REMOTE TACTILE FEEDBACK ON INTERACTIVE SURFACES

DISSERTATION

an der Fakultät für Mathematik, Informatik und Statistik
der Ludwig-Maximilians-Universität München

vorgelegt von
Diplom-Medieninformatiker
HENDRIK RICHTER

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ABSTRACT

Direct touch input on interactive surfaces has become a predominating standard for the manipulation of digital information in our everyday lives. However, compared to our rich interchange with the physical world, the interaction with touch-based systems is limited in terms of flexibility of input and expressiveness of output. Particularly, the lack of tactile feedback greatly reduces the general usability of a touch-based system and hinders from a productive entanglement of the virtual information with the physical world.

This thesis proposes *remote tactile feedback* as a novel method to provide programmed tactile stimuli supporting direct touch interactions. The overall principle is to spatially decouple the location of touch input (e.g. fingertip or hand) and the location of the tactile sensation on the user's body (e.g. forearm or back). Remote tactile feedback is an alternative concept which avoids particular challenges of existing approaches. Moreover, the principle provides inherent characteristics which can accommodate for the requirements of current and future touch interfaces.

To define the design space, the thesis provides a structured overview of current forms of touch surfaces and identifies trends towards non-planar and non-rigid forms with more versatile input mechanisms. Furthermore, a classification highlights limitations of the current methods to generate tactile feedback on touch-based systems. The proposed notion of tactile sensory relocation is a form of sensory substitution. Underlying neurological and psychological principles corroborate the approach. Thus, characteristics of the human sense of touch and principles from sensory substitution help to create a technical and conceptual framework for remote tactile feedback.

Three consecutive user studies measure and compare the effects of both direct and remote tactile feedback on the performance and the subjective ratings of the user. Furthermore, the experiments investigate different body locations for the application of tactile stimuli. The results show high subjective preferences for tactile feedback, regardless of its type of application. Additionally, the data reveals no significant differences between the effects of direct and remote stimuli. The results back the feasibility of the approach and provide parameters for the design of stimuli and the effective use of the concept.

The main part of the thesis describes the systematical exploration and analysis of the inherent characteristics of remote tactile feedback. Four specific features of the principle are identified: (1) the simplification of the integration of cutaneous stimuli, (2) the transmission of proactive, reactive and detached feedback, (3) the increased expressiveness of tactile sensations and (4) the provision of tactile feedback during multi-touch. In each class, several prototypical remote tactile interfaces are used in evaluations to analyze the concept. For example, the *PhantomStation* utilizes psychophysical phenomena to reduce the number of single tactile actuators. An evaluation with the prototype compares standard actuator technologies with each other in order to enable simple and scalable implementations. The *ThermalTouch* prototype creates remote thermal stimuli to reproduce material characteristics on standard touchscreens. The results show a stable rate of virtual object discrimination based on remotely applied temperature profiles. The *AutmotiveRTF* system is implemented in a vehicle and supports the driver's input on the in-vehicle-infotainment system. A field study with the system focuses on evaluating the effects of proactive and reactive feedback on the user's performance.

The main contributions of the dissertation are: First, the thesis introduces the principle of remote tactile feedback and defines a design space for this approach as an alternative method to provide non-visual cues on interactive surfaces. Second, the thesis describes technical examples to rapidly prototype remote tactile feedback systems. Third, these prototypes are deployed in several evaluations which highlight the beneficial subjective and objective effects of the approach. Finally, the thesis presents features and inherent characteristics of remote tactile feedback as a means to support the interaction on today's touchscreens and future interactive surfaces.

ZUSAMMENFASSUNG

Die Interaktion mit berührungsempfindlichen Oberflächen ist heute ein Standard für die Manipulation von digitaler Information. Jedoch weist die Bedienung dieser interaktiven Bildschirme starke Einschränkungen hinsichtlich der Flexibilität bei der Eingabe und der Ausdruckskraft der Ausgabe auf, wenn man sie mit den vielfältigen Möglichkeiten des Umgangs mit Objekten in unserer Alltagswelt vergleicht. Besonders die nicht vorhandenen Tastsinnesrückmeldungen vermindern stark die Benutzbarkeit solcher Systeme und verhindern eine effektive Verknüpfung von virtueller Information und physischer Welt.

Die vorliegende Dissertation beschreibt den Ansatz der 'distalen taktilen Rückmeldungen' als neuartige Möglichkeit zur Vermittlung programmierter Tastsinnesreize an Benutzer interaktiver Oberflächen. Das Grundprinzip dabei ist die räumliche Trennung zwischen der Eingabe durch Berührung (z.B. mit der Fingerspitze) und dem daraus resultierenden taktilen Reiz am Körper der Benutzer (z.B. am Rücken). Dabei vermeidet das Konzept der distalen taktilen Rückmeldungen einzelne technische und konzeptionelle Nachteile existierender Ansätze. Zusätzlich bringt es Interaktionsmöglichkeiten mit sich, die den Eigenheiten der Interaktion mit aktuellen und auch zukünftigen berührungsempfindlichen Oberflächen Rechnung tragen.

Zu Beginn zeigt ein Überblick zu relevanten Arbeiten den aktuellen Forschungstrend hin zu nicht-flachen und verformbaren berührungsempfindlichen Oberflächen sowie zu vielfältigeren Eingabemethoden. Eine Klassifizierung ordnet existierende technische Verfahren zur Erzeugung von künstlichen Tastsinnesreizen und stellt jeweils konzeptuelle und technische Herausforderungen dar. Der in dieser Arbeit vorgeschlagene Ansatz der Verlagerung von Tastsinnesreizen ist eine Form der sensorischen Substitution, zugrunde liegende neurologische und psychologische Prinzipien untermauern das Vorgehen. Die Wirkprinzipien des menschlichen Tastsinnes und die Systeme zur sensorischen Substitution liefern daher konzeptionelle und technische Richtlinien zur Umsetzung der distalen taktilen Rückmeldungen.

Drei aufeinander aufbauende Benutzerstudien vergleichen die Auswirkungen von direkten und distalen taktilen Rückmeldungen auf die Leistung und das Verhalten von Benutzern sowie deren subjektive Bewertung der Interaktion. Außerdem werden in den Experimenten die Effekte von Tastsinnesreizen an verschiedenen Körperstellen untersucht. Die Ergebnisse zeigen starke Präferenzen für Tastsinnesrückmeldungen, unabhängig von deren Applikationsort. Die Daten ergeben weiterhin keine signifikanten Unterschiede bei den quantitativen Effekten von direktem und distalen Rückmeldungen. Diese Ergebnisse befürworten die Realisierbarkeit des Ansatzes und zeigen Richtlinien für weitere praktische Umsetzungen auf.

Der Hauptteil der Dissertation beschreibt die systematische Untersuchung und Analyse der inhärenten Möglichkeiten, die sich aus der Vermittlung distaler taktiler Rückmeldungen ergeben. Vier verschiedene Charakteristika werden identifiziert: (1) die vereinfachte Integration von Tastsinnesreizen, (2) die Vermittlung von proaktiven, reaktiven und entkoppelten Rückmeldungen, (3) die erhöhte Bandbreite der taktilen Signale und (4) die Darstellung von individuellen Tastsinnesreizen für verschiedene Kontaktpunkte mit der berührungsempfindlichen Oberfläche. Jedes dieser Prinzipien wird durch prototypische Systeme umgesetzt und in Benutzerstudien analysiert.

Beispielsweise nutzt das System *PhantomStation* psychophysikalische Illusionen, um die Anzahl der einzelnen Reizgeber zu reduzieren. In einer Evaluierung des Prototypen werden mehrere Aktuatortechnologien verglichen, um einfache und skalierbare Ansätze zu identifizieren. Der *ThermalTouch*-Prototyp wird dazu genutzt, distale thermale Reize zu vermitteln, um so Materialeigenschaften auf Berührungsbildschirmen darstellen zu können. Eine Benutzerstudie zeigt, dass sich auf Basis dieser Temperaturverläufe virtuelle Objekte unterscheiden lassen. Das *AutomotiveRTF*-System wird schließlich in ein Kraftfahrzeug integriert, um den Fahrer bei der Eingabe auf dem Informations- und Unterhaltungssystem zu unterstützen. Eine Feldstudie untersucht die Auswirkungen der proaktiven und reaktiven Rückmeldungen auf die Benutzerleistung.

Die vorliegende Dissertation leistet mehrere Beiträge zur Mensch-Maschine-Interaktion: Das Prinzip der distalen taktilen Rückmeldungen wird eingeführt als Alternative zur Erzeugung nicht-visueller Rückmeldungen auf interaktiven Oberflächen. Es werden technische Verfahrensweisen zur prototypischen Implementierung solcher Systeme vorgeschlagen. Diese technischen Prototypen werden in einer Vielzahl verschiedener Benutzerstudien eingesetzt, welche die quantitativen und qualitativen Vorteile des Ansatzes aufzeigen. Schließlich wird gezeigt, wie sich das Prinzip zur Unterstützung heutiger und zukünftiger Interaktionsformen mit berührungsempfindlichen Bildschirmen nutzen lässt.

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Introduction

In our daily lives, we are under the continuous influence of manifold haptic sensations. We actively collect and make use of them during our interactions with the world. A scenario such as playing the acoustic piano illustrates this matter: We use several fingers from both our hands, jump from key to key and press them with changing velocities. Furthermore, we are aware of the posture of our fingers, hands and arms as they move in the air. Without looking, we can distinguish between black and white keys and rapidly position our fingers as we perceive the form, size and position of the touched keys. With the fingertips, we palpate the edges of the music book to turn to the next page. A lot of these haptic cues affect us unconsciously: we know how to change our posture when reaching for lower or higher keys, we might register the warmth of the room or we even might get hungry. Depending on our skills, we create music which serves as an immediate feedback to our actions. Additional touch feedback comes from the varying resistances as we press the keys and from vibrations and oscillations of the instrument. These subtle haptic sensations act on our skin on diverse parts of our body, such as the feet when we touch the piano's pedals or the back of the thigh resulting from vibrations of the floor and the seat. These additional tactile cues confirm our actions, help us to fine-control our movements and can create a more immersive and emotional connection with the interaction.

1.1 Motivation

All the described sensations are collected, organized and interpreted by the human haptic perception. Especially the stimulation of the skin is tightly interweaved with every manipulation of physical matter. The German word *ertasten* describes the bidirectional nature of the skin (i.e. tactile) senses: We actively *ertasten* tactile characteristics such as form, surface structure or malleability of objects in our environment. The word *ertasten* describes the need to manipulate our environment to gain knowledge about it. Additionally, every interaction with physical matter results in the collection of cutaneous information, we receive and manipulate at the same time.

Together with our other senses, we form an internal representation of the world around us and our relationship with it.

The importance of haptic feedback for the interaction between people and technology has been recognized in many fields such as virtual reality, accessibility or the design of consumer electronics. However, our sense of touch is neglected on one of today's most predominating forms of interfaces: On touchscreens and interactive surfaces, we but prod and wipe on planes that are flat, hard and equally tempered.

More and more devices include surfaces that superimpose screens for visual output and touch sensors as primary means of input. Touchscreens are omnipresent as part of vending machines, mobile phones, tablet PCs, electronic reading devices or handheld gaming consoles. Among the reasons for this widespread use are the robustness and the small size of the hardware as well as the flexibility of the implementation and the visual design of the GUI. Furthermore, touchscreens and interactive surfaces allow for easy learning of their functionality and can create a feeling of competence and enjoyment, as they embody the principle of **direct manipulation** [Shneiderman, 1984]. When designed right, the virtual 'object of interest' is constantly visible and can be directly manipulated, thus resembling our interactions with objects in the physical world.

Mark Weiser envisioned today's ongoing dissipation of technology into our environment [Weiser, 1991]: His term **ubiquitous computing** describes computing technology which vanishes into the background as it is hidden in interconnected low-power devices of different sizes with "a diversity of input and output forms" [Weiser, 1991]. Weiser and his team proposed computers of different sizes (tabs, pads and boards) which are connected wirelessly, adapt to their location and can be used for dedicated tasks. Today's devices which embody this vision such as tablet computers are often manipulated by direct touch. Furthermore, novel developments such as electronic paper might come close to Weiser's vision of disposable computing technology which is not associated with a certain user. The underlying concept is 'embodied virtuality': the ""virtuality" of computer readable data - all the different ways they can be altered, processed and analyzed - is brought into the physical world" [Weiser, 1991]. Primary goals are the fostering of social interaction and the reduction of sensory overload.

This embodiment of information and the creation of novel manipulation facilities is illustrated by Durrell Bishop's 'marble answering machine'[1]. Together with other systems, it inspired the concepts of **Tangible Bits** and **Tangible User Interfaces (TUIs)** [Ishii and Ullmer, 1997]. Tangible user interfaces tightly couple digital information with physical objects and environments, thus making digital information graspable or tangible. These 'tangible bits' bridge the gap between virtual and physical world. The interactive surface is in the center of this concept and is transformed into a more "active interface between the physical and virtual worlds" [Ishii and Ullmer, 1997].

This notion of adaptability of the interactive surface greatly influences the current concept of **Organic User Interfaces**: Here, the displays and touch surfaces are flexible and can alter their

[1] Marble Answering Machine `http://tangint.org/v/1992/bishop-rca-mam/` [cited 2013/02/13]

shape [Vertegaal and Poupyrev, 2008]. Furthermore, manipulations such as bending and folding are used as means of input. Supported by the advances in display technology, the form of the display can also equal its function, thus dynamically realizing Weiser's vision of devices "suited to a particular task" [Weiser, 1991]. Finally, organic user interfaces are intended to actively change their form and structure and reconfigure themselves in order to "reflect data in physical shapes" [Vertegaal and Poupyrev, 2008]. The goal is to create devices that allow for easier and more flexible interactions, thus reducing sensory and cognitive overload.

These ongoing developments are generalized by Hiroshi Ishii and colleagues in their concept of **Radical Atoms** [Ishii et al., 2012]: They describe their vision of hypothetical future materials that change their physical characteristics such as form, color, size and stiffness as they embody digital information. "Radical Atoms is a vision for the future of human-material interactions, in which all digital information has physical manifestation so that we can interact directly with it" [Ishii et al., 2012]. Key concept of the interaction with these materials is direct touch, as it offers high-precision manipulation and direct haptic feedback.

In summary, interactive surfaces are the predominant border between physical and digital world today. We manipulate digital information by direct touch, but input and feedback modalities are still greatly limited. As Brygg Ullmer states in his 2012 article: "our current virtual and physical forms are at best loosely entangled, bringing varied costs and lost opportunities" [Ullmer, 2012]. Furthermore, he stresses that the ongoing separation of the diverse realms might result in "psychosis-like, "loss-of-contact" states" [Ullmer, 2012], as we have to allocate our full attention to one of these un-entangled worlds. Consequently, one can say that all of aforementioned concepts and visions share the struggle to entangle these separate areas. Jun Rekimoto points out that in "the near future, interaction will also involve more physical experience (such as illumination, air, temperature, humidity, and energy)" [Rekimoto, 2008]. The utilization of our haptic perception is the crucial method to generate this physical experience. The above-mentioned seminal visions and concepts inspired and influenced the subject matter of this thesis: *remote tactile feedback* on interactive surfaces as a new medium of *entanglement*.

1.2 Problem Statement

"The full subtlety and potential of our sense of touch might be the biggest loser emerging from the current stampede of touch interfaces"[2]. This quote summarizes the fact that programmed tactile stimuli are still heavily underused as feedback mechanism on today's omnipresent interactive surfaces. The disparity between visual and tactile feedback is increasing with the constant advances in display technology. Furthermore, as described above, interactive surfaces will likely evolve into non-flat, non-solid and more flexible embodiments, thus demanding for more versatile forms of input and output. Simple forms of tactile feedback have been shown to be beneficial on mobile devices during text input in scenarios with increased visual or cognitive load, as they helped to

[2] Bill Buxton (@wasbuxton) via Twitter on 2011/06/11.

decrease task completion times, to reduce the number of input errors and to improve the subjective appraisal of the interaction (see section 3.3.2). However, the full potential of programmed cutaneous sensations on interactive surfaces is far from being tapped.

This **underuse of haptic stimulation** as feedback has numerous reasons such as the technical complexity of necessary actuator systems, high production costs, the reduced versatility of created tactile sensations and missing standards for the design of haptic feedback [Wright, 2011]. Current solutions for tactile feedback on interactive surfaces show diverse conceptual disadvantages such as limited scalability, occlusion of the screen or a loss of direct manipulation.

The emerge of novel forms of interactive surfaces and interaction modalities call for **alternative ways to create and communicate tactile sensations**. Current mechanisms for programmed tactile feedback are not versatile enough to support larger or non-flat interactive surfaces, on which users can interact with multiple fingers, with varying input pressure or using gestures.

The central goal of this thesis is to develop an alternative method for tactile feedback on interactive surfaces. This alternative method should avoid problems of existing solutions and must have properties which support the interaction with current and future types of interactive surfaces. At the same time, the novel method must preserve the quantitative and qualitative benefits of existing solutions. This general goal opens up two problem fields: First, technical prototypes have to be designed and implemented to realize and explore the principle. Second, these prototypes have to be used in evaluations and controlled usage scenarios in order to analyze the subjective and objective effects of the approach.

1.3 Research Approach

1.3.1 Concept

This thesis proposes the spatial separation of direct touch input and resulting programmed tactile output. This notion is termed *remote tactile feedback*, as it describes the spatial distance between the location of contact with the interactive surface (usually fingertip or hand) and the location of the synchronized cutaneous sensations which are applied on the user's skin by actuator systems. Relocated tactile stimuli as a side-effect of a manipulation also exist in our everyday world: As described above, relocated cutaneous sensations occur when we play instruments such as a violin or use tools such as a hammer. They subtly confirm our actions and help to dynamically correct our movements. The dissertation motivates the concept of remote tactile feedback based on findings from research fields such as psychology, neurology, sensory substitution and prosthetics on a conceptual and technical level.

The thesis describes remote tactile feedback during the direct manipulation of interactive surfaces as a medium to communicate digital content which is encoded as cutaneous stimuli. Thus, remote tactile feedback forms a channel of information about the interaction with virtual graphical elements. It transfers content which can be redundant to the existing visual or auditory information or which delivers additional meaning: More specifically, remote tactile feedback can replicate physical characteristics of the virtual elements such as texture or temperature or it can render abstract information such as the type of an interactive element or the current state of the interaction.

1.3.2 Objectives

This thesis addresses two main research questions:

Research Question 1:
Does remote tactile feedback improve the direct touch interaction in terms of reduced error rates, increased interaction speed, decreased distraction and better subjective ratings?

