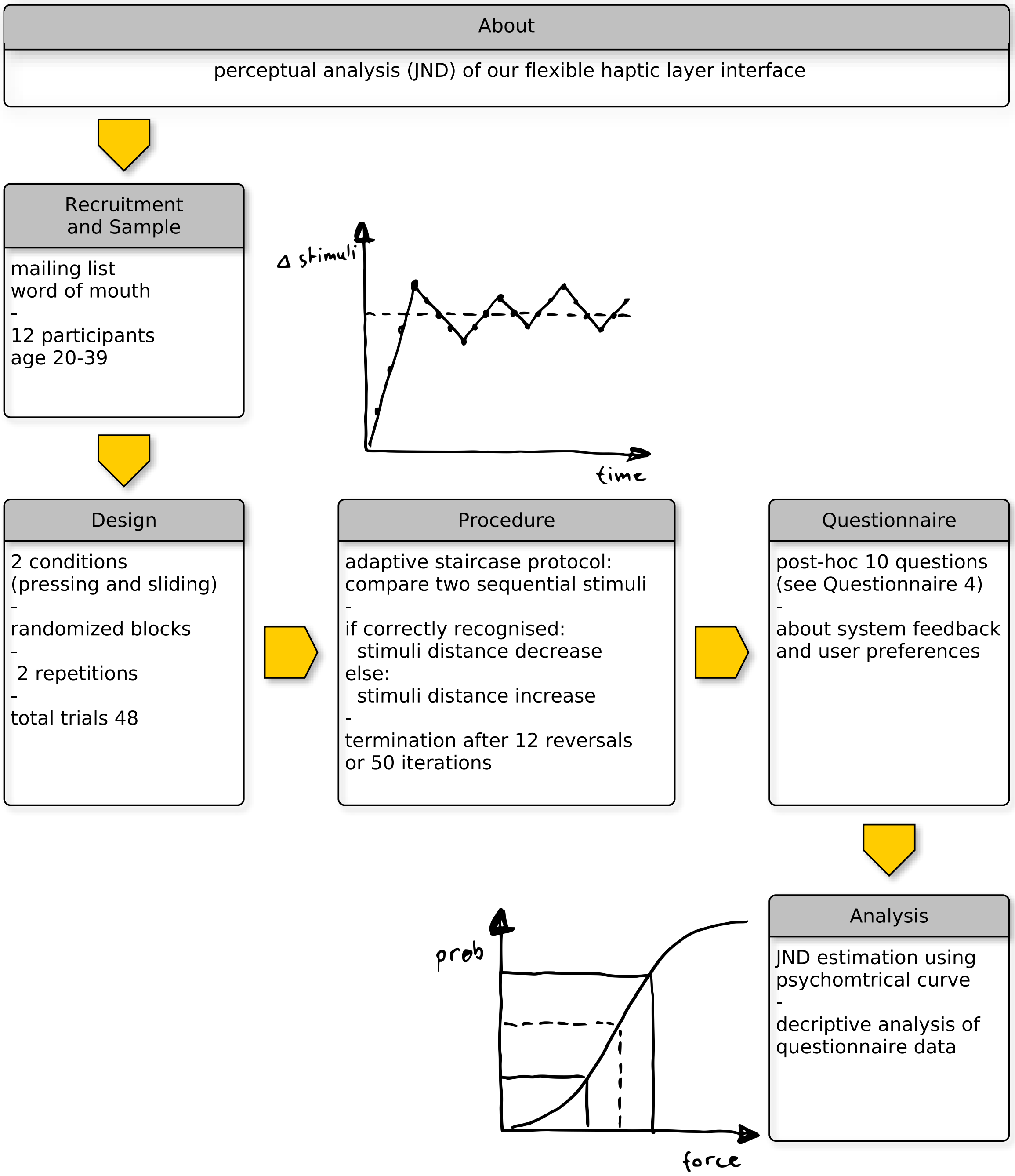


Figure 4.15: A schematic representation of the psychophysical study conducted to determine the perception threshold.

To look into further aspects of research question (RQ1), we explore the potential of our flexible layer to convey different haptic properties. Therefore we looked closely at the perception of firmness (by varying surface tension through stretching the material). In doing so, a just noticeable difference (JND) experiment was performed. A schematic representation of the study can be found in Figure 4.15. In our case, we wanted to know how well users can perceive and differentiate between different tensions of the flexible haptic layer. In a subsequent subsection a potential application is presented, it shows in various ways how different feedback can be mapped to particular interaction components.

Prior to the main study, we conducted a pilot study to confirm that all parameters were set correctly and to ensure that the feedback from the system was reliable and that all components were performing robustly. Unlike to the first study in this chapter (see Section 4.2), where the index finger was used to interact with the touchscreen, the following experiment focused on pen interaction. Furthermore, we see a press event, for example when using a button, and a sliding event, for example in drag and drop gestures, as the main interaction metaphors of the interface. For this reason, these two metaphors will be examined more closely and it is hypothesised that:

H1: Interaction metaphor (slide, press) has an impact on the perception threshold

Participants

12 subjects (one female) with an average age of 28.67 years ($SD = 5.94$) and a range from 20 to 39 years participated in the experiment. Most had normal vision; 4 people who wore glasses or contact lenses. The majority had at least some experience with pen-based interaction, 9 participants had used them sometimes (75 %) and 2 frequently (16.7 %). All the participants took part in the study voluntarily. No money was paid for participation. Furthermore, all participants were informed before the experiment that they could withdraw from the study at any time without consequences.

Apparatus

Both the experiment and the complete interface (see Figure 4.16) are designed for landscape usage. Throughout the study, users wore noise-cancelling headphones playing white noise to filter any potential external audio cues. A wooden box covering all parts except the screen was installed to avoid visual cues such as moving side bars The study participants were able to place their hands on this box to enable an ergonomic posture. All users operated the system in a sitting position.

Figure 4.16: Apparatus, with sound and visual cover (Left), top and side/top view of setup showing art application (Right).

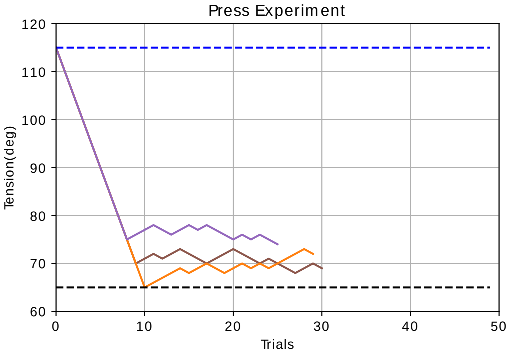


Figure 4.17: Three representatives of the conducted staircase protocol. When a line descends, the difference is correctly detected, when a line ascends, the difference is incorrectly detected.

Design and Procedure

Study 1 followed a standard staircase protocol for calculating the JNDs, in which users had to compare two different tension stimuli, stating if they felt different or the same [JT13]. This adaptive method was used to identify at which threshold the users could still feel a difference, by iteratively increasing or decreasing the tension based on the users last response. Users performed the protocol for both pressing and sliding separately, as both are considered as typical metaphors for the interface; both pressing and sliding tasks were repeated twice. The base tension ("standard value") was chosen at 2 mm stretch (65° servo angle), where the surface is flat. The staircase procedure started at an stretch of 10 mm (110°) and went down in steps of 5° until the user has entered a false response - a reversal point. This can either be when the user does not notice a difference between the "standard value" and the "reference value" although there is a difference, or when the user perceives a difference but the two stimuli are the same. After the first reversal point the step size was reduced from 5° to 1° to get a more accurate result. We chose 110° (1.63N) as the starting point, as it offers a tension clearly different from 65° (0.74N). The procedure was stopped after 50 steps, or 12 reversals. These equal distance servo steps can be used as the relationship between stress differences (N) and servo angles is linear, as can be seen in Figure 4.12. In order to make the procedure more clear, we have selected three representative to visualise the applied staircase protocol (see Figure 4.17).

Besides haptic feedback, visual feedback was additionally provided. Therefore, a button was shown at the centre (position 3, see Figure 4.12) that either had to be pressed or which users had to slide the pen over. For sliding, a marker was moved along the button that the user should follow, starting at 1.4 cm to the left of the button and ending 1.4 cm right of it. This velocity guided method, similar to the interface presented in the previous section, is intended to ensure that all users perform the activity at almost the same speed. Pressing and sliding was performed at 6 mm surface depth. A colour indicator was provided (button or moving marker turned green), once the correct pen depth was achieved. We implemented this by reading the pen tip pressure and comparing it to the calibration measurements.

In both tasks, sliding and pressing, all users had to lift the pen entirely from the surface. This guarantees that users do not receive feedback when switching to the second stimulus. Furthermore, when switching between the simulated buttons, the pressure was set to neutral before setting the tension again, to avoid giving users visual cues based on the motion of the flexible surface. After pressing or sliding, users had to indicate if they could detect a difference or not, by pressing a button on the screen. During training and the main experiments, the user's hand holding the pen rested on the ledge provided by the support box. After the study, a questionnaire (see Questionnaire 2) recorded subjective ratings for the system, with a 5-point Likert scale (from 1, disagree to 5, agree).

Results

All participants could to a certain part well distinguish between the provided tensions within the press and slide tasks. Based on the collected staircase data, the probability of correctly identified tension differences between the two sequentially provided stimuli were determined. These probabilities were used to estimate both psychometric curves, one for pressing and the other for sliding (see Figure 4.18). The estimation was done using the python toolbox for psychometric function estimation from the University of Tübingen [1].From the psychometric curve the point of subjective equality (force at probability(0.5)) and the JND ((force at probability(0.75)-force at probability(0.25))/2.0) can be derived, according to [JT13]. For our interface a JND threshold for pressing ($\Delta 0.18$ N) and for sliding ($\Delta 0.15$ N) could be defined. This results in a Weber fraction for pressing =21 % and for sliding =18 %. Both fractions are in line with the range for firmness (stiffness) experiments (15 % to 22 %) defined by Jones. According to our hypothesis (H1), the participants were able to distinguish better between tensions during sliding than during pressing. Therefore, the hypothesis can be accepted because the interaction metaphor has an influence on the perceptual threshold.

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[1] https://github.com/wichmann-lab/psignifit/wiki (last accessed 19th April 2021)

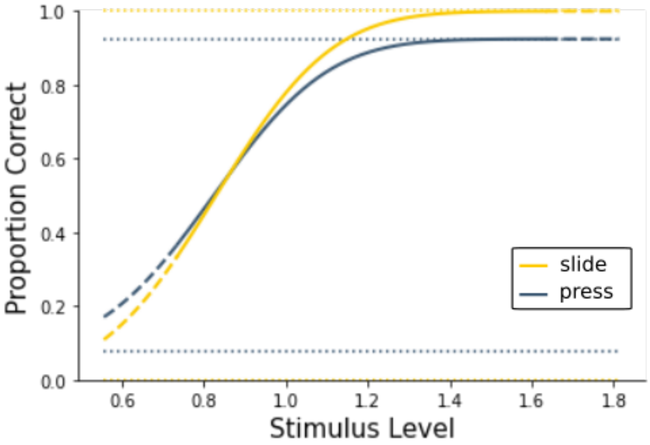

Figure 4.18: Psychometric curves (forces in N). Pen press/slide depict results of the pilot study.

The analysis of the questionnaire indicated that the interface was easy to use and to learn for sliding ($M = 4.25/SD = 0.45$; resp. $M = 4.42/SD = 0.51$) and for pressing ($M = 4.58/SD = 0.51$; resp. $M = 4.5/SD = 0.67$). Participants were neutral about the white noise sound they heard during the experiments ($M = 3.10/SD = 1.50$), however, they reported that the servo motors could not be heard and therefore the goal of applying white noise sound was successfully achieved. Moreover, participants did not feel frustrated by the task (press $M = 3.58/SD = 1.31$; slide $M = 3.67/SD = 1.07$), felt confident operating the system (press $M = 4.08/SD = 0.79$; slide $M = 4.0/SD = 0.85$), and could sense cues well with the pen (press $M = 3.67/SD = 1.07$; slide $M = 3.58/SD = 0.9$). In general, ratings were quite similar for both experimental conditions and ranged from neutral to positive.

Due to the flexible surface we offer a continuously variable, compliant feedback, which is force-wise in a continuum between the soft mid-air feedback, such as that provided by ultrasonic sound waves [CSL$^+$13], and the more firm, solenoid-based or vibration feedback provided by haptic pens, such as [CST15]. The feedback range can best be understood when looking at the different sensations felt when touching human skin in different places on the hand (often referred to as the "doneness test" when grilling steaks) - it shows both the softness and the ability to regain the original shape. Although further research is needed, we assume our feedback that is variably compliant and soft can potentially be associated with different types of materials, ranging from soft fabrics to rubber or silicone.

4.3.3 Application scenarios

Alongside the analysis of perceptual aspects that can be helpful for interaction with GUI elements, we also see great potential for possible applications. For example, the elasticity of the material used is suitable for simulating haptic properties, for example, tools. Therefore, we will discuss how the pen can be actuated, and how these kinds of actuation - including flexible and rigid state transitions - can be used within a sample application, an art application. Afterwards, we discuss the higher-level functionality that can be derived.

The presented interface can generate a variety of different feedback, including force feedback, tactile and auditory feedback. Figure 4.14 (A-E) looks closely at how the pen can be operated. If there is a minimum tension, different degrees of hardness can be simulated (A), which the user can feel when the pen is pressed down. It is also possible to generate an upward force (B), by raising the tension quickly the pen will move away from the tablet display. By adding the vibration motor and the speaker touching the flexible material, vibrations, sound and combined feedback could be provided by the interface (C, D). In cases where the tablet-pen interaction should be performed as usual, the flexible surface can be relaxed to a degree that the pen touches the screen, resulting in a rigid feedback. This means that the interface can also handle the physical constraints that are common when interacting on a rigid screen: the movement is limited to a 2D surface (E). These cues are similar to cues provided in mobile devices (e.g. [KIP13], [LOM+11], [VDH14]), but are here directly coupled to the feedback provided over the flexible haptic layer. Note that the membrane vibration can also be felt (though slightly dampened) while the pen touches the rigid screen.

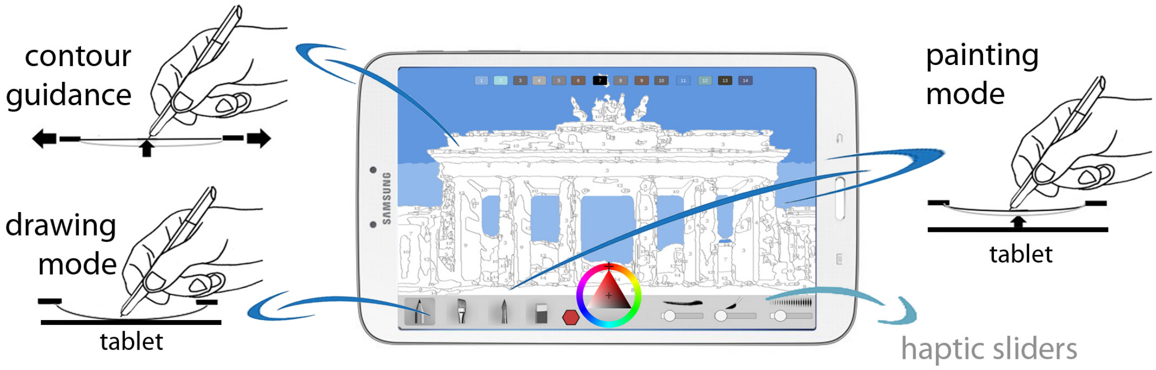

Figure 4.19: Art application: rigid and variable compliant (flexible) states simulate different tools. The paint-by-numbers application displays upward force to warn users when passing over a boundary of an area.

Art application

To demonstrate the potential of the interface an art application was designed and implemented (see Figure 4.19). With this application the versatile possibilities of the system can be illustrated clearly. It enables the user to draw and paint with different media (oil and watercolour painting with different brush types) by adjusting the "feel" of the different tools (e.g. brush type versus pencil) and surface properties (e.g. paper roughness) - the application actively uses transitions between flexible and rigid states. Moreover, we studied novel widgets by introducing, for instance, a haptic slider. In the application the slider allows the user to adjust the settings for tool like brushes and surface properties like paper roughness. A benefit of the haptic slider is to feel the effect immediately and directly. By changing the position of the slider we assign the new value to the tool property to be manipulated. Thus, the properties of the tool can be adjusted and simultaneously perceived through the feedback provided.

The novel haptic layer plays a central role in the application by switching between the "full flexible mode" (which represents watercolours and oil brushes) and the "rigid mode" in which the flexible surface touches the display. In contrast to the flexible mode, the latter provides a pen-on-paper feeling. All tools actively use the pressure sensitive tip to change the line/stroke thickness. Through the speaker and vibration motor, which are attached to the flexible surface, we can simulate the roughness of the paper structure during a painting process. Finally, we demonstrate an active form of guidance using a painting-by-numbers example. This painting method, often used by children, has coloured areas with strict boundaries where the paint only needs to be applied within the borders. As soon as a user moves over a defined boundary with his/her pen, a dedicated feedback is provided.

In particular, the art application illustrates how we can map pen actuation to functionality. In the following a more abstract view and discussion of the system will be provided. Based on the material properties of used flexible surface the haptic exploration is bound to the simulation of soft deformable materials, similar to [MKG$^+$14], but more controllable. Mueller et al. focus on push and pull gestures on a large elastic display. Their interface uses the similar elastic properties as ours to provide haptic feedback. But compared to the one presented here, Mueller et al.'s can be actively actuated. Moreover, the coupling of both (a) the speaker and vibration motor and (b) the rigid surface of the touchscreen allows the generation of cues that map well to application requirements. Cues can be associated with standard widget elements, such as buttons and sliders, as introduced in previous paragraphs. In our current implementation, the system provides different kinds of haptic feedback for widgets. Selection of widget elements is supported in the flexible haptic layer by measuring pen-tip pressure, or by pressing the pen down to touch the rigid surface.

Finally, audio and vibration can be used to provide selection cues, similar to [WRS17]. Tactile or flexible cues can augment the interaction with tools that exhibit elastic properties. As we showed in our application, such cues can enhance the user experience and potentially also performance with such tools. Such cues provide indications of the real-world haptic properties that help the user understand how the tool performs while using it. Besides improving performance or user experience using haptic cues, the richness of haptic feedback – such as brush properties – stimulates artists, and could therefore support creative processes by bringing more realism into the interaction [BSLM01]. At least, the system can be used for guidance. Simulated rims [KIP13] or textures, but also other sudden changes of feedback, such as an abrupt upward force, can be used to display a warning or to guide hand motion. As an example, the pen can be forced upward a bit once the user starts to press a delete-all button, to indirectly warn the user about the implications.

4.3.4 Discussion

The second interface emphasizes the potential of haptic feedback with a unique approach designed for touchscreen interaction and thus contributes to answering RQ1. Additionally, the proposed interfaces differs essentially from previous haptic pens. Such pens often require physical contact with a rigid screen in order to explore physical aspects. Further pen interfaces provide basic force feedback while operating in the air. It is a challenge to transfer our combined haptic feedback into a pen with a small form factor: most pens only support a subset of our functionality and are often tethered. This means compared to pen interfaces discussed in Chapter 2 is that our pen do not require any additional components. The feedback is transmitted using the elastic material. This makes the pen light, requires no additional power and the fact that the feedback is outsourced allows increased force to be applied to the pen. All this enables, a haptic feedback continuum between the very light feedback in the air, e.g. through ultrasonic feedback [CSL+13], and the firmer haptic feedback in rigid screen interaction, e.g. through the haptic pens mentioned above.

Although this interface offers a broad spectrum of haptic feedback, it only support a subset of all potential haptic features. For instance, weight, temperature and volume are not supported in the current system. By allowing components to be integrated into the pen, it is easy to integrate temperature feedback into the pen. It can be realized using a

Peltier element. However, if the pen is to remain without additional components, warm air can be generated externally using a coil and provided to the user through a small fan, similar to [WLT+20]. In contrast to temperature, weight could be difficult to simulate without tethering. Volumetric feedback can currently only be rendered in a very small range. With the system presented in this section, larger intervals could, of course, be mapped to the defined range, but this in turn means that the spatial resolution of the feedback becomes decreased. In addition, with the introduced interface only a limited range of variable compliant stiffness can be simulated (about 0.7N to 1.6N). With the present technical design it would be difficult to simulate much stiffer materials, as the servos will not be able to actuate the used material. Also, the current surface material blocks direct finger interaction. Yet, as long as the material is transparent, other flexible surface materials could simulate different ranges of softer flexible materials. Perceiving textures through the flexible surface material likely has some limitations as the material absorbs vibration differently under different tensions (especially when it touches the rigid display), which warrants further study. Finally, while the sound of the servos could not be heard during experiments due to the headphones, it might have to be blocked by other means for situations where headphones are not an option.

At least, pen latency should be discussed. In the current implementation pen latency led to some limitations. Although the latency is similar to that of other conventional pens (e.g. Wacom Cintiq), it is higher than that of the latest systems (Apple Pencil 50 ms or MS surface, where there is almost none). Although the haptic feedback in the interface was decoupled from the visual feedback, still, the latency was hardly noticed, especially in our art application, as painting movements were rather deliberate and slow. Furthermore, there is only low servo latency for continuous static feedback, such as while using a brush. This may be similar to other haptic exploration tasks, such as pressure sensing and especially contour exploration, which are typically performed more slowly [LK09]. In a future iteration of the system, we plan to use a lower-latency tablet.

4.3.5 Conclusion

In order to obtain further details of the research question RQ1 a multilayer feedback approach for pen-based tablet interaction was introduced. To our knowledge, the interface introduced in this section is the first system that demonstrate a combined elastic, tactile and rigid feedback in a single interface. Within pen-based technologies, haptic feedback, especially force feedback, tends to be difficult to achieve without connecting the pen to a force mechanism, a issue that we overcome with FleXurface. Through an art application, we showed how the different feedback possibilities afforded by the system can enhance interaction through its multilayer approach, illustrating the potential of the system.

Taking into account our Aim 1 and Objective 2 (see Section 1.2), our sub-question (How can elastic materials be combined with touchscreen interaction?) and the resulting perception aspects and limitations, the following sub-contributions could be achieved with the interface:

- A novel haptic pen-based touchscreen interaction approach that allows the exploration of various haptic features, for instance firmness, textures, material characteristics and interaction properties was proposed. **Multilayer haptic interaction approach** uses two interaction layers – a flexible haptic and a rigid screen layer – and the user can seamlessly transition between flexible and rigid states with the untethered pen.
- Perception-based aspects of the flexible haptic layer have been studied to show the limitations of the interface. Therefore, we **estimate perceptual properties** of the flexible layer through a user studies. Therefore, we performed a just noticeable difference (JND) experiment to assess how well users can perceive tension (firmness) differences.

Previous work has also shown that tactile cues may improve performance with widgets [BCB07], [FS01], [LMBS07]. As we do not have to substitute haptics (kinesthetic cues) through tactile feedback, we assume that our multilayer approach can further enhance performance for such tasks and support higher accuracy. Though previous work shows initial positive indications [FLO+12], this latter aspect deserves further study, to show to what extent variable compliant haptic feedback would be truly better than vibration-only feedback. Furthermore, as we did not alter the visual appearance of buttons when they were pressed, visual feedback did not modulate firmness perception. Previous work [KTC+12] indicated that haptic firmness discrimination performance could be improved when visual feedback is provided along with haptics. While haptic cues work within the non-visual sensory channel, they also afford eyes-off interaction, another area that deserves follow up. In addition, it will be interesting to assess to what extend the system can improve expressiveness [BSLM01] – while initial feedback with our art application was positive, we are confident our system can deliver to this extent, which we aim to address in a more elaborate study.

Notwithstanding that the current interface has mainly been used to study the design space of the multilayer approach, miniaturization is an interesting option to explore similar feedback mechanisms within the mobile domain. One potential solution is to make use of deflection rollers to wrap the material more effectively around the display with smaller servos or to use linear actuators which are also quieter. Finally, while the pen interaction has shown good performance, finger input is a further interesting direction to explore. To support direct finger interaction, other flexible materials, such as those that include, for instance graphite particles, could be used.

4.4 Pin-based Feedback on the Back-of-the-Device

In the previous sections of this chapter, it was shown how force feedback can enhance touchscreen interaction. Therefore, two individual haptic user interfaces have been introduced. In this section we will explore our third prototype to investigate further details of RQ1, for which purpose HapticPhone was developed. In this section, we will explore how a smartphone can be enriched with haptic feedback and what impact pin-based haptic feedback has on touch accuracy. Our approach uses the back of the smartphone for interaction, similar to fingerprint sensors. In order to achieve our first aim (Aim 1) we have realized our objective 2 and thus research on the third sub-question in this context.

Since the appearance of first prototypes about a decade ago, researchers exploring the possibilities of back-of-device (BoD) interaction. Motivated by efforts to minimize screen occlusion through fingers, early prototypes like LucidTouch [WFB$^+$07] made use of pseudo-transparent displays. At the back, users could interact with the full screen content using touch input without occluding content. One hope was that back interaction could compensate for poor pointing performance, especially for the selection of smaller objects.

Instead of touch input on the back, we explore the potential of pin-based force feedback at the back to enhance thumb-based touch interaction on the front-of-the-device (FoD) screen. Adding force feedback to smartphones could have great potential, as many force events currently are substituted through tactile (vibration) or visual-only feedback mechanisms, which affects the perception of those events [KWBT91]. Consider pressing a button: in real life, we receive physical (force) and tactile (surface) feedback while pressing the button down. With current smartphones, audio-tactile feedback ("click") and a change in button colour indicates when a button is pressed, which is not compliant with real-world interaction. Based on our previous work, we assume that force feedback could affect performance positively, in particular for thumb-based interaction that often suffers from occlusions. Moreover, as we will investigate in our studies, force feedback might improve performance in tasks that, in the real world, do not depend on such feedback.

Studies have shown that tactile feedback can increase performance in target selection tasks [AS94], [CCKB15]. However, the exploration of force feedback in smartphones is rare. A major cause is that adding force feedback actuators to the front display has many physical form factor constraints, which makes physical construction challenging. For example, mounting an actuator on the front would occlude part of the display, and likely hinder input. In contrast, the main research problem our approach faces is how well force feedback at the BoD works.

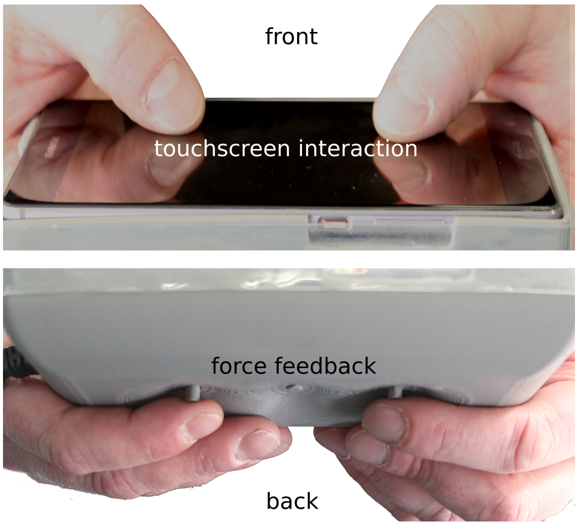

Figure 4.20: Illustration of the prototype, a touchscreen for thumb interaction is shown on top and the force feedback pins in landscape orientation are depict below.

4.4.1 Implementation

We designed and developed a BoD approach (see Figure 4.20), a device for exploring the haptic design space at the back of smartphones. We use BoD feedback to overcome physical form-factor challenges for adding force feedback to the front of the device and explore this novel design space by looking into the human and technical aspects of our interface.

As showed in Section 4.2 and Section 4.3 and also discussed in the literature review - force feedback could improved interaction [JKT+16]. Therefore, our main design goal was to combine BoD interaction and haptic feedback with thumb-based interaction. Continuous, assisting force feedback can provide a secondary cue for improved touch performance and increase the user experience in terms of subjective performance. To do so, we have attached a force feedback mechanisms to the back of the device that relays feedback to touch-input on the screen at the FoD. As such, our design couples front touch-based screen interaction and BoD feedback.