Evaluations in research fields such as mobile interaction have shown that direct tactile feedback can greatly improve the usability of touch-based systems (see section 3.3.2). Before we can explore the inherent potentials of remote tactile feedback, it is important to analyze its quantitative and qualitative effects. By answering the following questions, we can refine the concept of remote tactile feedback and improve both the actuator technology and the communicated signals:

- In which scenarios does remote tactile feedback have beneficial effects?
- How do tactile stimuli have to be designed to improve the touch interaction?

For this purpose, we have to formally evaluate and compare both approaches for tactile output and their effect on the user's performance and subjective estimation of the interaction. The outcome of these evaluations will determine the further procedure: On the one hand, remote tactile feedback could degrade the user's performance. In this case, the assumed inherent benefits of the approach, which are addressed in RQ2, might not compensate for the decrease in general usability. On the other hand, remote tactile feedback could improve the touch interaction in quantitative and qualitative metrics, comparable to direct tactile feedback. In this case, the approach would form a valid alternative for existing concepts. Furthermore, the results would help to identify scenarios in which the concept is most helpful. In summary, it is essential to answer RQ1 in order to focus on RQ2:

Research Question 2:
Does remote tactile feedback provide additional inherent characteristics which are beneficial for direct-touch interactions?

The spatial separation of touch input and tactile output has numerous implications for both the haptic feedback and the underlying interactive surface: The approach could open up new possibilities for the design of actuators. They could be placed on the user's body, differing in size, form and type of generated modality. This could simplify the integration of actuator technology and allow for more versatile haptic sensations. Furthermore, no actuators have to be integrated into the interactive surface. Thus, programmed cutaneous output could also become possible on non-flat or non-solid touch surfaces. Additionally, one could try to provide several individual tactile stimuli during multi-touch input. When the actuators are in permanent contact with the user, also gestural interactions close to the touchscreen could be augmented with programmed cutaneous sensations. In order to identify the individual characteristics which are the most promising to analyze, we first have to answer the following questions:

- What could be the future of interactive surfaces?
- What are the benefits and drawbacks of existing techniques for tactile feedback?
- How do humans integrate own manipulations and resulting tactile stimuli on the body?

Answering these questions will help to decide which inherent characteristics could be most helpful to support the interaction on existing and future interactive surfaces. Furthermore, remote tactile feedback could avoid the challenges of existing approaches for cutaneous feedback. However, the effective design of remote tactile interfaces is only possible when physiological and psychological factors are taken into account. The overall goal of the approach is to conceptually and technically simplify and extend the utilization of touch stimuli. The concept of direct manipulation must be preserved. The prototypical implementation and evaluation of the identified inherent characteristics will provide researchers and practitioners with technical advice and conceptual guidelines for the integration of remote tactile feedback in appropriate usage scenarios.

1.3.3 Procedure

The thesis is an example for the multidisciplinary nature of HCI, as it draws concepts and techniques from natural sciences, design and engineering. As Wendy Mackay and Anne-Laure Fayard describe it, we are "constantly borrowing, inventing and re-inventing techniques" [Mackay and Fayard, 1997]. The authors describe that HCI integrates two scientific models: the *deductive model*, which starts from theory and tries to explain the real world with a set of hypotheses, as well as the *inductive model* which starts from an observation of phenomena in nature and constructs a description. In HCI, we do usually do not observe the 'real world' but rather study the "interaction between people and artificially-created artifacts" [Mackay and Fayard, 1997]. This creation and evaluation of technical prototypes demands for work on the theoretical, technical and empirical level. Thus, Mackay and Fayard propose the **cross-disciplinary-triangulation** across the component disciplines of HCI to understand and improve our work. Following this argumentation, the procedure to answer the two research questions of this thesis is described accordingly (see figure 1.1). The research was divided into three specific tasks:

First, I performed an intensive literature review in the fields of interactive surfaces, haptics and tactile feedback as well as relocated stimuli in sensory substitution. This literature review helped to identify ongoing developments of interactive surfaces. Furthermore, I gained an overview of the existing hardware for haptic actuation and classified common techniques for tactile feedback on touch surfaces. Consequently, it was possible to uncover benefits and conceptual challenges of each approach. Finally, existing techniques such as tactile sensory relocation helped to substantiate the general concept of remote tactile feedback.

Second, these foundations from literature supported the first evaluation of the approach. In order to answer RQ1, we used simple and effective actuators in experiment prototypes. These proto-

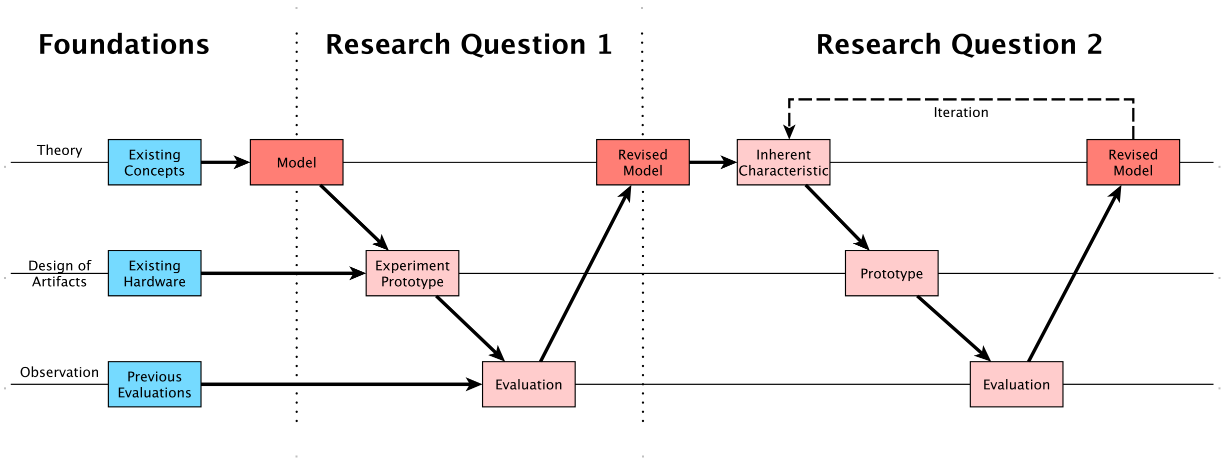

Figure 1.1: The general approach of this thesis on the theoretical, technical and empirical level. Details can be found in the text.

types were embedded in user studies, in which we recreated study settings from evaluations of direct tactile feedback. The goal was to gain valid and comparable results. The evaluations and corresponding outcomes were a valuable source for improvements on the theoretical and technical level as they helped to identify appropriate scenarios of use and showed the need for more meaningful and versatile stimuli. Most importantly, the results of the evaluations allowed to answer RQ1 and corroborated my intention to explore the inherent characteristics of the approach.

Third, I now started to analyze and evaluate the inherent characteristics of the approach based on a refined and revised concept of remote tactile feedback. This procedure had three consecutive parts: After highlighting existing challenges and options of the approach, we created working prototypes of remote tactile interfaces on different levels of fidelity. These prototypes embodied the inherent characteristic and were implemented into diverse laboratory studies, field studies or observations. The results of these evaluations helped to validate or contradict the assumed benefits of the tested inherent characteristic. The sequence of implementation, evaluation and refinement was performed iteratively. This procedure made it possible to refine the concept of remote tactile feedback on the theoretical and technical level. Furthermore, by "moving cyclically back and forth between theory and observation" [Mackay and Fayard, 1997], I could answer RQ2.

1.4 Main Contributions

In the following, I present the contributions of the dissertation on a more abstract level. In the end of the thesis (see section 7.1), the contributions will be discussed again:

1.4.1 Defining a Design Space

As a first contribution, the thesis defines and structures a design space for remote tactile feedback. Therefore, the thesis provides a classification of current concepts for interactive surfaces. Ongoing developments in the field are structured to highlight conceptual trends and future tendencies. Furthermore, the overview shows drawbacks which result from the lack of tactile feedback. Consequently, a classification for current methods to provide programmed tactile stimuli is given. This taxonomy allows to compare the methods along the three dimensions *technical feasibility*, *tactile expressiveness* and *general usability*. Accordingly, individual benefits and weaknesses are identified. The thesis substantiates the notion of remote tactile feedback by highlighting psychological and physiological fundamentals of the human sense of touch. Thus, the thesis names a list of factors which indicate that humans can integrate own touch interactions and resulting tactile stimulation on the body into a coherent perception. The dissertation provides concepts and systems from the field of sensory substitution which provide a conceptual and technical basis for the approach. This work allows to define a distinct model and framework for the concept of remote tactile feedback.

1.4.2 Technical Concepts and Prototypes

The notion of remote tactile feedback is exemplified and formally analyzed using diverse prototypical interfaces. These prototypes differ in the way they are used (e.g. wearable or embedded) and in the modalities they create (e.g. electromechanical or thermal stimulation). The description of these technical concepts and prototypes is the second contribution of the thesis. This allows the reader to compare common actuator technologies and to analyze how they can be used to create this novel form of feedback. The interfaces are prototypes and often use off-the-shelf components. This allows researchers to easily recreate and adapt the concept.

1.4.3 Improved Direct Touch Interactions

To further analyze the concept, the thesis describes evaluations in which the effect of remote tactile stimuli on the user's performance was measured. Furthermore, I provide results of evaluations which formally compared the quantitative and qualitative effects of direct and remote tactile feedback. These user studies were performed to answer RQ1. As a contribution, the results provide insight into what form of stimulation in which situation is most helpful for the user of interactive surfaces.

1.4.4 Versatile Feedback and Simple Integration

The identification and analysis of the unique characteristics of remote tactile feedback and their implications is the main contribution of this dissertation. For example: no actuators are integrated into the touch surface and the contact of the skin with the actuators is not restricted to the moment of touch. These features have manifold beneficial implications for the use of tactile feedback and the touch interaction itself. This matter is also in the center of RQ2. The dissertation highlights that remote tactile feedback can simplify the technical integration of cutaneous output, allows for more versatile stimuli, can provide feedback before and after touch and makes it possible to augment multi-touch input with 'multi-haptic' output. The diverse inherent features are implemented on different levels of fidelity and are exemplified and analyzed in diverse forms of evaluation.

In summary, the dissertation provides researchers and practitioners with the theoretical framework, first technical concepts and empirical backup for the use of remote tactile feedback. Thus, the thesis contributes a valid alternative concept for tactile feedback on interactive surfaces.

1.5 Thesis Structure

The thesis is structured as depicted in figure 1.2 and can be organized in three main parts:

- Fields of Research and Underlying Basics: chapters 2 and 3
- Conceptual Foundations: chapter 4
- Contributions: chapters 5 and 6

Chapter 2 – Interactive Surfaces: This chapter describes the principle of direct manipulation as the defining concept of touch interactions and surveys the diverse types of interactive surfaces. The chapter highlights the ongoing development of the field towards more flexible and versatile forms and interactions. In this chapter, I also provide an overview of challenges and limitations of touch interfaces which also result from limited non-visual feedback.

Chapter 3 – Haptics and Tactile Feedback: In this chapter, I provide fundamentals of the human sense of touch from psychology and physiology. Furthermore, I structure the existing terminology and show the differing characteristics of the cutaneous senses depending on the body location. In the next step, I describe the properties of haptic interfaces and provide examples for haptics in fields such as teleoperation or virtual reality. Afterwards, the chapter focuses on tactile feedback and provides an overview of its benefits on touch interfaces known from HCI literature. Then, the chapter classifies existing methods for the actuation of interactive surfaces and provides a taxonomy to structure individual limitations.

Chapter 4 – Relocated Haptic Stimuli: This chapter introduces the notion of relocated tactile stimuli and reviews concepts and technologies which corroborate the idea. Specifically, I draw from the fields of sensory substitution and tactile sensory relocation. I provide a classification of sensory substitution systems and show that the underlying concept of brain plasticity and the existence of a proprioceptive-tactile perceptual feedback loop allows to integrate remote tactile stimuli and manual interactions. Furthermore, the chapter provides examples for existing implementations of the concept from prosthetic medicine, accessibility and human-computer in-

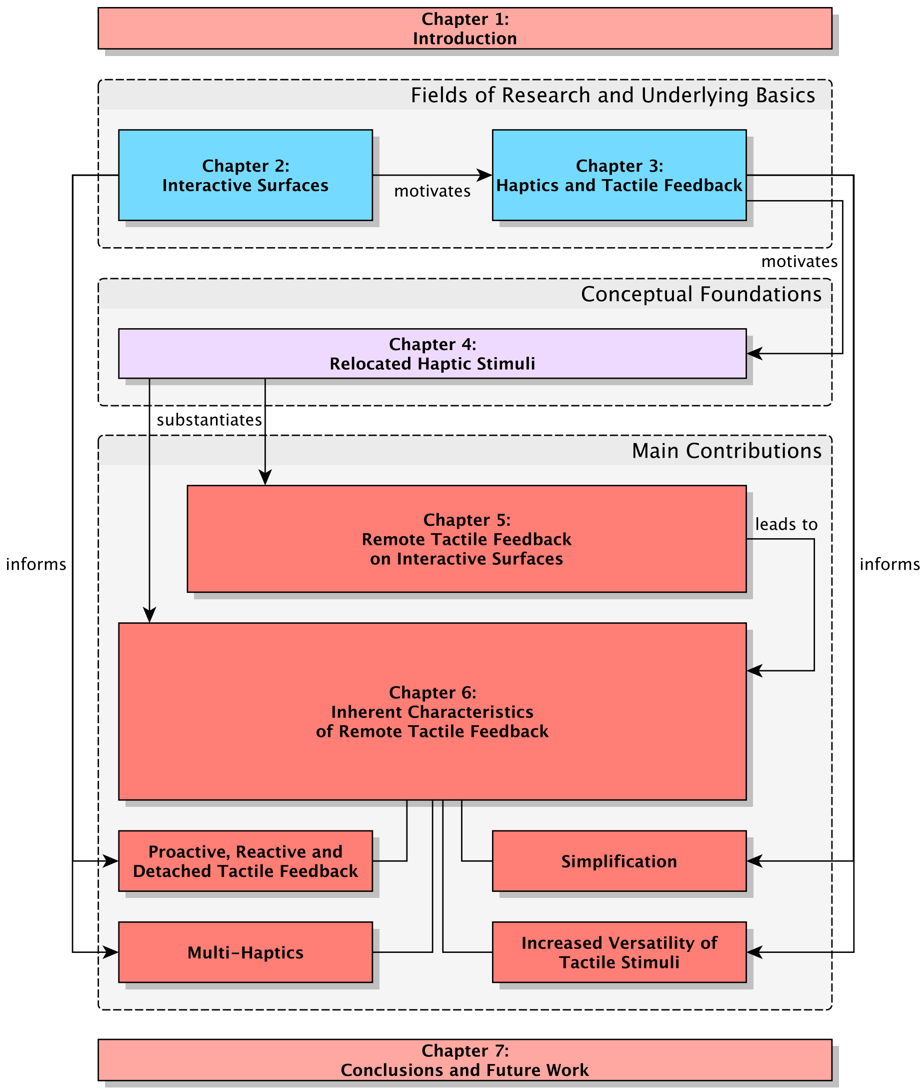

Figure 1.2: The roadmap of this thesis.

teraction. The chapter closes with a summary of concepts that allow to establish the design space of remote tactile feedback.

Chapter 5 – Remote Tactile Feedback on Interactive Surfaces: This chapter starts with a formal definition of the concept and defines a problem space. In the next step, it presents three consecutive user studies in which me measured the effects of direct and remote tactile feedback on the user's performance. The chapter closes with a summary of the results and a discussion of the implications for the concept.

Chapter 6 – Inherent Characteristics of Remote Tactile Feedback: This main chapter identifies the inherent characteristics of remote tactile feedback and analyzes the potentials of four specific properties. For each of these four properties, the chapter gives a short overview of related work, describes the implemented prototypes on the conceptual and technical level and presents the evaluations and results. In the chapter, I also present an outlook towards scenarios in which multiple people interact simultaneously on multiple interactive surfaces and receive dedicated remote tactile feedback. Finally, the chapter discusses and summarizes the presented results.

Chapter 7 – Conclusions and Future Work: This chapter closes the dissertation. After a summary of the contributions, I discuss the limitations of the approach and highlight possible next steps.

Chapter 2

Interactive Surfaces

The generic term 'interactive surfaces' denominates a heterogeneous class of human-computer interfaces which react to direct contact (i.e. touch) with physical objects or the human body and superimpose visual output and direct input. In general, interactive surfaces include an output medium or screen and input sensor technology which is communicating with software to interpret the location of the user's input. Touch surfaces support both discrete (e.g. taps, pushes) and continuous input (e.g. stroke or 'pinch' gestures).

The principle of direct manipulation is the core-characteristic of interaction with this type of interface. This notion reduces the semantic and articulatory distance between user and manipulated item, which in turn reduces the effort for the user to accomplish own goals [Hutchins et al., 1985]. The principle of direct manipulation and its significance for interactive surfaces is part of this chapter. In the main part of this thesis the term direct manipulation is additionally restricted to interactions which are executed *directly* using the human hand without intermediate devices such as input styli, tangibles or light pens.

Since the early 1990s, interface research has explored the relationship between physical representation and digital information. Other than input devices such as the keyboard and mouse, tangible user interfaces are both physical embodiment and control devices for their digital interpretation [Ullmer, 2002]. These discrete physical artifacts help to overcome the limitations of communication with digital systems by incorporating our trained human senses and learned skills. This principle of minimizing the distance between physical and digital world by immediate interpretation and response closely follows the notion of direct manipulation. Using Ishii's and Ullmer's definition, I understand interactive surface as 'an active interface between the physical and virtual worlds' [Ishii and Ullmer, 1997]. My research partly shares the motivation: to enrich and improve the interaction with digital data by utilizing the human senses.

Finally, I discuss challenges and limitations of interactive surfaces. For input, parameters such as distance or pressure are utilized to broaden the communication channel from the user to the device. Approaches such as multitouch input, distance sensing and measurement of input force are discussed. Even greater limitations exist for the flow of information from the device to the user (i.e. output). Touch interfaces are often used in dynamic multi-tasking scenarios such as mobile or in-vehicle environments. Still, feedback from interactive surfaces mostly relies on visual cues, resulting in problems such as increased visual and cognitive load or reduced accuracy and interaction speed. Active tactile feedback has been demonstrated to be greatly beneficial here.

2.1 Direct Manipulation

The concept of 'Direct Manipulation' was originally introduced by Ben Shneiderman in 1984 [Shneiderman, 1984] to describe desired characteristics of emerging interactive systems at that time. With an increasing dependence on electronic data processing resulting from technological advances, non-technically-trained people became users of computing systems such as office automation or personal computers at home. Shneiderman emphasizes the importance of a user-centered design process when developing interactive systems to include novice users and to take into account the growing organizational and social dependence on interactive devices. This design-approach should help to reduce error-rates, to decrease response times and to boost the performance and attractiveness of the interactive system. By analyzing user's feedback during the evolutionary design process, Shneiderman identifies three core principles for designing advantageous systems:

1. "Continuous representation of the object of interest.
2. Physical actions or labelled button presses instead of complex syntax.
3. Rapid incremental reversible operations whose impact on the object of interest is immediately visible" [Shneiderman, 1984].

He states that using these "three principles it is possible to design systems which have these beneficial attributes:

1. Novices can learn basic functionality quickly, usually through a demonstration by a more experienced user.
2. Experts can work extremely rapidly to carry out a wide range of tasks, even defining new functions and features.
3. Knowledgeable intermittent users can retain operational concepts.
4. Error messages are rarely needed.
5. Users can immediately see if their actions are furthering their goals, and if not, they can simply change the direction of their activity.
6. Users have reduced anxiety because the system is comprehensible and because actions are so easily reversible" [Shneiderman, 1984].

Hutchins et al. elaborate on the aspect of directness, which for them is an "impression or a feeling about an interface" [Hutchins et al., 1985]. The user of an interactive system has a task or an interest which he wants to realize using the system. In direct-manipulation interfaces, there should be no intermediary between the user and the objects of the task domain themselves. The authors strongly relate the feeling of directness to the distance between the user's goals and intentions and the level of descriptions that are provided by the interactive system. These mental gaps are described as 'gulf of execution' and 'gulf of evaluation' [Norman, 1968]. To bridge the gulf of execution, the user has to interpret and use the tools that are presented by the system. For semantic directness, the descriptions that are coming from the machine have to match the user's intention. To bridge the gulf of evaluation, the user has to understand whether his goal was achieved. Here, semantic directness refers to minimizing the difficulty for the user to interpret the system's state. Depending on the quality of the user interface, the principle of direct manipulation has the potential to make a system easier to learn, to enhance expert performance, to reduce error rates and to provide better feedback [Shneiderman, 1986]. In other words: "The better the interface to a system helps bridge the gulfs, the less cognitive effort needed and the more direct the resulting feeling of interaction" [Hutchins et al., 1985]. Frohlich [Frohlich, 1997] points out that the virtues of direct manipulation do not refer to graphical interfaces with manual interactions in general. He states the importance being less dogmatic and proposes the use of 'mixed mode interfaces' which also allow for conversational interactions to resolve the limitations of direct manipulation for programmed or scheduled tasks.

The *SAGE* system (semi-automatic ground environment) developed in the 1950s by M.I.T and the US military, can be considered the first direct manipulation interface [Everett et al., 1958]. Part of the large computing systems to process air-defense data is the central radar monitor on the operator's terminal. Here, the operator supervises the air space represented as a map on the display. Aircrafts are shown as moving symbols on the screen. Specifically, the operator can use a light gun (similar to a drilling machine) to directly manipulate digital information: the lightgun is put on the vertical screen and fired at unknown objects on the radar. Thereby, the computer is instructed to track the object and can subsequently calculate a path for a missile. *Sketchpad*, a graphical design program, was another early instance of a direct manipulation interface [Sutherland, 1964]. The *Sketchpad* system is used to create geometrical, architectural and artistic drawings. The system incorporates a graphical user interface instead of a typed statement or command line. Lines and figures are drawn on the screen using a light pen. The user's actions are visible on the screen and structural interactions such as copy or merge are possible. Another early system making use of the principles of direct manipulation is the *Xerox Star*, presented in the year 1981 (described in [Johnson et al., 1989]). The system presents a graphical user interface with cursor-based WYSIWYG editing, windows, icons and integrated text. In general, the display and manipulation of virtual information on the screen is analogue to the manipulation of physical objects on an office desktop ("desktop metaphor").

Today's interfaces of systems such as mobile phones, desktop computers or gaming consoles which are controlled using via touchscreens, mice or gaming controllers strictly follow the principles of direct manipulation. Especially the touchscreen, which has become the de-facto interface standard on mobile devices and public terminals is an embodiment of these principles. As early as 1993, Ben Shneiderman states that touchscreens provide "unrivaled immediacy, a rewarding sense of control, and the engaging experience of direct manipulation" [Shneiderman, 1993]. He also suggests for designers of touchscreen devices to facilitate additional input mechanisms such as pressure sensing or multitouch input. The goal is to break away from simple buttons and "to explore how we might use sliding, dragging, and other gestures to move objects and invoke actions"[Shneiderman, 1993]. Today's touch interfaces, interactive tabletops and walls increasingly implement these notions.

2.2 Types of Interactive Surfaces

Interactive surfaces are used as the integral interface part of a variety of devices today. Realizing Mark Weiser's seminal vision of 1991, today's computers come in different sizes and roles [Weiser, 1991, Weiser, 1999]. Weiser and his colleagues at Xerox PARC built devices they called taps, pads and boards, with each device dedicated to a particular task. Linked wireless, they served as personal active badges, 'scrap' computers to be sketched or written upon without a individualized identity or as larger displays for video-screening or as white boards. As Gregory Abowd points out in [Abowd, 2012], "many of Weiser's predictions have come true, most clearly the proliferation of connected devices of different scales and ownership models". However, some of these predictions have not appeared yet, such as the sheet-of-paper sized pads, which are disposable and do not have an individualized ownership.

In order to structure the following overview on interactive surfaces, I will loosely adhere to Weiser's structure. His classification of tabs, pads and boards is based on the size and the primary usage context of the particular devices. Interactive surfaces are user interfaces, i.e. input and output devices that "connect the human and the machine" [Hewett et al., 1992]. Accordingly, interactive surfaces can both be a part of a device (such as the touchscreen of a mobile phone) or can the most obvious and name-giving feature, such as tabletop or interactive wall (see figure 2.1). Therefore, I define touchscreens as interface components of superior devices, which are used by one user at a time. Examples are mobile phones, tablet PCs or ATMs. By contrast, interactive tabletops are larger non-mobile, devices with horizontal touch displays for multi-user interactions. Finally, interactive walls or wall displays, floors and ceilings are integrated into architectural structures or form these structures themselves. These largest interactive surfaces can be used by multiple users at he same time. Furthermore, I show the ongoing evolution of interactive surfaces towards transformable and 'organic' surfaces. Disadvantages such as reduced accuracy, arm fatigue, visual occlusion, high cognitive/visual load and limited sensory feedback are shared drawbacks of interactive surfaces and are discussed in section 2.3.

2.2.1 Touchscreens

Touchscreens are the oldest class of interactive surfaces and consist of a touch sensor panel which is spatially superimposing a screen [Buxton, 2007]. Touchscreens are user interfaces that allow for a flexible integration of a large number of functionalities, simple maintenance and update of the GUI, reduced form factor and easy cleaning for public use [Shneiderman, 1993]. Embodying the principles of direct manipulation, touchscreens have been found to often be faster, easier to control and favored by the users when compared to other pointing devices such as mice or keyboards [Shneiderman, 1993, Ostroff and Shneiderman, 1988, Karat et al., 1986].

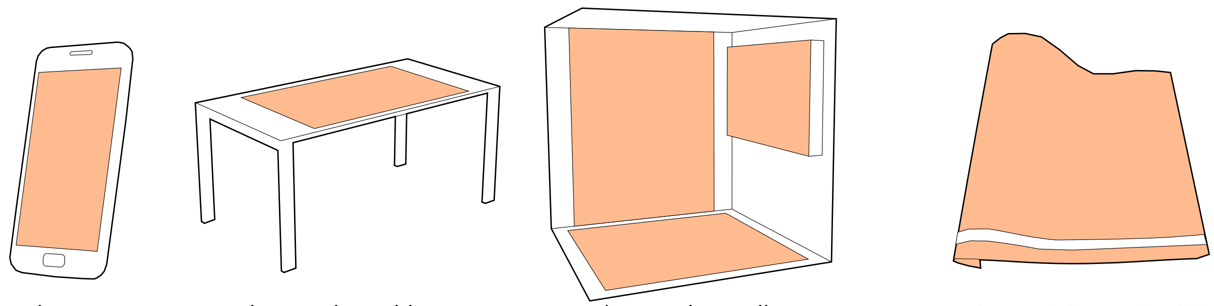

Figure 2.1: The classification of types of interactive surfaces which is used in this thesis.

History

The first interface superimposing display and touch sensor was the *Touch Panel* presented by E. A. Johnson in 1967 [Johnson, 1967] (see figure 2.2). Based on capacitive sensing, the device supports single-touch input and is activated when the finger is lifted from the display. Proposed as an universal input mechanism for 'the whole field of data-processing systems', Johnson already stated the importance the benefits for the flexibility, as the touch panel allows for the consecutive control of many different functionalities. Johnson describes the operation of the touch display as 'programmed control', because the range of choices for input can change when required. The goal is to simplify the task and to reduce the number of erroneous omissions. The commercialization and research for touchscreens intensified in the 1960s and 1970s. In 1971, Samuel Hurst, teacher at the University of Kentucky, invented the *Elograph* (electronic graphics) system as a digitizer for paper-based strip chart data. Although this system was controlled by pen input, it did not include a display [1]. In 1977, the company Elographics advanced the 5-wire technology of the *Elograph* into the *Accutouch* system, a curved glass sensor or touchscreen. Another well-known system incorporating a touchscreen was the *PLATO* computer (Programmed Logic for Automated Teaching Operations) [Bitzer and Skaperdas, 1968]. Used in the computer-based education research laboratory at the the University of Illinois, the infrared-based interface had a resolution of 16 x 16 touch-sensitive locations [2]. In 1984, Robert Boie from Bell Labs developed the first multi touch display [Boie, 1984, Buxton, 2010]. Until the 1990s, touchscreens were primarily used in more public scenarios: kiosks, ATMs, restaurants and industrial controls. With the rise of personal mobile devices such as Personal Digital Assistants (PDAs), Personal Navigation Systems (PDAs) and mobile phones, touchscreens gained more attention.

The introduction of the *iPhone* and later the *iPad* have created what market analysts call the "iPhone effect" [Lee, 2011], which led to grow rates for touchscreens that are 10 times faster

[1] The History of Elo `http://www.elotouch.com/AboutElo/History/default.asp` [cited 2012/08/31]

[2] Bill Buxton: Multi-Touch Systems that I Have Known and Loved `http://billbuxton.com/multitouchOverview.html` [cited 2012/08/31]

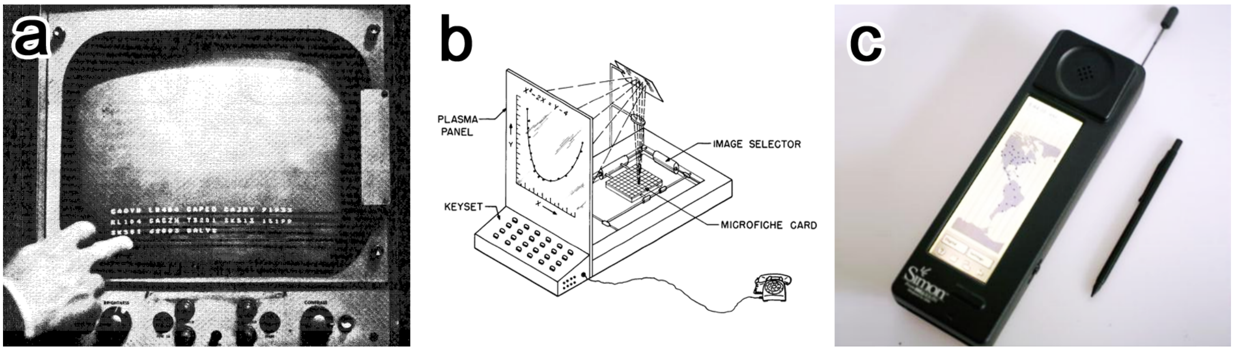

Figure 2.2: First touchscreen systems: a: Touch Display presented by Johnson [Johnson, 1967], b: Proposed student terminal of the *PLATO IV* system [Bitzer and Skaperdas, 1968], c: *Simon*, first smartphone with touchscreen-interface by IBM and Bell South from 1993 [Buxton, 2010]

than the average display market[3]. In the year 2014 (two years from now), 800 million out of 1.6 billion mobile phones world-wide are expected to be touch-enabled, compared to 31% in 2011 [Lee, 2011]. For touch-enabled tablet PCs, 56 million were sold in 2011. A total of 375 million devices will be sold in 2016, with 760 million already in use [4]. In total, 494 million touchscreen panels were sold in 2010, 1.35 billion are expected to be sold in 2014 [Lee, 2011]. Another growing class of pad-sized personal devices with growing importance are ebook-readers such as the *Amazon Kindle* [5] or the *Sony Reader* [6] which use microparticle-based displays with integrated sensor-capabilities (e-ink). With growing functionality such as faster or colored e-ink displays and less power consumption, the trend of electronic paper could emerge into touch interfaces that vanish into the background. In general, we can state that touchscreen panels are increasingly embedded in our everyday life.

Sensing Technologies

Touchscreens are used primarily as user interfaces which are embedded into devices and consist of both a display and a transparent sensor panel. Embedded multi-layer sensors use passive sensing, no additional device such as a wireless digitizer or conductor stylus is needed for input. For touchscreens, today's prevalent sensor technologies are based on resistance or capacitance, which are described in the following. It has to be noted that input or sensing technology is not

[3] Touchscreen market growing 10 times faster than other displays `http://venturebeat.com/2011/08/17/touchscreen-market-growing-10-times-faster-than-other-displays/` [cited 2012/09/04]

[4] The Guardian: How tablets are eating the PC's future - but might save the desktop computer `http://www.guardian.co.uk/technology/2012/apr/25/tablet-pc-market-analysis` [cited 2012/09/04]

[5] `http://amazon.com/kindle` [cited 2012/09/04]

[6] `http://sony.com/reader` [cited 2012/09/04]

in the center of this thesis and is not discussed in detail. More thorough sources of information such as Bill Buxton's multi-touch web-page[7] exist.

Resistive Touchscreens: In resistive touchscreens, the touch unit consists of a glass or acrylic panel which is coated with two electrically resistive and conductive layers. Wire matrices are embedded into the plate, forming two coordinate-pair dimensions. When an outside pressure is applied, both conductive layers are brought together and are supplied with voltage consecutively by the system. This creates a voltage divider at that point, making it possible to determine both X and Y coordinates. Interestingly, a third dimensions for measuring input pressure can be added to the system [Downs, 2005]. Resistive touchscreens are inexpensive, energy-efficient, durable and can also be activated using styli or when wearing gloves. However, the touchscreen's softish surface is part of the sensor panel, no additional protection layer can be applied.

Capacitive Touchscreens: Capacitive panels require proximity or physical contact with conductive body parts or objects, precluding the use whilst wearing gloves. They react to electromagnetic actuation other than to mechanic actuation like resistive touchscreens. Two types of capacitive sensing are existing: surface capacitance and projected capacitance. Surface capacitive sensing is based on an uniform and transparent coating of one side of the glass panel. An electrode at the panel's edge distributes low voltage over the conductive coating, creating an uniform electrostatic field. When a conductor such as the human finger comes in contact with the uncoated surface, the draw of current is measured by sensors in the four corners of the panel. In this way, the location of the touch can be measured indirectly. Projected capacitive sensing works with a grid of conductive materials which is embedded into the glass panel. Low voltage is applied to the grid forming an electrostatic field. When a touch is applied, the capacitance of the grid at this particular location is changing which in turn can be measured by the touch sensor system [Schöning et al., 2008, Rekimoto, 2002, Kuhlmann, 2012]. Capacitive screens are capable of multi-touch input and the finger can already be sensed in close proximity to the screen [Schöning et al., 2008]. Capacitive screens are nearly transparent, which makes them the technology of choice for most of today's mobile devices[8]. With In-Cell-Touchscreens, the sensing elements are integrated into the display circuitry, thus further reducing screen height[9].

[7] Bill Buxton: Multi-Touch Systems that I Have Known and Loved `http://billbuxton.com/multitouchOverview.html` [cited 2012/08/31]

[8] Touch Screen Modules: Technologies, Markets, Forecasts 2012-2022 `http://www.idtechex.com/research/reports/touch-screen-modules-technologies-markets-forecasts-2012-2022-000303.asp` [cited 2012/09/06]

[9] The Wall Street Journal: Next iPhone to Slim Down - New Touch Technology for the Apple Smartphone Will Make Screen Thinner `http://online.wsj.com/article/SB10001424052702303754904577532121136436182.html` [cited 2012/09/06]

2.2.2 Interactive Tabletops

In HCI research, the term 'interactive tabletops' denotes horizontal planar surfaces which present digital content that can be manipulated in various ways. In other words, "a large surface that affords direct, multi-touch, multi-user interaction" [Benko et al., 2009]. Tabletops were primarily developed to couple the collaborative work using paper-based media with the virtues of digital technology. Scott et al. give an overview on existing types of tabletop systems (in 2003) and state the importance of interpersonal communication, fluid transitions between activities and the need to support the use of physical objects [Scott et al., 2003].

Main Characteristics

Interactive tabletops are popular in the research community and new commercial releases such as the Microsoft *PixelSense*[10] (formerly called Microsoft *Surface*) gain increased attention of the media. However, compelling usecases that require the use of this technology for a wider audience are still missing. To analyze the needs and usage behavior of tabletop researchers and developers, Benko et al. [Benko et al., 2009] provide a survey with 58 long-term users. Their work shows the infrequent use of tabletop systems. Main uses are the development of novel interfaces and the display of media such as movies or images. A main result of the survey is the need for direct touch: both for the scenarios long-term individual use and appeal to novice users, direct touch was stated as the most important feature. Additionally, this distinctive feature is missed the most when desktop computers are used [Benko et al., 2009].

In the results of their evaluation of tabletop user experiences 'in the wild', Ryall et al. [Ryall et al., 2006] state another characteristic of tabletop interactions: The table is not seen as an input device for a traditional desktop PC, but as a stand-alone interactive piece of furniture. Tabletops were often used in playful scenarios including multiple interacting persons. Again, this notion of computing technology blending into the background seems to support Weiser's vision of ubiquituous computing.

In general, interactive table-like surfaces can be classified into four types which differ in size and usage context [Scott et al., 2003]: Digital desks include digital media into the interaction with traditional paper-based equipment. Drafting tables such as the *Active Desk* used by Fitzmaurice et al. [Fitzmaurice et al., 1995] resemble a single drafter's or artist's workplace. Workbenches allow for the integration of tangible user interfaces or augmented reality components (see section 2.2.2).

Finally, collaborative tabletops are larger interactive surfaces for small-group activities: Raskar's *Office of the Future* [Raskar et al., 1998] presents a vision of using interconnected visible surfaces in the office for projection of digital information, interaction and collaboration. Rekimoto's *Augmented Surfaces* [Rekimoto and Saitoh, 1999] allow for a smooth interchange of information across multiple systems such as portable computers, tabletops and wall displays. The *Roomware*

[10] `http://www.pixelsense.com` [cited 2013/02/09]

Figure 2.3: Interactive Workbenches with Tangibe User Interfaces: a: *Bricks* with *Grasp-Draw* prototype [Fitzmaurice et al., 1995], b: *Digital Desk* with calculator application [Wellner, 1993], c: *metaDesk* with *Tangible Geospace* application and physical constraint instrument (videostill) [Ullmer and Ishii, 1997]

project by Streitz et al. [Streitz et al., 2002] incoporates interlinked digital components (*DynaWall, InteracTable, CommChair*) and software to collaboratively work with digital information.