Technical Design Rationale

To overcome physical form-factor constraints - such as screen occlusion, input hindrance, and an unergonomic grip - at the front of smartphones, we explore the feasibility of adding force feedback to the back of a smartphone

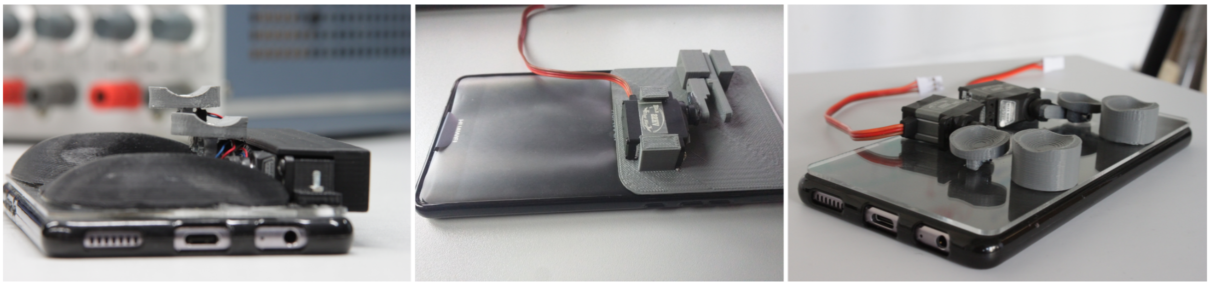

Figure 4.21: Photos from different iteration stages all pursued the same goal of providing haptic feedback on the back of a smartphone.

We designed the new system for both one-handed (portrait) and two-handed (landscape) interaction. Input is performed by either the left or the right thumb or both on the FoD, while haptic feedback is relayed to the index fingers at the BoD. After several hardware design iterations (see Figure 4.21), that looked into ease-of-use, grip stability, and reachability of the feedback elements, and informed by the results of Le et al. [LMBH18] on appropriate finger locations for one-handed BoD interaction, we chose a three pin layout. The arrangement and dimensions are shown in Figure 4.22. This layout allows users to use the outer pins comfortably while interacting in landscape mode, just as the middle or top pin can be used for one-handed portrait interaction.

The remaining fingers grasp the ergonomically shaped bottom part of the device, to stabilize and balance the device during interaction and feedback. To improve the grip on the device, we attached a rubber based grip tape around the edge of the unit. The grip has also been designed to afford comfortable device usage in both portrait and landscape mode. However, one-handed usage may suffer from limitations, as previous work has shown that one-handed interaction can lead to more fatigue, less precision, and a less secure grip of the device [BLC+12].

Force feedback is provided by three actuated pins at the back of the device (see Figure 4.22), at the locations where the left or the right index finger naturally rest. Three dimples in the housing help to keep the fingers at the ideal locations, where force feedback is provided.

Hardware

Our interface comprises three high voltage (7.4V) micro servos (BMS-22HV), each measuring 23.0 x 12.0 x 25.4mm, running with a speed of 50ms per 60°rotation at no load. Each servo has a pulse width of 1200μm and a maximum torque of 0.245N/m. We estimate that the servos have a resolution of 0.2°as follows: a pulse width of 1200μm for 120°results

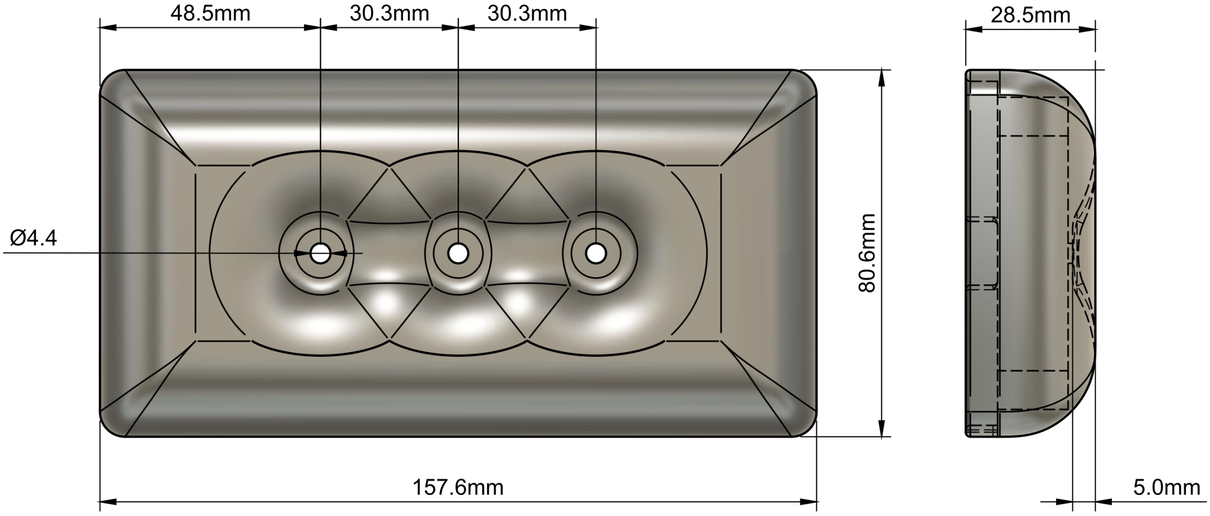

Figure 4.22: Technical drawing of the top and side view of our interface to show dimensions and the chosen pin layout.

in 1200 steps for 120°. With a dead band width of 2μs this results in 600 controllable steps for 120°. All in all, the servos can be controlled with a resolution of 0.2°, which corresponds to a radian measure of 0.049mm with an arm length of 14mm(see Figure 4.23 left).

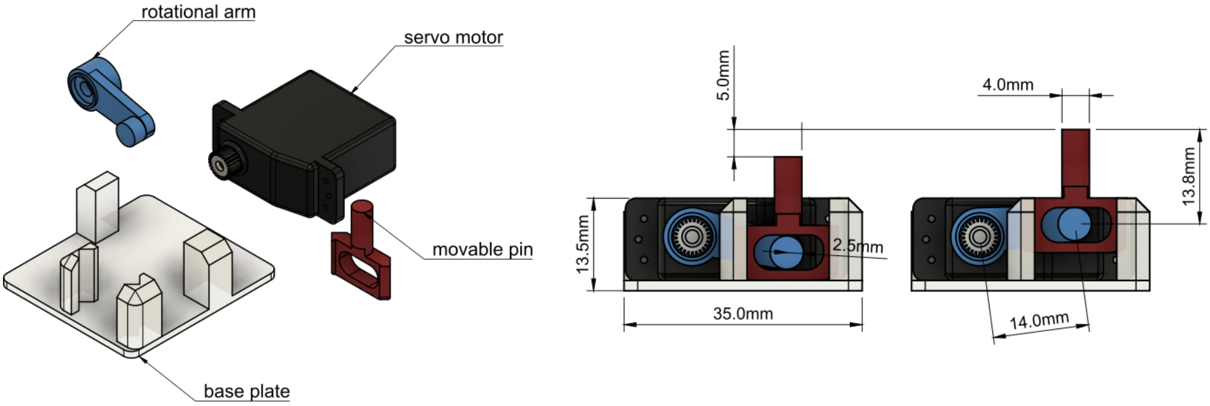

Figure 4.23: Modified scotch-yoke mechanism to translate rotational into linear movements. An exploded diagram to introduce the used components (right) and a front view of a fully retracted and extended pin (left).

For each of the three pins a modified scotch-yoke mechanism was developed to convert the servos' rotational movement into a linear movement (see Figure 4.23). Through two guiding rails on both sides of the base of a pin (highlighted in grey and red) and through an additional sliding mechanism (highlighted in blue and red), a linear movement can be created. For smaller pin movements, e.g., amplitude 1mm, our approach achieves a frequency of 50Hz. In idle mode, when no counter-force is applied, the power consumption

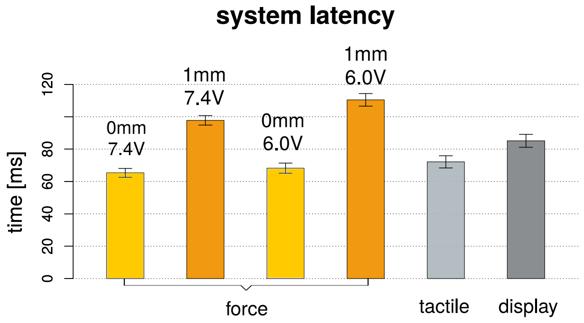

Figure 4.24: System latency measurements (in milliseconds) for force, tactile and display, shown as a bar plot. The actuators were operated either with 6V or with 7.4V and latency was measured with 0mm or 1mm pin height.

of the prototype is about 10mA. With a strong counter-force the consumption is about 500mA.

The design enables a feedback range along a single axis from 0 up to 5mm. All hardware components are mounted in a self-contained unit at the back of an Android 7 Huawei P9 Plus mobile, which also supports pressure-based input. All other parts, such as the case or the scotch-yoke mechanism, are 3D printed, which ensures easy reproducibility. The entire prototype measures 157.6 x 80.6 x 28.5mm, weighs about 200g and has a resolution of 1920x1080. A 16-bit Adafruit Feather (M0 Basic Proto) micro-controller, directly connected via USB (OTG) to the smartphone, handles the communication between feedback elements and the application, which means that touch input is forwarded with low latency to the pins.

The current prototype relies on a cabled solution. However a completely self-maintained unit can be created using an Arduino Nano and communication over Bluetooth. Servo motors could be powered with a buck-boost converter, which can increase or decrease the input voltage and which can permit the use of small battery packs.

Figure 4.24 lists the latency of the systems hardware components in milliseconds. In an experimental setup, latency of the touchscreen (visual), the vibration (tactile), and the proposed feedback (force) were measured. Force feedback was measured under multiple conditions, with 6V vs 7.4V and pin heights of 0mm vs 1mm to show the influence of the described parameters on latency. A two pole relay was used to trigger a touchscreen using a micro-controller, similar to Deber et al. [DAJ+16]. After triggering the touchscreen a photodiode (Tru Components 5013M1C) was used to measure the time between touchscreen event and visual feedback. To obtain tactile feedback latency, the photodiode was replaced by a vibration sensor (Phidgets 1104). To obtain force feedback latency, an electric circuit was mechanically closed. This mechanism allows to measure the elapsed time of the touchscreen event and its associated feedback, known as latency. For each feedback modality, 100 measurements were performed automatically. Figure 4.24 shows the average measured latency and the standard deviation of the measurement data. Opinions differ on the influence of latency on performance [JH05], [KBL14]. The modality latencies are slightly above those recommended by Kaaresoja et al. discussed in the literature review (see Section 2.2.1). Nonetheless, we believe that a performance comparison of the three components is valid for an exploratory study.

Implementation

In our implementation, we support two different types of touch input, namely position- and force-based interaction. The latter makes use of the pressure-sensitive touchscreen of the smartphone.

In contrast to conventional tactile feedback through vibration on the screen, the introduced force feedback can support several clearly distinguishable levels of intensities, as our psychophysical study will demonstrate. These intensities can be rendered in a continuous and discrete way. For the proposed haptic feedback two main software components are important. Firstly, the implementation on the smartphone, which takes care of the orientation of the smartphone and offers developers the possibility to address the three pins individually for their application. The smartphone communicates with a micro-controller via I^2C. The second component, the software on the micro-controller, receives data from the smartphone and passes it directly to the motors.

To support people with different thumb lengths, our implementation enables customization, where the front interaction areas shown on the screen can be scaled to match the thumb reach. With this, users are able to define their interaction radius according to their thumb size. This approach ensures that all graphical interface elements are reachable on the screen. In landscape view the screen is thus separated into a right and a left interaction area, meaning that the left and right thumb have their "own" interaction areas.

4.4.2 Experiment 1 - Psychophysical Perception Study

We conducted this study to determine the relationship between stimuli and sensation at the index finger using HapticPhone. The study examines haptic perception aspects and constraints of the BoD system. We performed a just noticeable difference (JND) experiment to address which force signals can users easily distinguish. This study is an important step towards answering RQ1, as the accuracy of differentiation will later influence touch accuracy. In addition, we studied the relationship between thumb and index finger movements through a second task (spatial compliance). This investigates if it possible to transfer movements of the index finger to the thumb and how the users perceive such movements.

Participants

12 users (3 female, age $M = 30.7/SD = 5.8$) volunteered to participate in this study. All were right handed. Participants had various experiences with force feedback, ranging from no to regular experience. All participants used smartphones regularly. Each participant completed all 60 trials, which took on average 12 minutes. The index fingers of the subjects were 88.0mm (SD=10.8mm) and the thumbs were 62.0mm (SD=5.9mm) large on average.

Apparatus

Users operated the mobile system as described in the system design section, while being seated comfortably at a desk. Users could rest their arms on the desk, and were allowed to take small breaks between tasks. During the whole user study, users wore noise-cancelling headphones that played white noise to prevent users from hearing the servo actuation, as the servo sound could provide some information about the force feedback.

Tasks and Procedure

The psychophysical perception study consists of two tasks. The first task investigates the just noticeable difference of force stimuli afforded by the pins, while the second task looks at spatial compliance. Both tasks were performed in a counterbalanced order. Participants were asked to use their dominant hand for interacting with the system. This ensured that the dominate thumb was used for touch interaction and the index finger of the same hand for the relayed feedback. To do so users were asked to place their index finger on one of the outer two pins, while holding the device two-handed in landscape mode. In addition, users were advised not to apply force to the pin.

In contrast to FleXurface, where we performed the JND study using a staircase protocol, this time we used the principle of constant stimuli with a 2AFC, similar to Geschneider [Ges97]. This decision was made due to the fact that in our pin-based approach we wanted to predefined the values, as they were strongly limited to the system. This protocol specifies that n times a randomly chosen stimulus from an appropriate interval must be compared to a standard stimulus. This can take place either spatially or temporally shifted.

In the experiment the standard stimulus S was set to 1mm while the comparison stimuli C_n were one of 1.2, 1.4, 1.6, 2.0 or 2.4mm. Stimuli were defined by the distance the pin was moved towards the index finger, i.e., away from the device. Each participant completed 10 repetitions. Each repetition was fully randomized, resulting in a total of 60 trials. For each trial, users were prompted to press a start button, to enable them to prepare themselves for the task. Each stimulus was presented for 2 seconds, with a pause of 1 second in between. The order of stimuli was chosen randomly, meaning the standard stimulus was presented either first or second. Users then had to determine which of the two stimuli was higher. Before the experimental tasks, users were allowed to do three practice trials. All training trials were marked visually so that the users knew when the actual study started.

The other task focused on the psychophysical perception of depth and height, which combines visual feedback and touch interaction (thumb) on the screen with BoD force feedback on the index finger. With this task we explored the spatial compliance between index finger and thumb, where we assume that the thumb can "perceive" height data from the index finger. This explores whether users perceive a valley at the thumb when the distance between thumb and index finger increases or will they perceive a hill and vice versa? This is important in order to use the feedback metaphor appropriately. For example, when creating the feeling that the thumb is sinking into the display, the correct feedback should be applied. In this task, participants were asked to explore a 3D Gaussian-like shape with the thumbs on the touchscreen. Since the screen has 2 physical dimensions, the 3rd dimension was mapped to the index finger, like a height map.

The maximum feedback (height/depth) was set to 2.4mm whenever the thumb reached the maximum of the shape displayed on the screen. While visual feedback remained constant over all trials, force feedback was designed so that either the distance between the index finger and the thumb became smaller or larger. Because the task was simple and easy to understand, only 8 trials were performed in random order per user. After each trial, users were asked if they felt that the 3D Gaussian-like shape was directed either into (valley) or out (hill) of the display.

Table 4.2: List of the results of the psychophysical perception experiment

depth perception			
participant	PSE [mm]	JND [mm]	WF [%]
1	1.20	0.11	8.89
2	1.28	0.07	5.88
3	1.06	0.04	3.90
4	1.23	0.13	10.80
5	1.21	0.11	9.43
6	1.21	0.12	9.62
7	1.29	0.12	9.62
8	1.23	0.10	7.82
9	1.21	0.06	4.91
10	1.15	0.17	14.74
11	1.10	0.08	7.01
12	1.14	0.04	3.83
Mean	1.18	0.10	8.29
SD	0.06	0.04	3.43

Results

The JND experiment was analysed using the psignifit MATLAB toolbox[2], similar to [JKT+16]. Three relevant values were determined: point of subjective equality (PSE) and stimulus values at 25% and 75% probability. With these three values the JND and the Weber Fraction (WF) were determined. The results of the psychophysical perception study are summarized in Table 4.2. The (index finger) depth perception threshold of our system is on average 0.1mm. All psychophysic curves of this study can be found in Figure B.1. Our results are in line with what Jang et al. [JKT+16] reported, who found an average JND of 0.15mm.

The evaluation of the answers shows that in the second part of the study 8% of all subjects felt a valley whenever the distance between index finger and thumb decreased and 91% felt a hill whenever the distance increased. Since users were asked what they perceived with their thumbs on the touchscreen this indicates that users seem to experience the sensation that their thumbs sink into the smartphone when the distance between index finger and thumb increases and vice versa.

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[2] https://github.com/wichmann-lab/psignifit/wiki (last accessed 19th April 2021)

4.4.3 Experiment 2 - Touch Accuracy Study

This study mainly examined touch accuracy of the BoD feedback mechanisms, comparing force with tactile and visual-only ("without") feedback. An overview of the conducted study is provided in Figure 4.25. Since thumb interaction offers a relatively smaller interaction area due to physical constraints for reaching compared to using the index finger, a higher accuracy might offer the possibility of comfortably controlling denser interaction elements on a smaller area. To determine touch accuracy we used two tasks, a drag-n-drop and a selection task. The drag-n-drop task is designed to determine the accuracy of a constant force feedback stimulus and to compare this with other feedback metaphors. The selection task pursues the same goal, however, the intensity of the force feedback was varied here. In a questionnaire we additionally explored user experience in terms of subjective performance of completion time, precision and quality of the feedback. Since the proposed system employed thumb-based interaction, multi-touch metaphors were excluded from the studies. For both parts, the drag and drop and the selection task, it was hypothesized:

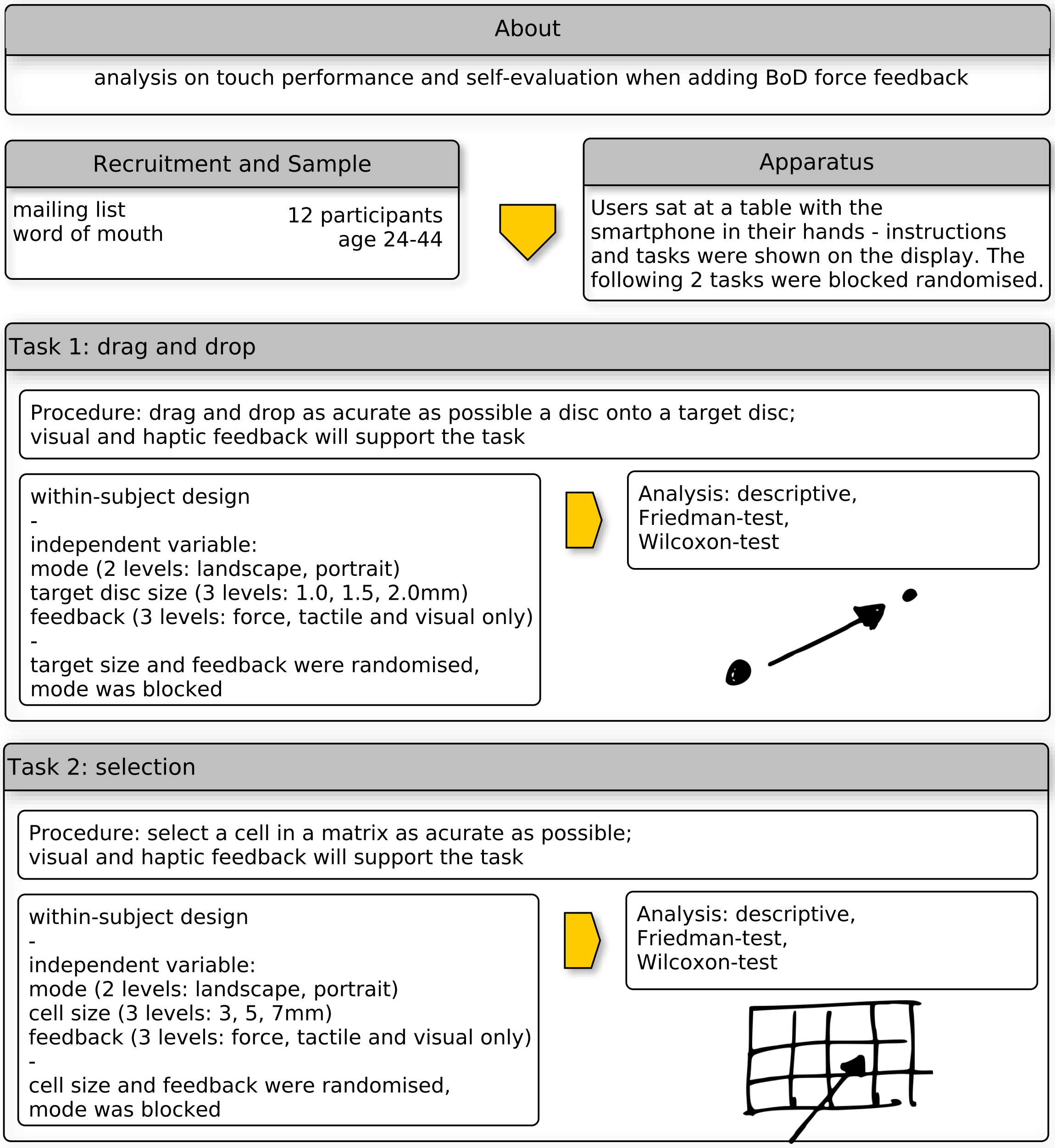
H1: The proposed feedback mechanism will increase touch accuracy.
H2: Haptic feedback will increase the subjective performance of the participants.

Participants

12 users (4 female, age $M = 32.0/SD = 5.4$) volunteered to participate in the laboratory experiment. Again, all participants were right handed. Participants had varied experience with force feedback, ranging from none to regular experience. Each participant completed all of the 108 trials, which took an average of 20 minutes. As in the previous studies, participation was voluntary and the subjects could stop at any time without any effect.

Apparatus

The apparatus for landscape interaction was similar to the one used in the first study reported above. In addition, we investigated interaction in portrait mode in this study, where the thumb of the dominant hand was used to handle the touch input and the corresponding index finger receives the force feedback of the middle pin. Users were allowed to use the other hand to keep the smartphone stable.



About

analysis on touch performance and self-evaluation when adding BoD force feedback

Recruitment and Sample

mailing list
word of mouth

12 participants
age 24-44

Apparatus

Users sat at a table with the smartphone in their hands - instructions and tasks were shown on the display. The following 2 tasks were blocked randomised.

Task 1: drag and drop

Procedure: drag and drop as acurate as possible a disc onto a target disc;
visual and haptic feedback will support the task

within-subject design
-
independent variable:
mode (2 levels: landscape, portrait)
target disc size (3 levels: 1.0, 1.5, 2.0mm)
feedback (3 levels: force, tactile and visual only)
-
target size and feedback were randomised,
mode was blocked

Analysis: descriptive,
Friedman-test,
Wilcoxon-test

Task 2: selection

Procedure: select a cell in a matrix as acurate as possible;
visual and haptic feedback will support the task

within-subject design
-
independent variable:
mode (2 levels: landscape, portrait)
cell size (3 levels: 3, 5, 7mm)
feedback (3 levels: force, tactile and visual only)
-
cell size and feedback were randomised,
mode was blocked

Analysis: descriptive,
Friedman-test,
Wilcoxon-test

Figure 4.25: A schematic overview of the touch accuracy study. The diagram illustrates the apparatus, procedure and design of the two task.

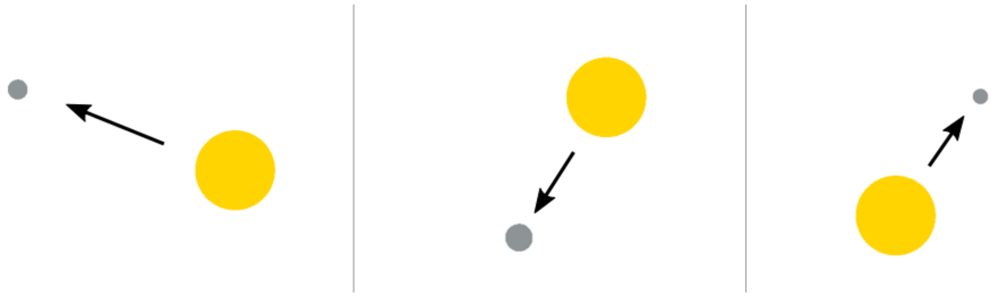


Figure 4.26: Exemplary representation of the target sizes in the drag-and-drop study. Users had to drag the orange disk onto the grey one.

Design and Procedure

Participants had to complete two tasks, a drag-and-drop and a selection task. Since the proposed BoD approach is comparable with more common feedback metaphors, users were asked to use all three different feedback metaphors (force, tactile, visual-only) to gain an understanding of each feedback modality and their differences.

Can interaction of the thumb be influenced by controlled movements induced on the index finger? To investigate this question, this study focuses on the interplay of relayed feedback from the index finger at the BoD to the thumb with the aim of increasing accuracy of thumb interaction on the front of the device. In addition, since the offset between fingers could also affect touch accuracy, we also investigated the influence of the offset in the axis orthogonal to the touchscreen between the thumb position on the touchscreen and index finger on the back. All tasks were performed in landscape and portrait mode, as both modes are common in every-day smartphone interaction.

After the study, users completed a questionnaire (see Questionnaire 3), in which we queried them about the three parameters accuracy, completion time and quality for each feedback modality using a 7-Point Likert scale, ranging from "strongly disagree" to "strongly agree", through statements such as: *I could perform the task precisely*, *I could complete the task quickly*, and *The quality of the feedback was excellent.* Finally, the participants had to fill out the SUS questionnaire [Bro96] to get feedback about the usability of the introduced interface.

Drag-and-Drop Task

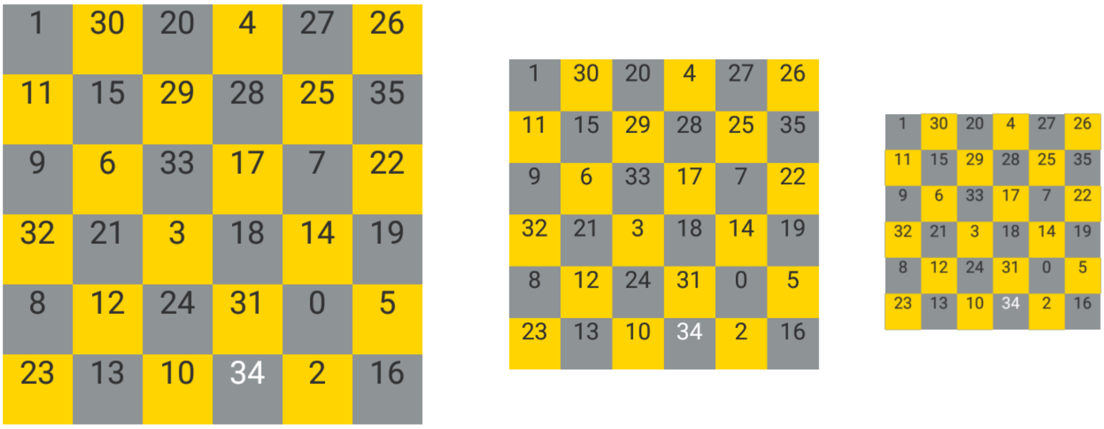
In this study, participants were asked to perform a drag-and-drop task by moving a disc as accurately as possible onto another (see Figure 4.26). We used a within-subject design to examine touch accuracy and user experience, through a (3x3x2) factorial design with 3 independent variables: screen orientation (levels: landscape and portrait), target disc size (levels: 1.0, 1.5, 2.0mm) and feedback type (levels: force, tactile and visual-only). The factors disc size and feedback type were fully randomized over the trials, whereas the factor screen orientation was counterbalanced. The dependent variables were touch accuracy and user experience. Touch accuracy was measured with an error rate in mm, representing the distance to the centre of the target disc. The user experience was measured through the questionnaire described above.