Tabletops as Interactive Workbenches

Interactive tabletops which are augmented with tangible user interfaces or augmented reality components were developed with intentions that inspired my research on remote tactile feedback. For example, Fitzmaurice states several advantages of input with graspable user interfaces which are the same I am pursuing with remote tactile output, particularly "improving the expressiveness or the communication capacity with the computer" [Fitzmaurice et al., 1995]. In the context of tangible user interfaces, interactive tabletops may serve as 'interactive workbenches'. Physical graspable objects are integrated into the interaction process. Diverse parameters of these objects are tracked electronically, such as position, arrangement, identity and selection information. The concept was introduced with *Bricks* by Fitzmaurice et al. [Fitzmaurice et al., 1995]. These physical electronic handles are placed atop the *Active Desk*, an almost horizontal (30 degree angle) desktop surface with a rear projected computer screen and an input stylus (see figure 2.3). Another early example is Wellner's *Digital Desk* [Wellner, 1993], which includes physical paper documents into the interaction. Information can be projected onto the paper and paper documents can be digitized using cameras. The *Digital Desk* is sensitive to direct manual touch (see figure 2.3). A third classical concept of an interactive workbench is *metaDesk* by Ullmer and Ishii [Ullmer and Ishii, 1997]. The desk itself is a back-projected graphical surface with object-tracking capabilities. The *metaDesk* system incorporates several tools for the transfer of the GUI desktop-metaphor into the physical world: Physical models (phicons) of architectural structures are serving as both physical control handles and container of digital information. An arm-mounted, freely movable flat panel display (active lens) shows additional alternative views of the workbench situation, serving as a real-world instantiation of a GUI window. The passive lens uses the *Magic Lens* metaphor [Bier et al., 1993] to show additional representations of the data

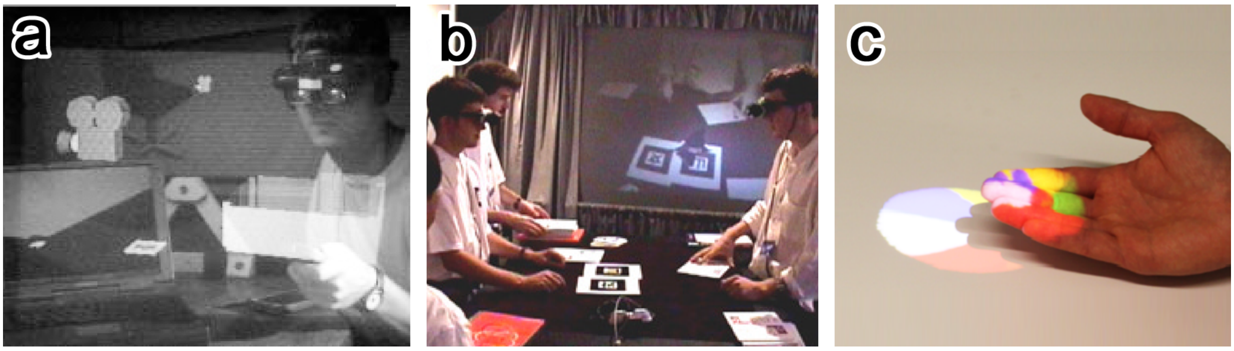

Figure 2.4: Tabletop interaction with 3D virtual components: a: *EMMIE* user manipulates a 3D model [Butz et al., 1999], b: *Shared Space Siggraph 99* tabletop gaming application [Kato et al., 2000], c: 'Bowling' on the *MirageTable* [Benko et al., 2012]

when placed atop the table. Finally, input ambiguities resulting from conflicting manipulations of the phicons are dissolved by physically constraint instruments (see figure 2.3).

Other tabletop scenarios incorporate three-dimensional mixed-reality components to extend and enrich the interaction with digital information. Similar to TUI research, non-flat objects representing digital data are used to manipulate non-physical information. However, 'Tangible Augmented Reality' objects can be defined as interfaces which combine the understandability of the physical input devices with enhanced visual feedback possibilities provided by virtual three-dimensional image overlays [Kato et al., 2000]. Butz et al. [Butz et al., 1999] combine virtual three-dimensional information with two-dimensional displays (see figure 2.4). Incorporating laptops, stylus-based interactive displays and larger screens, the *EMMIE* (Environment Management for Multi-user Information Environments) system creates a shared 3D workspace for collaborative work. Kato et al. [Kato et al., 2000] adapt Tangible User Interface design methods to create a tabletop AR application for face-to-face collaboration (see figure 2.4). Applied design principals include support "for physically based interaction techniques (such as using object proximity or spatial relations)" [Kato et al., 2000]. Finally, the *MirageTable* by Benko et al. [Benko et al., 2012] merges real and virtual world on a non-flat interactive surface using stereoscopic projection and depth-camera tracking. This allows for perspectively correct display of virtual 3D objects, which are manipulable using touch or object input on and above the tabletop surface (see figure 2.4). However, in contrast to physical TUIs, no tactile sensation communicating form, structure or state of the virtual TUI can be given.

Sensing Technologies

The interaction using multiple fingers or hands is a key feature of interactive tabletops. Additionally, concepts such as the interactive workbench require the sensing of additional physical artifacts. For collaborative purposes, an individualization and unambiguous assignment of touch inputs to users is an helpful feature. Additionally, interactive tabletop systems should be cost-effective and simple as they are often used as prototypes in dynamic research scenarios where scalability is an issue. An overview on the most commonly used technologies is given in the following, more detailed technical descriptions can be found in [Schöning et al., 2008, Müller-Tomfelde, 2010].

Capacitance: Sensing technologies stemming from touchscreen devices such as resistance-based or capacitance-based sensing provide high resolution and do not suffer from lighting problems, but are less useful for tabletop systems because they need industrial fabrication. This makes them expensive and hardly scalable for larger prototyping systems. An example is Rekimoto's *SmartSkin* system [Rekimoto, 2002] which uses capacitive sensing to recognize multiple inputs and objects on and above the surface. The sensor antenna grid is embedded into the tabletop surface area. Another system based on capacitive sensing is *DiamondTouch* [Dietz and Leigh, 2001]. To support simultaneous and spontaneous interactions use in collaborative work environments, each touch can be associated with a particular user. For this capacitive coupling method, users have to be seated in receiver-equipped chairs, antennas are implemented into the touch surface.

Vision/ Optics: Today's most commonly used sensing technology in tabletop systems use a pane made from acrylic glass, a projector and a camera. The FTIR (Frustrated Total Internal Reflection) principle rediscovered by Han in 2005 [Han, 2005] is based on the measurement of the amount of infrared light refracted outwards from a lit wave-guide. When this surface is touched, the index of refraction changes and infrared light escapes the acrylic plate and can be measured using a camera. The Inverted FTIR sensing uses the same principle with the camera placed above the touch surface. This principle is prone to occlusion, but can be applied to standard LCD panels [Moeller and Kerne, 2012]. The DI (Diffuse Illumination) principle places the infrared lighting behind the projection surface. This way, objects above the surface reflect infrared light back into the camera, making object recognition based on shape and fiducial markers possible. Systems such as Microsoft's *Surface* 1 or the *ReactTable* [Jordà et al., 2007] use the principle of vision-based sensing. Vision based sensing is simple, robust and easily scalable, but prone to interference with environment light.

In order to avoid the drawbacks of bulky camera- and projection-based systems, optical sensing systems use pairs of emitters and sensors to detect multitouch input. Multiple LEDs and phototransistors are either implemented into the edge of the touch surface or into the surface itself. The former uses infrared transmitters and receivers surrounding the touch surface. Objects or hands which occlude the light beams over the surface are sensed and their position is determined in the x and y plane [Moeller and Kerne, 2012]. The *Entertaible* by Phillips [Hollemans et al., 2006] is an example of this simple and robust approach. The DViT technology[11] uses four cameras to implement this principle. Up-to-date implementations of this principle provide scalability and stability at a reduced price [Moeller and Kerne, 2012]. The second class of optics-based multitouch sensing technology requires the modification of the display itself. Pairs of optical emitters and senors are implemented directly in or behind the LC display. The *PixelSense* system by Microsoft[12] (also called Samsung SUR40 with Microsoft *PixelSense*) uses an integrated infrared backlight which provides light through the LC display. Light reflected back from contacting fingers or objects is reflected back into the integrated sensors. This way, also scanning of documents

[11] `http://www.smart-technologies.com/dvit.html` [cited 2013/02/09]

[12] `http://www.pixelsense.com` [cited 2013/02/09]

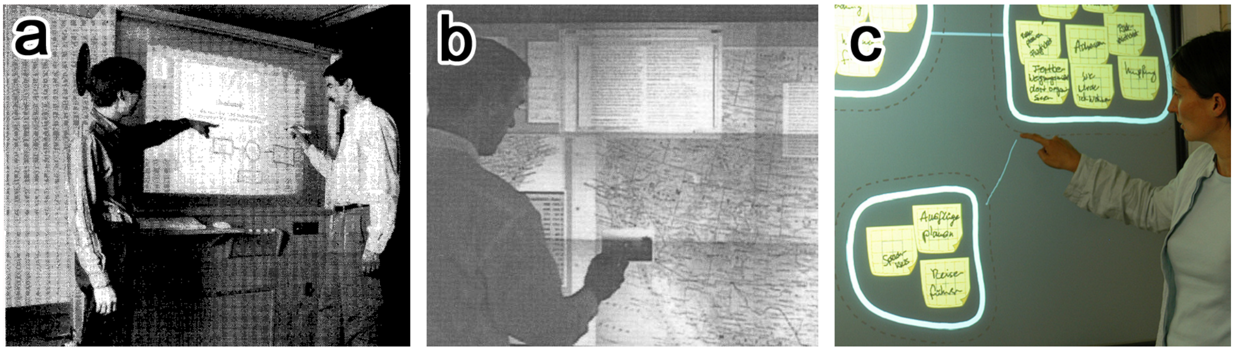

Figure 2.5: Interactive whiteboard systems in collaboration or organizing: a: Sketching on the *Liveboard* [Elrod et al., 1992], b: Annotating on an interactive wall [Guimbretière et al., 2001], c: Connecting idea clusters [Hilliges et al., 2007]

is possible. Similar to vision-based approaches, almost all of these optoelectric techniques suffer from interference with natural light, especially when unmodulated light is used for the sensing mechanism [Moeller and Kerne, 2012].

2.2.3 Interactive Walls, Floors and Ceilings

Another class of interactive surfaces are interactive walls, floors or ceilings. These touch surfaces can either be a stand-alone touch device or can form architectural structures indoors and outdoors. Due to advances in display devices (projection, LCDs) and sensing technology, they allow for multitouch and multi-person input. Similar display and sensing technologies as for tabletops are used, such as infrared and rear-projection [Matsushita and Rekimoto, 1997] (see also section 2.2.2).

In general, most interactive walls or vertical touch displays extend the concepts of whiteboards or blackboards. Accordingly, they often are components in integrated collaborative working environments. Here, they are used for dynamic interpersonal activities such as brainstorming or sense-making (e.g. [Elrod et al., 1992, Guimbretière et al., 2001, Hilliges et al., 2007]. The interactive whiteboards are used to view, annotate and organize collections of information. Additionally, results can be archived and processed digitally. Part of this process often is informal sketching and writing (see figure 2.5).

Other incarnations of direct touch walls are put up in public. An example is the project 'It's mine, don't touch!', in which an interactive wall display showing media content such as photos is installed in a city center. Users of this installation were found to perform "crowding, massively parallel interaction, teamwork, games, negotiations of transitions and handovers, conflict management, gestures and overt remarks to co-present people, and "marking" [Peltonen et al., 2008]. The concept of using large displays to foster interpersonal interaction has already been used in the art project *Hole-In-Space* by Kit Galloway and Sherrie Rabinowitz in the year 1980[13].

[13] *Hole-In-Space* `http://www.ecafe.com/getty/HIS/` [cited 2012/09/13]

Figure 2.6: Integration of real-world concepts and physical objects: a: *Digital Tape Drawing* emulates techniques of automotive designers [Balakrishnan et al., 1999], b: a shared workspace using *ClearBoard* and physical markers [Ishii et al., 1994], c: physical post-its as part of an digitally supported brainstorming system [Klemmer et al., 2001]

Physical media and real-world mechanisms have been integrated into the interaction with wall displays. For example, the *Digital Tape Drawing* system by Balakrishnan et al. [Balakrishnan et al., 1999] digitally replicates the work process of an automotive designer who uses tape to lay out a car's exterior design on a large sheet of paper on the wall (see figure 2.6). The *ClearBoard* by Ishii et al. [Ishii and Kobayashi, 1992] supports eye-contact, gaze-awareness (awareness of other user's focus) and the interpretation of facial expressions in a collaborative task. Two users of this prototype can physically draw on a glass surface which also shows the other person's drawings in corrected perspective (see figure 2.6). Others use the principle of tangible user interfaces and integrate physical post-it notes and images into the digitally supported brainstorming process [Klemmer et al., 2001] (see figure 2.6).

Flat interactive surfaces superimposing manual/pedal input and display output have been implemented in floors for gaming [Grønbæk et al., 2007], virtual reality [Law et al., 2008] (see figure 2.7) or arts[14]. Augsten et al. present the *Multitoe* project [Augsten et al., 2010]. They use the FTIR technology to allow for the direct manipulation of a large floor surface. The system can recognize posture of the users and it is possible to identify users based on their shoe sole patterns (see figure 2.7).

Also ceilings have been used as direct manipulation surfaces. Examples include ambient displays [Tomitsch and Grechenig, 2007], art installations[15] and collaborative gaming applications[16]. As ceilings or very large interactive walls normally can not be touched directly, direct manipulations are performed using techniques such as laser pointer input, hand tracking or pointing, eye tracking and tangible remote controls (e.g. [Jansen et al., 2012]).

[14] *Boundary Functions* `http://www.snibbe.com/projects/interactive/boundaryfunctions/` [cited 2012/09/13]

[15] *electroland: Target Breezeway* `http://electroland.net/projects/targetbreezeway/` [cited 2012/09/13]

[16] *Atari Light* `http://www.vvork.com/?p=13249` [cited 2012/09/13]

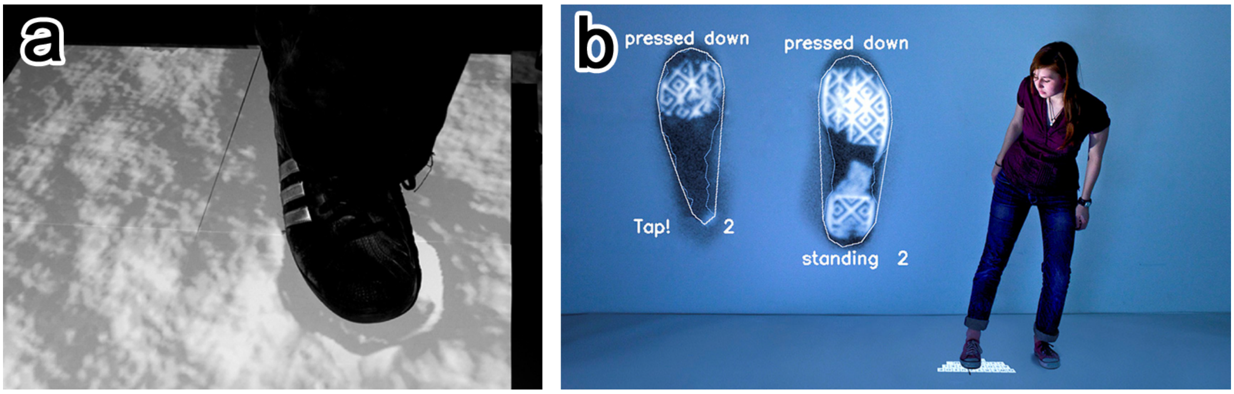

Figure 2.7: Direct manipulation on interactive floors: a: Virtual snow is deformed by footsteps [Law et al., 2008], b: *Multitoe* project senses pressure distribution on the user's soles for interactions and user identification [Augsten et al., 2010]

The aforementioned systems show the great variety of existing direct-manipulation touch interfaces. This interaction principle has become a standard in HCI and computer-mediated human-human interaction and is still emerging. The chapter showed that the integration of physicality and additional feedback modalities is an ongoing challenge for researchers and practitioners in the field. I see my work as part of this development. Before I identify the challenges of current touch surfaces, the next section highlights feasible tendencies and developments in the field of interactive surfaces.

2.2.4 Beyond Flat and Solid Interactive Surfaces

Despite their differences in size and usage contexts, all direct-touch interactive surfaces mentioned above (e.g. touchscreens, tabletops, interactive walls) have one thing in common: they provide flat, non-deformable, rigid surfaces to the interacting user's fingertip or hand. In this section, I will present approaches that break open this limitation. This enumeration of interface examples is organized in no chronological order and is targeted to illustrate the trend towards the vision of 'organic user interfaces' [Vertegaal and Poupyrev, 2008] and 'radical atoms' [Ishii et al., 2012]. I propose a classification in figure 2.8.