To examine touch accuracy, users had to drag one disc (the action disc) and drop it onto another (target) disc. As we specifically wanted to investigate the accuracy of the event, the participants were asked to do this as accurately as possible. Throughout the entire study the size of the action disk (diameter=4mm) was the same. The size of the target disc varied (diameter=1.0, 1.5, 2.0mm), with the largest target size chosen so that users still had a chance to see or estimate where the disc is located, without completely covering the target. In contrast, the smallest target was completely covered by the thumb when both centres intersect. Both discs appeared at random, but reachable, locations. Once participants assumed that the centre of the action disc was above the centre target disc, participants had to submit their position result by pressing a button with the other thumb.

We designed the visual feedback to be similar across different feedback types, while the perceived stimuli at the index finger/thumb were different. To initially select the action disc, users had to select it for at least 400ms. Thereafter, participants were able to drag the disc with their thumb. In the 'visual-only' mode there was only visual feedback. In the other conditions, tactile respectively force feedback was enabled whenever the centre of the action disc was inside the target disc, which means that either standard vibration was turned on or a 2mm force feedback event was rendered on the BoD.

Selection Task

In the selection task a within-subject design was used to examine touch accuracy and user experience. We used a 3x3x2 factorial design, with 3 independent variables: screen orientation (levels: landscape and portrait), cell size (levels: 3, 5, 7mm) and feedback type (levels: force, tactile and visual-only). Each user thus completed 36 trials. The factors cell size and feedback type were fully randomized over the trials, whereas the factor screen orientation was counterbalanced, so that participants completed all trials for the same screen orientation in one block. This avoids users having to constantly rotate the screen, which could lead to unnecessary fatigue and increased stress. The dependent variables



1	30	20	4	27	26
11	15	29	28	25	35
9	6	33	17	7	22
32	21	3	18	14	19
8	12	24	31	0	5
23	13	10	34	2	16

1	30	20	4	27	26
11	15	29	28	25	35
9	6	33	17	7	22
32	21	3	18	14	19
8	12	24	31	0	5
23	13	10	34	2	16

1	30	20	4	27	26
11	15	29	28	25	35
9	6	33	17	7	22
32	21	3	18	14	19
8	12	24	31	0	5
23	13	10	34	2	16

Figure 4.27: Exemplary representation of the different target matrix sizes in the selection task. Users had to select a specific cell in the matrix. Cells have alternating intensities (tactile) or heights (force).

were touch accuracy and user experience. Touch accuracy was measured with an error measurement in mm, corresponding to the distance of the touch centre to the centre of the selected cell. User experience was assessed with the questionnaire described above.

We used a matrix of abstract targets, as a representation similar to common interaction targets, such as menus, toolbars, tool palettes or links. Users were asked to search and select an element in a 6x6 matrix, in landscape as well as portrait mode (see Figure 4.27). The centre of the matrix was located exactly above the feedback pin. For each cell of the matrix a unique number from 0 to 35 was randomly generated. The number to be selected was visually marked. Users could then use the thumb of their dominant hand to select the cell as best they could, as close as possible to the centre of the cell. To submit the target position participants had to press a button with the other thumb. We chose three cell sizes of 3, 5 and 7mm for this study, based on earlier research on appropriate target sizes for thumb interaction [PKB06], [HKAI16].

Depending on the feedback type, we implemented different approaches to search for and select a cell. For visual-only feedback, as the name suggests, no additional cues were rendered. For tactile feedback, we provided vibration via the in-built functionality of the touchscreen device. This means that the feedback was rendered to the whole device, including the front screen. Since Android does not natively offer the possibility to change the intensity of the vibration, we used a binary approach, i.e., only on or off. Thus, vibration feedback was either switched on and off, alternating with the cells, with yellow cells receiving vibration feedback (see Figure 4.27). This enables the user to sense the transitions between cells. For force feedback we also alternated feedback with the cell matrix cell, but increased the intensity of the feedback towards the centre of the (whole) matrix, up to a maximum of 2.4mm in discrete steps, depending on the size of the matrix. For example, the step size was 0.8mm for the 6x6 matrix. We chose to increase the feedback towards the middle of the matrix so that users can not only sense the transitions from cell to cell (local position), but also determine the (global) position in the matrix based on the intensity.

Before each experiment, users were asked to explore each of the feedback modalities for about a minute. Completion time was measured per trial and logged for both tasks.

Results

Drag-and-Drop As the data were not normally distributed, we used a Friedman-test to analyse the data of the drag-and-drop task. The completion time in milliseconds per trial and feedback are listed in Table 4.3. The time difference between the conditions was not significant.

Table 4.3: Mean time and standard deviation per trial for the drag-and-drop task in seconds (standard deviation in brackets).

	portrait	landscape
visual-only	5.32 (4.42)	5.12 (3.95)
tactile feedback	6.66 (5.78)	6.01 (5.20)
force feedback	6.12 (5.03)	5.69 (3.61)

Through the error distance measure we identified that that users performed the task significantly more precisely with tactile and force feedback for both landscape ($\chi^2 = 11.03$, $df = 2, p = 0.004$) and portrait mode ($\chi^2 = 10.53$, $df = 2$, $p = 0.005$), see Figure 4.28. A pairwise comparison identifies a significant effect between tactile and visual-only (landscape $p = 0.099$/portrait $p = 0.042$) and force and visual-only (landscape $p = 0.013$/portrait $p = 0.006$). There was no significance between tactile and force feedback, according to the Nemenyi *post-hoc* test. Regarding the first hypothesis (H1), it can be concluded that haptic feedback on the back can improve touch accuracy compared to no feedback ("visual-only"). There was no difference between tactile and pin-based BoD feedback in this study.

The results for the questionnaire data (see Figure 4.29) identify that force and tactile feedback were perceived to be more precise. A pairwise Wilcoxon-test identified a significant effect for the accuracy ratings. Participants felt more accurate with force ($M = 6.0/SD = 0.9$; $W = 8, p < 0.001$) and tactile feedback ($M = 5.3/SD = 0.8$,

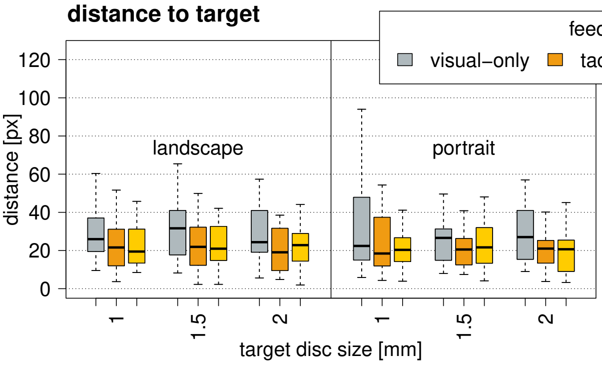


Figure 4.28: Box-plot for touch accuracy in the drag-and-drop study. For smaller target sizes force and tactile feedback have a significantly lower error than visual-only.

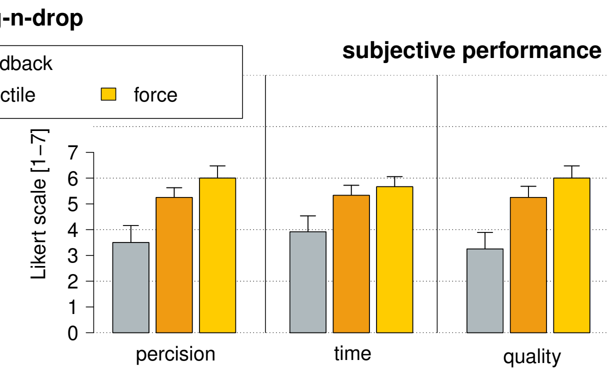


Figure 4.29: Subjective drag-and-drop performance in terms of precision, completion time and feedback quality.

$W = 17.5, p = 0.001$) compared with visual-only feedback ($M = 3.5/SD = 1.3$). The subjective scores of completion time reveals a similar trend. Thus users felt faster with force ($M = 5.6/SD = 0.8$; $W = 17, p = 0.001$) and tactile feedback ($M = 5.3/SD = 0.8$; $W = 25, p = 0.006$) compared with visual-only feedback ($M = 3.9/SD = 1.2$). Previous shows that hypothesis H2 is true for the drag and drop task. The assessment of self-performance increases with haptic feedback.

In conclusion, in both landscape and portrait mode tactile and force feedback were on average 1.3 times more accurate compared to visual-only feedback. This corresponds to a mean difference of about 1mm in touch accuracy between tactile and force feedback. The results also indicate a higher variance for the average accuracy without feedback compared to other forms of feedback. This can be interpreted as that the users felt more confident in their selection with tactile and force feedback than without feedback. Additionally, any potential offset between touch and pin position seems to have had no observable influence on accuracy and time per trial in the study.

Selection We were primarily interested in touch accuracy for the selection task. As the proposed BoD force feedback condition involved several intensity levels, this meant that participants were able to determine not only their local but also the global position in the matrix. Therefore, we assumed that the touch accuracy would be higher with force feedback compared to the visual-only or tactile conditions. As the data were not normally distributed, we applied a Friedman-Test instead of an ANOVA. We conducted a Nemenyi-Test to calculate pairwise comparisons between feedback groups in the post-hoc analysis. For sake of completeness, the means and standard deviations of the completion times per trial are listed in Table 4.4.

Table 4.4: Mean time and standard deviation per trial in seconds for the selection task (standard deviation in brackets).

	portrait	landscape
visual-only	3.28 (4.16)	3.24 (1.96)
tactile feedback	3.23 (1.72)	2.64 (1.40)
force feedback	3.66 (3.41)	3.30 (3.67)

We found a significant effect of touch accuracy in landscape mode ($\chi^2 = 7.75$, $df = 2$, $p = 0.021$). A pairwise comparison with the Nemenyi post-hoc test between visual-only, tactile and force feedback showed a significant difference between force and no feedback ($p = 0.016$), but no significance between tactile and no feedback. The analysis of the selection accuracy in portrait mode indicates also a significant effect ($\chi^2 = 14.53$, $df = 2$, $p < 0.001$). The post-hoc test for portrait mode reveals a significant difference of touch accuracy for force and visual-only feedback ($p < 0.001$) and tactile and visual-only feedback ($p = 0.010$). This demonstrates that BoD force feedback can increase touch accuracy in both conditions. Similar to the first task, the proposed feedback approach improves touch accuracy compared to no feedback. However, unlike in the first task, a higher touch accuracy was also found when compared to tactile feedback. Thus, hypothesis H1 is true.

This means users were able to select smaller targets with higher accuracy with force feedback than without. Users were able to select all cell sizes with a probability of 66.6% (force feedback), 63.9% (tactile feedback) and 59.7% (without feedback) in landscape mode. Considering only the smallest cell size (3mm) in landscape mode, users could select the cells correctly with a probability of 45.8% (force feedback), 37.5% (tactile) and 12.5% (without feedback).

In portrait mode the results look similar. Participants were able to select cells of all sizes with a probability of 68.1% (force feedback), 70.8% (tactile feedback) and 59.7% (without feedback). Considering only the smallest cell size, participants were able to select the cells with a probability of 37.5% (force feedback), 41.6% (tactile feedback) and 20.0% (without feedback). Figure 4.30 depicts the results for all cell sizes.

The questionnaire data was evaluated using a pairwise Wilcoxon-test, which indicates that both accuracy and time per trial were significant (see Figure 4.31). Participants felt more accurate with force ($M = 5.9/SD = 0.8$; $W = 6, p < 0.001$) and tactile feedback ($M = 5.3/SD = 0.8$; $W = 15.5, p < 0.001$) compared with visual-only feedback ($M = 3.3/SD = 1.3$). Additionally, users felt also faster with force ($M = 5.7/SD = 0.9$;

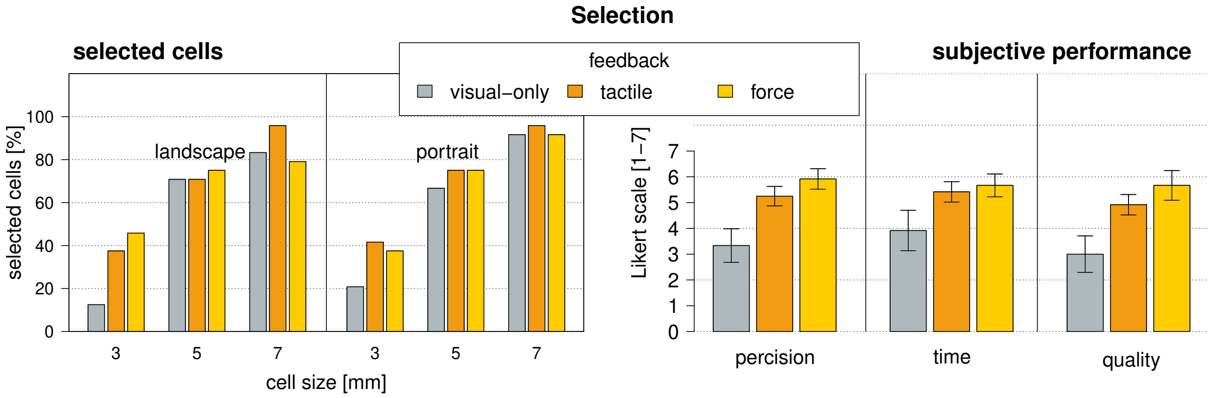


Figure 4.30: Percentage of successfully selected cells per size and mode. The influence on accuracy without feedback decreases dramatically as soon as the thumb covers the target.

Figure 4.31: Subjective selection performance in terms of precision, completion time and feedback quality. For all three parameters participants liked force feedback most.

$W = 23.5, p = 0.004$) and tactile ($M = 5.4/SD = 0.8$; $W = 28, p = 0.009$) feedback than with visual-only feedback ($M = 3.9/SD = 1.5$). Haptic feedback also leads to a higher subjective performance in the selection task, which means that hypothesis H2 can also be accepted for the second part of the study.

The improved selection accuracy of smaller targets is an important finding, extending previous research in BoD interaction, such as [WFB$^+$07], showing that haptic feedback is also a valuable method to overcome occlusion problems. When looking at the smallest cell size of 3mm, force and tactile feedback can on average increase accuracy by a factor of 2.5 compared to visual-only feedback. This means that the presented feedback mechanism can improve selection tasks, including text selection, considerably.

Participants filled out the SUS questionnaire to evaluate system usability. They rated our new system on average at 81 with a standard deviation of 13. According to Bangor et al. [BKM09] this means that the average is between "good" and "excellent" usability.

4.4.4 Application scenarios

To show how HapticPhone supports higher-level tasks, we implemented three applications that extend the basic (low-level) functionality demonstrated in experiments (see Figure 4.32). These applications demonstrate other instances where force feedback at the BoD is also useful.

Figure 4.32: Exemplary application scenarios for the proposed BoD force feedback approach: (top), a volume viewer, a racing game, a map viewer, all supported by force feedback on the back of the smartphone. The different pin lengths are an example of how data can be mapped to the pins.

Pressure input. We implemented a *3D Volume Viewer* application based on stacked images that can be explored through pressure input. In the first iteration, the applied pressure was directly transferred to the intensity of the servo motor. In this case force feedback was used to enhance scene navigation, as force feedback indicates where the user is in the scene: feedback is spatially compliant, as it is based on displacement with more/less pressure. Specifically, the user can directly feel if the currently viewed slice is further up or down in the 3D volume stack, aligned with the displacement axis. Thus, we assume that force feedback can be useful to afford more precision for finding a given layer in a volume.

Height perception. We created a *Map Exploration* application that supports simultaneous exploration of multivariate, map-related data. With normal map viewers, exploring multivariate data in parallel can become difficult. Thus, complex visualization methods are normally needed for such scenarios. In our application, we pass different geographic data to different feedback elements, e.g., output elevation profiles via a servo and map environmental pollution data to tactile stimuli. This choice effectively implements multi-channel feedback to provide feedback about different aspects of the data. The application builds on the JND results, which showed that users can interpret fine differences through force feedback. We assume this accuracy can assist users in finding, e.g., a location on a map that is desirable in multiple dimensions.

Gaming experience. Finally, in a *2D Racing Game*, we explore a combination of pressure input and height perception. Here, the car is steered through the touch position and input pressure is mapped to speed, while force feedback gives indication of the speed, by mapping the speed to the force pin. While force feedback has been shown to improve fun and immersion [LB13], we specifically targeted subjective control accuracy here.

4.4.5 Discussion

In our first study, we assessed if relayed feedback at the back of a device can support touch-based interaction on the front. Doing so, we explored different back-to-front feedback mappings to investigate both perception (psychophysical limits) and performance. In our second experiment, we showed that relayed feedback can indeed improve both objective and subjective performance. In some instances results are comparable to tactile feedback, while in others (selection accuracy of small targets) objective and subjective performance and preference are better, which demonstrates the potential of our approach.

Here, we discuss important factors that need to be considered when applying back-to-front relayed feedback in applications.

Design space In our device design and studies, we only explored a subset of the whole design space afforded by interaction on the back of a smartphone. A smartphone provides many different input and output modalities at different locations, which can be combined to create different mappings. e.g., a microphone, speaker, buttons, or notification LED are normally located at the front, while a fingerprint scanner, torchlight, or camera, are typically located at the back of the device. Consequently, the design space has many dimensions, as the same hardware mapping can be used to elicit different back-to-front feedback N:M mappings, especially for force feedback at the BoD.

Direct vs. indirect mapping Feedback can be directly or indirectly mapped. While we studied only directly mapped feedback, where a direct connection between the type of action and feedback exists, indirectly mapped back-to-front actions are also possible. Moreover, similar to tactile or auditory warnings, back-of-device feedback can communicate information about other processes than the one the user is involved in, for example to draw attention to a notification. Additionally, the presented prototype could also be used to enable in-pocket or other eyes-off interaction.

Spatial compliance We explored spatially compliant and non-compliant feedback. Our feedback mechanism provides displacement along a single axis, afforded by the mechanical constraints of the servo. When users press down on the screen, force feedback that moves the index finger away from the phone is spatially consistent, which matches the direction of the touch input action. Our analysis of the results indicates that users could interpret such spatially consistent feedback well, also because such consistency was preferred by users. Users stated that spatially inconsistent feedback, for example mapping up/down dimple displacement to sliding left/right, was more difficult to interpret.

Range and resolution Remapping values to work within the provided (force) range is an issue for spatial consistency, in particular when fine-grained feedback is required. The resolution of actuation is both a technical and human issue. Technical limitations may affect the physical range and levels of feedback one can provide. With our current device, the range was a physical displacement of 5mm, with 160 steps. Through the just-noticeable difference experiment, we showed that users can detect differences of around 0.1 mm, showing the differentiable range is high.

4.4.6 Conclusion

In this section, we presented a concept of back-to-front relayed feedback on smartphones and discussed the results of our evaluations. HapticPhone is a continuation of the two prototypes presented in the previous sections, with the claim to make haptic feedback more mobile and compact. According to research question (RQ1) we showed the possibility of haptic feedback being implemented together with a smartphone; additionally, we showed how to improve touchscreen accuracy. Our design and studies focused on a novel smartphone interface that provides servo-actuated force feedback at the back of the device, which overcomes physical form-factor constraints for providing force feedback on the front. The prototype and the evaluation answer our sub-question 3 and serve to achieve Aim 1. In contrast to Jang et al. [JKT+16], who have also researched haptic feedback for smartphones, we use the smartphone's rear for feedback and not its edges. Our approach allows direct feedback, as thumb and index finger are connected more naturally. Through numerous hardware iterations we have also noticed how important a stable grip and ergonomic aspects are. Experience has shown us that both aspects are very important when designing a compact device. With the acquired knowledge, further development and refinement could take place in this area in particular. The questions could be, how can different finger lengths be supported and how can a stable grip be guaranteed.

Through our evaluations, we showed that relayed feedback can improve interaction on the frontal display. Based on the results, we discussed several factors affecting the relayed back-to-front feedback paradigm. Beside our developed prototype we would like to summarize our main findings:

- Psychophysical analysis revealed that perception of force stimuli using the presented mechanisms resulted in a Weber Fraction (8.29%) that is comparable to other devices, confirming that feedback works appropriately and affords the perception of fine differences.

- Both selection and drag-and-drop task show encouraging results. In most situations, force and tactile feedback performed about equally well. For both selection and drag-and-drop, as expected, feedback yielded much better objective performance than without. Accuracy for small targets was increased by factor of 2.5 (for selection) and 1.3 (for drag-and-drop). Especially for selection of smaller targets, force feedback can produce better results than tactile, extending previous findings that showed the potential of back-of-device interaction for selection of smaller targets [WFB+07]. Users preferred force feedback over tactile or no feedback, feeling more accurate, yet not faster. Thus, in terms of subjective performance, force feedback was the best option.

As a next step, we intend to look into eyes-off interaction and how to easily code informations using a pin-based approach, can these pins also be used as input. Another direction could be, looking at factors affecting relayed feedback points to the potential for many different types of devices, for example those that can flip or move. We did not discuss these options, as this is beyond the scope of back-to-front feedback relay. Finally, as HapticPhone already is a fairly compact design, we are considering if it can be offered as a compact extension to existing smartphone setups.

4.5 Summary

All three sections in this chapter have shown how versatile the approaches for augmenting touchscreens with haptic feedback can be. All three objectives were achieved. ForceTab, our first prototype actuates the whole touchscreen through a motion platform. With this prototype, we were able to show the limitations and advantages of haptic exploration through three sub-studies (Objective 1). With regard to our hypotheses, it was shown that the users can clearly distinguish between three different resistance levels. Furthermore, it was shown which shapes can be perceived via the implemented feedback mechanism. It is not possible to perceive complex shapes without visual support. Larger shapes or a slower exploration speed increases the recognition rate. When finding and differentiating a specific region, it can be said that smaller differences are harder to identify and that the shape has an influence on the accuracy. Finally, the approach of finding a specific region with haptic feedback is very well suited, and the users were able to achieve a good result regardless of the shape.

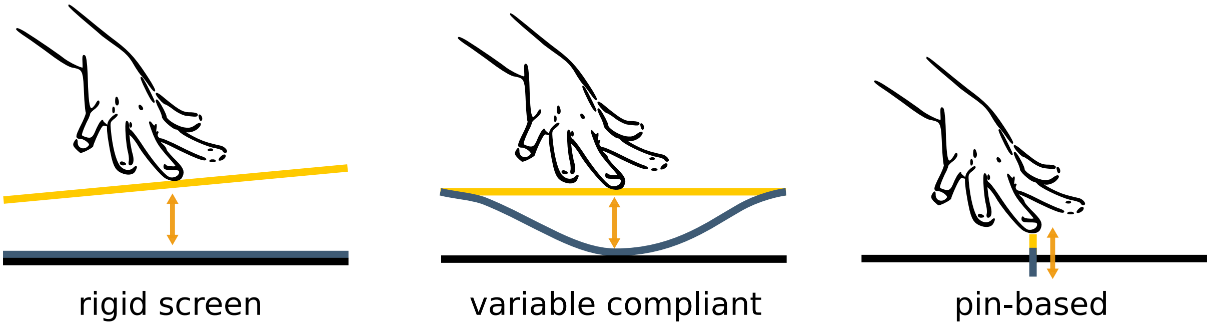


Figure 4.33: Sketch of implemented haptic feedback approaches. From rigid to compliant to pen-based haptic feedback. All three approaches extend the interaction with a touchscreen (black). Yellow and blue symbolised possible actuations.

With our second prototype, the second objective was realised. A prototype was developed that uses an elastic material above a touchscreen to provide haptic feedback. The material's tension can be changed using servo motors, thus creating different levels of resistance, enabling a novel haptic exploration. In the most relaxed state, the touchscreen can also be included in its original rigid form. We were able to identify the perceptional threshold for a press and a slide event through a psychophysical study. The results of the study were incorporated into an application that has been presented.

Finally, HapticPhone was presented. There were two challenges to overcome: firstly, to combine haptic feedback with a mobile touchscreen (smartphone) and secondly, to increase the touch accuracy with the help of the designed feedback approach (objective 3). As with the previous prototypes, a perception study was first performed in order to identify the limitations. Subsequently, two standard tasks (selection and drag-and-drop) were explored to show the influence the implemented haptic feedback. The third sub-question could thus be answered, a smartphone prototype that supports a pin-based haptic feedback approach has been developed. Additionally, both of our hypotheses in this section could be accepted. The presented approach can increase the touch accuracy as well as the subjective perception of the performance.

The creation and evaluation of the three prototypes presented have shown the multifaceted possibilities of the interplay between haptic feedback and touchscreen interaction. Research question 1 was addressed in different ways with all three prototypes. The results of all studies are included in the answer RQ1. Several improvements could be shown, limitations identified and several approaches demonstrated, reflecting the versatility. The haptic feedback range regarding touchscreen interaction was extended by 1) an actuated tablet providing rigid haptic feedback, 2) a variable compliant feedback approach using a stylus and 3) a back-of-the-device approach providing pin-based haptic feedback. The studies, conducted in Section 4.2 provided an understanding of the capabilities and limitations of comparable platforms such as those used by Kim et al. [KHSK14]. The system of Sinclair et al. [SPB14] showed a better recognition rate in 1-DOF, but compared to our study, users could see the visual display device, which strongly supports the identification of shapes [Gru08]. The interface presented in Section 4.3 shows further possibilities and exceeds previously presented pen interfaces [CBMB16], [WRSS16]. Finally, a third feedback mechanism for smartphones has been introduced (Section 4.4), which makes use of the back of the device. The variety also becomes visible when comparing the two psychophysical experiments. Looking at the participants' comments, it becomes clear that the differentiability of flexible material was more complicated compared to our pin-based feedback. From a technical point of view, both experiments are difficult to compare, since one was done with a pen and the other provided feedback directly on the index finger. Looking at the haptic exploration and perception described by Lederman [LK09], FleXurface could instead be put into the category pressure (hardness), while ForceTab fits into the category global shape; however, there is no clear category for HapticPhone. Additionally, the wrist also plays a role in perception. Just as ForceTab and FleXurface allowed partial wrist movements, HapticPhone only moved the fingers.

To conclude, in this chapter, we have explored three different approaches to augment touchscreens. We have studied performance and perception-based aspects. In the next chapter (see Chapter 5), we will continue exploring haptic interfaces and address the second research question of this thesis. Instead of touchscreens, we will explore haptic interfaces in virtual and remote environments. Specifically, two prototypes will be presented that investigate perceptual aspects.

Chapter 5

Foot Haptic Interfaces for VE and RE

5.1 Introduction

While the previous chapter (see Chapter 4) dealt with the augmentation of touchscreen interaction with haptic feedback, thus mainly focusing on hand-driven interaction. Doing so, three prototypes were presented, all pursuing a goal: introducing novel ways of haptic feedback. Accordingly, we explored aspects such as touch accuracy, the perception of shapes and recommended a set of application scenarios. In this chapter, additional haptic user interfaces are introduced, the focus shifts from user interfaces designed for the hands to interfaces focusing on the feet. Therefore, unconventional interface concepts will be considered. While the first three prototypes were confined to touchscreen interaction, in this chapter, we will explore how haptic feedback on the feet can affect realism within virtual and remote environments. In the following, remote environments are considered as telepresence as well as virtual reality scenarios. Since in both cases, the user immerses in either an artificial or remote environment.

In line with the previous chapter, further haptic user interfaces are presented. Specifically, this chapter addresses the second research question (RQ2):

> **How can foot haptics for navigation tasks be designed to improve self-motion perception and spatial awareness in virtual and remote environments?**

Similar to the previous chapter, we will pursue objectives (Objective 4 and 5) in this chapter, which will help to achieve Aim 2. Additionally, for this purpose, two sub-questions were formulated in Section 2.3.2 in order to answer research question 2. The wide spectrum of haptic feedback design remains and is also visible in the following sections.

There are many ways to provide haptic feedback, and of course, we can haptically stimulate any part of the body that is capable of doing so. However, the feet were chosen because we see great potential in foot-based haptic feedback. Firstly, they are rarely involved in the interaction between human and computer and are, therefore, unlike the hands, "free". Secondly, the feet are also haptically stimulated in everyday life - for example, when walking. Thus, for some applications, it can be useful to experience similar stimuli as in real life. Several haptic feedback interfaces in each of our application areas have been presented in the Chapter 2. For example, research on the simulation of ground textures was introduced [NNTS12], [PFC$^+$10], to make the user experience more realistic.