Non-Flat

The growing integration of interactive surfaces such as tabletops and interactive walls in office scenarios or public environments has brought up concepts for the seamless transfer of information from on device and surface to the other (e.g. [Rekimoto and Saitoh, 1999]). In addition to the transfer of digital information across different panes, researchers have proposed to physically merge interactive surfaces of different orientations. The *Starfire* prototype presented as a concept video by Tognazzini in 1994 [Tognazzini, 1994] illustrates the vision of a non-flat interactive surface of the year 2004. The systems offers merged horizontal and vertical planes. Another non-flat,

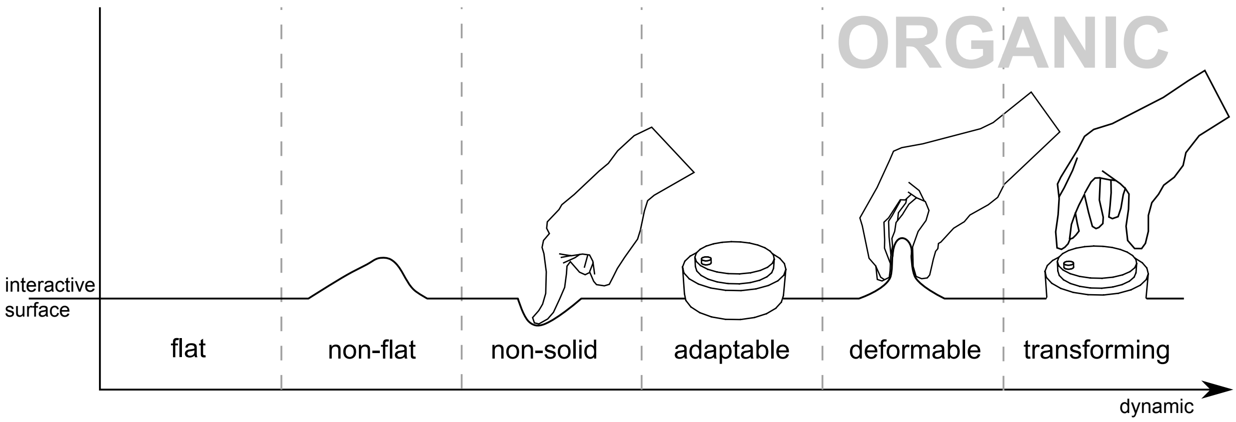

Figure 2.8: My vision of the ongoing evolution of interactive surfaces towards deformable and actively transforming surfaces and interfaces. **Non-flat** interactive surfaces can unify properties of vertical and horizontal touch surfaces. **Non-solid** interactive screens can allow for increased tactile expressiveness and input mechanisms such as force sensing. Interactive surfaces can be made **adaptable** to the intended interaction and to the manipulated digital information by applying tangible user interfaces. **Deformable** touch surfaces present their ductility as a means of input. Finally, **transforming** interactive surfaces flexibly develop input mechanism and manipulable materializations of underlying digital information. The interactive systems in this chapter are indexed according to this classification.

rigid interactive surface is the *Sphere* prototype presented by Benko et al. [Benko et al., 2008] (see figure 2.9). They present technical and conceptual solutions for non-flat multitouch surfaces. The *Curve* prototype by Wimmer et al. is an digital desk which "combines vertical and horizontal working areas using a continous curved connection" [sic] [Wimmer et al., 2010] (see figure 2.9). They motivate their work with ergonomic considerations, flexible data transfer from the vertical to the horizontal panel and a suitability for different tasks. Roudaut et al. [Roudaut et al., 2011] evaluate the curvature of non-flat touch surfaces and show the influence of surface curvature and slope on input error rates.

Non-Solid

In the next step, non-flat interactive surfaces can step away from the surface's rigidness and utilize passive material properties. Examples include properties such as flexibility using transparent rubber interfaces [Sato et al., 2009], softness with furry interfaces [Nakajima et al., 2011] (see figure 2.9) or flexibility using interactive surfaces made from drapable cloth [Lepinski and Vertegaal, 2011]. The object properties are used to enrich the input utilizing distance sensing or measurement of deformation.

Another approach to extend the interactive surface is to use both touch display and the adjacent space as a 'continuous interaction space' [Marquardt et al., 2011]. Marquardt et al. describe several scenarios in which touch, gestures, and tangibles are used as input in this continuum and are moved between surface and environment. Also Hilliges discusses above-the-surface interac-

Figure 2.9: Non-flat and non-solid interactive surfaces: a: the *Sphere* prototype [Benko et al., 2008], b: the interactive desktop *Curve* [Wimmer et al., 2010], c: the *FuSA*^{2}, a furry multitouch display made of plastic fiber optics [Nakajima et al., 2011]

tion and presents tracking techniques to "unlock the space above digital tables for interaction" [Hilliges, 2009].

Adaptable

In the next step, the form or composition of the interactive surface can be actively altered by the user to fit his needs. An example is a dynamically placeable semi-transparent interactive display which extends the display and shows parts of a 3D model [Chia-Hsun et al., 2003]. Of course, the concept of tangible user interfaces helps to extend digital information into the physical world and to customize the interactive surface for specified tasks. The TUI can be seen as an adaptable physical extension to the interactive surface. This extension can be general-purpose or bound to a certain task [Ullmer and Ishii, 2000] (see section 1.1).

Deformable

Standard TUIs such as *Urp* [Underkoffler and Ishii, 1999] which embody digital information are physical artifacts that lack the ability to change their shape. Ishii elaborates on the drawbacks: "Users must use a predefined finite set of fixed-form objects (building models in this case) and change only the spatial relationship among them, not the form of individual objects. All tangible objects in *Urp* must be predefined (physically and digitally) and are unable to change their forms on the fly" [Ishii, 2008]. Novel TUIs composed of continuous tangible materials such as clay or sand are used to embody and control digital data in non-solid but deformable representation. The project *Illuminating Clay* [Piper et al., 2002] incoporates laser distance scanners and projectors to allow for rapid form sculpting (see figure 2.10). The system is used to digitally enhance a deformable clay landscape model with properties such as simulated water flow (see figure 2.10). Other non-flat interactive surfaces which are deformable by the user consist of paper [Makino and Kakehi, 2011] or even the human body surface [Harrison et al., 2011] (see figure 2.10). Dynamic projection (e.g. [Sukaviriya et al., 2004]) and enhanced sensing devices (e.g. [Sato et al., 2012]) allow for the usage of arbitrary physical surfaces or objects as touch interfaces. The notion of deforming interactive surfaces can also be used as input technique. *Gummi*

Figure 2.10: Deformable touch surfaces: a: *Illuminatic Clay* [Piper et al., 2002], b: physical paper used as deformable display [Makino and Kakehi, 2011], c: bendable computer prototype *Gummi* [Schwesig et al., 2004]

by Schwesig et al. [Schwesig et al., 2004] is a deformable mobile device prototype incorporating a flexible OLED display, bend sensors and circuitry. Bending the device as a whole is translated into zooming and scrolling interactions on the device (see figure 2.10). Thus, the *Gummi* prototype closely follows the notion of 'organic user interfaces'. A very recent development is the *PaperTab* system[17], a lightweight tablet-sized plastic display, which recognizes touches, bending and folding as input mechanisms.

Transforming

The last class of interactive surfaces presented here can actively transform themselves to embody digital information or to match a certain task. Actuated workbenches actively move objects in two dimensions. Shape displays create 3D physical shapes directly or alter their tactile surface characteristic. Tactile tangibles, tactile displays and shape displays heavily rely on the creation of artificial tactile cues as an additional channel of information. Therefore, they will be discussed in detail in chapter 3.

In 2012, Ishii proposes the term 'Radical Atoms' to denote reconfigurable particles of future materials. In this vision, all digital information will have physical representation and is directly manipulable. The envisioned development from GUIs over TUIs to 'Radical Atoms' is depicted in figure 2.11. Ishii repeats the notion of 'tangible bits', the physical embodiment of digital information for manipulation. However, he states that unlike pixels on the screen, physical tangibles do not change their form, color or position. The vision of 'Radical Atoms' describes hypothetical dynamic materials, which

"*Transform* its shape to reflect underlying computational state and user input;
Conform to constraints imposed by the environment and user input; and
Inform users of its transformational capabilities (dynamic affordances)" [Ishii et al., 2012].

'Radical Atoms' are not restricted to flat, interactive surfaces but can be a form that is sensitive to touch or gestural input or that forms a tool-like device. The concept is closely related to

[17] `http://www.hml.queensu.ca/papertab` [cited 2013/02/08]

the *Claytronics* project [Aksak et al., 2005] which develops intercommunicating modular robots that can dynamically form 3-dimensional displays of electronic information. Ishii envisions the future interface as materials we can interact with. "We may call these human-material interactions (HMIs) or material user interfaces (MUIs), in which any object - no matter how complex, dynamic, or flexible its structure - can display, embody, and respond to digital information" [Ishii et al., 2012]. This vision of future interfaces heavily incorporates direct touch and manipulation and thus can be seen as a possible future for interactive surfaces.

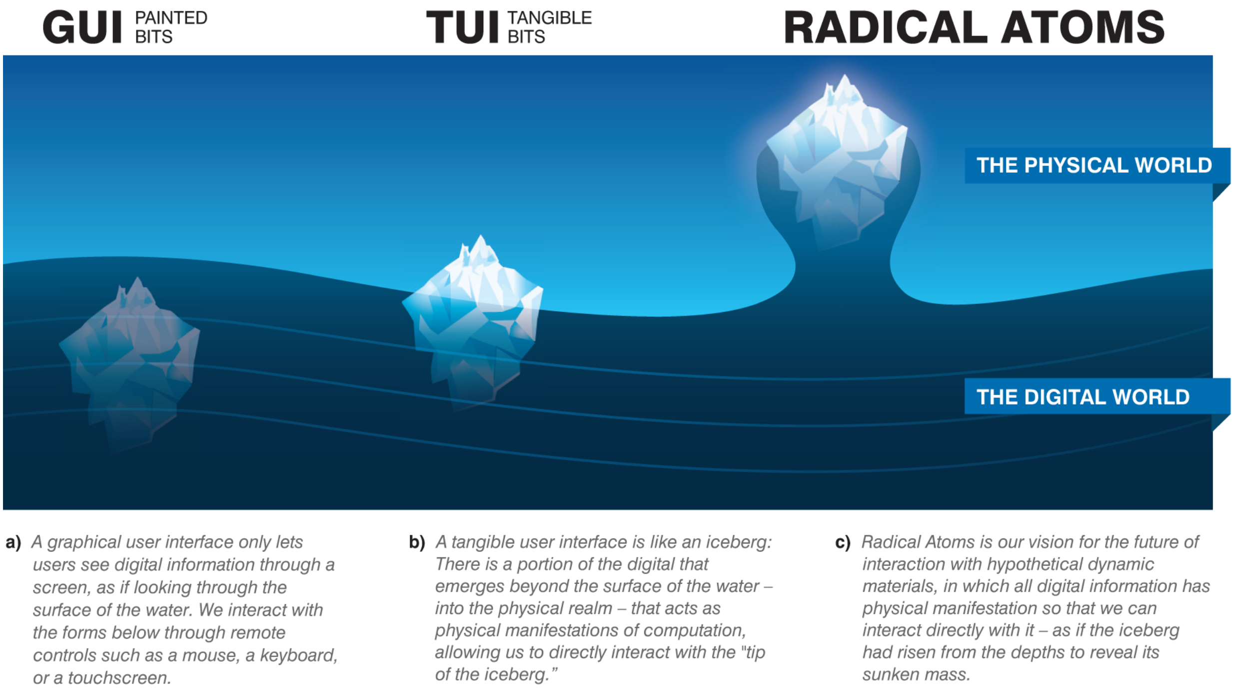

Figure 2.11: From GUIs over TUIs to 'Radical Atoms': Hiroshi Ishii's vision of dynamic physical materials [Ishii et al., 2012]

I share this vision of more versatile interfaces which tightly integrate the concept of physicality and embodiment and allow for more diverse interactions and manipulations. The provision of programmed tactile feedback is an essential component of this development. The next section summarizes current technical and conceptual problems of interactive surfaces. Tactile feedback can help to address these challenges.

2.3 Challenges of Direct Touch Interaction

As illustrated above, direct touch interactions are present in heterogeneous usage scenarios such as mobile, stationary, single or collaborative use. In the following, I will present limitations in the input and output domain of interactive surfaces. As Bill Buxton states in 1985, "there is no such thing as a "good input device," only good interaction task/device combinations"

[Buxton et al., 1985]. The drawbacks discussed here are no limitations of interactive surfaces 'in general', but apply to specified usage contexts and device types. Accordingly, the presented technical and conceptual approaches to avoid these limitations can be seen as specific solutions for specific tasks and devices. In his 1986 paper "Touch-sensitive screens: the technologies and their application" [Pickering, 1986], J.A. Pickering discusses individual characteristics of touch techniques and their drawbacks at that time. He lists issues from the fields ergonomics, sensing and display technology, user performance and feedback. Interestingly, most of these limitations have not been fully resolved on today's touch interfaces and are still in the focus of designers and researchers. Accordingly, I will classify current challenges of interactive surfaces and research work on solutions following Pickering's classification. With this list, I try to give a broad overview of current challenges in the field. As we will see, the lack of tactile feedback is a pressing problem and hence a major part of the list.

Ergonomics: The orientation, size and composition of interactive surfaces such as tabletops or interactive walls have been the subject of several user studies. Recommendations on the ergonomics of non-flat interactive surfaces exist [Wimmer et al., 2010, Bi et al., 2010]. Neck strain was stated as an issue after prolonged work on a tabletop; users would like to adjust the surface angle to prevent fatigue and physical stress [Benko et al., 2009]. Slight inclinations (20° to 30°) are preferred [Ahlström et al., 1992]. For tabletops, multiple user studies found the importance of providing the possibility to rest the arm or elbow to reduce arm fatigue (the infamous 'gorilla-arm-effect') [Ahlström et al., 1992, Ryall et al., 2006].

When interacting with very large touch displays such as interactive walls, items can be hard or impossible to reach. Solutions from related work include additional devices such as laser-pointers [Olsen and Nielsen, 2001], additional widgets to zoom into distant screen areas [Bezerianos and Balakrishnan, 2005] or forms of remote controlling using mobile devices [Boring et al., 2010].

Display and Sensing: Over the years, touchscreens have become flatter and display and sensors were fused into a glass surface, thus preventing from disadvantageous parallax effects and surface scratches. However, grease on the display can still be a problem[18].

Another more prevailing problem is the disparity between the resolutions of visual output and manual input. With technological progress, the resolution of display and touch sensors is increasing, but the size of the user's fingertips or hands merely stays the same. The decreased physical dimensions of pixels on the screen would allow for smaller and more GUI elements on the displays, but this can not be utilized due to the user's ambiguous touch input, also known as 'fat finger problem' [Siek et al., 2005]. Additionally, the user is visually occluding relevant sections of the screen. The need for precise selection techniques to improve accuracy on touch surfaces has been addressed by techniques such as stabilization software filters [Sears and Shneiderman, 1991], re-

[18] And can be exploited using 'smudge attacks', where an attacker can figure out graphical passwords on a mobile device by analyzing the oily residues from the owner's finger [Aviv et al., 2010].

located pointers [Potter et al., 1988, Vogel and Baudisch, 2007] or 'back-of-device' interaction [Baudisch and Chu, 2009][19].

Unintended activation by touch has been identified as another common problem of touch interfaces [Ryall et al., 2006, Hinckley and Sinclair, 1999]. Users tend to rest their fingers, hands or arms on the touch surface and this contact is interpreted as input by the system. This phenomenon has been termed the "Midas Effect" [Wellner, 1993]. Potter et al. proposed the 'lift-off metaphor' as a solution, which allows the user to drag the finger on the screen, adjust the position on an input element and finally activate it on lift-off, thus creating a "finger-mouse" [Potter et al., 1988]. Another technique to separate tracking/targeting and activation on touch surfaces is the integration of pressure sensing in the touch surface: tracking and targeting is performed with the finger on the screen, applying minor pressure. As soon as an element has been selected, more pressure is applied to activate the element. These individual states of touch interaction are discussed in [Buxton, 1990]. Also, additional tactile feedback can be applied during this on-screen tracking phase before input.

In 1993, Shneiderman stated the need "to break free from the older notion that touchscreens are for buttons, and to explore how we might use sliding, dragging, and other gestures to move objects and invoke actions" [Shneiderman, 1993]. In 2012, sliding, dragging and gestural input is a regular feature of touch devices such as smartphones and tabletops [Wobbrock et al., 2009]. The same holds true for multi-touch input, i.e. the recognition and processing of multiple inputs (single hand, multiple hands, multiple persons) at the same time by the system. However, touch systems which can differ between multiple users are rare, *DiamondTouch* by MERL is an exception [Dietz and Leigh, 2001]. Another, less used dimension of input is the sensing of input pressure. Most of today's touch interactions abide to Buxton's three-state model of graphical input of 1990 [Buxton, 1990]: On an interactive surface on which 'touching' a virtual element means 'activation', the finger is either 'out of range' and has no effect (state 0) or performs a 'selection' (state 2). As the finger itself is the tracking symbol, the 'tracking' on the screen is impossible, state 1 is bypassed. Stated as early as 1984 by Margaret Minsky [Minsky, 1984], sensing force in z-direction (pressure) helps to enrich the potential of touchscreen gestural input. Depending on the input technology, pressure sensing can be performed by utilizing the fact that a harder press causes a larger area of contact of the soft fingertip with the screen surface. Hence, it is possible to measure the change of capacitance which varies with the size of finger contact or to process the size of the input finger using vision-based sensing. However, as Buxton states, "the challenge is, the harder one pushes, the more friction there is in sliding the finger along the surface. Hence, there is an inherent conflict between force vs. gesture articulation with touch interfaces" [Buxton, 2010].

Pressure sensing on touchscreens, its impact on the performance of the user and potentials for tactile feedback are part of my publication "HapTouch and the 2+1 state model: potentials of haptic feedback on touch-based in-vehicle information systems" [Richter et al., 2010] and are discussed in detail in section 3.3.3.

[19] Please note that mentioned approaches from related work refer to direct touch interactions, the use of a stylus also increases input resolution.

Multimodal Feedback: Touch interactions are often performed in dynamic multi-tasking scenarios such as on mobile devices [Buxton, 2010], in the car [Tsimhoni et al., 2004] or during collaborative work [Hilliges et al., 2007]. Users have to dynamically shift their attention between tasks on the touch interface (reading, information input) and 'outside' tasks (walking, driving, personal communication). These tasks compete for the user's limited cognitive resources [Oulasvirta et al., 2005]. Additionally, influences in mobile scenarios, such as walking movements, can decrease user performance [Bergstrom-Lehtovirta et al., 2011].

The interaction with interactive surfaces is visually highly demanding due to the limited screen size, occlusions and the disregard of non-visual feedback[20]. For input, users have to perform the targeting task in mid-air and thus need to control the movement of the finger towards the interactive element with the eyes. Additionally, the feedback that is informing the user about the consequences of his actions (e.g. acknowledgement, decline, change of GUI mode) is communicated visually.

The prevalent need for adequate text input on touchscreens illustrates this correlation between feedback and user performance: In a survey of 58 users of tabletop systems, Benko et al. [Benko et al., 2009] state that a physical keyboard is the most missed feature for users of direct touch tabletop systems. Users stated problems with "typing, soft keyboard works poorly, no feedback". The paper suggested the integration of standard input devices into the tabletop usage context. Ryall et al.[Ryall et al., 2006] state that "bare fingers are insufficient for text input" and propose to avoid text input tasks on touch interfaces. Participants of a long term evaluation of tabletop use [Wigdor et al., 2007] stated that "a reasonable person would not use an on-screen keyboard", but still does use it to maintain the use of direct touch. For text input on interactive surfaces, the provision of non-visual feedback such as auditory or tactile cues has been shown to be highly beneficial (e.g. [Lee and Zhai, 2009, Hoggan et al., 2008a, Lee et al., 2009]).