However, the literature review has also shown that there are still open questions. Therefore the following chapter is dedicated to answering RQ2. In order to do so, objective 4 was implemented with our fourth prototype. An approach was developed that maps spatial data of a remote environment onto the user's feet to increase spatial awareness. To sense the remote environment, a telepresence robot is extended with a for this purpose developed sensor ring. The fourth sub-question (RQ 2.1) was to investigate *how foot haptics support the user's awareness when interacting in remote environments.* Of course, there are many approaches that use haptic feedback combined robots, however, they are mainly used for assembly support [HWMZ91], when handling dangerous objects or to navigate unmanned vehicles [JS19]. All of them have only one main task, unlike in our system where the social component is more important than the manipulation of a robot. With our interface, proximity (vibrations) and collision (small impacts) cues are passed from the remote robot to the feet. More specifically, to the side of the feet, as these reflect the main directions (forward, backward, left and right). We will present two studies that address the challenges and direct our attention towards Aim 2 to address RQ 2.

Our fifth and final prototype is designed for use in virtual realities. It has been designed to implement cue combinations using two interaction metaphors to investigate *how can haptic feedback be designed to enhance self-motion perception in virtual environments?* (RQ2.2). Through an exploratory study with five different sessions, we will implement objective 5. Which will further contribute to answering RQ2. It additionally explores how foot-based haptic feedback can be used to improve realism and related aspects of perception in a standing and sitting condition. As mentioned previously, this chapter addresses research in the areas: virtual reality and telepresence. For both cases the prototypes itself will be presented, similar to the previous chapter, the design of the studies performed and the results achieved will be presented and discussed.

5.2 Foot-based Haptic Proximity Cues in VE und RE

Telepresence robots are mobile platforms allowing people to interact remotely. A mobile telepresence robot typically contains a video conferencing system, and it can be controlled from the remote. They can enable people to participate remotely in a variety of spaces and situations, including remote attendance at academic conferences [NVPH16], [RN17], home schooling [NO17], and remote office work and meetings [RTM12]. Research has identified benefits for mobility in remote spaces and situations, including an increased sense of social presence [YJNS18]. However, despite these advantages, it is not always straightforward when using a telepresence robot and being aware of the surrounding environment, especially in crowded places such as conferences and social meetings, where large numbers of people move around, often unpredictably [RN17], and where people often try to follow or actively participate in conversations.

In order to support users to immerse stronger into a remote environment and to become more aware of spatial structures, we have developed a haptic feedback approach. The prototype could also help users to navigate the robot more precisely while at the same time increase spatial awareness and confidence of the user. When using the interface, users have to simply place their feet inside the system and receive haptic feedback on their feet when approaching obstacles in the remote space (Figure 4.32). The main objective of the user interface is to provide additional non-visual feedback on the physical space in the remote environment to the users so that they can better identify and understand obstacles and make improved navigation decisions. Another aim is how this type of feedback can be designed to enhance the feeling of spatial presence, since a greater presence cloud sometimes lead to more focus and investment in an activity or space. We specifically chose the feet in order to keep the hands free for other tasks, including using a keyboard/mouse or gaming controller to drive the robot. Additionally, the orientation of the feet helps to provide directional feedback, as feet, unlike the hands, normally reflect the direction of movement. Therefore, users should be able to infer the direction an obstacle is at based on where on their feet they feel the feedback. Even more so, the feet might naturally bump into things when moving about a space in person, and are not typically used at all to interact with telepresence robots.

Two user studies were conducted to explore the potentials and limitations of the designed user interface. The goal of the first study was mainly to gain an early understanding of how it affected users' behaviours in a virtual environment as well as their understanding and awareness of the environment. Moreover, this first study sought to explore the potential impact of the system on spatial presence, i.e. the feeling of "being there" [WS98]. While the first study was a strong controllable environment, the second study, focuses more into real environments or scenarios, respectively. Here, the goal was to study how people would use and experience the system while driving the robot in an environment with other people and obstacles.

5.2.1 Implementation

In many telepresence configurations, both visual as well as audio channels are already used for the key activities (e.g. talking to people, looking at objects, etc.). Consequently, it is important aspect of the introduced haptic feedback is that an unused sense for spatial perception in included to ensure that other sensory channels remain free for other activities. Therefore, we have chosen the feet as target of the interface, as it is often the first part of the body that is touched when a person walks into something or is bumped by something and the feet can be seen as the natural place for providing this kind of feedback. It may also be one of the best places on the body to provide directional (i.e., left, right, forward, backward, etc.) feedback, as it is easy to place sensors all around the users' feet and keep them relatively stable (e.g., versus their hands, which may move frequently throughout use) when users operate the system while being seated. In addition, the feet normally point forwards or in the direction of walking, and thus they make a good virtual reference point.

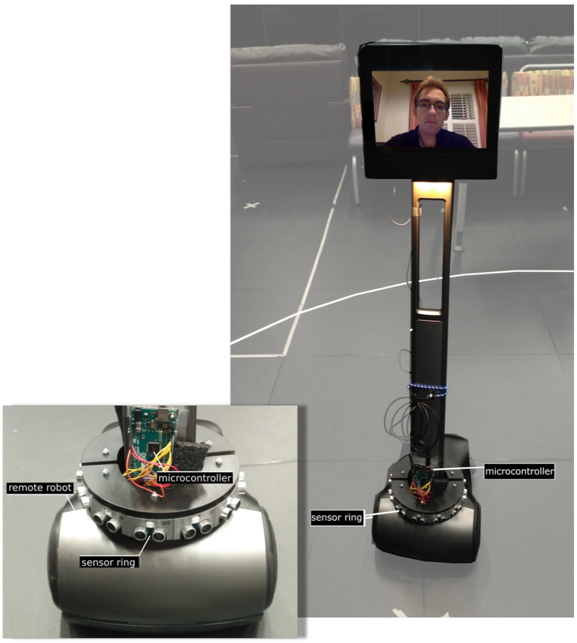


Figure 5.1: The ring consisting of 12 ultrasonic distance sensors attached to the Beam+ telepresence robot enables 360°coverage with a radius of up to 4m.

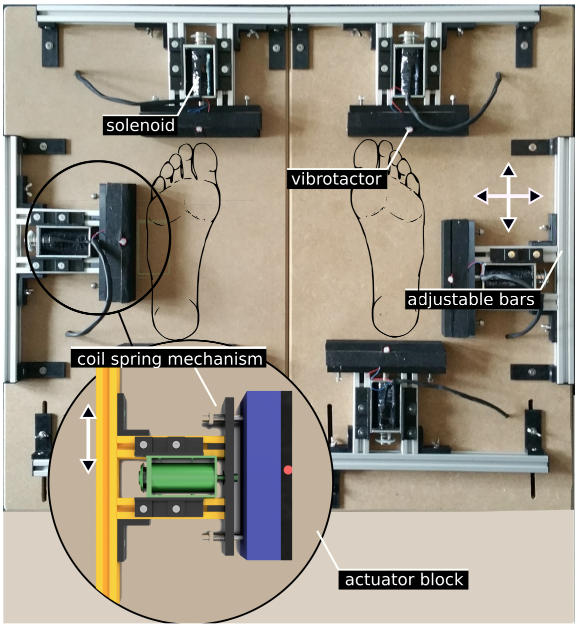


Figure 5.2: The foot platform consisting of six movable actuator blocks. In the detail drawing the vibration motors in red (proximity feedback), the solenoid is shown in green (collision).

In our experiments we used an augmented version of a Beam+ telepresence robot created by Suitable Technologies. The Beam is 134 cm tall with a 25.4 cm (10 inch) LCD monitor and a maximum speed of 2km/h. Two wide-angle HDR cameras are attached to the robot. One camera points towards the floor to provide a navigational view (e.g., it shows other people's legs and feet), while the other points forward to show other people (e.g., their bodies and faces) and the environment. We extended the telepresence robot with a purpose-built sensor ring (see Figure 5.1) consisting of 12 ultrasonic range sensors (HC-SR0). Our prototype system is composed of a high-density wood and aluminium foot platform to which actuator blocks are attached (see Figure 5.2). Users remove their shoes and place their feet within the foot platform. Based on the distance sensors on the robot's sensor ring, users receive directional vibration cues when an object is sensed, and vibration frequency increases as the object gets closer to the robot. Once an object is in a predetermined collision range, a solenoid is triggered and provides a soft but noticeable impact to the user's foot. This is similar to a collision with a wall, but before actually hitting an obstacle, so users have enough time to avoid a collision. An overview about all components is depict in Figure 5.3.

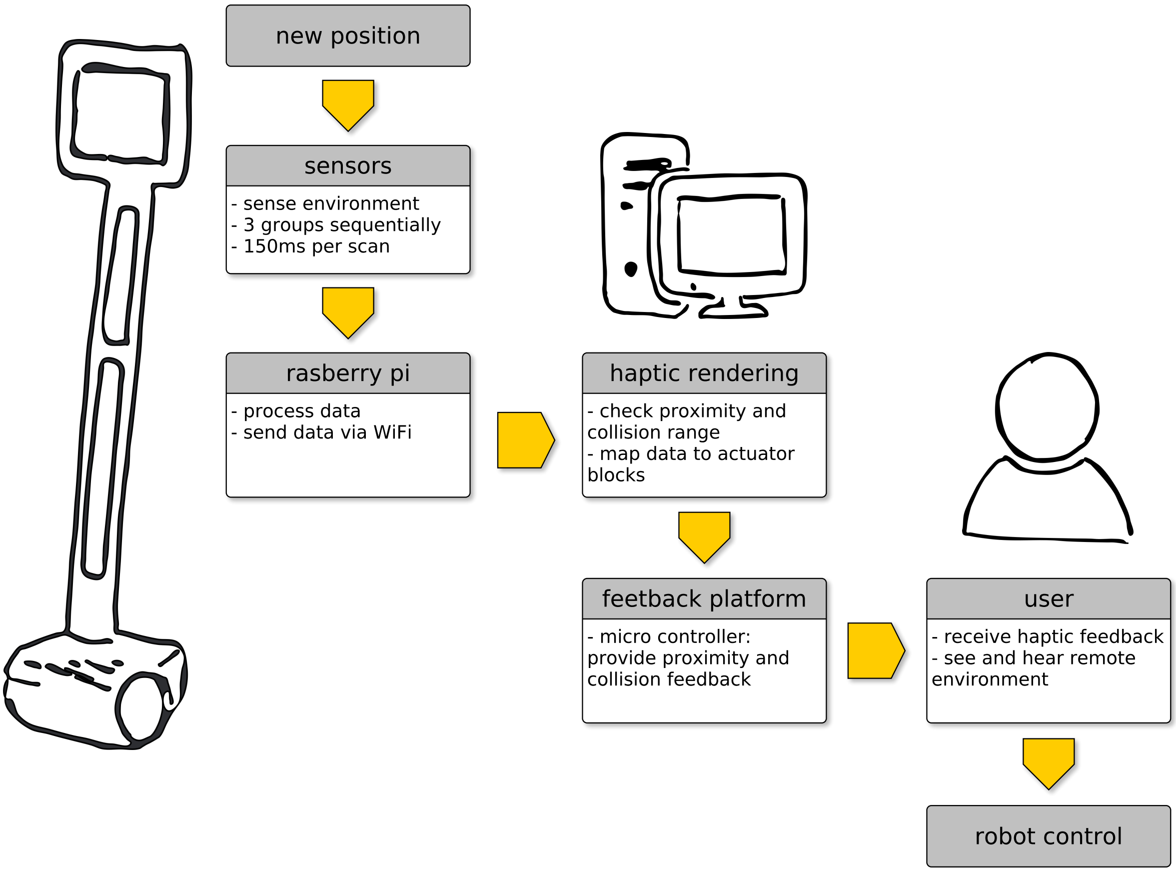


Figure 5.3: A schematic representation of the whole interface and its components. An iteration from sensing to robot control is shown.

Sensor Ring Design

The distance range afforded by the sensors on the ring is between 2 and 400 cm at a frequency of 40 kHz, with a horizontal sensing cone of 30°. As such, the robot can detect objects in a radius of approximately 400 cm around the robot. The selected sensors are sufficient for the requirements of the interface, as we initially aim to collect feedback in both following exploratory studies. For higher precision or faster response times, an optical sensor, for example on a laser basis, would probably be recommended.

The sensors were connected to a Raspberry Pi 3 (Rev3 Model b+). In order to cover 360° and to avoid signal overlap, all 12 sensors were grouped into 3 disjunct classes. This allows controlling all 3 groups sequentially with a delay of 50 ms, so that the entire area can be scanned within 150ms with an accuracy of up to 3mm according to the specification of the sensors. A microcontroller (Arduino Uno Rev3) manages the introduced grouping and collects distance data from the sensors, and passes it to a Python script on the

Raspberry Pi. All distance data are then sent via Wi-Fi to the remote-control PC using OpenSoundControl. Both the Arduino and Raspberry Pi are self-contained, powered by the robot's battery using the 5v connections provided.

Feedback Design

The foot platform contains a series of actuator blocks as illustrated in Figure 5.2, individually adjustable by moving the bars to support most foot sizes (between 21.0cm and 30.0cm). An actuator block consists of a vibration motor (Precision Microdrive 304-116), a solenoid (ROB 10391, 36V), and a coil spring mechanism to provide a movable linkage required for collision feedback. For a more comfortable fit, a 1cm thick of compressible firm foam is attached to the foot-directed surface. A 5mm cylindrical vibration motor was integrated into the foam to provide tactile proximity feedback. Our prototype platform consists of three actuator blocks per foot, mounted at the front, the back and the outer edge of each foot. In addition, the six locations of the actuator blocks reflect potential collision points of the real robot. Both inner sides of the feet were not equipped with actuation blocks, as there is no potential collision point at these locations. Two Arduino Mega were used to control all actuator blocks, one for each foot. In addition, a graphical user interface displays the distance data of the sensors and allows the configuration of the parameters, such as proximity range.

Since 12 sensors were required to cover 360°, a mapping was necessary to map the 12 sensors to the six actuator blocks on the foot platform. Both the left and right sensor groups were explicitly assigned to the corresponding actuator blocks. Each front and back actuator block shared a front and rear facing sensor, plus a position-dependent neighbour that was added either to the right or left block. In order to guarantee unique feedback to the users, no cross-fade occurred, the feedback group that recognized the closest obstacle was activated.

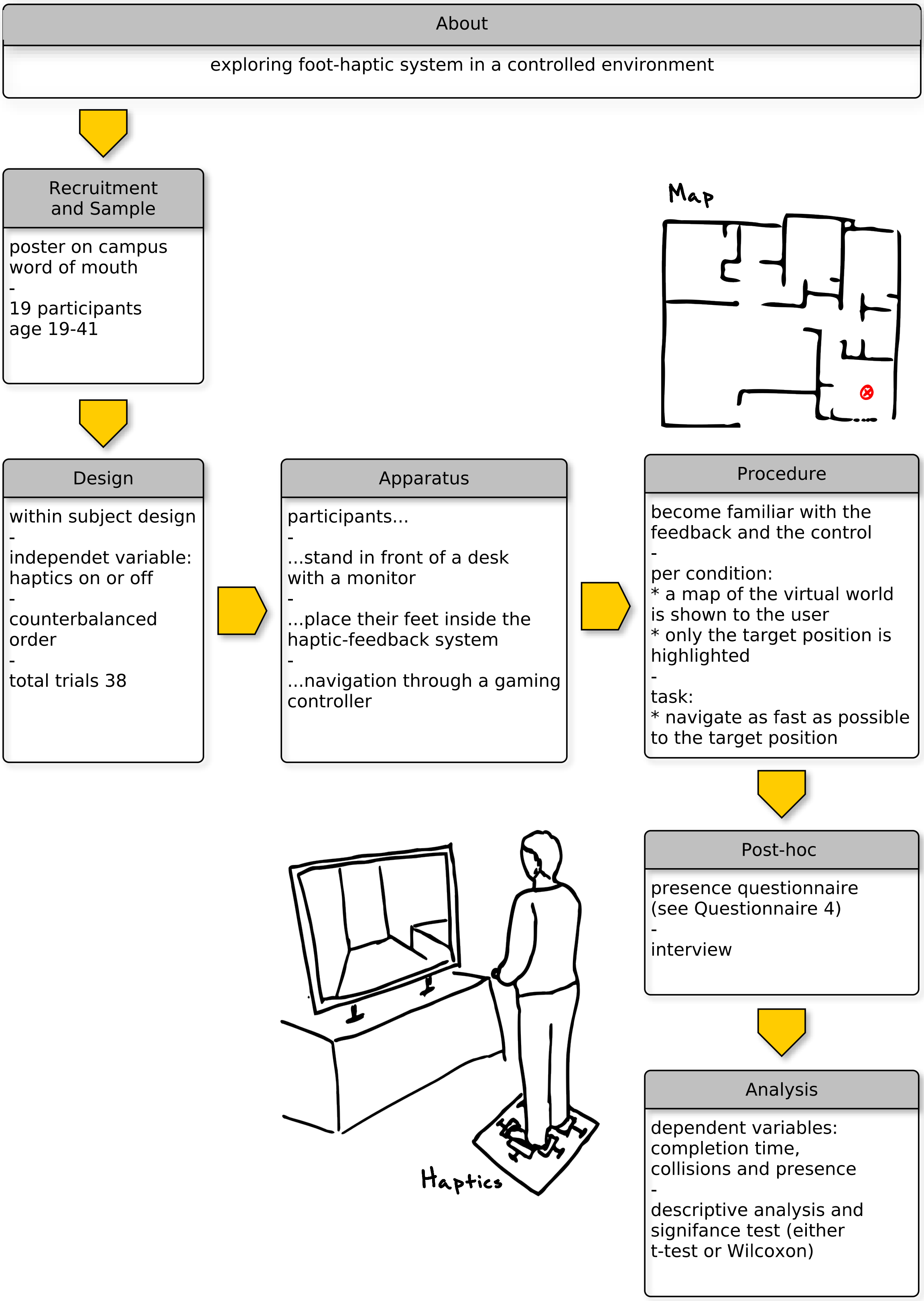
The design of the foot platform was made to be easily adaptable to different foot sizes. The design allowed us to easily and quickly adjust the vibrotactile contact points so that they touch the user's feet on all sides (front, back, left, right), thus allowing the user to feel the feedback on all sides. While we could have instead designed a different form factor (e.g., a pair of shoes), we chose the platform design because it was a good balance between (a) making sure all of the motors touch at the right points (for directional feedback), ensuring proper feedback, and (b) being easy and quick to adjust to the various foot sizes of our participants. The form factor was not ideal (i.e., big and bulky). However in our studies we mainly focused on the higher-level idea of providing gradual directional haptic feedback in telepresence situations instead of the underlying technology.

Two major modes for proximity feedback are supported in our implementation: *continuous vibration feedback* that increases the intensity and *pulsing feedback* that increases frequency in relation to the distance when an object is sensed. The closer an object gets to the robot, the higher the intensity or frequency of the vibration, respectively. Our implementation supports a linear as well as a polynomial proximity function, and an adjustable range for activating proximity and collision feedback. In addition, the duration of the collision feedback and a maximal intensity for proximity can be adjusted. Both amplitude and the frequency of vibration are determined by the hardware and ranges from 0-1.4g (amplitude) and 0-300Hz (frequency). This means that the bump of the collision is clearly distinguishable from the vibration. Values chosen for the current studies were based on pilot testing.

5.2.2 Experiment 1 - Virtual Environment Navigation

The aim of the following two studies is to gain an understanding of how the introduced interface affects users behaviour and their perception of spatial presence. The key difference between both experiments is that the first was conducted in a virtual environment, so that all parameters were well controllable. In contrast, the second study was designed to evaluate the system in real world scenarios. This means that in our first study we used the haptic feedback platform for the feet, but the telepresence robot was simulated in a virtual environment (see Figure 5.4). For an initial exploratory evaluation this has several advantages: firstly, a prototype can be developed quickly and adapted if necessary. Secondly, if the feedback has a negative effect on the robot's navigation, neither the environment nor the robot can be damaged. Both visual feedback and robot control were adapted to the real use of a Beam+. For example, as in the second study, the users use a game controller to operate the robot. The first study was mainly designed to test the following hypotheses:

H1: Proximity cues on the feet increase spatial awareness while navigation in VR.
H2: Users will complete the task faster with the proposed feedback approach.
H3: With haptic feedback, users will make fewer collisions.



About

exploring foot-haptic system in a controlled environment

Recruitment and Sample

poster on campus
word of mouth
-
19 participants
age 19-41

Design

within subject design
-
independet variable:
haptics on or off
-
counterbalanced
order
-
total trials 38

Apparatus

participants...
-
...stand in front of a desk
with a monitor
-
...place their feet inside the
haptic-feedback system
-
...navigation through a gaming
controller

Procedure

become familiar with the
feedback and the control
-
per condition:
* a map of the virtual world
is shown to the user
* only the target position is
highlighted
-
task:
* navigate as fast as possible
to the target position

Post-hoc

presence questionnaire
(see Questionnaire 4)
-
interview

Analysis

dependent variables:
completion time,
collisions and presence
-
descriptive analysis and
signifance test (either
t-test or Wilcoxon)

Figure 5.4: A diagrammatic representation of the study design, structure and procedure as well as the methods of analysis.

Participants

A total of 19 participants were acquired either via social media postings, posters on our university campus or an online study registration system for the students of our department.. The participants were 19-41 years old (M=24/SD=5), 12 women, six men and one non-binary gender. Most participants were students, while the others were casual workers. All the participants took part in the study voluntarily and no money was paid for participation.

Apparatus and Procedure

As the first study was designed to have a greater influence on the environmental parameters, it has been performed in a simulated virtual environment. To do so, the participants stood in front of a large television screen and navigated a virtual robot through a 3D scene. In order to simulate the real distance sensors, a ray-casting approach was implemented to determine the distance between the robot and the environment, as well as mappings for collision and proximity ranges were computed.

We used an within subject design. All participants had to operate the robot two times along a similar, but not the same, track, in a counterbalanced order - once with and once without the proposed feedback. Both tracks were defined by a start and an end position. The display we used was an 147 cm-wide TV screen (in 16:9 format) standing on a 75 cm table. Participants stood about 1m from the screen, and stood in the same position in both conditions. Controlling the robot was also the same in both conditions (with and without feedback), and users were limited to only use the analogue stick of a PlayStation 3 controller for navigation. During navigation a sideways shifts (strafing) was excluded, so that navigation only allowed forward or backward movements and turns to the left or right. Based on pilot testing, we used a collision range of 20cm and a proximity range of 2m with a linear proximity function. Maximum intensity of the tactile feedback was set to 100 % (about ± 1 G peak amplitude; about 240 Hz) and the solenoids were driven with 24 V.

Before each condition the participants were asked to test-run the particular interface. This training was intended that the user get used to the system and to get an understanding of how the system, especially the feedback works. The test-run scenario was a small virtual room that contained objects. As soon as the participants felt confident in using the system they were asked to began the task. Per condition all participants were given an overhead map of the virtual environment and they were told where the final position was located.

They were not told where their starting position was (i.e. they had to find out where they were in the surroundings). To further look into spatial presence aspects, the virtual environment includes walls, static obstacles and moving avatars. In both conditions, a click sound played whenever the simulated robot collided with an object or an avatar. The sensation of the subject's spatial presence was measured with a slightly modified version of the Witmer & Singer questionnaire [WS98]. The modified questionnaire asked 19 questions on 7-point Likert scale and measured six different aspects of spatial presence (see Questionnaire 6), which were combined to give a general understanding of spatial presence. The six individual factors were: realism, possibility of action, quality of the interface, possibility of investigation, self-assessment of performance.

The modified questionnaire is the same as the original, except that three questions on sound and two questions on haptics (questions 20-24 in the Witmer & Singer questionnaire) have been removed. The three sound questions have been removed as the virtual environment did not have much sound. The two haptics questions have been removed for two reasons: haptics was not part of the experience for the no-feedback condition, and we were interested instead in the impact that haptic feedback had on the other six individual factors measured in the presence questionnaire.

As mentioned above, the order of both feedback conditions and environment layout were counterbalanced. After completing the study tasks, we conducted short semi-structured interviews with participants to get their thoughts about the interface and its feedback. In total, each navigation task took approximately 5-10 minute, while the survey took 10-15 minutes to complete, and interviews lasted about 5 minutes. The quantitative data was analysed using dependent (repeated-measures, within-subjects) t-tests. A Shapiro-Wilk test was used to test the normality of the data, and Wilcoxon Signed-ranks test were used in place of t-tests when the data was not normally distributed. All data were analysed using the statistical functions of SciPy an open-source software for mathematics, science, and engineering [1].

Results

Quantitative Findings The Witmer and Singer Presence Questionnaire was chosen for analysis as it is important to know to what extent the users felt involved into the remote environment. In accordance with the questionnaire, the following six factors have been assessed: presence, realism, possibility to act, interface quality, possibility to examine and self-evaluation of performance. All six factors were questioned for both study

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[1] SciPy.org https://docs.scipy.org/doc/scipy-0.14.0/reference/index.html

conditions (with haptics, no feedback). All results are shown in Figure 5.5; the box-plots represent the means (circle), medians, first and third quartile, minimum and maximum plus detected outliers. A significant effect was found for two factors (presence and realim). Since one participant answered only some of the items on the questionnaire, the following results refer only to the 18 participants who answered all questions.

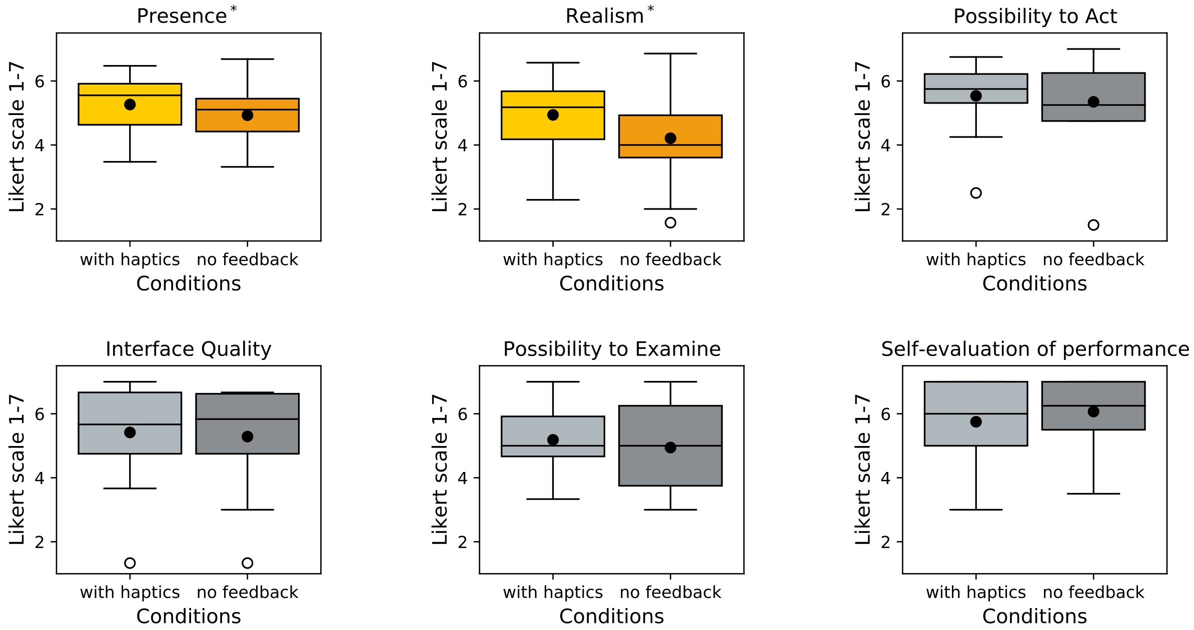

Figure 5.5: Summary of the individual ratings of the Wittmer and Singer Presence questionnaire for both conditions of study one. There was a significant effect for those highlighted in orange.

The overall ratings of the participants for spatial presence were significantly higher with haptics ($M = 5.26/SD = 0.82$) than without ($M = 4.93/SD = 0.91$). A t-test showed that participants had a stronger sense of presence with the proposed interface ($t(17) = 2.42, p = 0.03$). A similar result was achieved by the sub scores relating to the sensation of realism(with haptics: $M = 4.94/SD = 1.10$, no feedback: $M = 4.21/SD = 1.45$). Users felt the remote environment with haptic feedback significantly more real than the environment without feedback ($t(17) = 3.13, p = 0.006$). For the remaining four factors, there were no significant findings, however, for sake of completeness, a list of the means and standard deviation follows, that are also depict in Figure 5.6. Subjects scores for a slightly higher possibility to act with haptics ($M = 5.53/SD = 0.99$) than with no feedback ($M = 5.35/SD = 1.21$). A similar trend has also been observed for the factors: interface quality (with haptics $M = 5.42/SD = 1.41$, no feedback $M = 5.29/SD = 1.53$) and possibility to examine (with haptics $M = 5.19/SD = 1.07$, no feedback $M = 4.95/SD = 1.25$). Self-assessment of performance does not follow the preceding tendency (with haptic

$M = 5.75/SD = 1.24$, no feedback $M = 6.01/SD = 0.93$), participants felt to perform better without the introduced interface.

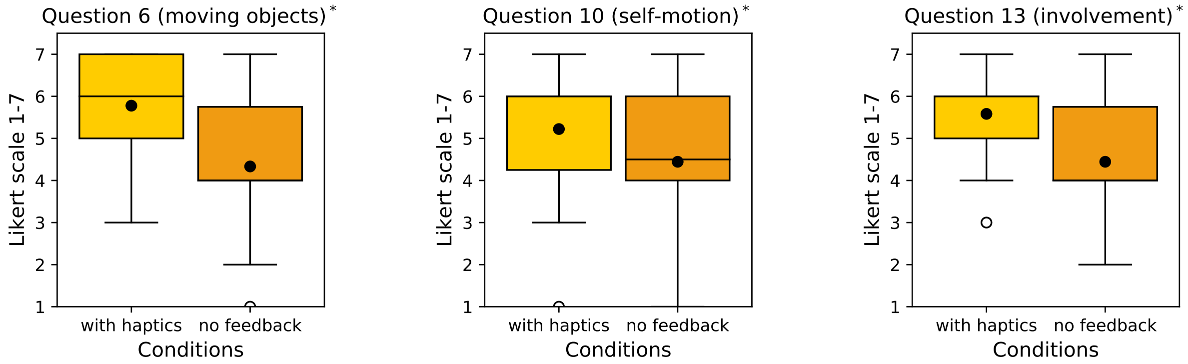

Figure 5.6: Ratings of the individual questions that showed a significant effect.

When analysing the questionnaire in detail, a significant effect can be observed for three individual questions (6,10 and 13). Question 6: *"How compelling was your sense of objects moving through space?"*, participants found that moving objects were more intensively with than the presented interfaces ($M = 5.78/SD = 1.31$) than without ($M = 4.33/SD = 1.70$). A Wilcoxon test shows a significant effect of the responses ($Z = 70, p = 0.006$). Similarly, question 10: *"How compelling was your sense of moving around inside the virtual environment?"*, participants also found that the sense of moving around inside the virtual environment was significantly more compelling with haptics ($M = 5.22/SD = 1.62$) that without ($M = 4.45/SD = 1.78; Z = 55.5, p = 0.021$). Showing that a higher sense of self-motion can be achieved through the interface. Lastly, question 13: *"How involved were you in the virtual environment experience?"*, participants reported higher involvement with haptics ($M = 5.58/SD = 1.11$) than without ($M = 4.44/SD = 1.61; t(17) = 3.64, p = 0.002$). Looking at the hypotheses, we can accept H1. The approach can significantly improve the overall spatial presence and create a more realistic experience when navigating in virtual space.

Besides the analysis of the above-mentioned presence questionnaire, additional performance parameters were also collected during the study. These included the total time per task and condition and the number of collisions during the task. No significant effect was found for either parameter total time nor number of collisions. Nevertheless, a brief summary of the results is given in the following. On average participants independent of the condition needed in total $M = 352.84$ s with a $SD = 191.51$ s. Surprisingly, the participants needed 14 % more time compared to the average. When looking at the collisions per minute it can be seen that with haptics ($M = 0.453/SD = 0.31$) there were slightly less collisions than without feedback ($M = 0.48/SD = 0.59$). Even the two slightly different rooms had no influence on the total time and collisions under the respective conditions. Finally, the influence of the order of conditions was examined, showing that the second run was independent of the condition, clearly faster with a similar number of collisions. The participants needed longer in the first session (with haptics $M = 478.61\,\mathrm{s}/SD = 183.30\,\mathrm{s}$; no feedback $M = 334.90\,\mathrm{s}/SD = 163.76\,\mathrm{s}$) than in the second (with haptics $M = 317.11\,\mathrm{s}/SD = 250.13\,\mathrm{s}$; no feedback $M = 275.37\,\mathrm{s}/SD = 126.38\,\mathrm{s}$). The hypotheses H2 and H3 that with our approach the participants are faster and make fewer collisions must be rejected. Surprisingly, users took longer with haptic feedback than without. Two possible reasons for this are that the feedback has to be understood and interpreted before interacting or that the users are more cautious because of the feedback.

Users' Perceptions In line with the quantitative analyses, the qualitative analysis shows that the participants enjoyed the interface and found it helpful for most of them, thus fulfilling its purpose. Participants described the vibration as providing a tingling sensation at its strongest and being only a little noticeable at its weakest. They described the collision feedback as a light tap which was sometimes surprising, but never painful. Due to the haptic feedback, a greater attentiveness or caution in controlling the robot in the remote environment could be observed.

> *"The vibration caused me to be cautious, just as in the real world..."* (P9)

A comment suggests a similar effect towards the awareness of objects in the remote environment.

> *"[The interface] made me more aware of how close objects were..."* (P8)

A further participant reported:

> *"Vibrations made me want to stay away [from objects]..."* (P2)

In this case, the sensation of awareness or caution has been slightly too strong, the aim of the interface is to make the user more aware of the environment, but not to block users from "normal" action. However, it was not only objects that were given more attention by the interface, but also the avatars were perceived with a more focused sensibility.

> *"I was trying not to hit people and objects..."* (P3)

Participants said they consciously and subconsciously moved around the space more cautiously when using our feedback than without, often being more hesitant in their actions. While this hesitance allowed participants to be more careful not to bump into things, it also prevented some participants from exploring more.

> *"I was less inclined to explore a bit [with haptic feedback]. Because of the size of the doorways, I would always get a buzz when walking in."* (P12)

Likely due to being worried about bumping into something. Participants also found that haptic feedback increased their anxiety and stress.

> *"Vibrations made me feel anxious at times (definitely more than having no vibrations).... It's good for alerting of the odd object, but when I'm moving through a narrow walkway, it feels more stressful than helpful"* (P2)

There are further comments in a similar direction, however, none of them express that haptic feedback is too stressful, but that it is simply too much. Therefore, some felt that the feedback distracted attention from the actual task.

> *"I get a lot of warnings when I'm close to something, but sometimes too much..."* (P2)

> *"It felt harder doing the task [with haptic feedback], but that's probably because my feet was getting constant feedback. My feet were vibrating almost all the time, so that was a little bit distracting."* (P12)

However, most agreed that even with the distraction that the haptic feedback caused, it was still useful in certain cases. Rather, they felt that it should only be used in crucial circumstances (e.g. when the perception of a nearby object could prevent a collision). Participants generally found the feedback most useful when they were moving or when they were addressed by a moving object while they were stationary.

Many participants said that their involvement and immersion in the activity with foot haptics has increased, which has made participants feel more responsible for their behaviour and more aware of the consequences of their actions.

> *"Haptic feedback made me feel more engaged."* (P6)

> *"Moving without the haptic feedback definitely felt emptier. And there was less awareness of proximity to objects as there was no move vibration."* (P5)

> *"It felt great to experience real consequences while exploring [the] virtual environment."* (P9)

Summary The findings from our study showed that our approach could significantly improve the overall spatial presence and create a more realistic experience when navigating in a virtual space. This was promising as it demonstrated the potential for the proposed interface. It provides additional spatial awareness and increases the sense of presence and participation when operating a telepresence robot. It was also found that our interface caused some users to be more careful with their environment, which we found positive. However, under certain circumstances the feedback was distracting and caused anxiety. This indicated that it would be important to adjust the amount and frequency of feedback and consider adjusting the feedback intervals. We were also interested to see if these results could be transferred to practice. We were also interested to see how the prototype would affect user behaviour and interactions with other people when a telepresence robot is operated in a real environment. Our results and further aspects of RQ2 led us to our second study.

5.2.3 Experiment 2 - Real Environment Tasks

Motivated by the results of the first study and driven by our Research Question 2 we are interested in researching the interface within real telepresence environments that are less controllable. In the second study, participants are asked to visit a university campus with the introduced telepresence robot (see overview in Figure 5.7). They will encounter a range of activities that include many real-life situations that people would experience when using a telepresence robot either at work or at a conference; e.g., talking to people, finding places, navigating through corridors, searching for objects. The objective was to understand how user behaviour with foot haptics would look like compared to that no feedback. Similar to the first experiment we tested the hypothesis:

H4: Proximity cues on the feet increase spatial awareness while navigation in VR.

Participants

A total of 17 participants were recruited through snowballing (word of mouth), social media (Twitter and Facebook) and posters placed around our university. Fourteen participants had never used a telepresence robot before, and two participants had used a telepresence

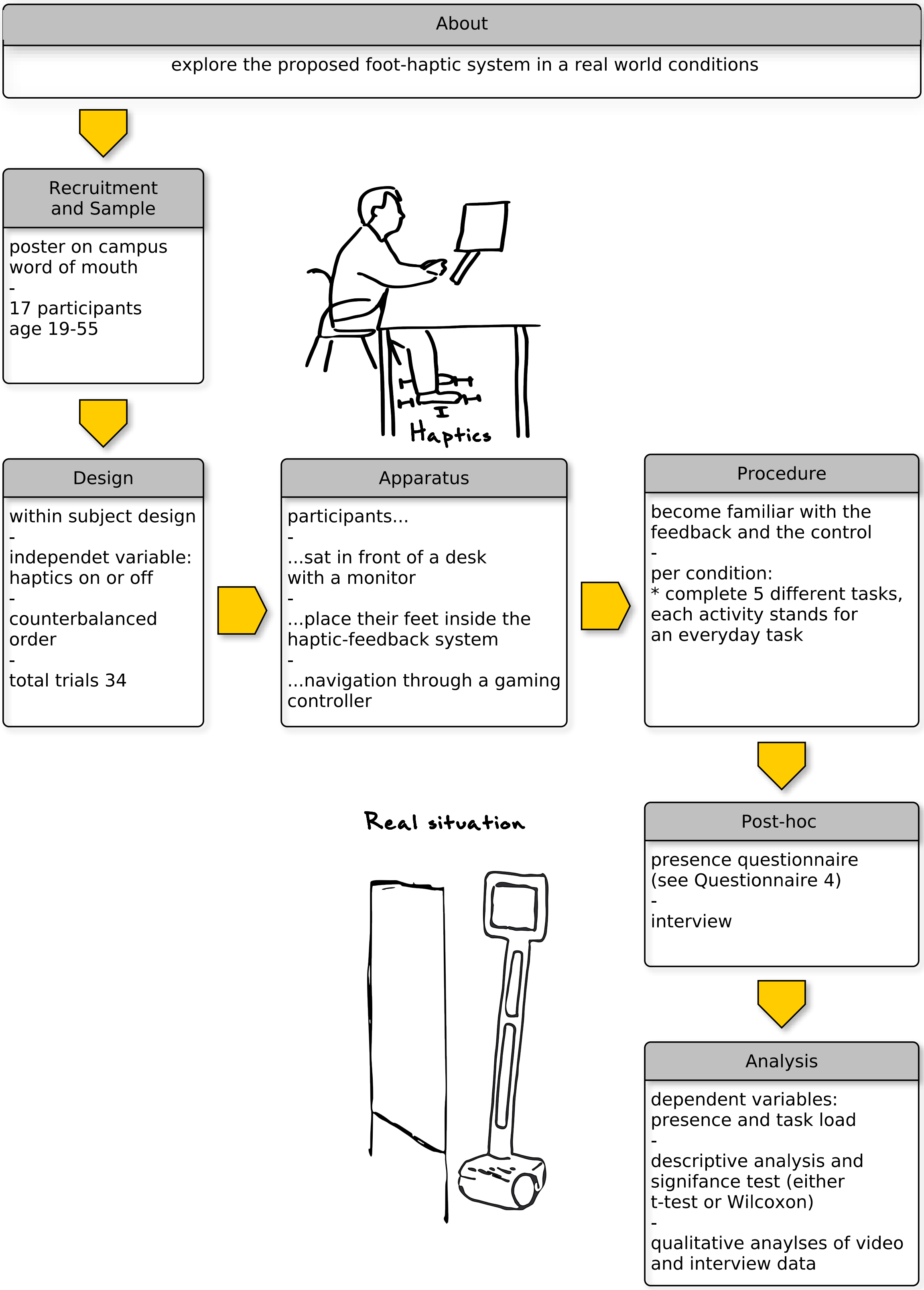

Figure 5.7: A diagrammatic representation of the study design, structure and procedure as well as the methods of analysis.

robot, but without any haptic feedback. Among the participants were eight women and nine men aged 19 to 55 ($M = 25/SD = 8$). The professions covered a range of occupations and activities (e.g. university students, consultants, administrative staff). All participants had smartphones and used video conferencing technologies (e.g. Skype). All participants were paid 15 dollars for participation.

Apparatus and Procedure

The second study was designed as an exploratory study, as we were mainly interested in how haptic feedback effects the behaviour of the participants in real world situations. We also wanted them to be able to compare their experience with haptics and with the experience without. Based on the results of experiment 1, we set the feedback parameters to a collision range of 20 cm and an proximity range of 1 m with a linear approach function (experiment 1 had a collision range of 20 cm and an approach range of 2 m). The one-meter length was based on measurements of all rooms where the participants were asked to perform the tasks. The maximum intensity of the vibrators was set to 60% (approx. ± 0.6G peak amplitude; approx. 150Hz) and the magnets were driven at 24V (experiment 1 had 100% vibration intensity and 24V). We assumed that the new settings would lead to a lower level of distraction (lower intensity) and less stress due to too much feedback (lower proximity range). Furthermore, it was important for us to ensure that the robot's navigation was as real as possible. For this reason, the participants sat in front of a 55 cm wide monitor with their feet placed on the foot platform and used a PlayStation 3 controller to control a beam telepresence robot, similar to a normal telepresence user would do. A diagrammatic overview of the second study can be found in Figure 5.7.

There were four different tasks, the tasks were chosen in a way that allowed studying a wide range of everyday tasks. These included tasks to provide opportunities for social interactions (e.g., asking people to open a door, press an elevator button, and ask a question from an advisor) as well as manoeuvring in both confined (e.g., narrow hallway, book-store aisles) and wide-open spaces. External factors such as the number of people in the places where each task took place and physical obstacles on the way were taken into account when designing the tasks. In contrast to the first study, we are aware that the parameters of real situations change from task to task. In contrast to the first study, we are aware that the parameters of real situations change from task to task. However, in order to keep the changes low, we have scheduled each session at the same time of day. The participants received relatively few instructions so that they could "go their own way", i.e. the variant that seems most suitable for each participant. A schematic reference map was given to the participants, on which the locations of the four tasks were marked.

Similar to the first study, each task was completed twice, in the opposite direction - once with feedback and once without.

Task 1 Navigate through a narrow hallway and find the poster board. Then look at the poster which has "The Code" in its title and take a screenshot of that poster.

Goals driving in narrow spaces, move along a wall, search for patterns

Task 2 Find out what kind of courses you can take. Go to room 2747 or 2745 (on the same hallway) and ask a student advisor to show the course table for undergraduate program.

Goals entering a room, interact directly with another person

Task 3 Drive through an "accessibility door", ask passers-by to push the handicap-door button to open it. Then go the the book-store and find the textbook for IAT ARCH 100.

Goals interact with passers-by, navigate and search in a store

Task 4 Move toward the tables in the mezzanine as shown on the map. Find this person [headshot shown on an iPad] and say “hi”. Then park the robot next to the person.

Goals search for something at distance, navigate around many obstacles

After completing the above four tasks for the first time, the participants completed two questionnaires. The first was the same presence questionnaire used in the first study (based on [WS98]), but we added the questions about sound (questions 20-22 in the original questionnaire) again because this experiment included sound (see Questionnaire 6). We still excluded the questions on haptics and touch (questions 23 and 24 in the original questionnaire). The second questionnaire was the NASA Task Load Index (TLX) [HS88] to measure the perceived workload on six scales. In addition to its effects on spatial awareness, we were also interested in finding out whether our interface affected the participants’ feeling of how hard they were working or mentally concentrated. Participants were asked to rate mental stress, physical demand, temporal stress, performance, effort and frustration using 7-point Likert scales from "very low" to "very high".

Before the second session the feedback condition (with haptics, no feedback) is switched, and participants have to perform similar four tasks but in reverse order. Of course, we did not modify the tasks fundamentally, only the information to be sought was exchanged. For example, participants had to find a different person in the crowded table configuration, look for a different course textbook in the book-store, etc. After completing the final four tasks, participants drove back to the start point of the study. They then completed the spatial presence and NASA TLX questionnaires again for the second condition. The order of conditions (with haptics or no feedback) was counterbalanced across participants.

Before each condition participants are asked to practice. The study began as soon as they said they were used to the interface condition.

Similar to the first study, we conducted semi-structured interviews after completing the tasks. The first phase of the interview focused on understanding their previous experiences using telepresence technologies and video conferencing systems. The second phase of the interview focused specifically on their experiences using the robot with the introduced haptic interface.

Data Collection and Analysis

All eight tasks took about 40 minutes in total (~20 minutes for each condition), while the questionnaires lasted 10-15 minutes in total. We recorded all our interviews on audio with the consent of the participants and made detailed notes. The interviews lasted about 15 minutes and all interview data was transcribed. We recorded a video of the user driving the robot by recording the screen showing the robot's two cameras

A pattern analysis of our interview data was performed in order to identify key issues and categorise them. All videos were reviewed to gain additional understanding of what was happening. The quantitative data were analysed in the same way as in the first experiment. P10 was not able to complete all eight tasks due to battery problem, so we have not considered P10's quantitative data in the analysis. In contrast, we have decided to include P10's qualitative data in the analysis.

Results

Quantitative findings Participant scores for overall spatial presence were similar with ($M = 5.09/SD = 0.49$) and without the use of haptic feedback ($M = 5.06/SD = 0.69$). Unfortunately the analysis of the overall spatial presence and the partial aspects, such as realism, possibility to act, quality of interface, possibility to examine, self-evaluation of performance, did not show a significant effect. Both conditions reached similar results in all aspects of the questionnaire (see Figure 5.8). For completeness, the mean values and the standard deviation for all sub-scores are listed in the following: realism (haptics: ($M = 5.06/SD = 0.74$); no feedback ($M = 5.05/SD = 0.97$)), possibility to act (haptics:

($M = 5.27/SD = 0.58$); no feedback ($M = 5.23/SD = 0.77$)), interface quality (haptics: ($M = 5.17/SD = 1.08$); no feedback ($M = 5.15/SD = 1.17$)), possibility to examine (haptics: ($M = 4.15/SD = 1.09$); no feedback ($M = 4.44/SD = 0.97$)), self-evaluation of performance (haptics: ($M = 5.59/SD = 0.59$); no feedback ($M = 5.47/SD = 0.72$)).

When looking the Hypothesis H4 and the results of the individual questions of the questionnaire, we found that, unlike in the first study, in which our approach increased the feeling of spatial presence and involvement in the environment, none of these effects were transferred to the telepresence situations we tested and H4 have to be rejected.

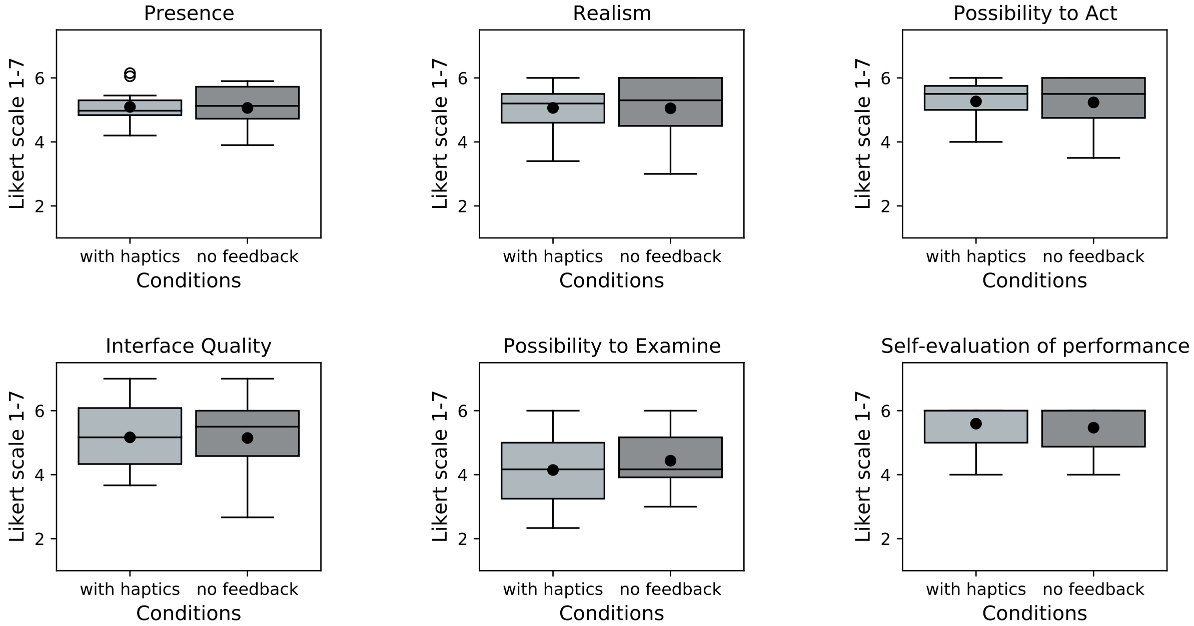

Figure 5.8: Summary of the individual ratings of the Wittmer and Singer Presence questionnaire for both conditions of study two.

In terms of the perceived workload measured by NASA TLX, participant ratings were similar with ($M = 36.90/SD = 18.09$) and without haptic feedback ($M = 36.60/SD = 16.15$. Thus, the questionnaires did not show any noticeable difference in either presence or perceived workload when driving the robot with haptic feedback compared to without. A comparison of the respective sub-aspects of the two conditions (haptics and no feedback) can be found in Figure 5.9.

User's perception The main themes that could be identified from the interviews are confidence in haptic feedback, behaviour to avoid collisions and contextual differences that influenced the feedback.

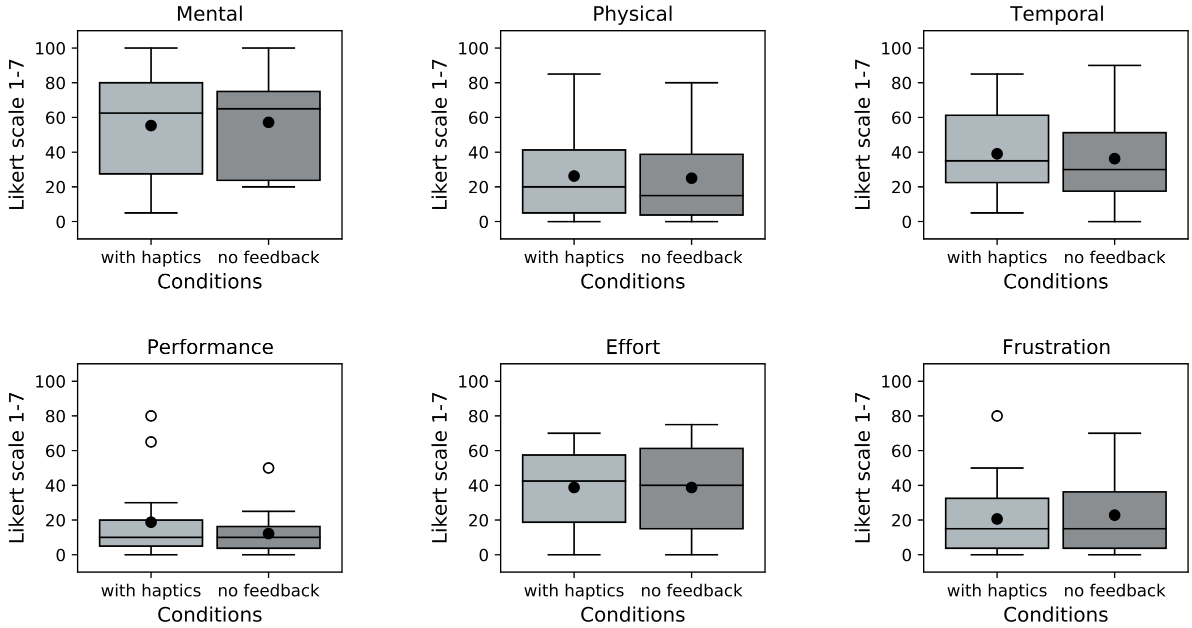

Figure 5.9: Overview of the individual sub-scores of the NASA-TLX questionnaire for the both conditions of the study.

During the qualitative interview, 11 out of 17 participants reported that they found haptic feedback useful for better understanding the remote environment. They also found that they could feel if they came too close to obstacles and if someone was approaching from behind or beside the robot, especially if they could not see them on the screen. The haptic interface is a useful background warning system that provides additional information to what they have already seen, noted three participants. Two participants found it most useful when driving in an unfamiliar environment for the first time, but did not have a strong preference for using it once they had learned more about the remote location and got used to driving there. Furthermore, some participants believed that the interface helped them avoid collisions with objects and people. For example, it could be observed that some participants left more distance to objects or persons with haptic feedback than they did with no feedback.

> *"What it [haptic feedback] did was that in the first trial it trained me"* (P1)

> *"It was pretty useful because obviously, I was getting close to obstacles."* (P10)

> *"The vibration was kind of useful. Like looking at the rear mirror in a car, it kind of provided a different layer on top of what I already have and used to."* (P2)

The haptic feedback also had an effect on the paths taken by the participants while driving the robot. For example, in tasks 1 and 2, where they had to drive through a narrow passage and ramp (see Figure 5.11, left), some participants drove in the middle of the ramp to get the least vibration, while some drove on the side to leave more space for others. This may be due to a increased understanding and perception of the environment. However, some users felt frustrated by the continuous tactile feedback.

> *"On the ramp, the robot was not in danger but it kept vibrating; it makes me ignore the feedback."* (P5)

> *"In small places, like small corridor where there is nothing I can do, so the vibration feedback was making me annoyed and after a while, I stopped paying attention to it. There was nothing I could do, so I was just driving at the center."* (P5)

In contrast to the above, the proximity feedback, i.e. the vibrations, does not feel disturbing. The levels of intensity chosen appear to be just right for some participants.

> *"Other vibrations were great, because it starts off slow, and then slowly increases as you get closer in the radius of objects in your way. That felt really great because it tells you are slowly getting closer."* (P1)

> *"The intensity worked pretty well because it didn't feel like it was overwhelming to me and to the point that I was always distracted by it."* (P2)

The feedback had clear effects on the behaviour of participants. For some, it meant changing their behaviour immediately and, for others, it meant questioning the feedback and thinking through what they should do next. Nine out of 17 participants took immediate action in order to avoid hitting objects and people whenever they received collision feedback; they would immediately slow down or stop the robot when the feedback occurred. This immediate reaction to collision feedback mostly happened in confined spaces where there were many obstacles within the collision range (see Figure 5.11, right).

> *"The kick really helped out in providing feedback that you're getting way too close that you'll hit it."* (P10)

It was observed that some participants chose to keep more distance between the robot and the objects and people (see Figure 5.10). Although this behaviour was seen in a

Figure 5.10: A difference observed between haptic feedback and no feedback.

Figure 5.11: Driving the robot down a ramp (left) and driving in a confined space (right).

few cases, it was not consistent among all participants. That is, some participants, on occasion, performed the opposite - keeping less distance to the person and more distance to the object. This behaviour suggests that there might be other social and environmental factors that affect behaviour.

Other participants were not sure whether the feedback meant that they had collided with an obstacle or that they were getting too close to objects, but had not yet hit them. Thus, they could not clearly differentiate what in particular the feedback was alerting them to. In these cases, subjects would either continue on or investigate. For example, some subjects used the bottom-facing camera to learn and understand when the collision feedback was being triggered, and this was seen as being useful. In some cases, an immediate change in direction of the robot as a response to the feedback led to colliding with other nearby objects.

> *"I don't know if I hit any of those chairs or not, because when it kicks, does it mean that I'm really close or does it mean that I'm hitting the thing?"* (P1)

Participants see a correlation between the context, i.e. the nature of the environment (e.g. limited vs. wide open, the number of obstacles or people in the environment) and the individual tasks. The feedback depends strongly on the environment, the task and also the navigation skills of the operator. In order to adjust the feedback in an optimal way, the minimum width of all rooms in which the participants were supposed to perform the tasks was measured before the study started, and thus the proximity range was set at 1 m. This meant that feedback would be given if the robot was within 1 m of an object.