In general, the lack of non-visible feedback has been in the focus of attention of researchers and designers of interactive surfaces from the start. Being direct-manipulation interfaces, touch interfaces "must provide the user with a world in which to interact" [Hutchins et al., 1985]. In that sense, tangible user interfaces do provide a physical embodiment of digital information and thus deliver haptic cues to the interacting user's hand. However, one reason for their use was their ability to provide tactile feedback, because "tactile feedback is essential; it provides a way of safeguarding user intent" [Fitzmaurice et al., 1995]. Concepts such as 'organic user interfaces' and visions such as 'radical atoms' introduce the sensory richness of the real world into interactions with touch surfaces. Additional tactile feedback on interactive surfaces can take a share here with the goal to provide a more complete representation of digital information. For usability, non-visual feedback can help to eliminate current drawbacks of interactive surfaces such as high visual load, reduced input resolution and resulting decreased user performance.

Tactile feedback on direct touch interfaces has been used to address the mentioned limitations of interactive surfaces. Tactile stimuli can help to increase accuracy, reduce visual and cognitive load and increase expressivity of feedback. Examples are given in 3.3. In summary, it is impor-

[20] Bill Buxton: Multi-Touch Systems that I Have Known and Loved
`http://billbuxton.com/multitouchOverview.html` [cited 2012/08/31]

tant to design non-visual feedback that outreaches simple acknowledgement of an action such as 'beep' or a 'buzz'. Properly designed non-visual feedback can also be proactive feedback, sensory cues for the tasks of locating and identifying appropriate controls without activating them. Additionally, non-visual cues could help to make you aware of ongoing changes in the digital domain after activation, so called reactive feedback.

With this thesis, I advocate the utilization of our sense of touch as additional channel of information between human and machine. The following chapter 3 shows the importance of our haptic channel in everyday life and the long history of its utilization in (general) HCI. However, tactile feedback on today's and future interactive surfaces entails several problems which can be addressed by the utilization of the concept of remote tactile feedback.

Chapter 3

Haptics and Tactile Feedback

Our sense of touch is an integral part of our sensory system. Together with the senses of vision, hearing and smell, the sense of touch helps us to form a complete internal representation of our environment and our relation to it. The haptic sense delivers cues on touch or temperature, on the position of our limbs, the balance of our body and the condition of our visceral system. The full capabilities of our sense of touch mostly happen outside our conscience. The haptic organ which is involved the most with our active exploration of our environment is the skin. The skin contains receptors which are excited by deformations, temperatures or react to injuries of our body. The skin senses enable us to form our environment by using tools and to socially interact with other people. Namely, the hand is our primary tool to actively collect information on an object by exploring its form, flexibility and surface structure. In general, the sense of touch is closely coupled with active interaction. We have to move our fingers to capture the tactile characteristics of an object. Furthermore, we can stroke, rub or caress someone to actively evoke all kinds of emotions.

Tactile cues are an integral channel of information about physical interfaces. The mechanical snaps and clicks coming from mechanical control elements such as buttons or sliders tell us their position, function and state before, during and after an interaction. These cues can be actively designed to make these interfaces discriminable and to evoke impressions of quality or stability (e.g. haptic design of vehicle interiors). With the increasing dissemination of computing systems, tactile cues have been used to support visual and auditory cues coming from the machine or to communicate tactile messages. Application domains include virtual reality, telepresence or accessibility. Publications describe wearable, embedded and tangible actuator devices.

However, when interacting with interactive surfaces, we can not utilize the passive tactile cues coming from the flat, uniform surface. Therefore, actuator systems for active tactile cues have been integrated into the touch surface. This has been shown to be highly beneficial in terms of reduced error rates, enhanced interaction speed and improved user experience. However, the common approach to superimpose visual and tactile cues entails technical and conceptual chal-

Figure 3.1: Das menschliche Denken (Human Reasoning)[a], mid 17th century, copper engraving, Sudhoff-Institut Leipzig: In the era before the Age of Enlightenment in the 18th century, the earth's 'five elements' terra, aqua, aer grossus (coarse air), aer tenuis (fine air) and lux seu ignis (light or fire) are believed to be perceived using the corresponding 'five senses' tactus, gustus, odoradus, auditus and visus. The classification of the five senses is still used today, but with reference to the involved body organs.

[a] With kind permission of the Kustodie University of Leipzig ©2012

lenges such as limited scalability, mechanical complexity and diminished tactile expressiveness. The principle of remote tactile feedback can help here.

In this chapter, I give an overview of the physiological fundamentals of human perception in general and our sense of touch in particular. Knowledge about these principals is indispensable when designing and implementing interfaces for programmed tactile stimuli. Additionally, I show the rich history of haptic interfaces in HCI. After introducing common actuator technologies, I exemplify the benefits of active tactile cues on touch surfaces. Own work on direct (non-remote) tactile feedback on an in-vehicle touchscreen is part of the chapter. Common approaches to integrate actuators into the touch surface can be classified into three categories, I discuss benefits, implications and drawbacks.

3.1 Fundamentals

The five special senses are vision, audition, smell, taste and touch (see figure 3.1 for an illustration from the 17th century). The fivefold classification of the senses exists since the times of Aristotle. In fact, this classification is still used in today's psychology, physiology and anatomy. Usually, each sense subsumes several 'extra' senses according to the various feelings which are perceived. The greatest diversity of qualities of feelings is handled by the sense of touch: "pressure, contact, deep pressure, prick pain, quick pain, deep pain, warmth, cold, heat, muscular pressure, articular pressure, tendinous strain, ampullar sensation or dizziness, vestibular sensation or sense of translation, appetite, hunger, thirst, nausea, sex, cardiac sensation, and pulmonary sensation" [Geldard, 1964]. Although the senses can be grouped together on the basis of their observational similarity or on the basis of the type of physical energy which activates them, the common way is to group them anatomically, i.e. according to the corresponding system of sense organs. In the context of human-computer interaction, the human senses are channels of perception and can be seen as perceptive media.

Our surrounding world and our relation to it can only attain meaning if we actively perceive and make sense of it. Changes in the internal and external environments (people, objects, events, situations and activities) can be defined as **sensations** [Marieb and Hoehn, 2007]. The process of selecting, organizing and interpreting sensations is called **perception**. Based on patterns of nerve impulses delivered from receptors, our brain creates a conscious interpretation of the external world. This interpretation depends on the limited abilities of our receptors, the filtering done by precortial processing and the selective mechanisms in the cerebral cortex. Furthermore, our perception is heavily shaped by learning, memory and expectations [Sherwood, 2008].

The sensory system can be organized into three levels (classification from [Marieb and Hoehn, 2007]):

Receptor level: The stimulus excites a sensory receptor only when the stimulus energy matches the specificity of the receptor and happens in its receptive field[2]. Information about the stimulus is encoded into the frequency of nerve impulses.

Circuit level: Nerve impulses are then transported to the appropriate section of the cerebral cortex. Impulses from haptic sensations such as pain, temperature and coarse touch impulses are also delivered to parts of the brainstem, where they are processed preparatively. This results in faster processing and forms emotional aspects of perception (e.g. pleasure, pain).

Perceptual level: The cerebral cortex interprets the sensory input depending on the specific location of the stimulated nerve cells (neurons). This location of the neuron is coupled with the type of sensory receptor and its position in the body. That way, a certain stimulus at a specified location (e.g. touch of the right earlobe) results in the stimulation of a certain neuron at a specified location in the cerebral cortex[3]. Interestingly, the stimulation of a certain receptor results in the perception of the dedicated sensation, no matter how the receptor is stimulated (e.g. pressing the eyeball excites photoreceptors and lets you see light) [Marieb and Hoehn, 2007]. Furthermore, the neuron can also be stimulated using artificial receptors. Finally, even the electrical stimulation of the precise spot in the cerebral cortex leads to the perception of its dedicated sensory sensation. The plasticity of the brain and its ability to adapt its own structural organization and functioning is the basis of sensory substitution and sensory augmentation [Bach-y Rita and Kercel, 2003]. The relocation of tactile information on the body is part of these concepts and is discussed in more detail chapter 4.1.

3.1.1 The Human Sense of Touch

If touch is not a single sense but includes more senses than one,
there must be a plurality of tangible objects also.
Aristotle (384-322 BC) De Anima

This quotation illustrates the manifold tasks and characteristics of the human sense of touch, a classification which is still valid in psychology, physiology and perceptual research. The sense of touch helps to develop object categorizations at an early age. At the age of 6 months, infants are able to distinguish 'animate' (e.g. animal, person) and 'inanimate' (e.g. stone, toy) objects. This helps to develop first global classes such as 'animal' or 'vehicle' [Kiese-Himmel, 2008]. Diverse receptor organs in our bodies supervise our body balance, sense the position and movement of our limbs and monitor deformations, damages and temperature changes of our skin. Particularly the skin fulfills manifold functions, Seikowski et al. list numerous tasks [Seikowski and Gollek, 2008]: The skin as an organ serves as border or contact (i.e. interface) to our environment, is a protection and sensing device and can present internal activities by sweating or blushing. In the following, I present terminology and physiology of our sense of touch

[2] Specifities of cutaneous receptors are given in section 3.1.1

[3] This is a heavily simplifying example, as the touch excites several receptors resulting in numerous nerve impulses.

and show the efforts of researchers and engineers to use the sense of touch for human-computer interaction.

Terminology

In order to establish a clear definition of remote tactile feedback and to limit the scope of this work, I have to clarify the wide terminology regarding the concept of our sense of touch. The term ’haptic’ refers to everything "relating to the sense of touch, in particular relating to the perception and manipulation of objects using the senses of touch and proprioception"[4] coming from the Greek word *hapticos* (’able to touch or grasp’) and *haptein* (’fasten’). In experimental psychology and physiology, the term refers to the active exploration of our surroundings (typically with our hands) [Robles-De-La-Torre, 2006]. Likewise, the term ’haptic perception’ refers to tactual perception of distal stimuli using the cutaneous sense and kinesthesis [Loomis and Lederman, 1986]. Alternatively, the terms ’haptics’ and ’haptic interaction’ are often used to refer to technology that invokes our sense of touch [Hale and Stanney, 2004, Wright, 2011]. The word ’haptic’ is an umbrella term covering significant distinctions. Subterms differ and overlap in subject depending on their origins such as physiology, psychology, anatomy or human-computer interaction. In figure 3.2, I present a systematic overview of subterms and subjects connected with haptic perception. In literature, the terms are often used synonymously or ambivalently, especially when it comes to non-English literature. However, I found the terminology in figure 3.2 to be the most consistent in literature from perceptional research and human-computer interaction:

Haptic perception can be sub-divided in three physiological concepts: interoception, proprioception and exteroception. Interoception comprises visceroception and enteroception and handles the states of internal organs (chemical changes, tissue stretch, internal temperature). Usually, we are unaware of these activities [Marieb and Hoehn, 2007]. Proprioception is related to stimuli which are produced inside of the body, especially those connected with the position and movement of the body and limbs [Sherwood, 2008]. The sense of spatial orientation (vestibular sense) with the organs located in the inner ear is part of proprioception. Finally, exteroception is related to stimuli coming from the outside such as temperature or skin touch.

The ’sense of touch’ refers to the detection of various stimuli which activate proprioception as well as exteroception [Loomis and Lederman, 1986]. First, we are aware of the position and movements of our limbs and head using kinesthesis: Receptors in our muscles and fibers are used to draw conclusions on our posture [Geldard, 1964]. In HCI, systems such as robotic arms for telepresence or flight-simulator joysticks address the kinesthetic sense, this concept is called ’force feedback’ (see section 3.2). Second, the ’sense of touch’ also contains our skin sense (cutaneous sense) including tactile perception (touch, pressure, deformation), thermoception (heat, cold) and nociception (pain) [Loomis and Lederman, 1986, Geldard, 1964]. These sensations handled by the sense of touch are occuring anywhere in the body (in contrast to one sensory organ such as sight) and are therefore called somesthetic sensations [Sherwood, 2008]. Both proprioception and exteroception are anatomically classified as part of the somatosensory system,

[4] The Oxford Dictionary Online: ’haptic’
`http://oxforddictionaries.com/definition/english/haptic?q=haptic` [cited 2012/09/25]

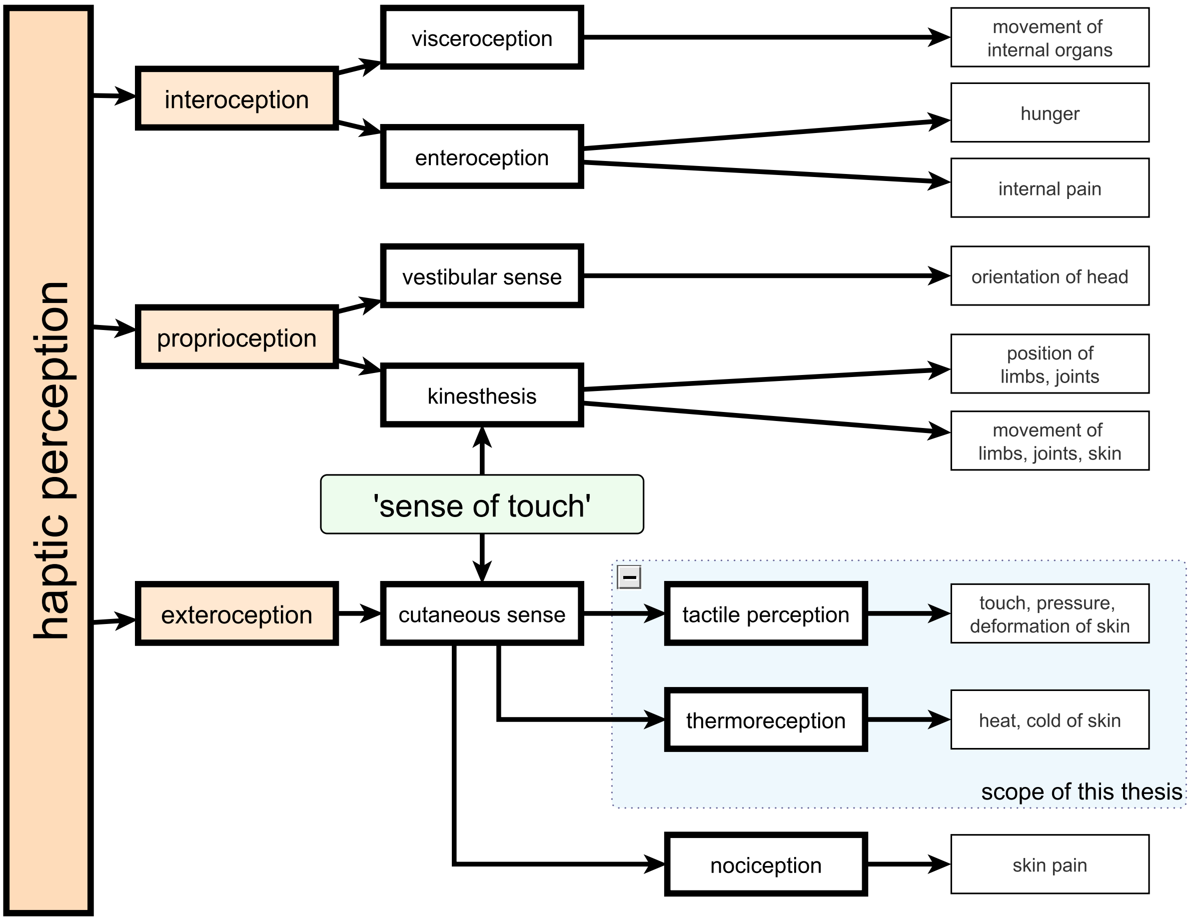

Figure 3.2: Classification of terminology for haptic perception, explanations in the text.

i.e. they are related to "the body walls and limbs" [Marieb and Hoehn, 2007]. Please note that this thesis is primarily centered on using the cutaneous sense, i.e. tactile perception and thermoception. Therefore, the following explanation of physiologic principles is limited to this small fraction of the haptic system.

Physiology

In order to utilize the expressiveness of tactile (cutaneous) stimuli, one has to know the basic sensory characteristics of tactile reception in the human skin. The human body surface is a "highly variegated structure" [Geldard, 1964]. The skin is hairy in some portions, hairless in others and mucous in the mouth or other body openings. In general, the tactile sensitivity is greatest in the hairless (glabrous) areas such as the fingers, the palmar surface of the hand and the soles of the feet or the lips [Kandel et al., 2000]. The glabrous skin is characterized by individual ridges (e.g. used for fingerprints), which support the indentation and deformation of the tissue during active touch.

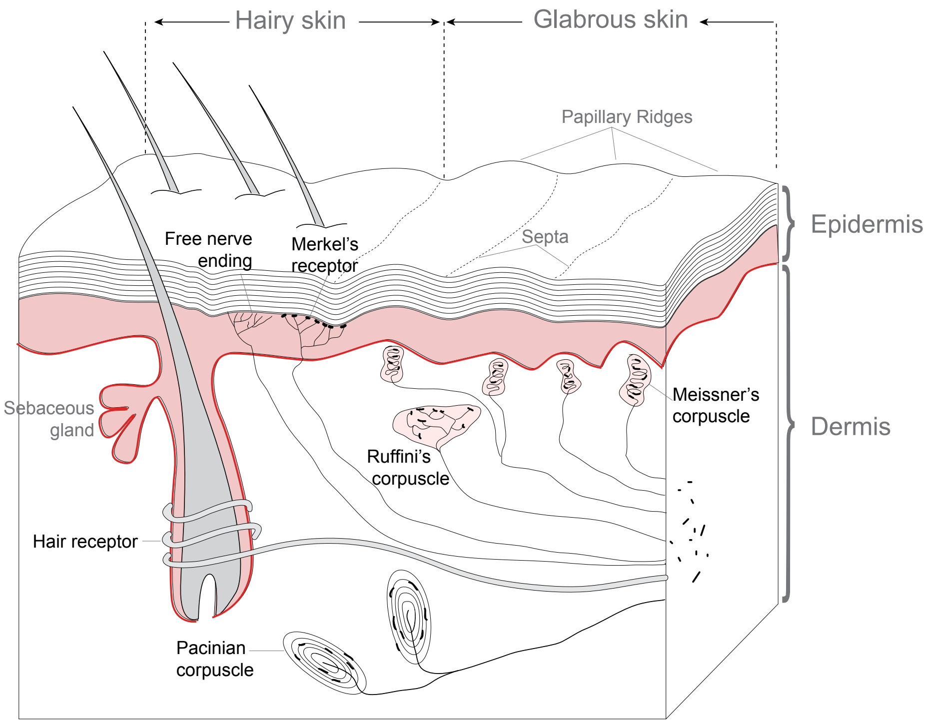

Figure 3.3: Schematic drawing of tactile mechanoreceptors in the human hairy and hairless (glabrous) skin[a]

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Several miniature organs in the layers of the human skin are closely connected to nerve endings and are sensitive to mechanical stimulation. These sensory cells are called mechanoreceptors and transduce tactile stimuli into electrical activity. Mechanoreceptors are located in all layers of the skin: in the superficial skin, in the junction of dermis and epidermis and more deeply in the dermis and subcutaneous tissue [Halata and Baumann, 2008] (see figure 3.3). The four main types (Meissner's corpuscles, Merkel disk receptor cells, Ruffini endings, Pacinian corpuscles) are named after their discoverers and can be classified based on both their temporal adaption properties as well as the size of their receptive fields. The abbreviations SA and RA/FA denote slow and rapid/fast adaption. Roman numbers I or II denote small or larger receptive fields [Visell, 2009]. Together with hair follicles and free nerve endings, the receptors can encode four elementary attributes of tactile stimuli - modality, location, intensity, and timing [Kandel et al., 2000]. Main features of mechanoreceptors are given in the following (from [Geldard, 1964, Kandel et al., 2000, Loomis and Lederman, 1986, Halata and Baumann, 2008]), figure 3.4 sums up the information:

Meissner's corpuscles: Located in the superficial layers of the glabrous skin, these mechanoreceptors react to stroking, fluttering and light touch. Being rapidly adaptive sensors, these globular corpuscles react to changes of force (differential behavior). Meissner's corpuscles have a small receptive field of 2-3 mm diameter in the fingertips and 10 mm on the palm. This results in more exact localization of touch. Responsible for the detection of fine mechanical variances, these receptors are connected to the ridges in the human skin and are most numerous in the fingertips. These corpuscles respond to varying frequencies between 10 Hz and 200 Hz. One square millimeter of skin can contain up to 24 Meissner's corpuscles, this number decreases with age.