This decision was taken to ensure that the participants received relatively consistent feedback throughout the tasks they were performing. However, it was found that this configuration was not practical for some of the tasks. For instance, the configuration was seen by participants to be useful for manoeuvring in the book-store and the advisor's office because the spaces were more constrained and participants wanted to avoid bumping into things. However, the same configuration was less useful when driving in spaces with consistent width and straight paths, such as hallways and ramps where the walls were within 1m. In these cases, participants received constant haptic feedback while there was nothing they needed to avoid (see Figure 5.11, left).

5.2.4 Discussion

Two different studies were conducted to evaluate the presented interface; both were exploratory. The first study examined the interface in a controlled virtual environment, whereas the second study dealt with real situations and was therefore less controlled. There were also differences in the technical implementation, whereas in Study 1 the feedback platform was "directly" connected to the virtual world, a network interface had to be added in the second study. Furthermore, in the first study the sensing of the environment was solved using software and in the second study a sensor ring was added to the robot. All this can of course lead to unwanted side effects such as higher latency or a misinterpreted object through the hardware ring.

User Behaviours and Reactions Our studies have shown that users find value in receiving haptic proximity feedback on the feet while driving a telepresence robot, and that such feedback is both easily understandable and can be usable for future design. After a short period of learning, all participants were able to appropriately interpret the feedback and were able to react to it in a proper way. In study 2, participants felt that their behaviour had changed when using the interface in telepresence situations compared to without. In both studies, the designed feedback had a positive effect on user behaviour in terms of improved awareness, encouraging participants to be more cautious in the distant environment. However, there were also participants who found the feedback disturbing and distracting. This is mainly due to the fact that in some cases the feedback was too intense or too continuous. In the following, the results will be discussed, with a focus on user behaviour and reactions and on use in different contexts.

Nonetheless, our findings suggest that there is value in continuing to explore haptic feedback options for telepresence robot operation as there is a range of uses for it. Such use may depend on the individual behaviour of the person using the robot; e.g., some people may desire feedback that is stronger vs. weaker, or in some types of environments and not others. There are design options for exploring ways in which users can easily control the mapping of haptic feedback to their understanding of the environment surrounding them. For example, haptic feedback could, at least initially, be combined with additional visual feedback on the screen so that participants can learn and understand which situations trigger which types of feedback. This could be reduced for more advanced drivers. The haptic feedback could also be used as a training mechanism for new drivers, and possibly removed for experienced drivers. This reflects our findings that some drivers only found value for the feedback while they were getting used to driving the robot.

While we have shown that haptic feedback can provides a heightened sense of presence in virtual environments (study 1), we cannot conclude that this is also the case for complex telepresence situations in which the user has to talk to people and respond to more demands from the remote environment (study 2). Thus, if the only goal is to provide a heightened sense of presence, our haptic feedback approach alone (at least in its current design) may not be the be-all-end-all tool to achieve this, at least for complex telepresence situations with many people and lots of obstacles. It may be worthwhile to explore, as future work, a more individual feedback per user which could be learned, and a more refined feedback that adapts to the environment, for example automatically adjust the velocity of the robot or proximity range.

Contextual Variations It was clear from the study that with systems such as the introduced, context is important. There were times when feedback was not necessary and participants were able to understand the environment from the camera perspective. At other times the feedback was too intense and continuous, and participants would have wished it had been adjusted accordingly. Our results also show that a future system will need to adapt more to the user and the context.

Naturally, providing context-dependent feedback solely on the spatial configuration of the scene is challenging. For example, in crowded locations (such as conferences), movements can be highly unpredictable [RN17]. Designers could potentially explore novel feedback mechanisms that consider context by addressing the range and density of objects surrounding the user, as well as the movement speed and time-to-contact with objects.

5.2.5 Conclusion

Both studies were to be formative in nature, allowing to explore design ideas around foot-based haptic feedback systems and to work on better understanding what works well and what doesn't. Study 1 was more controlled, and real world situations were not necessarily replicated, e.g. dynamic obstacles and human positions. Study 2 explored a wider range of situations and user reactions. As a result, not all participants were encountered with exactly the same tasks and scenarios, as the study was conducted in a public area of a university campus.

In addition, participants in both studies are not experienced to navigate a telepresence robot, most have done it for the first time, as opposed to experienced drivers who may already have developed navigation strategies when driving a robot. Furthermore, it is planned to investigate how the current results could be generalised to an extended use of the system, a wider range of users and capabilities with telepresence robots, and to other scenarios such as conferences and remote working environments. Further work is needed to understand how users might respond to a longer exposure to haptic feedback on their feet.

While we focused on understanding how directed haptic feedback affects the user's perception of the remote environment, there was less focus on methods of controlling the robot, but it would be useful to explore this in future work. For example, it might be worthwhile to investigate how to get both feedback and control on its feet. There are several ways of doing this, for example, controlling the robot based on leaning or based on walking-like metaphors.

5.3 Combining Haptic Modalities using a Foot-Platform in VR

In the previous section (see Section 5.2), a system was presented that explored the effect of haptic feedback on the feet when controlling a telepresence robot. It was shown that under certain conditions the user's presence can be increased. Furthermore, it was also found that haptic feedback depends strongly on context, especially when operating in realistic everyday situations. In order to continue addressing research question 2 (see RQ2), a further interface will be presented in this section, that also deals with the influence of haptic feedback on the feet. Similar to the previous prototype, the user will again be immersed in another environment, this time in a virtual environment, and it will again be examined how perception can be changed or even intensified.

Natural walking, in comparison to reality, is often not possible when navigating in larger virtual environments and computer games. The interface and research presented in this section explores how conventional navigation methods can be augmented with haptic feedback to enhance factors such as self-motion sensation, also referred to as vection. More specifically, gamepad-based and leaning-based navigation metaphors will be studied. For this purpose a custom-designed foot haptics prototype was designed and developed. Several multimodal stimuli will be presented to explore cues related to walking, reaching from vibrotactile cues (via vibrotactile transducers and bass-shakers under participants' feet) to auditory cues (footstep sounds) to visual cues (simulating bobbing head-motions from walking).

Although gamepads are popular interfaces for navigation in virtual reality (VR), they hardly provide the same self-motion cues associated with walking in real world environments. The ability to move freely in space while wearing a head-mounted display would offer appropriate physical cues of motion, however, it is often not feasible because of limited space, safety, cost, technical complexity or fatigue from long-term use. In contrast, there are leaning-based interfaces, some implementations are based on the Wii Balance Board [VSBH10], [JL12], recognizing the weight shift and using it to navigate. Some other approaches are based on optical methods to detect movements in the upper body or even the whole body [GPI+15], [MPL11]. However, regardless of the technical implementation, both approaches allow for long-distance movements and navigation without the above mentioned limitations, such as limited space. Compared to gamepad interfaces where the human body remains primarily passive and vestibular and proprioceptive cues are missing. Leaning-based interfaces can improve navigation performance [HNW+14] and provide a more immersive and embodied experience, as they allow at least some vestibular cues, which can improve self-movement perception (vection) [KRTK15], [RSP13].

A perfect locomotion interface should reflect all conditions, such as vestibular and proprioceptive cues from walking, air movements of our ears and haptic and auditory signals of our feet touching the ground, just like in reality. While the aim of the present interface was not to develop a perfect interface, it allows a number of questions to be examined. Specifically, the focus was on the effect of haptic feedback on self-motion and the overall experience, which is also important for answering research question 2. It has previously been shown that visual induced perception of illusory self-motion can be enhanced by appropriate auditory (e.g. dynamic sound fields) and vibration cues [LR14]. However, the impact of these cues on active locomotion conditions will be assessed in the following. Therefore, a comparison between a seated user navigating with a gamepad and a user navigating using a standing, leaning-based interface is investigated.

In order to get a more detail understanding, a prototype that provides fine-grained multisensory cues for standing leaning-based interfaces, extending work by Marchal et al. [MCV+13] and Feng et al. [FDL16] who focused on supporting seated users. The interface provides audio-visual cues as well as foot-based stimuli ("foot haptics") that partly substitute real-world cues. The focus of the proposed system is on "foot haptics", which are implemented through a dense grid of vibration motors, a bass shaker and a loudspeaker under each foot. The cues are physically co-located, similar to cues that are perceived when walking in the real world. It will enable to add various auditory, visual and vibrotactile cues related to walking, which could affect both standard joystick navigation (seated users) and leaning-based navigation (standing users).

5.3.1 Implementation

According to RQ2, the objective is to explore how foot haptics can improve the perception of self-motion and performance in leaning-based as well as gamepad-based navigation. For this purpose a prototype has been designed to augment virtual scenarios with foot-based feedback. In the next paragraphs a detailed overview of the implementation of the interface will be outlined, followed by a report describing the study conducted and the related results.

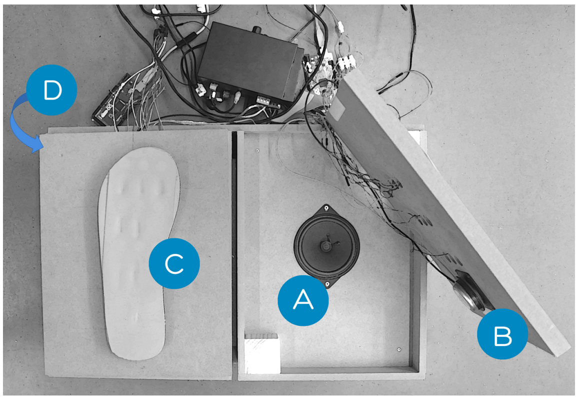

Figure 5.12: Feedback to each foot consists of A) a loudspeaker mounted in a solid case, B) a bass-shaker, C) eight vibration motors included in a flip-flop and D) the core frame of a Wii balance board.

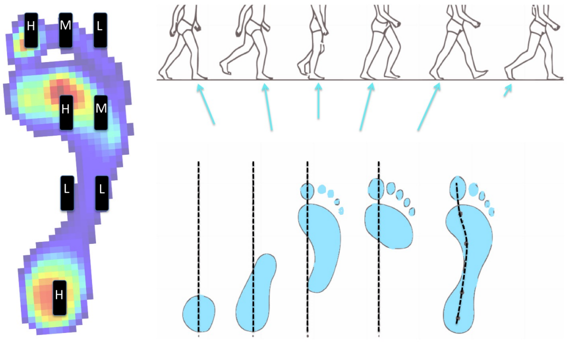

Figure 5.13: Foot pressure distribution zones of a standing user showing the vibrotactors locations, and the five phases during a half gait cycle.

System

The haptic interface (see Figure 5.12) consists of four feedback components that are placed under the feet. All components are set in a wooden housing made of medium density fibreboard. In addition, a Wii Balance Board has been mounted under the housing. The feedback is provided by various actuators (a speaker mounted in a speaker housing, a bass shaker and a grid of vibration motors). Moreover, walking like visual cues are provided by a head-mounted display connected to the system, an Oculus Rift DK2.

The overall system (see Figure 5.12) consists of a feedback components mounted underneath the feet, placed on top of the Wii balance board load sensors and electronics in a wooden (medium-density fibreboard) case. Cues are provided by actuators mounted underneath each foot: a loudspeaker mounted in a speaker case, a bass-shaker, and a grid of vibration motors. Furthermore, additional visual cues are provided through a head-mounted display connected to the system, an Oculus Rift DK2. To ensure that the feedback given to one foot is barely perceptible to the other, the two boxes have been separated by 1 cm thick insulation of solid foam. The aim of this prototype is to provide walking-like cues, including visual (head vibrations), acoustic (footstep noises) and vibration cues (rolling pressure and ground impact). The entire system runs in real time on a graphics workstation implemented in Unity3D. All vibration motors are controlled by two Arduino Megas, while the loudspeaker and bass shaker are driven by two amplifiers.

Navigation As mentioned in the introduction, two navigation metaphors are supported. Within the seated version, navigation is done using a Microsoft X-Box controller. In the standing version, navigation is performed by leaning the upper body. A Wii-Balance board allows to determine the centre of pressure, which in turn can be used to navigate in virtual environments. The implementation supports forward, backward, and sideways motions, as well as turning during forward motion.

Visual Head Movement In line with the head bobbing concept of Grossman et al. [GLA+88], a proprietary head bobbing algorithm has been implemented in Unity3D to simulate the horizontal and vertical oscillating movement of the head during real walking. In doing so, the translation is described by two sine waves, one representing the movement on the X-axis and the other the movement on the Y-axis. To simulate typical head movement, the vertical wave must have approximately twice the frequency of the horizontal wave. Followed an iterative design and pre-tests were used to fine-tune the frequency and amplitude for the up and down movement of the head synchronously with the speed of the user's movement.

Audio Realistic walking sounds were used as a source for the audio cues. The orgin of the sounds was chosen at the feet, as in real life, similar to [PFC+10]. Therefore, two loudspeakers (Visaton FR10 20W) were installed in the aforementioned wooden housing; both loudspeakers were powered by an amplifier (Samson Servo 200). Walking sounds are defined by two main characteristics: speed and surface texture. Based on the speed of movement, the walking sound duration is reduced or increased so that it corresponds to the walking phase duration in which the feet touch the ground and the associated airborne phases in which the feet do not touch the ground. In this way, the sounds are kept synchronised with the ground contact phases influenced by the walking speed, starting from the moment the heel hits the surface. A solid (wood) and aggregates (gravel) were selected, as we assumed that both can be distinguished quite well [GMV+08] and represent typical surface textures.

Vibrotactile Motivated by previous research that used plantar vibrations to improve self-motion perception [FDL16], [TMM+13] and navigation cues [VBV+12], a vibration approach and system has been developed that stimulates different parts of the foot soles. The aim was to reproduce the sensation of a rolling movement of the foot as best as possible. To do this, the interface uses eight vibrating actuators per foot (see Figure 5.13): seven below the metatarsus and toes (Precision Microdrives: Model No.

304-116; 5 mm;15 000 rpm) and one below the heel (Precision Microdrives: Model No. 307-103; 9 mm; 13 800 rpm). All vibration motors are positioned so that users with different foot sizes can still perceive the stimuli. All vibration motors are glued to a rubber surface which is stretched over a solid foam sole in which small holes are drilled to accommodate the vibration motors. In this way, each vibration motor can vibrate properly against the foot sole instead of absorbing and damping a heavy load when the users stand on it. This means that the feedback provides similar results under different conditions, as postures (such as standing or sitting) affect the pressure on the soles.

A bass shaker (Visaton EX-60) is used to amplify the heel impact on the floor. The bass shaker is mounted on the foot support platform underneath the heel and stimulates this part of the foot the most. Although the current design cannot isolate the vibrations in order to solely impact on the heel, there is a noticeable drop in power towards other parts of the foot, similar to the effect of ground impact when walking in real life. The vibration motors and the bass shaker are synchronised to simulate the different phases of walking. The gait pattern can be defined by stride phases and length, as well as by differences in pressure and duration of the foot sole impact (the "ground contact phase") experienced during the different phases of the foot rolling in a gait phase.

Each vibration motor can be controlled individually (see Figure 5.13), thus allowing the simulation of walking, slow or fast running, which in turn is again defined by the ground contact phase and its duration. When normal walking, either the left or the right foot is always stimulated, with some overlap. With increasing speed and a changed swing phase associated with the movement of the limbs the phases in which none of the feet receive (tactile) stimuli also increases. These phases coincide with an increase in stride length, frequency and ground contact. A basic vibration was used for the different surface textures. The sound also becomes louder when speed increased. This is achieved by increasing the basic volume: walking (10 %), slow (25 %) and fast running (40 %).

5.3.2 Experiments

In order to test our hypotheses and to find further answers to our research question, we conducted five sub studies in a single experiment. The aim was also to create a better understanding of the potential approaches and interaction of our implemented cues. Besides the post-questionnaire (see Questionnaire 6), which deals with overarching questions, there are five hypotheses, one per session. In the hypotheses the general term perception is used, which stands for the four specific perception aspects queried in Questionnaire 5. It is hypotheses that:

H1: Surface textures are perceived more strongly when using a leaning-based surface.

H2: Audio and vibrations affect perception the most.

H3: The perception of cue combinations differs in the navigation metaphors.

H4: Minimal walking in place will positively influence perception.

H5: Adding all haptic cues increases perception while navigating freely.

Participants

Twelve participants (25-48 years old, mean age 29, one female) have been recruited to participate in the experiment. Participants were recruited either through a mailing list or randomly on campus. Seven participants reported they played games daily or weekly, and the rest less frequently. All users had normal or corrected-to-normal vision. On average, the whole study took about one hour to complete. As in the previous studies, users received a briefing and a debriefing and participants were informed that they could quit at any time without consequences. Participation was voluntary, and no money was paid for participation.

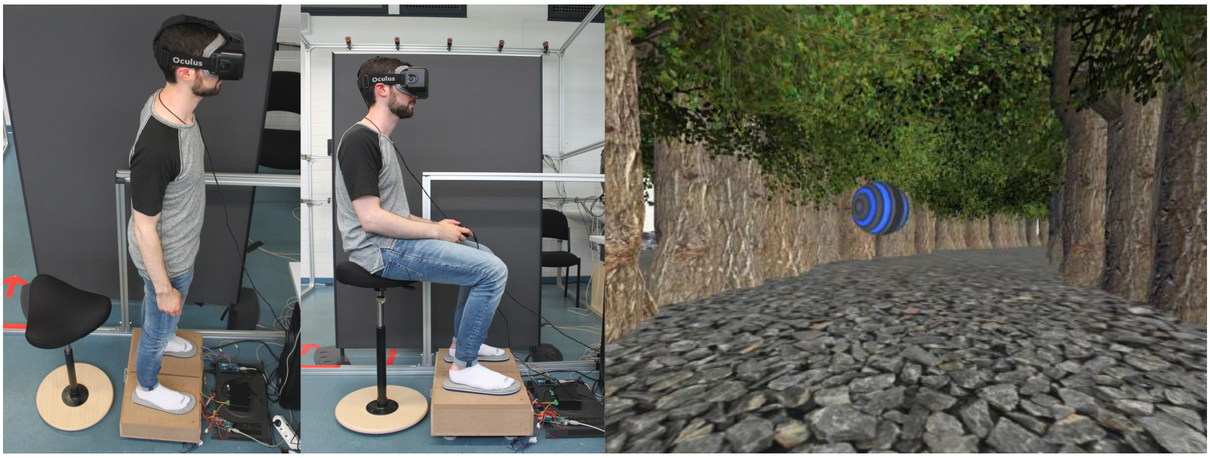

Figure 5.14: User in standing leaning (left) and seated (middle) pose. Test environment with follow-me object (right).

Apparatus

The following five sessions were performed with the prototype introduced earlier. Participants were seated during all gamepad conditions and stood in the leaning conditions (see Figure 5.14). In the following either the gamepad or the leaning condition will be mentioned, assuming that the leaning condition is performed standing while the gamepad is performed seated. The virtual camera was placed at the same height in both conditions, independent of the conditions. This ensured that visual perceptions were as identical as possible over all settings. When answering the questions, participants were asked to sit down again.

Design and Procedure

The experiment consisted of five individual sessions, all participants had to attend all sessions (within-subjects design). A diagrammatically overview can been seen in Figure 5.15. All sessions were performed in the same order. The focus of the study was more on participant perception and user experience than on task performance. Thus, even if there was a transfer of learning between sessions, this should not critically affect the observed results.

After each trial in each session participants were asked questions about self-motion perception. The in-study questionnaire (see Questionnaire 5) was based on an 11 point Likert scale (0-10) , whereas 10 points were total agreement and 0 total disagreement. Users to directly answer, after each trial, the following four questions. All questions were displayed in the HMD and were rated orally while the experimenter note the answers.

- "I had a strong sensation of self-motion" (*vection*)
- "I could judge velocity travelled well" (*velocity*)
- "I could judge distance travelled well" (*distance*)
- "I was not aware of my real environment" (*involvement*)

After each session, the HMD was removed and participants were asked to answer questions, which were displayed in a form on a computer screen. The questions included user comfort, ability to focus on the task, perceived navigation performance, ease of learning, fun, ability to use the interface for a longer time, intensity of the vection and ease of use Questionnaire 6. Additionally, after the first session, the participants scored the degree of confidence in walking on the idifferent surface textures. The participants were allowed to take a short break and to remove the HMD whenever motion sickness was an issue. Before and after, the total experiment participants reported whether they were fresh and relaxed, and the degree of their motion sickness. Finally, it was asked which condition (seated or standing) had a more positive influence on self-motion.

In all sessions participants were asked to navigate along a clearly visible curved trail. Six paths were created through a natural environment populated with trees at the side of each

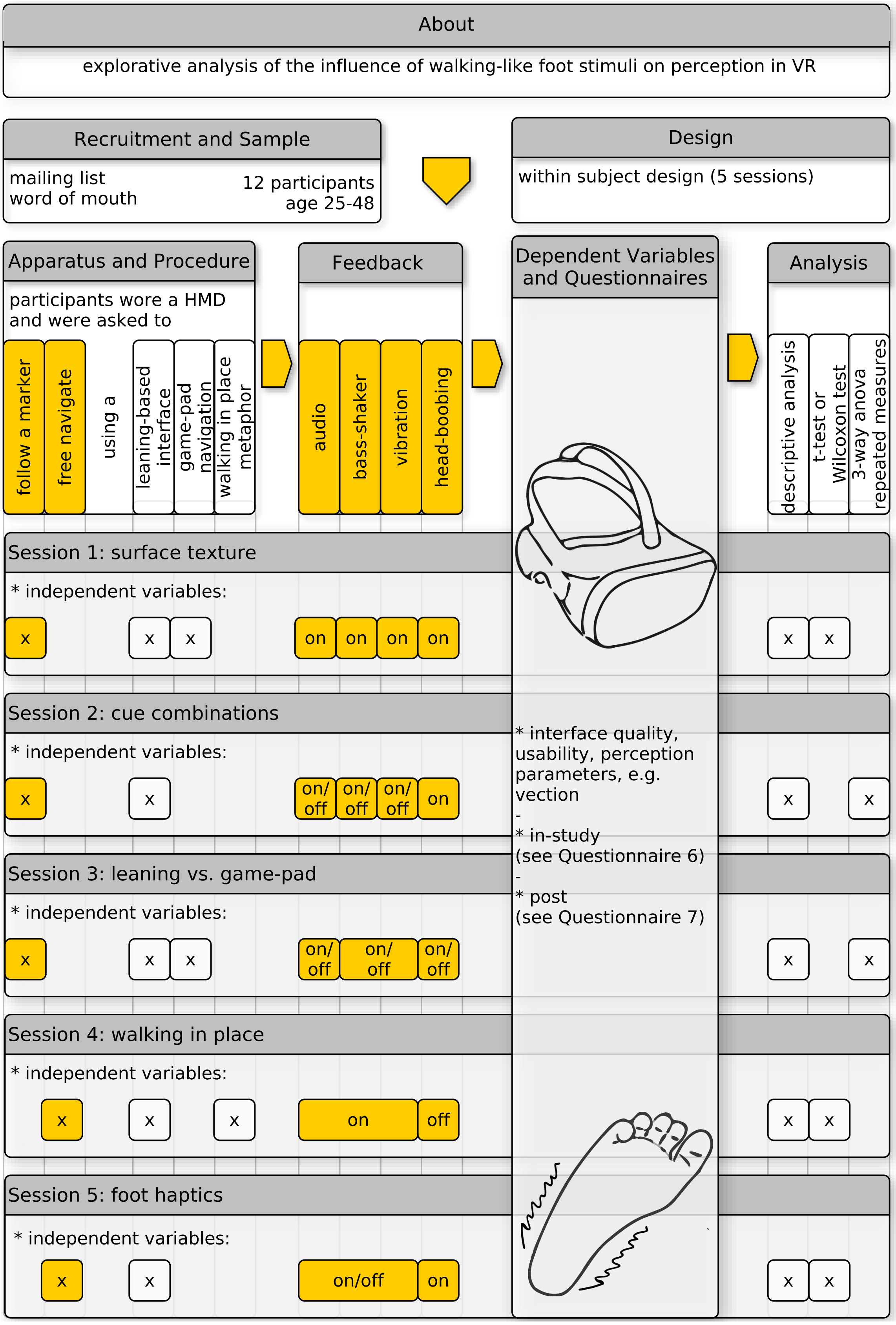

Figure 5.15: A diagrammatic view on the overall study as well as an overview of the individual sessions and their analysis.

trail (see Figure 5.14, right). All the trails had a similar curvature profile, and the trees were selected to provide some motion-cues in the peripheral visual field. To guarantee similar speed profiles despite active navigation, participants in sessions 1-3 had to follow a marker (a clearly visible blue ball, see Figure 5.14, right) that moved in front of them. The marker was moved at different speeds, starting with walking, followed by slow/fast or fast/slow running, changing every three seconds. The speeds were chosen to correspond to the profiles of walking, slow/fast walking and fast/fast running. Each trial lasted about 10 seconds. Pilot studies showed that 10 seconds was sufficient to experience vection and to learn and evaluate the different interfaces and cue combinations. In sessions 4 and 5 the participants were asked to move freely on the path, so that no marker was displayed.

As many users may not know what self-motion perception exactly means, a calibration phase was performed before the actual experiment, which all participants have to took. During the calibration users have to lean forward and navigate through a star field simulation which provides a strong self-motion perception. This experience should be used as reference for the evaluation of vection intensity. The study began immediately after the calibration. A description of the five sessions is provided in the next paragraphs, which are also illustrated diagrammatically in Figure 5.15:

Session 1: How well can multisensory cues be associated with different surface textures?

> **Description:** Participants were asked to practice both navigation interface by following a marker (blue sphere). All cues (tactile, bass shaker, audio and head bobbing) were activated. The path was divided into two zones (wooden or gravel ground). Participants had to travel in each zone twice, resulting in two trials in total.

Session 2: How do audio-tactile cue combinations affect vection while leaning?

> **Description:** The focus in this session is on cues combinations and the effect on self-motion perception and involvement using our leaning interface. Therefore a 2 x 2 x 2 factorial design was applied; each participant completed two repetitions, resulting in a total of 16 trials. The independent variables are tactile (on/off), audio (on/off) and bass-shaker (on/off). The repetitions were blocked, meaning that all cue conditions were completed before they were repeated. Head bobbing was on in all conditions.

Session 3: What influence do multisensory cues have on vection when comparing gamepad and leaning?

Description: In this session research focused on perception of self-motion and involvement of the implemented cues when comparing the leaning and gamepad interface. The study was based on a 2x2x3 factorial design; the independent variables were navigation interface (leaning/gamepad), head bobbing (on/off) and foot-haptics (off/audio/all). This results in a total of 24 trials with two repetitions, again blocked.

Session 4: What effect has minimal walking in place on leaning locomotion?

Description: The potential of adding a minimal walking in place (WIP) metaphor to the leaning interface is explored in this session. To ensure that participants received complete feedback during the study, all participants were advised not to move their feet during minimal WIP, the heel should rest on the platform, and users were asked only to pretend walking. Participants could freely navigate along the predefined path using the leaning interface either with or without added minimal WIP, repeated twice, totalling four trials. The independent variable was WIP (on/off). We allowed to practice WIP once before starting the actual trials. Participants were encouraged to synchronize their WIP with the foot haptics.

Session 5: Does foot haptics affect perception during free locomotion?

Description: Finally, the effect of foot-haptics while free navigate was studied. Participants were allowed to move freely along a path and were instructed to vary their speed dynamically. By doing so, we aimed to to explore the relationship between feedback and speed. Thus there was an independently variable: feedback (on/off). In this case, either all components were active or no feedback was provided. With one repetition there were four runs per participant. Although the exploration time in sessions 4 and 5 was not limited, the participants generally did not take more than 20 seconds.

Results

According the data from the post-questionnaire (see Chapter A) it can be concluded that in almost all aspects the common gamepad interaction was preferred by the users. Reviewing the data from all five sessions and comparing the three interfaces (gamepad, leaning and walking in place), a clear ranking of the three interfaces becomes noticeable (see Table 5.1). The gamepad interface has achieved the highest score, followed by the leaning-based interface and at least the walking in place interface. Interestingly, with regard to self-motion, the leaning-based interface received a considerably higher rating than the gamepad interaction. In general it can also be said that the gamepad and leaning-based interface was very positively received by the participants. The walking in place metaphor, on the other hand, did rather poorly. In terms of motion sickness, it was in average quite low, the average motion sickness scores received $M = 3.92/SD = 2.64$, only four of the 12 participants experiencing high levels (> 5). In the following paragraphs the results of the individual sessions are presented in detail.