Merkel disk receptor cells: These receptor cells exist in the superficial layers of the glabrous skin of finger tips, mouth and lips. A slightly differently organized receptor also named after Merkel exists in hairy skin. For the disk cells in the glabrous skin, the action potential is proportional to the intensity of the impacting force. The slowly adapting receptors have a small, highly localized receptive field and react to indentation of the skin with long lasting action potentials. Accordingly, these mechanoreceptors react to pressures and textures with a low frequency range of 0.4 Hz to 100 Hz.

Ruffini endings: Ruffini endings are generally larger than Meissner's corpuscles or Merkel disks. They are present in the dermis of both glabrous and hairy skin. Being slowly adapting, their action potential is proportional to the intensity of the applied force. They have a larger receptive field and perceive skin stretch when the nerve endings in the receptors are compressed. Ruffini endings also inform us on the movements which occur when we use our fingernails. The frequency range of these mechanoreceptors is very low, i.e. around 7 Hz.

Pacinian corpuscles: Also called Vater Pacini corpuscles, these receptors are similar to Ruffini endings regarding their size and location: they are larger than Meissner's corpuscles or Merkel disks and are present in the dermis of both glabrous and hairy skin. They cover larger sensitive areas and sense vibration in the entire skin due to their flexible attachment to tissue. Pacinian corpuscles react to frequencies between 40 Hz and 800 Hz and are most sensitive between 200 Hz and 300 Hz. The sensitivity for high frequencies is supported by the double-differential behavior: Pacini corpuscles react to the change of change of stimuli.

Hair receptors: Nerve endings can also be wrapped around the root of hairs. These hair follicles respond to displacement of the hair and thus can sense approaching objects. Hair receptors are rapidly adapting and have three sub-classes which differ in sensitivity.

Bare nerve endings: Finally, bare nerve endings in both glabrous and hairy skin act as polymodal nociceptors and respond to various potentially harmful stimuli such as damage or chemicals. Bare nerve endings also serve as thermal receptors, with two different types for cold and warmth. Cold receptors are 30 times more numerous than warm receptors. Again, fingertip and palm are most sensitive to this type of tactile stimulation [Jones and Berris, 2002].

Body Site and Tactile Sensitivity

As stated above, the characteristics of mechanoreceptors differ depending on the type of the skin. Furthermore, also the density of the mechanoreceptors differs across the body. This results in diverse tactile sensitivities depending on the body location. For this thesis, I applied tactile stimuli on body sites such as the fingertips, hands, wrist, forearm, back and thighs. In order to

receptor	class, type	receptive field (mm²) (median)	skin type	frequency range (most sensitive)	threshold skin deform on hand (median)	probable sensory correlate	receptors/ cm² fingertip (palm)
Pacinian corpuscle	FA, II	10-1000 (101)	G, H	40-800 Hz (200-300 Hz)	3-20 µm (9.2 µm)	vibration, tickle	21 (9)
Meissner's corpuscle	FA, I	1-100 (12.6)	G	10-200 Hz (20-40Hz)	4-500 µm (13.8 µm)	touch, tickle, motion, vibration, flutter, tap	140 (25)
Merkel's cells	SA, I	2-100 (11.0)	G	0.4-100Hz (7Hz)	7-600 µm (56.5 µm)	edge pressure	70 (8)
Ruffini corpuscles	SA, II	10-500 (59)	C	7 Hz	40-1500 µm (33 µm)	stretch, shear, tension	9 (15)
hair follicle receptor	FA	-	H	-	-	touch, vibration, proximity	-

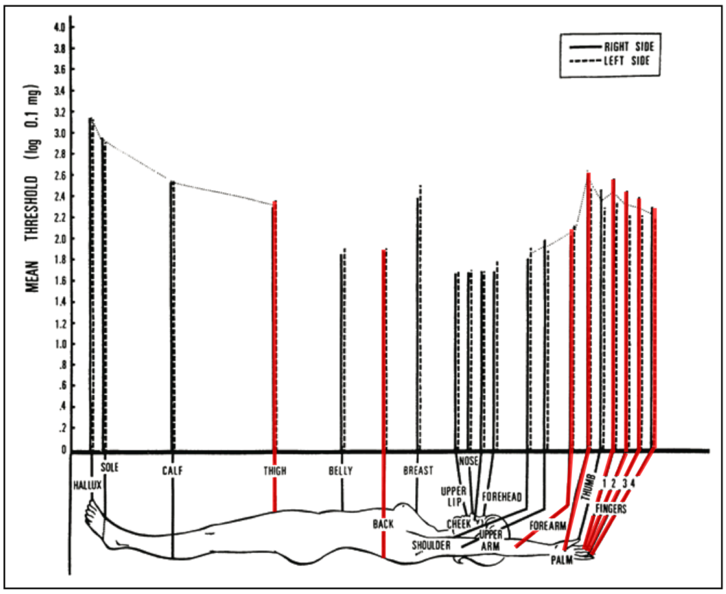
Figure 3.4: Properties of tactile mechanoreceptors in the skin. From [Geldard, 1964, Kaczmarek et al., 1991, Visell, 2009]. FA = fast adapting, SA = slowly adapting, G = glabrous, H = hairy, C = connective tissue

fully utilize the tactile channel on these locations without overloading it, the location-dependent spatiotemporal resolution of the cutaneous senses has to be taken into account.

Three main measures for spatial resolution and sensitivity of the skin have been established:

- The **minimum noticeable intensity** of pressure describes the amount of weight needed to make a stimulus perceivable (see figure 3.5). Women are more sensitive to tactile pressure than men. The most pressure sensitive parts of the skin are on the face, the trunk and the fingers. The lower extremities are least sensitive to pressure [Myles and Binseel, 2000]. The soles of the feet are least sensitive to pressure, supporting upright walk [Weinstein, 1968].
- The **point localization** task is used to measure the accuracy of humans to localize a point-sized object on the skin (see figure 3.5). Again, the fingertips are the most sensitive with errors in localization of about 1.5 mm. The back is the least accurate with 12.5 mm error [Lederman, 1997].
- The **two-point discrimination** value is the best-known measure for tactile sensitivity across the body. First studied by German anatomist and physiologist Ernst Heinrich Weber (1795-1878), this threshold or 'limen' describes the ability to distinguish between two simultaneous touches on the skin [Grunwald and John, 2008]. Weber used a compass with dulled points to measure the minimum distance between two perceivable tactile stimuli across the body surface. When the two touches are given in short succession, the accuracy of perception is higher and the two-point limen is lower. Again, the values vary greatly with the tongue being the most sensitive, followed by the lips, fingers (2 mm), palms (10 mm), toes, forehead and arm (40 mm) [Myles and Binseel, 2000, Kandel et al., 2000] (see figure 3.6). For HCI, this value delivers a minimum distance of two applied tactile actuators which have to be perceived independently.

Changes and differences in tactile stimuli can also be described using mathematical ratios. In psychophysics, the smallest detectable difference between a starting level and a secondary level of a stimulus can approximatively be described using the **law of just-noticeable difference (jnd)** or **Weber's law**. It describes that the sensitivity of a sensory system to changes depends on the absolute strength of the stimuli [Kandel et al., 2000]. It is easy to distinguish 1 kg from 2 kg,



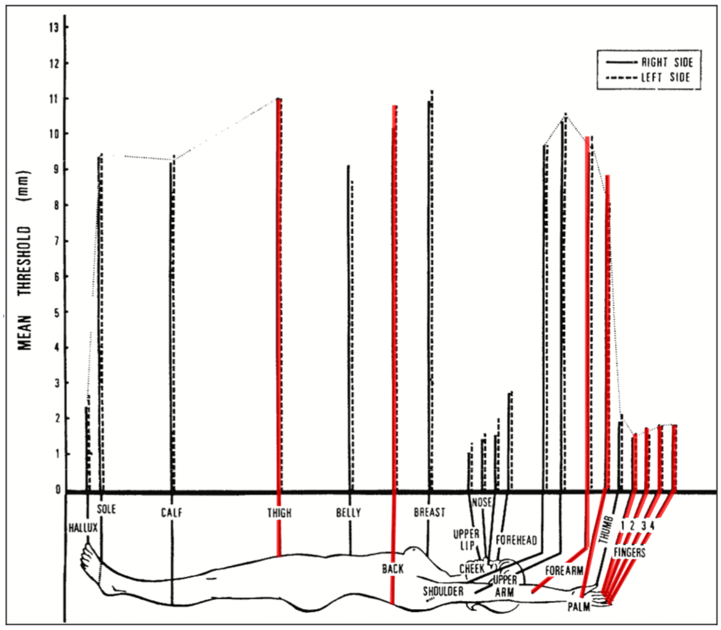


Figure 3.5: Pressure sensitivity thresholds (upper figure[a]) and point localization thresholds (lower figure) for females for different areas of the body, the data is similar for males (taken from [Myles and Binseel, 2000], originally from [Weinstein, 1968]). Body locations used in this thesis for the application of remote tactile feedback are marked in bold red.

[a] The vertical axis does not represent a physical value. Pressure is measured using a nylon monofilament which is pressed against the skin. The common log of the force created by these filaments is an approximate linear function. This provides an interval scale for the computation of threshold. The scale can be represented in units of log (0.1 mg) [Holewski et al., 1988].

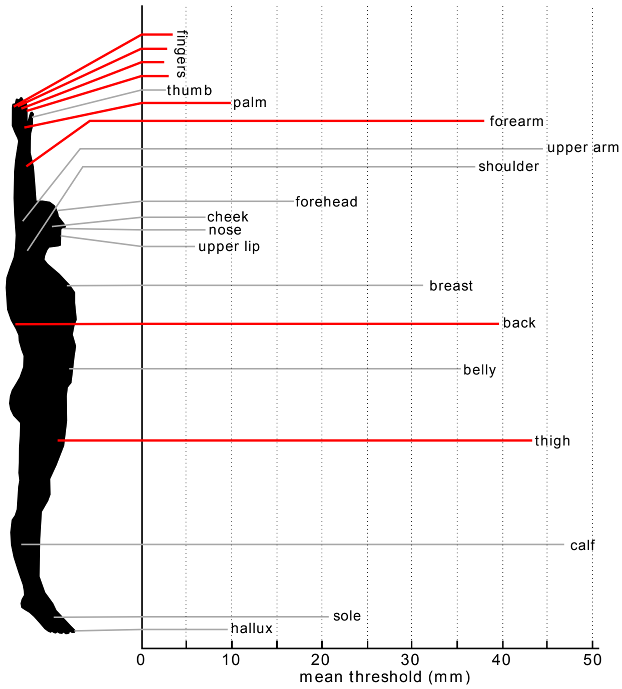


Figure 3.6: Average two point discrimination thresholds for various body regions (adapted from [Visell, 2009, Kandel et al., 2000]). Body locations used in this thesis for the application of remote tactile feedback are marked in red.

but difficult for 50 kg and 51 kg. The equation for Weber's law is $\Delta S = k \times S$. Here, ΔS is the minimal difference between the intensity of a stimulus S and a second stimulus needed to perceive a change and k is a constant (called Weber constant). Doubling the intensity of the stimulus will cause a doubling of the difference threshold. On the fingers, Weber fractions of about 0.2 exist [Lederman, 1997].

3.1.2 Stimulus Parameters and Specifications

Due to the high density and specialized characteristics of the mechanoreceptors in the glabrous skin of the fingertips and palm of our hands, it is a "truly marvellous organ" [Lederman and Klatzky, 1998] and our primary haptic sensing device. The fingertips are highly sensitive to light touch and can exactly localize it due to the Meissner's corpuscles which are closely connected to the skin's ridges. We can recognize fine textures and forms which helps us to use the hand - with tools or on its own - to recognize, grasp and manipulate manifold objects. Quintessential component of these abilities is 'active touch', the active manual exploration of object properties such as texture, hardness, temperature, weight or volume [Lederman and Klatzky, 1998]. The brain composes a coherent image of the object based on successive tactile touches of small portions of the object. Specific exploratory procedures exist for specific features of the object [Lederman, 1987]. Our physical environment provides manifold tactile cues. Designing haptic devices to replicate these cues and apply it to the hand is problematic for two reasons: First, attached tactile actuators could impede the movement and tactile sensing of our surroundings. Even if tactile actuators could fit in a glove-like system, a long term usage outside of specialized environments (such as virtual reality, see section 3.2) is cumbersome. Second, in respect of the high resolution and sensitivity of the hand's mechanoreceptors, tactile actuators have to be diminutive and numerous to address all the available features, resulting in high technical complexity.

Several researchers have proposed to use the body surface beyond the hand as a channel for the communication of tactile information [Gallace et al., 2007]. As early as 1960, the skin has been recommended to be used as a valuable supplement to ears and eyes when messages have to be transmitted [Geldard, 1960], however, the technical capabilities of transducer weren't sufficient. With technical advances, tactile cues on the body have been used for various purposes such as non-visual information presentation [Brown et al., 2006], the treatment of phobias in virtual reality scenarios [Carlin et al., 1997], as warning signals to present spatial information to drivers [Ho et al., 2005] or to provide navigation cues using a waist belt [Erp et al., 2005]. My research on remote tactile feedback for interactive surfaces is based on both the physiological and psychological principles of the sense of touch and on work from the field of haptic communication (further examples of haptic interfaces from different areas of application are given in 3.2). Accordingly, six basic parameters have to be taken into account when designing on-body tactile interfaces [Geldard, 1960, van Erp, 2002, Hoggan, 2010].

The first parameter is the **location** of the stimulus. As said before, the skin's sensitivity to tactile stimulation differs across the body. The human skin is mostly hairy, apart from the inner side of the fingers, the palms, soles of feet, lips, labia and glans penis. On hairy skin, two-point discrimination and localization of stimuli is generally moderate, apart from the facial skin (see figures 3.6 and 3.5). However, belly, back and arms have a sensitivity to differences in pressure which is superior to the finger's sensitivity (see figure 3.5). A phenomenon frequently encountered with stimuli which are located very close by is lateral masking [Loomis, 1981], this is resulting from the limited spatial resolution of mechanoreceptors on the body. The next parameter to consider is the tactile **modality** which is to be conveyed such as deformation, vibration or temperature. A very commonly used tactile modality is vibration, which can be easily perceived on the body due to the high sensitivity of the Pacinian corpuscles to fast changes of stimulation. The hairy skin is sensitive to pressure as well, with the above mentioned drawbacks in resolution. For temperature, the size of the stimulated body area has to be taken into account [Jones and Berris, 2002]. Another parameter to consider and evaluate is the **intensity** or **amplitude** of the applied stimulus. Again, this parameter is highly individual and depends on the structure of the skin at a specified location [Geldard, 1964]. Finally, a stimulus is also defined by its **duration** and **frequency**.

In summary, when body locations other than the hands are used for the transfer of tactile information, the stimuli don't have to be very small or very close together. Actually, phenomena such as lateral masking and limited receptor density hinder from high-resolution tactile actuators. Additionally, the absolute localization of stimuli on the body can be more than 10 mm off (see figure 3.5). It can be stated that the use of differing pressure levels via vibrotactile or electromechanic actuators is the most effective way to provide tactile information. In the following, I will give an overview on the diversity of haptic interfaces on the body which apply these design principles.

3.2 Haptic Interfaces

Haptic interfaces are human-computer interfaces which incorporate hardware and software components to generate computer-controlled and thus programmable signals that stimulate human kinesthetic and touch channels [Hayward et al., 2004]. The term 'touch' refers to intention, manipulation and gesture as well as haptic perception [MacLean, 2000]. Therefore, haptic interfaces consist of both a *sensor* to determine the human operator's motion and *actuators* to apply stimuli to the operator [O'Malley and Gupta, 2008]. Consequently, haptic interfaces provide humans with the means to manipulate their environment which allows for a bidirectional exchange of energy, and therefore information, between the user and the environment. In this chapter, I will characterize the properties of haptic interfaces and classify exemplary systems by their scenarios of use. Tactile interfaces are a subclass of haptic interfaces and solely address the cutaneous senses. The body surface can be used to apply programmed tactile stimuli. Examples from virtual reality, gaming, military use and laboratory prototypes for perceptional research are given. A large percentage of tactile interfaces have been developed and utilized for accessibility (e.g. active Braille systems) and sensory substitution (e.g. tongue displays). These systems are a conceptual basis for my approach of remote tactile feedback and are therefore discussed in more detail in chapter 4.

3.2.1 Structure and Components

Vincent Hayward describes the characteristics of a haptic interface by comparing a standard computer mouse and a 'haptically enabled' mouse with programmable mechanical properties[7] [Hayward et al., 2004]. The standard mouse does contain fixed mechanical characteristics such as weight, shape, surface structure or friction. In contrast, the haptic mouse can change its mechanical behavior under computer control. This results in an extended bidirectional information flow between user and haptic mouse which is controlled by the computer. Thus, a haptic interface is designed to read and write from the user's body. An early example for a haptic mouse is the system by Akamatsu et al. which is able to vibrate a user's fingertip and to simulate different friction effects [Akamatsu and Sato, 1994].

Primary motivation behind the use of haptic interfaces is the establishment of an additional channel of information between user and machine. Initially used to support visually or hearing impaired people by providing information non-visually or non-auditory, haptic interfaces are also applied to increase the rate of involvement in virtual reality scenarios. The application of force feedback devices can improve an operator's task performance and enhance the user's sense of telepresence [Tan, 2000]. Other motivations for the use of haptic interfaces are increased immersion (force feedback joysticks), finer motor control (telesurgery devices) or increased feedback in teleoperation (remotely operated robots) [Wright, 2011].