Table 5.1: Overall ratings of the studied interfaces (likert scale 0-10); complete questions can be looked up in Questionnaire 6.

	Interface		
	gamepad	leaning	walking in place
comfort	$M = 9.0/SD = 1.6$	$M = 7.3/SD = 1.7$	$M = 6.1/SD = 2.2$
focus	$M = 8.9/SD = 1.3$	$M = 7.8/SD = 1.7$	$M = 3.6/SD = 2.7$
navigate	$M = 9.0/SD = 1.2$	$M = 7.6/SD = 1.5$	$M = 3.6/SD = 2.8$
learn	$M = 9.2/SD = 1.2$	$M = 7.8/SD = 1.5$	$M = 3.4/SD = 2.9$
fun	$M = 8.3/SD = 1.2$	$M = 8.1/SD = 1.8$	$M = 3.8/SD = 2.6$
long-time	$M = 8.2/SD = 1.5$	$M = 6.8/SD = 2.4$	$M = 3.7/SD = 2.5$
self-motion	$M = 7.7/SD = 1.3$	$M = 8.1/SD = 1.4$	$M = 4.0/SD = 2.8$
usability	$M = 8.5/SD = 1.6$	$M = 7.4/SD = 1.7$	$M = 3.2/SD = 3.0$

Session 1 offered the possibility to become familiar with the introduced interfaces. In addition, the perceptibility and influence of two surface textures (wood and gravel) was explored. Data from the in-study questionnaire (see Questionnaire 5) were we looked into self-motion, judgement of the travelled velocity and distance and also at the level of involvement showed that independent of the surface texture the level of involvement was significant higher when navigating with the leaning-based interface (gamepad $M = 7.12/SD = 1.63$/leaning $M = 7.76/SD = 1.24$; $Z = 28; p < 0.038$) (see Figure 5.16). Thus, the hypothesis (H1) for the first three factors (vection, velocity and distance) must be rejected. For the factor involvement, the hypothesis is correct. It can be assumed that the surface textures are perceived more strongly in the standing, leaning-based interface, and thus the sensation of involvement is stronger.

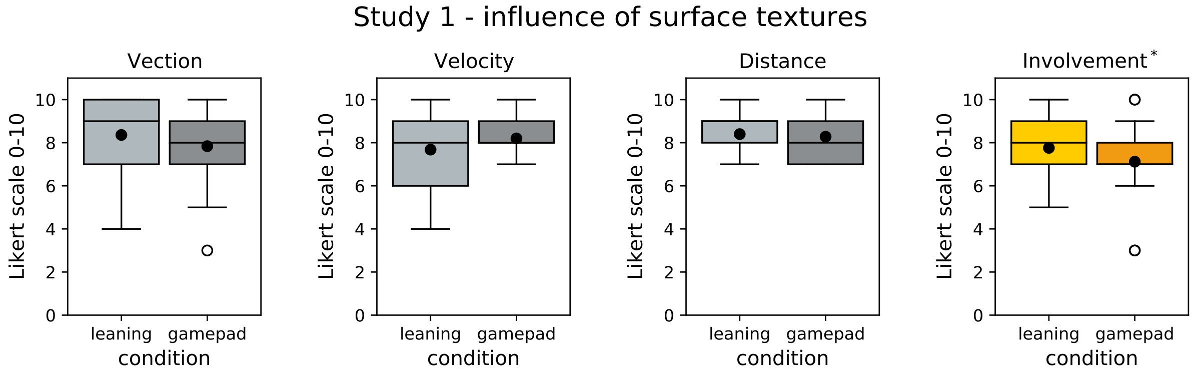

Figure 5.16: In-study questionnaire showed an significant effect of involvement, highlighted in yellow.

The post questionnaire (see Questionnaire 6) showed that participants found the feedback from both surface textures more convincing when using the leaning-based interface (wood $M = 7.08/SD = 1.62$; gravel $M = 6.42/SD = 1.89$) instead of the gamepad navigation (wood $M = 6.75/SD = 1.06$; gravel $M = 5.92/SD = 1.80$) (see Figure 5.17, 2nd row). In terms of the quality of feedback, users felt that walking on wood was received better than walking on gravel.

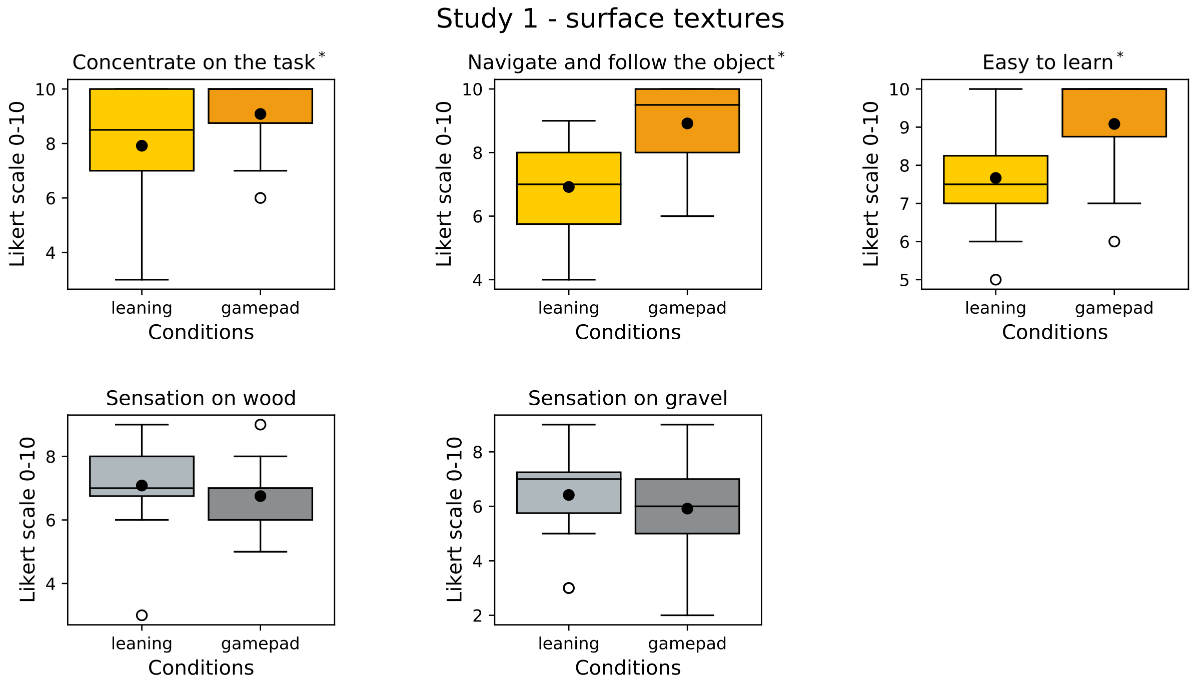

Figure 5.17: Users could better concentrate on the task and better navigate. Users also scored the learnability of the gamepad interface higher compared to the leaning-based interface. Sensation of surface textures received higher scores while standing.

When looking at the data from the post questionnaire it becomes visible that in this session the interface has a significant effect on focus, navigation and learnability (see Figure 5.17, 1nd row). This means that the users were able to focus better on the task when using a gamepad (gamepad $M = 9.08/SD = 1.38$/leaning $M = 7.92/SD = 2.23$; $Z = 0; p = 0.034$). Furthermore, the users also found the navigation using a gamepad significantly better compared to the leaning-based interface (gamepad $M = 8.92/SD = 1.38$/leaning $M = 6.92/SD = 1.62$; $Z = 0; p = 0.006$). Finally, the learnability of the gamepad interface has also convinced the participants (gamepad $M = 9.08/SD = 1.38$/leaning $M = 7.67/SD = 1.50$; $Z = 2; p = 0.017$). A significant influence on the remaining factors of the questionnaire (comfort, fun, long-time usage, self-motion and usability) could not be determined. However in average the users had slightly more fun with the leaning-based interface (gamepad $M = 8.42/SD = 1.16$/leaning $M = 8.83/SD = 1.47$) and also a higher self-motion perception (gamepad $M = 7.75/SD = 1.71$/leaning $M = 8.42/SD = 1.38$). Interestingly, participants found the leaning-based interface on average better for long-term usage (gamepad $M = 8.17/SD = 1.19$/leaning $M = 8.33/SD = 1.61$). It is probably not surprising that in many cases the gamepad variant was rated better by the users, as most of them already know this kind of interface very well.

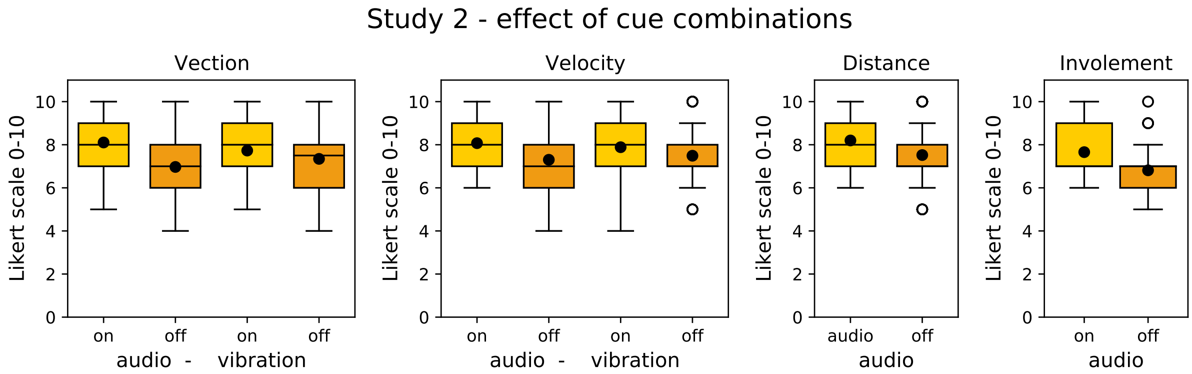

Figure 5.18: Audio and vibration are the most relevant parameters with regard to the perceptual factors studied.

In **session 2** the influence of the implemented cue combinations on perception was studied. The focus was on perceptual factors such as the sensation of self-motion, the perceived speed and distance and the level of involvement. According to Figure 5.15 the emphasis was on the leaning-based interface. The visual feedback (head-bobbing) was always enabled. All results of the in-study questionnaire are also depicted in Figure 5.18. It turns out that audio and vibration feedback are the driving factors. A 3-way ANOVA with repeated measures showed significant effect on self-motion perception when either adding audio ($F(1, 11) = 43.78, p < 0.001$) or vibration ($F(1, 11) = 5.01, p = 0.026$) is enabled. Participants could further judge travelled velocity better when either adding audio ($F(1,11) = 20.14, p < 0.001$) or vibration ($F(1,11) = 5.31, p = 0.022$) is enabled. The vibration feedback has no significant influence on the participants' judgement of the distance travelled (on: $M = 8.01/SD = 1.28/$ off:$M = 7.71/SD = 1.30$) and their presence (on: $M = 7.34/SD = 1.14/$ off:$M = 7.12/SD = 1.24$). However, audio feedback underneath the feet can significantly affect the perception of distance ($F(1,11) = 13.72, p < 0.001$) and presence ($F(1,11) = 26.77, p < 0.001$). H2 can be accepted, vibrations and audio are the dominating factors. Surprisingly, the feedback of the bass-shaker has no significant effect. Different combinations, such as audio and vibration, did not have an influence on perception. Audio seems to be more effective, as it achieved a significant result for all factors studied, while the vibration feedback only increases the perception of self-motion and velocity.

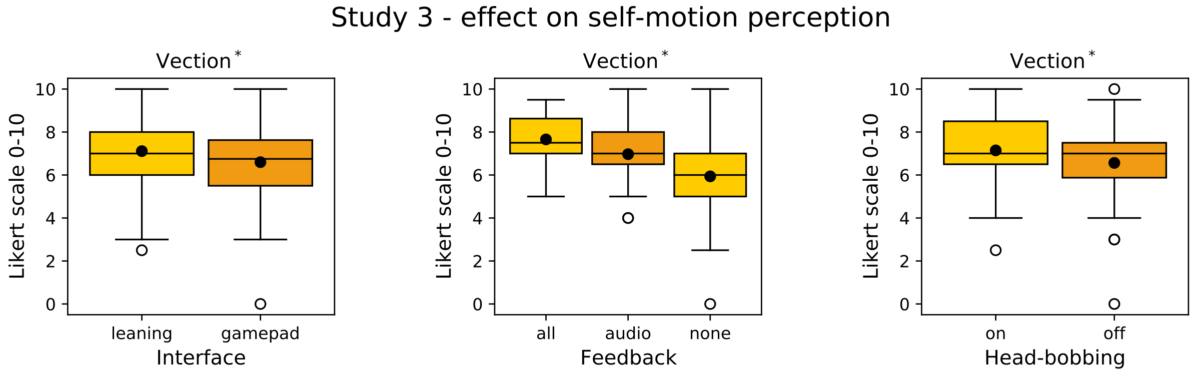

Figure 5.19: A significant effect was found for all variables when comparing the two navigation metaphors.

In **session 3** the two interfaces were compared. For this purpose different feedback modalities were turned on and off. In this way, the influence of the modalities (audio, haptics and head-bobbing) on our perception parameters could be measured. Looking at the ratings of the in-study questionnaire, all three conditions have a significant effect on self-motion perception. A 3-way ANOVA with repeated measures found that the leaning-based interface ($F(1,11) = 4.19, p = 0,043$) has a significant impact on vection among all participants. But also feedback ($F(2,11) = 14.42, p < 0.001$) and head-bobbing ($F(1,11) = 5.39, p < 0,022$) can significantly influence the perception of self-movement (see Figure 5.19). With regard to our hypothesis (H3), a pairwise comparison of the two interfaces and the remaining three perceptual parameters (velocity, distance and involvement) shows a significant effect. A Wilcoxon signed-ranks test resulted in velocity ($Z = 447.0, p = 0.027$), distance ($Z = 370.0, p = 0.024$), and involvement ($Z = 236.0, p = 0.031$).

Further results show a similar trend as in the previous two sessions, haptic feedback below the feet seems to be the most important component. It was found that participants could significantly better judge velocity ($F(2, 11) = 8.43, p < 0.001$) and distance ($F(2, 11) = 6.48, p = 0.002$) with haptic feedback. Furthermore, the feeling of presence can significantly improve through haptic feedback ($F(2, 11) = 9.44, p < 0.001$). Looking at the findings of the post questionnaire comparing both interfaces, it becomes clear that the gamepad solution is significantly preferred by the users. The ratings showed higher scores for the gamepad versus leaning-based interface for comfort, concentration, ease of navigation, learnability, prolonged usage, and overall usability (see Figure 5.20). While all ratings for the leaning interface were fairly high, there is a clear need for improvement to bring them close to the gamepad level. This of course also influences the hypothesis H3 and would mean that if the quality of the leaning-based interface is increased, H3 can be better tested.

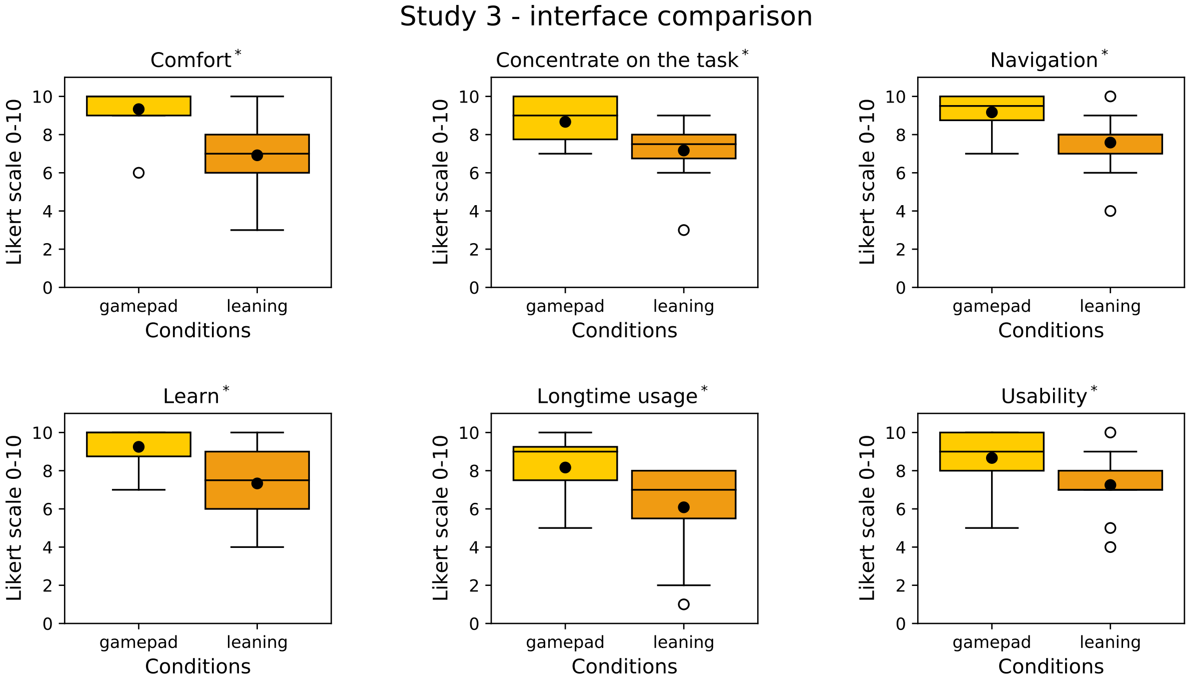

Figure 5.20: Gamepad interaction was clearly preferred by users.

Session 4 dealt with the comparison of walking in place in combination with the leaning-based interface and with the pure leaning-based interface. Preliminary tests suggested that the addition of a walking-like metaphor could increase perception factors like self-motion perception. Unfortunately, there were some problems with the implementation and the realisation of the metaphor. The walking in place metaphor made it difficult to navigate by shifting the weight, furthermore the synchronization of the stimuli had to match with the steps performed by the participants, which also proved to be difficult. All except two participants had problems to complete the task correctly. This in turn led to poor results for the WIP condition, which scored significantly lower than the leaning-based interface in both the in-study (see Figure B.2) and the post-study questionnaire (see Figure B.3). The results of the two questionnaires can be found in the appendix. All factors, self-motion perception, judgement of velocity and distance as well as the level of involvement were worse in the WIP condition. Since the results from the post questionnaire were just as bad, the results from session 4 cannot be taken into account. To conclude, the idea of implementing WIP with the presented interface must be further developed, and thus, in this case, it makes no sense to explore our hypothesis (H4) further.

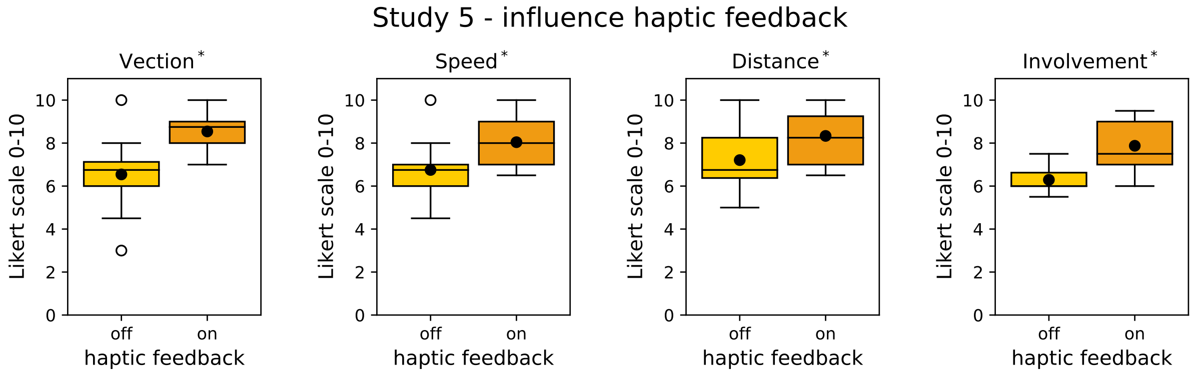

Figure 5.21: When enable all haptic cues, perception will increase for all studied parameters.

In the last session (**session 5**) the impact of foot haptics in free exploration was studied by using either no foot haptics or full foot haptics. The focus was again on the leaning-based interface, and the trend was further confirmed - there was a positive effect of foot haptics on perception. In detail, this means that adding combined haptics (bass shaker, audio and vibration) to the feet can significantly increase self-motion perception (haptics off $M = 6.54/SD = 1.66$/on $M = 8.54/SD = 0.95$; $t(11) = -3.88, p = 0.003$), the estimation of velocity (haptics off $M = 6.75/SD = 1.30$/on $M = 8.04/SD = 1.22$; $t(11) = -2.95, p = 0.013$) and distance (haptics off $M = 7.21/SD = 1.46$/on $M = 8.33/SD = 1.23$; $t(11) = -3.0, p = 0.012$), and the level of involvement (haptics off $M = 6.29/SD = 0.59$/on $M = 7.88/SD = 1.21$; $t(11) = -4.42, p = 0.001$) (see Figure 5.21). In general, the ratings were slightly higher than in the previous sessions. This is consistent with the participants' statement in the post-session interview that they were better able to focus on the effect of the cues when they did not have a main task, for example, to follow a moving object. In summary, hypothesis (H5) can be accepted. The combination of all haptic cues significantly increases all examined perception parameters.

In a concluding step, data from the different sessions were analysed in order to draw further conclusions. The focus was on completion time and the influence of different stimuli on self-motion perception. Although users were asked to follow a blue sphere, it was interesting to see if there was a difference in completion time. For this purpose, the participants' time spent per trial was logged. Another interest was the influence of the four stimuli (vibration, audio, bass shaker and head bobbing) on self-motion, which was asked in the second part of the post-questionnaire. Looking at the first sessions in which the users had to follow a marker, and considering the influence of the interface on completion time, a one-sided hypothesis test shows that when using the gamepad interface ($M = 48.96\,\mathrm{s}/SD = 8.14\,\mathrm{s}$) the participants completed the courses significantly faster than when using the leaning-based variant ($M = 52.39\,\mathrm{s}/SD = 7.57\,\mathrm{s}$; $W = 54.0, p = 0.028$). The influence of interface on completion time was confirmed again in session 3, where participants were significantly faster with the gamepad ($M = 44.05\,\mathrm{s}/SD = 9.30\,\mathrm{s}$) than with the leaning-based interface ($M = 53.78\,\mathrm{s}/SD = 16.63\,\mathrm{s}$; $W = 1440, p < 0.001$).

The influence of cue combination on perceptual parameters was investigated in session three. When analysing the completion time in this session, audio (on $M = 49.82\,\mathrm{s}/SD = 15.02\,\mathrm{s}$/off $M = 49.95\,\mathrm{s}/SD = 16.54\,\mathrm{s}$) and vibration (on $M = 51.00\,\mathrm{s}/SD = 16.83\,\mathrm{s}$/off $M = 48.77\,\mathrm{s}/SD = 14.60\,\mathrm{s}$) did not show significant differences. Surprisingly, with the assumption that the paths could be completed faster with feedback, the participants completed the tasks significantly slower with bass-shaker feedback (on $M = 51.40\,\mathrm{s}/SD = 17.14\,\mathrm{s}$/off $M = 48.37\,\mathrm{s}/SD = 14.16\,\mathrm{s}$; $W = 1760.0, p = 0.038$). The main results of the completion time are also shown in Figure 5.22.

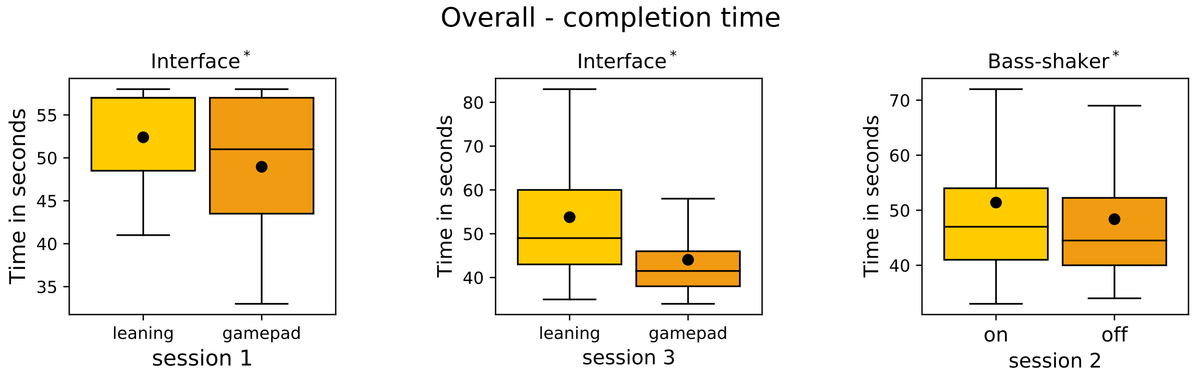

Figure 5.22: Main results of the first three sessions in terms of completion time. The graph shows that in sessions 1 and 3 the interface had a significant influence on the completion time. Session 2 showed that users with an active bass shaker were noticeably slower.

As mentioned at the beginning, the impact of the individual feedback components, independent of the task and interface, on self-motion perception needs to be studied. For this purpose, the answers from all sessions were summarised. A pairwise comparison of the four feedback modalities showed that audio ($M = 8.43/SD = 1.97$) and vibration ($M = 8.28/SD = 1.87$) feedback clearly improve the feeling of self-motion compared to bass-shaker ($M = 7.94/SD = 2.10$) and head-bobbing ($M = 7.84/SD = 2.48$), Figure 5.23 illustrates these results. Finally, the recognition of the stimuli was queried, and the users' ratings showed that all feedback modalities could be easily distinguished from the others (audio: $M = 8.83/SD = 1.52$; vibration: $M = 8.50/SD = 1.55$; bass-shaker: $M = 8.83/SD = 1.95$; head-bobbing: $M = 8.17/SD = 1.95$)

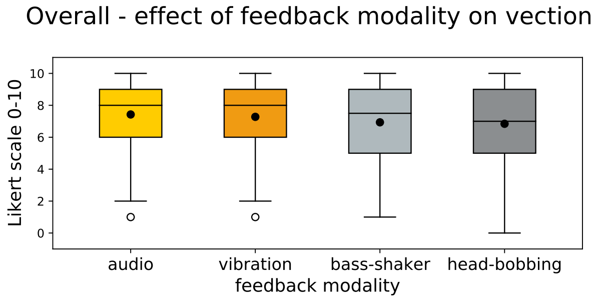

Figure 5.23: Effect of our four feedback components on vection over all sessions. The figure shows that audio and vibration feedback have a stronger influence on vection.

5.3.3 Discussion

Focused on RQ2 and our hypotheses we have we presented a prototype combining leaning-based navigation with a foot-haptics mechanisms. Results showed that both self-motion perception (vection) and involvement/presence could be significantly enhanced by adding walking-related vibrotactile cues (via vibrotactile transducers and bass-shakers under participants' feet), auditory cues (footstep sounds), as well as visual cues (simulating bobbing head-motions from walking). Moreover, participants' self-reported ability to judge self-motion velocities and distances travelled was enhanced by adding footstep sounds and vibrotactile cues. Interestingly, all these observed benefits of adding walking-related cues occurred independently of whether participants controlled self-motion via joystick while seated or via leaning while standing. This suggests a more general benefit of adding walking-related cues that might generalize to further locomotion paradigms and interfaces, with many potential application areas.

Together, the outcomes support the assumption that haptic and proprioceptive cues experienced during natural walking can at least to some degree be substituted for by other feedback channels such as vibrotactile feedback, and can be further supported by audio-visual cues. This outcome is in line with previous studies, such as the system and study by Terziman et al. [TMM+12], showing similar effects for seated users.

A key finding of ours is that leaning while standing improved self-motion perception significantly compared to seated users using a joystick, even though participants had extensive experience using joysticks but no experience using leaning-based interfaces. This extends prior work showing that passive (but not active) seated leaning on a manual gaming chair could enhance self-motion sensations [RF12].

5.3.4 Conclusion

Motion sickness was an issue for some users. While this might at least in part be attributed to the long duration of the experiment inside a head-mounted display, as even with breaks it took around one hour, further research is needed to investigate which factors might have contributed and how motion sickness could be reduced. Because of the marker-following procedure, we could only ask participants to introspectively rate their ability to judge velocities and distanced travelled. Future work is planned to investigate if this self-assessment also translates to improved behavioural measures of distance/velocity and more complex navigation behaviour. Pilot data suggests that seated leaning can indeed reduce distance underestimation for VR locomotion. However, the current results suggest that compared to seated joystick usage, standing leaning interfaces, in particular when combined with minimal WIP might require additional cognitive/attentional resources, and would benefit from additional practice and further interface improvements.

In the future, we intend to extend the base system by looking into the potential of including limited haptic feedback to the feet, for example to provide collision feedback. We are also interested in the addition of other motion cues, such as wind and barely perceptible wind sounds that occur when someone is moving through the physical world. Furthermore, we will investigate how we can generalize the system to better include rotations, for example by using torso-directed locomotion [BKH98].

Despite the need for further system improvements, the current results already highlight the potential of sensory substitution and incorporating walking-related auditory, visual, and vibrotactile cues for improving user experience and self-motion perception in applications ranging from virtual reality and gaming to telepresence and architectural walk-throughs.

5.4 Summary

Both prototypes presented showed in several ways how perceptual aspects could be improved in virtual and remote environments. For this purpose, both approaches used the feet for haptic feedback, once the sole and once the sides of the feet. The objectives and sub-question should help to answer RQ2. Objective 4 was successfully implemented with the fourth prototype. A haptic foot platform was presented that maps spatial data of a remote environment captured by a telepresence robot to increase spatial awareness. To answer the sub-question (RQ2.1: *How can foot haptics support users awareness when interacting in remote environments?*), two separate studies were conducted. While the first study was conducted in a simulated virtual environment, the second study was conducted in a real environment with real tasks. A quantitative evaluation showed that in the first study, the added feedback could significantly increase spatial awareness. The users moved more carefully with haptic feedback than without. Unfortunately, this did not apply to our second study with real tasks. In summary, we can say that the feedback approach is promising and we see great potential in it. However, it still needs further development for real tasks, especially with regard to the adaptation of different environments. The algorithm for calculating haptic feedback must be designed differently for open spaces or crowded places to exploit the haptic feedback in the best possible way. Nevertheless, it could be shown that the feedback approach, to implement proximity cues with vibrations and collision cues with light impacts, works.

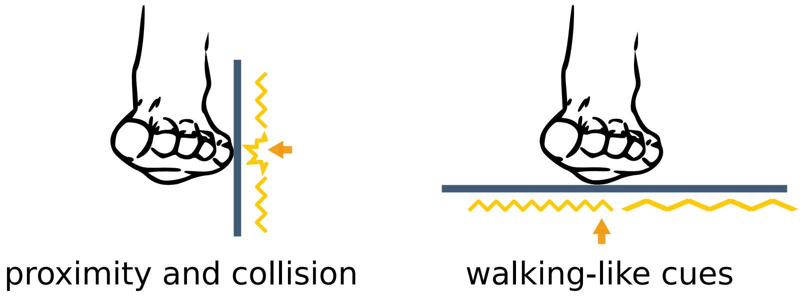

Figure 5.24: Sketch of both implemented foot haptics approaches. It can be seen that different locations of the foot have been stimulated (blue). While vibrations are supported by both prototypes, collisions are represented with a slight impact and walking-like cues augmented with audio feedback (yellow).

With regard to our last, the fifth prototype, and the associated sub-question (R 2.2), *how can feet-based haptic feedback be designed to enhance the self-motion perception in virtual environments?* it can be concluded that perceptual parameters such as self-motion perception could be increased. In detail, we were able to achieve further results beyond the confirmation of the improvement of perception factors [TBS13], [WTC+20] already known in literature. As the study was highly exploratory, five different sessions were conducted to investigate various combinations of conditions. This included the combination of different haptic feedback modalities as well as combinations of our two interaction metaphors. Overall, the haptic feedback provided to the foot was perceived more intensively in the standing version than in the sitting version. In the analysis, we examined four main factors: self-motion perception, the judgement of the distance and speed travelled, and the users' involvement. Furthermore and in general, audio and vibration cues have in most conditions displayed a significantly higher effect on the four perceptual aspects. Objective 5 has been achieved, and we have introduced a foot platform that allows us to improve self-awareness, but also to improve other parameters, for example, the involvement of the users.

To conclude, Figure 5.24 shows, as we did in the previous chapter, the two basic ideas of the implemented approaches. Two prototypes were developed that can provide haptic feedback in different ways to the feet. These two designs also demonstrated how spatial awareness and self-motion perception could be increased, and contributed significantly to answering research question RQ2. In summary, it can be said that in our studies the haptic feedback achieved better effects while standing. Furthermore, the users were satisfied with the feedback on the feet, it was only perceived as uncomfortable when there was too much. In the next chapter, we want to summarise the main chapters, highlight the main contributions, but also the limitations, and conclude with ideas for future work.

Chapter 6

Conclusion

There is no doubt that the visual and auditory sensory channels are currently the most essential and efficient interface between humans and computer [OVV+16]. Rendering physically correct images in real-time and generating realistic sounds is still a challenge. However, compared to our other senses, i.e. the sense of touch, smell and taste, research is more advanced in the context of human-computer interaction. Nonetheless, when considering the possibilities of haptic feedback, it has already been proven that a mouse or a keyboard or, as has become increasingly popular in recent decades, small touchscreens have a considerable impact on human-computer interaction [OSC+17]. In this thesis, we have explored further potentials, which we would like to summarize in this chapter.

6.1 Summary

Since the domain of multimedia, mulsemedia, multimodal and multisensory interaction and especially haptic feedback (see Chapter 1) is quite broad [Sut03], [GTLG14], we have narrowed our focus to two areas. These areas have been used to show concepts and approaches to provide haptic feedback. In doing so, we looked at two key aspects - in particular: performance and perception, as we consider them essential and dependent. In short, often perceptual methods are required to adjust or even improve performance parameters, and when users interact efficiently with a computer, the user experience will increase.

Two focus areas are reflected in the overall structure of the thesis. Thus, the literature review (see Chapter 2), as well as our two main chapters, were divided into these areas. In the methodology chapter (see Chapter 3), we discussed different directions and methods that are important in order to address our two research questions mentioned in Chapter 2 and to achieve our objectives as specified in Section 1.2. Since all our research questions tend to suggest an empirical and artefact contribution, we introduced individual approaches, that look into the design and development of new prototypes (artefact contributions), or into the evaluation of such prototypes (empirical contributions) [WI16].

Five prototypes from two domains were presented. Each of the prototypes was evaluated with at least one study, and several specific applications were implemented and presented as well. While the two main chapters deal in detail with the combination of haptic feedback with touchscreen interaction [FS01], virtual [WTC+20] and remote environments [NVPH16], the whole thesis has to be seen as a framework that makes both topics part of coherent research. For each of these five interfaces, we have shown that there is potential for haptic feedback to improve performance, perception and user experience.

In Chapter 4, we proposed three unique methods through which haptic feedback can augment touchscreen interaction to show versatility. Our first prototype was ForceTab, an actuated touchscreen driven by a small motion-platform to provide force feedback to the fingers on the screen. The combination of flexible haptic feedback above and rigid feedback on a touchscreen was explored with our FleXurface prototype. With our third prototype, we investigated performance and self-perception aspects using back-of-device techniques to provide a pin-based stimulus to the finger. For all three prototypes, a perception-based study was performed to explore the possibilities and limitation of haptic feedback applied to touchscreens. The dependence of perception and performance became clear in this chapter. For example, in Section 4.4 a perception study was first carried out and the results were used to increase the touch accuracy.

Telepresence robots and virtual environments are not without their challenges. Therefore, in the second main chapter (see Chapter 5), we presented two further prototypes, both for which address the sensory augmentation. All prototypes in this chapter, focuses on haptic feedback provided directly at the foot in order to increase self-motion perception (vection) in virtual environments and to enhance spatial awareness in telepresence scenarios. In both scenarios studied, the users are either in an artificial or in a remote space. In this case, the visual interface can be seen as a window to a remote space or as a camera attached to a virtual character.

Both chapters and corresponding areas clearly show an overlap in the objectives and the way of achieving these objectives. The thesis aimed to explore and improve perception and performance aspects, which was achieved in touchscreen interaction and virtual and remote environments. Furthermore, the objectives were always achieved with the help of haptic feedback. For this purpose, the hands and feet were addressed. As could also be seen, the design of the interfaces was adapted to the respective body part. While we focused on more primary and concrete tasks within the finger-based prototypes, we provided more secondary, background feedback in our foot-based prototypes. However, both served in their individual way to support the user.

6.2 Contributions

In addition to the research questions raised in Chapter 2, two aims and five objectives were formulated in Section 1.2. In summary, three objectives cover the augmentation of touchscreens with haptic feedback and two objectives looking into the areas VE and RE. All of them helped to answer our two research questions. In detail, each of the main chapters answered a particular research question that served to achieve one or more of our five objectives. In the following, the main contributions are presented. In the summaries of the main chapters, it was already shown, that all objectives have been achieved.

However, before considering the contributions of the two main chapters, we would like to mention that the results would not have been achieved without the individual prototypes. Therefore, we consider the designed and developed hardware and software concepts as part of our contribution. Furthermore, in the course of this work, a procedure and methodology have progressively been established that allow us to develop and evaluate these kinds of novel interfaces. Our interfaces are mainly based on sensors and actuators that not only allow to interact with a user conventionally but also to stimulate a further sense in order to involve the user more realistically in the interaction. We have described this methodology in Chapter 3. As a result, the following contributions have been achieved with the introduced methodology.

The above leads to the key contributions of this thesis. We contribute in two areas, all focusing on haptic feedback to enhance interaction performance and perception. In Chapter 4, we explored ways on how to augment small and tab-sized touchscreens and thus addressed RQ1, which lead to the following contributions, parts can also be found in [MKHG17], [KBT$^+$19] and [MEK$^+$19]:

> **Contribution 1:**
> The limitations and possibilities of haptic feedback were explored by: (i) an actuated touchscreen, (ii) elastic layer above the screen and (iii) a pin-based approach mounted on the back of a touchscreen. ranging from force and pressure feedback, to stiffness and compliance sensations, to pin-based skin and finger stimulation. Using the designed haptic interfaces, it was possible to show the variety of haptic interaction capabilities; moreover, it was also shown how the implemented haptic interfaces could be used to enhance touchscreen interaction. While tactile feedback combined with touchscreens has been widely researched, the approaches introduced in this thesis has gone beyond that and has contributed by exploring novel approaches. It was also shown that the areas of perception and performance are very closely related. Perceptual aspects are essential for answering performance issues.

In the second area, we looked at how to improve perceptional aspects in virtual environments and in telepresence systems. With the main focus on RQ2, we have found the following contribution which parts were published [KMT+16] and [JMM+20]:

> **Contribution 2:**
> With the use of two further haptic prototypes, we contributed to explore and improve perceptual aspects. We were able to show that both self-motion perception and involvement in virtual environments can be significantly improved by adding walking-related haptic cues on the feet. In this context, it was shown that our leaning-based interface has a positive effect on perception. Furthermore, we studied novel cue combinations and showed how they affect perception. Similarly, within fifth novel approach, it has been contributed that proximity and collision feedback can lead users in telepresence scenarios to change their behaviour due to an increased sense of responsibility and to become more cautious when moving in remote environments. In a particular study, it was demonstrated that spatial awareness can be increased.

In summary, it can be said that all objectives have been obtained as the contributions listed above illustrate. We have presented haptic user interfaces for two in to areas that explored perception, performance or experience. Novel haptic feedback was implemented for touchscreens, with which we explored performance and perception limitations. We have shown the potential of feedback with the feet to increase spatial awareness in telepresence systems and to intensify immersion in virtual environments. In general terms, it has been shown that haptic feedback, when used thoughtfully, contributes positively to perceptual aspects and influences performance parameters in the both of the studied domains.

6.3 Limitations

In retrospect, there are a number of limitations for this research and creating haptic feedback has its challenges. Since five unique haptic interfaces have been developed in the context of this thesis, we would like to outline the limitations we have experienced in our studies. Firstly, it has been particularly difficult to calibrate and precisely measure the exact characteristics, such as vibration or pressure force, with our resources. Especially with built-in vibration motors or when interacting with elastic material, it was not very easy to ensure that every user gets the same feedback or stimulus. Although the data collected showed that users perceived the feedback similarly, there is no guarantee that it was precisely the same for all of them. Secondly, it was difficult, especially with haptic devices, to take into account all ergonomic aspects for all users. Take the HapticPhone as an example, a smartphone with three movable pins on the back: in the study, most users reported that the pins were easy to reach, and the interaction felt comfortable. However, since the pins were attached to fixed locations, it was difficult for users with smaller or very large fingers to imagine using the prototype over a longer period of time. This example also shows which individual characteristics have to be considered when designing haptic feedback. When comparing this individuality with the rendering of images or the generation of sound, it becomes clear that there is an essential difference between the considered media and the corresponding sensory channel.

Finally, the sampling and the request of self-assessments should be reflected. We have conducted eight studies with an average of 14 participants; which leads to approximate 4000 trials in total. On the one hand, the disadvantages of convenience sampling have already been discussed in the methodology and, on the other hand, increasing the number of samples would provide more accurate results [BACM11]. However, for exploratory research and to point towards new directions, our findings are still valid and can be generalized to a considerable degree to the sample population.

Besides, we have asked for a self-assessment in several studies - we would like to emphasize that there may be biases in such subjective surveys [Ban77]. The wow-effect of new technologies can also influence users to make spontaneous emotional decisions, which can also lead to biases. However, since the analysis of the questionnaires indicated a clear direction and the variance of the data was mostly small, this effect seems to have been rather small in our studies. Nonetheless, further work is needed to increase the validity and generalization potential of the research reported here.

6.4 Future Directions

We see great potential in an increased involvement of the user in the interaction with a computer, also referred to as human-centred design [OSC+17]. From our point of view, this means that communication must take place as naturally as possible. This also includes the integration of further sensory channels. We see particular potential in the fields: telepresence, virtual and augmented environments and human-robot interaction. To overcome some of our limitations and looking towards a human-centred design, we want to suggest ideas for future work in all three focus areas. It is obvious that we also have an ongoing process of refinement and development of our methodology, which will also be applied in our future work.

Limitations in haptic touchscreen interactions, but also in haptic interaction in general, means that it is challenging to generate physically correct haptic stimuli and usability and ergonomics depend very much on the particular individual. It would be interesting to use further materials to investigate which are well suited to provide versatile and realistic haptic feedback and exploration. This could also include the development of new actuators. In order to better stimulate the individual characteristics, such as finger lengths, with haptic feedback when augmenting touchscreens, we believe it would make sense to detach haptic technology from the device and design a small device, similar to a thimble, that would be able to provide tactile, force and temperature stimuli. The challenge with this question will be how to combine the various components in a small amount of space while maintaining haptic requirements. These small thimbles would then no longer be limited to interaction with touchscreens. They could be used in more versatile directions, such as in telepresence scenarios and virtual and augmented environments.

We see further directions in foot stimulation and robot control. As in the previous paragraph, a challenge could be miniaturising all haptic components further, possibly integrating them into a shoe - resulting in a haptic shoe that provides versatile haptic feedback. Such a shoe could be used in both scenarios, telepresence and virtual environments. Furthermore, it could also be connected with a touchscreen to explore similar interaction metaphors we did above. Our approach to perceive the environment via proximity and collision feedback on the foot could be continued, and we could focus on further aspects such as perception and performance. If one looks at the sensor ring developed in Chapter 5 for sensing the environment, the question arises how the environment can be better recognised and a kind of assistant driving, which adapts to the environment or could even perform specific tasks autonomously. Such a procedure could be learnt and adapted to the user over time to provide the user with personalised and effective control.

6.5 Final Words

With the ever-increasing number of technologies in our daily lives, we are more and more overwhelmed with different interfaces. Understanding complex processes and using interfaces correctly is becoming increasingly important. This also influences efficiency, however, individuals should also feel as comfortable as possible when interacting, in order to make the interaction as pleasant as possible. In this thesis, five novel prototypes that provide haptic feedback were designed, developed and evaluated. We have shown in two fields that it is worthwhile to include haptic feedback in the interaction to provide both, a higher performance and an enhanced experience. In the area of touchscreen interaction, three prototypes were presented that illustrated the versatility of haptic feedback. Psychophysical methods were used to evaluate the prototypes. Beyond that, it was shown that touch accuracy can be increased with haptic feedback. Perceptual aspects were investigated in the areas of Virtual and Remote Environments. The haptic interfaces were developed to make the user experience as pleasant as possible. We presented that haptic feedback on the feet increases spatial awareness, involvement and self-motion perception.

To conclude, I think it’s always worth looking at how interaction can be adapted to make it easier, better or maybe just more fun. When haptic aspects are involved, I would be pleased.

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Appendix A

Questionnaires

Questionnaire 1 (actuated screen Section 4.2)	-3	-2	-1	0	1	2	3
I could perform the experiment well using the separation between display and tablet	○	○	○	○	○	○	○
The pose to control the tablet was comfortable	○	○	○	○	○	○	○
I could fellow the speed markers easily	○	○	○	○	○	○	○
I was fully satisfied with the feedback of the system	○	○	○	○	○	○	○
per condition							
The interaction metaphor was good for this application	○	○	○	○	○	○	○
The tablet was easy to adjust to interact with the data	○	○	○	○	○	○	○
The position and inclination helped understanding 'physics'	○	○	○	○	○	○	○
I was fully satisfied with the app	○	○	○	○	○	○	○

Questionnaire 2 (flexible material Section 4.3)

per condition	1	2	3	4	5
I did not have to concentrate much while detecting a difference	**o**	**o**	**o**	**o**	**o**
Perceiving tension cues was easy	**o**	**o**	**o**	**o**	**o**
I found the system easy to use	**o**	**o**	**o**	**o**	**o**
I found the system easy to learn	**o**	**o**	**o**	**o**	**o**
I felt confident using the system	**o**	**o**	**o**	**o**	**o**
I did not feel frustrated when performing the tasks	**o**	**o**	**o**	**o**	**o**
I found the responsiveness of tension feedback adequate	**o**	**o**	**o**	**o**	**o**
I could well receive cues with the pen	**o**	**o**	**o**	**o**	**o**
The noise produced by the system did not disturb me while performing the task	**o**	**o**	**o**	**o**	**o**
I would like to use a similar system in the future	**o**	**o**	**o**	**o**	**o**

Questionnaire 3 (actuated pins Section 4.4)

per condition	1	2	3	4	5	6	7
I could perform the task precisely	**o**	**o**	**o**	**o**	**o**	**o**	**o**
I could complete the task quickly	**o**	**o**	**o**	**o**	**o**	**o**	**o**
The feedback quality was excellent	**o**	**o**	**o**	**o**	**o**	**o**	**o**
matrix selection							
Different feedback intensities enabled a better orientation in the Matrix	**o**	**o**	**o**	**o**	**o**	**o**	**o**

Questionnaire 4 (robot control Section 5.2)	1	2	3	4	5	6	7
How much were you able to control events?	o	o	o	o	o	o	o
How responsive was the environment to actions that you initiated (or performed)?	o	o	o	o	o	o	o
How natural did your interactions with the environment seem?	o	o	o	o	o	o	o
How much did the visual aspects of the environment involve you?	o	o	o	o	o	o	o
How natural was the mechanism which controlled movement through the environment?	o	o	o	o	o	o	o
How compelling was your sense of objects moving through space?	o	o	o	o	o	o	o
How much did your experiences in the virtual environment seem consistent with your real world experiences?	o	o	o	o	o	o	o
Were you able to anticipate what would happen next in response to the actions that you performed?	o	o	o	o	o	o	o
How completely were you able to actively survey or search the environment using vision?	o	o	o	o	o	o	o
How compelling was your sense of moving around inside the virtual environment?	o	o	o	o	o	o	o
How closely were you able to examine objects?	o	o	o	o	o	o	o
How well could you examine objects from multiple viewpoints?	o	o	o	o	o	o	o
How involved were you in the virtual environment experience?	o	o	o	o	o	o	o
How much delay did you experience between your actions and expected outcomes?	o	o	o	o	o	o	o
How quickly did you adjust to the virtual environment experience?	o	o	o	o	o	o	o
How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?	o	o	o	o	o	o	o
How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?	o	o	o	o	o	o	o
How much did the control devices interfere with the performance of assigned tasks or with other activities?	o	o	o	o	o	o	o
How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?	o	o	o	o	o	o	o
How much did the auditory aspects of the environment involve you?	o	o	o	o	o	o	o
How well could you identify sounds?	o	o	o	o	o	o	o
How well could you localize sounds?	o	o	o	o	o	o	o
How well could you actively survey or search the virtual environment using touch?	o	o	o	o	o	o	o
How well could you move or manipulate objects in the virtual environment?	o	o	o	o	o	o	o

Questionnaire 5 (walking-like cues Section 5.3)	0	1	2	3	4	5	6	7	8	9	10
I had a strong sensation of self-motion	o	o	o	o	o	o	o	o	o	o	o
I could judge velocity travelled well	o	o	o	o	o	o	o	o	o	o	o
I could judge distance travelled well	o	o	o	o	o	o	o	o	o	o	o
I was not aware of my real environment	o	o	o	o	o	o	o	o	o	o	o

Questionnaire 6 (walking-like cues Section 5.3)	0	1	2	3	4	5	6	7	8	9	10
per condition											
Walking on wood was convincing	o	o	o	o	o	o	o	o	o	o	o
Walking on gravel was convincing	o	o	o	o	o	o	o	o	o	o	o
I felt comfortable	o	o	o	o	o	o	o	o	o	o	o
I was able to concentrate on the task	o	o	o	o	o	o	o	o	o	o	o
I was able to navigate and follow the object	o	o	o	o	o	o	o	o	o	o	o
The interface was easy to learn	o	o	o	o	o	o	o	o	o	o	o
It was fun using the interface	o	o	o	o	o	o	o	o	o	o	o
I could imagine using the interface for a longer period of time	o	o	o	o	o	o	o	o	o	o	o
I had a strong sense of self-motion	o	o	o	o	o	o	o	o	o	o	o
I was fully satisfied with the usability of the interface	o	o	o	o	o	o	o	o	o	o	o
the following stimuli (cues) have had a positive influence on vection:											
audio	o	o	o	o	o	o	o	o	o	o	o
light vibrations	o	o	o	o	o	o	o	o	o	o	o
strong vibrations (heel)	o	o	o	o	o	o	o	o	o	o	o
head bobbing	o	o	o	o	o	o	o	o	o	o	o

Appendix B

Further Results

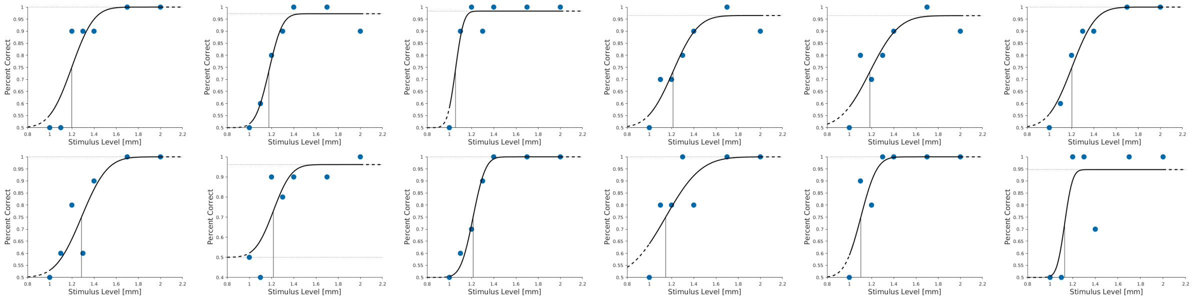

Figure B.1: Results of psychophysical study performed to analyse our third prototype in the first focus area. It shows the psychometric curves obtained in experiment (see Section 4.4)

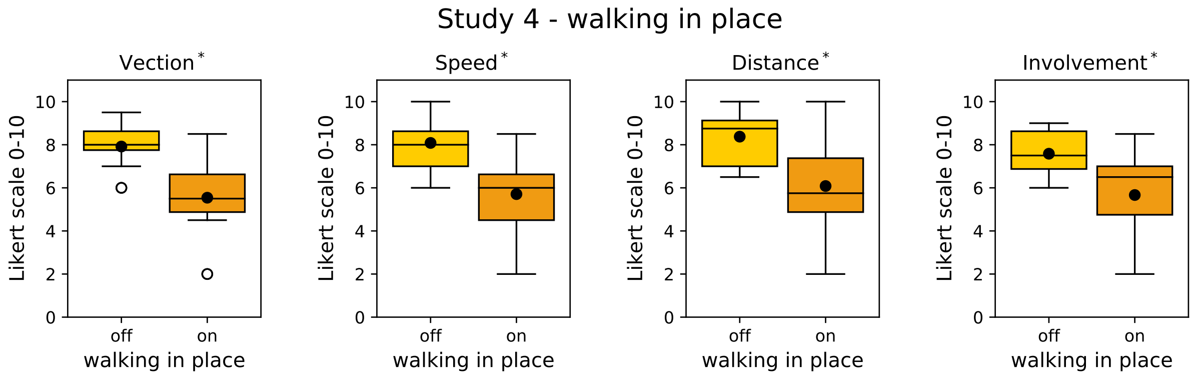

Figure B.2: Results of the in-study questionnaire of session 4. The graphs showed the worse scores of the walking in place metaphor (see Section 5.3.2).

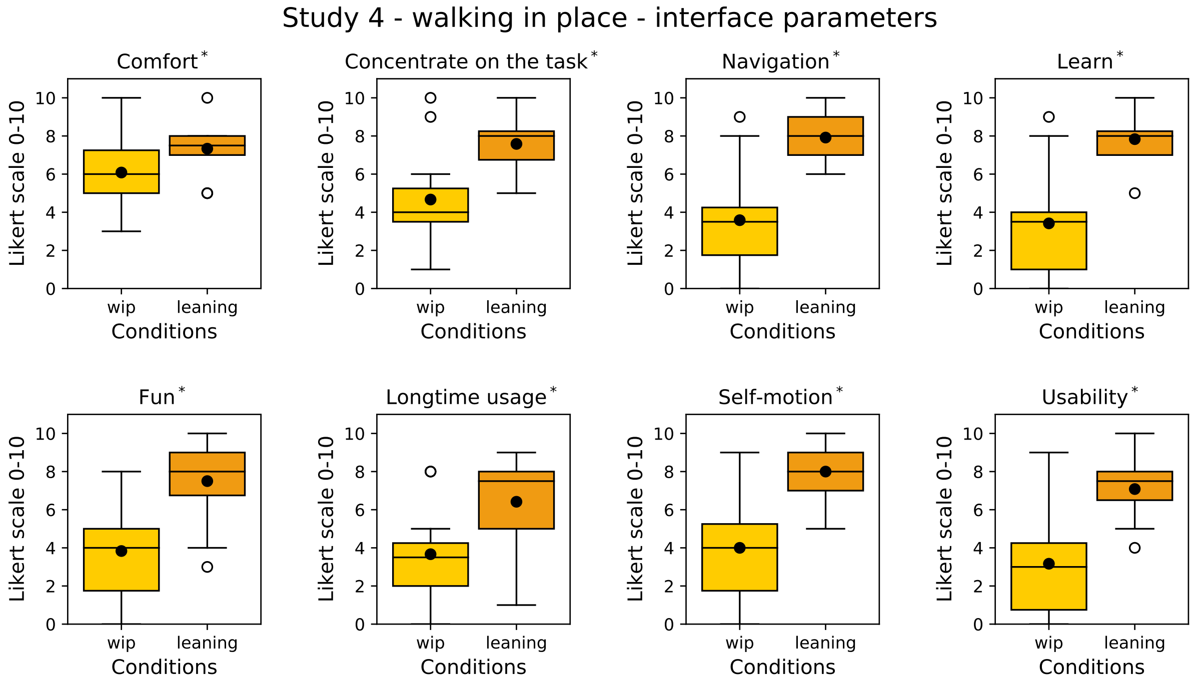

Figure B.3: Results of the post-study questionnaire of session 4. Again, the graphs showed the worse scores of the walking in place metaphor (see Section 5.3.2).