[7] A similar comparison can be drawn between a standard gaming joystick and a 'force feedback joystick' for flight simulators.

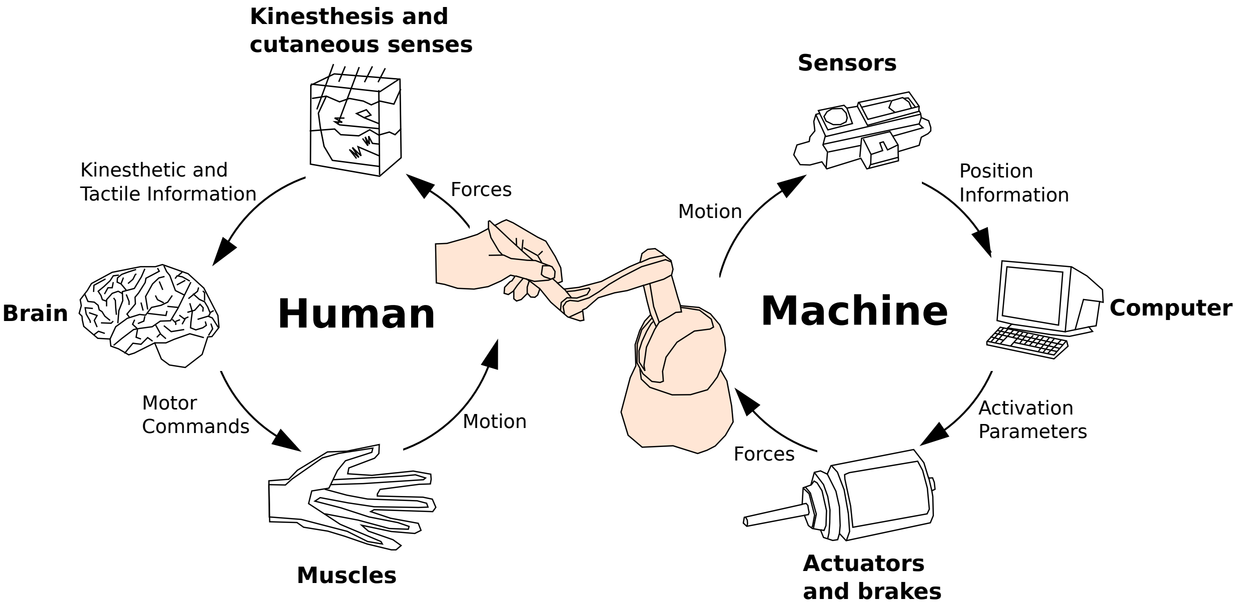


Figure 3.7: General structure of a haptic interface: A human (left) senses and controls the position of the hand to control the interface. A digital device (right) exerts forces on the hand to simulate contact with virtual information. Both systems contain sensors (mechanoreceptors, encoders), processing units (brain, computer) and actuators (muscles, transducers). Figure adapted from [Srinivasan et al., 1999].

Following the structure of haptic interfaces proposed by the MIT's Touch Lab depicted in figure 3.7, one can state that the design and implementation of haptic interfaces is a truly multidisciplinary task. Haptic interfaces borrow from various fields such as biomechanics, neuroscience, robotics, computer science and computational theory. Technically, the haptic interaface hardware consists of physical mechanisms to couple the human operator to the virtual information. The hardware can consist of common force-feedback joysticks, multiple degree-of-freedom (DOF) stylus, a wearable exoskeleton device, or an array of tactors which stimulate the skin surface [O'Malley and Gupta, 2008]. Haptic interfaces have three basic components: a mechanism to constrain and define the physical movements of the operator with the device, various sensors to track the operator's motions and transducers (actuators) which display the programmed stimuli according to the virtual model. An asymmetry of the number of sensors compared to the number of actuators is an issue of haptic interfaces. Under-actuated interfaces are cheaper, but can result in reduced realism of the haptic representation [Barbagli and Salisbury, 2003].

Several classifications of haptic interfaces are possible. Haptic interfaces can be classified according to the aspect of human sense of touch they address: interfaces which stimulate solely the cutaneous senses with cues such as roughness, rigidity or temperature and can be called 'tactile interfaces' whereas interfaces such as exoskeletons solely address the kinesthetic sense. Naturally both types can be combined. Haptic interfaces can be active or passive, however, they are always programmable: Passive interfaces constrain dissipation, velocity or elastic behavior. Active haptic interfaces incorporate actuators which act either as as a force source or position source

[Zhai, 1993]. Active interfaces acting as a force source are called **isotonic devices**: these mechanical devices provide zero or constant resistance and track the user's movement. An example is the SenseAble PHANTOM[8]. On the other hand, **isometric devices** do not change their position as a result of impacting forces. These interfaces can (in theory) provide infinite resistances. Although isometric devices are often allocated to active haptic devices [Hayward et al., 2004], they do not actively emit forces and thus can be used to simulate force feedback [Lecuyer et al., 2000]. An example is the *Spacepilot*[9].

3.2.2 Examples of Applications

Giving an exhaustive overview over the different forms of haptic interfaces is not possible in the scope of this thesis. More detailed surveys on haptic and tactile interfaces can be found in [Hayward et al., 2004, Iwata, 2008, Benali-Khoudja et al., 2004, O'Malley and Gupta, 2008]. The application areas of haptic interfaces are as diverse as the human sense of touch, the examples presented here show haptic devices from diverse usage scenarios such as teleoperation, virtual reality, medical training, accessibility and gaming (see figure 3.8). Please note that the layering of tactile cues and graphical user interfaces will be covered in more detail in section 3.3.

Teleoperation is the manipulation of remote objects, telepresence is the "ideal of sensing sufficient information about the teleoperator and task environment, and communicating this to the human operator in a sufficiently natural way, that the operator feels physically present at the remote site" [Stone, 2001]. Both fields are closely related to haptic interaction. Haptic feedback has been used to describe both physical and virtual remote objects [Hayward et al., 2004]. For example, Brooks et al. [Brooks et al., 1990] used the *GROPE III*, a 6 DOF (dimensions-of-freedom) haptic interface to simulate force fields which enable chemists to replicate and create drug docking positions.

In fully **virtual environments**, haptic stimuli can simulate gravity and haptic object characteristics. Exoskeletons can render highly immersive haptic sensations, but can create fatigue after longer use [Ott et al., 2005]. Several projects incorporate haptic feedback to simulate the haptic cues which occur during tool-based laparoscopic (i.e. 'keyhole') surgery, thus helping medical personal to prepare for operations on living patients (see [van der Meijden and Schijven, 2009] for an overview).

Haptic feedback is used extensively to communicate **navigational information**. Wearable interfaces such as belts or headbands use haptic actuators to non-visually communicate directional information or proximity of objects [Tsukada and Yasumura, 2004, Zerroug et al., 2009]. Similar principles have also been implemented on mobile devices (e.g. [Rümelin et al., 2011]). Wearable actuator systems can to support spatial orientation and navigation (e.g. tactile pilot vests [van Erp, 2005]) or provide warnings (e.g. haptic seat interfaces for drivers [Chang et al., 2011]).

[8] `http://www.sensable.com/haptic-phantom-omni.html` [cited 2012/10/11]

[9] `http://www.3dconnexion.com./products/spacepilot-pro.html` [cited 2012/10/11]

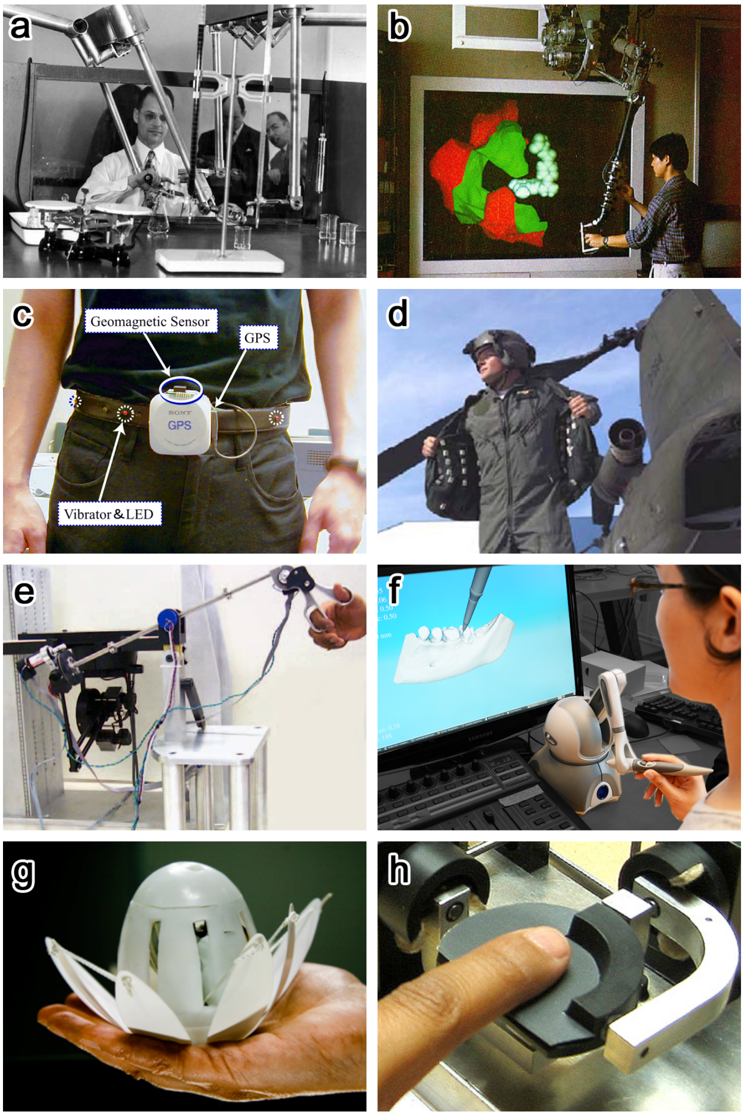


Figure 3.8: Different forms of haptic interfaces and usage scenarios:
a:Raymond Goertz' teleoperation system from 1951 (image from [Niemeyer et al., 2008]),
b:*Grope-III*, a 6DOF force reflective teleoperator with stereoscopic screen for manipulating virtual protein molecules [Brooks et al., 1990],
c:*ActiveBelt* prototype, a wearable tactile interface for navigational information [Tsukada and Yasumura, 2004],
d:Tactile vest for pilots equipped with vibrators for the spatial coding of positioning and bearing data [van Erp, 2005],
e:Master system of robot assisted endoscopic surgery system [Tavakoli et al., 2005],
f:Using a 6DOF *PHANToM* device to sketch material properties of a dental anatomy exploration application [Forsslund and Ioannou, 2012],
g:*Haptic Lotus* prototype, a themed haptic object which is used in an immersive theater environment [van der Linden et al., 2012],
h:Shape display prototype to measure the trajectories necessary to simulate curvatures of real objects [Dostmohamed and Hayward, 2005]

Haptic feedback has also been used as an additional channel of information in **gaming**. Examples are vibration actuators in hand-held console or PC controllers, voice-coil bass shakers to communicate low frequencies to seating furniture or the body[10] or recoil haptic feedback in plastic guns for augmented reality versions of ego-shooters [Piekarski and Thomas, 2002].

Haptic interfaces have been excessively used to **support sensory impaired people**. Visually impaired people gain access to information using haptic-based assistive technology such as Braille [Hatwell and Gentaz, 2008] or pin-matrix displays such as the *OPTACON* [Goldish and Taylor, 1974]. Deaf or hard of hearing people use systems such as the multi-finger tactile display *Tactuator* [Tan et al., 1999] to access digital information. The notion of providing sensory information to a human sense which is not normally the receiver of this information (i.e. 'tactile hearing', 'tactile vision') is called **sensory substitution**. Sensory substitution is a basis of remote tactile feedback and is addressed in more detail in chapter 4.

3.3 Tactile Feedback on Interactive Surfaces

The layering of graphical user interfaces and haptic cues has been one of the earliest areas of application for haptic interfaces [Hayward et al., 2004]. Early research focuses on the augmentation of input devices such as computer mice with force feedback (e.g. [Kelley and Salcudean, 1994]) or applying virtual textures on GUI elements using force displays (e.g. [Minsky et al., 1990]). With the emerge of mobile devices and touchscreen interfaces, tactile feedback has become a method of non-visual acknowledgement of input which helps to reduce cognitive and visual load.

Following the three-fold structure of haptic interfaces from 3.2.1, the combination of touchscreens with tactile feedback can be seen as a tactile interface. The screen surface constrains and defines the physical movements of the user and tracks the user's fingertips or hands, actuators implemented into the user's direct environment are used to communicate tactile stimuli resulting from the interaction.

In this section, I will show that tactile feedback on touch surfaces can be much more versatile than simple acknowledgments of input (i.e. reactive feedback). I will outline the importance of crossmodal congruence and show the benefits of tactile feedback for touch interaction.

3.3.1 Types of Stimuli

When designing active tactile stimuli to support direct-touch interactions on interactive surfaces, the tactile signals are used to communicate information, comparable to a language. This tactile language has a semantics, i.e. the information which is to be transferred. The tactile language also has a syntax, i.e. the parameters of the tactile stimuli. These parameters are discussed in the following and illustrated in figure 3.9.

[10] `http://www.bassshakers.com/` [cited 2013/02/09]

Interaction	proactive	simultaneous	reactive
Signal Type	**Signal Examples**		
object-related:	° form ° edge roundness ° surface structure	° force behavior ° pressure ° detent	° latching ° disappearance ° surface structure
object-independent:	° importance ° relationship ° function	° importance ° mode change ° state	° function ° relationship ° state

Figure 3.9: Examples of programmed tactile stimuli during different stages of a direct-touch interaction for object-related and object-independent information.

Tactile information can be conveyed during all stages of an interaction. For example, when pressing a button on the touchscreen, tactile feedback before the activation (i.e. proactive feedback, feed-forward) could communicate the form, type and state of the virtual element. Tactile feedback during the activation (i.e. simultaneous feedback) such as force-path-characteristics could inform the user about the reversibility of his action. Reactive tactile feedback such as a 'snap' could confirm the user's input.

In contrast to auditory feedback, tactile feedback can be given permanently (e.g. during manual exploration of material). With auditory feedback during a proactive stage, the system would emit sound permanently. Moreover, the tactile channel is a private and personal channel of information from system to human. No other person is aware of the tactile transfer. In contrast to this, auditory feedback is a broadcast to the environment. For example, auditory feedback on an in-vehicle touchscreen keyboard could be a potential disturbance to other passengers. In public scenarios such as underground trains, auditory feedback coming from an interaction with a mobile device's touchscreen is lacking social acceptance.

The semantics of tactile stimuli can both be concrete and abstract. Programmed tactile stimuli can be concrete in a sense that they render characteristics of virtual elements which make them similar to real-world objects. Following the notion of direct manipulation, the system provides tactile "representations of objects that behave as if they are the objects themselves" [Hutchins et al., 1985]. For example, concrete object-related information communicated via active tactile signals can be form, surface structure, hardness or mechanic force behavior. This information can be utilized by the user to analyze an element's type, state or function. Programmable tactile stimuli are not restricted to physical constraints and can be designed to make virtual elements discriminable and understandable on touch.

However, virtual elements do not have to resemble their real-world counterparts. Moreover, tactile characteristics can be programmed to encode information independent from the virtual objects. These object-independent contents can be used to encode stati such as importance, strength, recency or urgency. Active tactile feedback could describe topological relationships between virtual elements [Hayward et al., 2004]. Additionally, programmed tactile stimuli can be independent from an interaction, e.g. 'tactons' (i.e. tactile icons) have been used to convey abstract messages non-visually [Brewster and Brown, 2004].

The syntax of tactile stimuli synchronized with touch interactions depends on the characteristics of the tactile actuator and the capability of the human haptic system. Perceptional thresholds of the human sense of touch have been described in section 3.1.1, several general guidelines for the design of haptic widgets exist [Hale and Stanney, 2004, Oakley et al., 2002, Subramanian et al., 2005].

3.3.2 Benefits of Direct Tactile Feedback on Interactive Surfaces

In section 2.3, I have identified several current challenges of touchscreen interaction. Primary challenges are limited usability due to high visual and cognitive load, input ambiguities due to the fat-finger problem and unintended activation caused by unwanted touch. These challenges can be addressed by the utilization of synchronized non-visual stimuli to describe characteristics of touchscreen widgets and state of the interaction.

Multimodal systems "process two or more combined user input modes - such as speech, pen, touch, manual gestures, gaze, and head and body movements - in a coordinated manner with multimedia system output" [Oviatt, 2003]. Hence, multimodal feedback is only one aspect of multimodal interaction (besides multimodal input). Multimodal feedback is often used to reduce visual and cognitive load for the user of an interactive system. In general, "adding an additional modality to visual feedback improves performance overall" [Burke et al., 2006].

Different sensations coming from different modalities are combined in our brain to form an overall percept of an external object. However, individual separate modalities can affect and alter each other. As Shimojo et al. point out: "Sensory modalities are not separate modalities" [Shimojo and Shams, 2001]. The effects of mutual affection have been studied in perceptional research and psychology, the McGurk phenomenon is the most famous example: Here, vision can alter the perception of speech. E.g. the sound 'ba' is perceived as 'da' when it is coupled with a visual lip movement of 'ga' [McGurk and MacDonald, 1976].

In contrast to multimodal feedback (where the different senses receive different information), *crossmodal* feedback delivers the same information to different senses. An example is the tactile representation of a virtual button on a touchscreen: the tactile feedback provides information on form, height and edge roundness of a button. These parameters can also be communicated visually by shapes and color gradients of the interactive GUI element. For programmable tactile feedback on touchscreens of mobile devices, Hoggan et al. examined how visual and audio/tactile feedback can be combined in a congruent manner in order to "create realistic, congruent buttons by selecting the most appropriate audio and tactile counterparts of visual button styles" [Hoggan and Brewster, 2007]. Resulting from several user studies, they propose guidelines for designing interactive elements with crossmodal congruency, e.g. to use soft vibra-clicks to augment large, raised rectangular buttons. Crossmodal congruencies are to be incorporated into the design of future tactile feedback on touchscreens [Hoggan et al., 2008b].

In the following, I discuss benefits of combined tactile and visual feedback on touch surfaces shown by results of formal evaluations in related work.

Quantitative and Qualitative Measures

Fukumoto et al. attached a vibrotactile actuator to the body of a PDA and provided tactile feedback as a reaction to user input to the grasping hand [Fukumoto and Sugimura, 2001]. In a user evaluation with 10 participants, effects of tactile feedback and audio feedback on operation time and error rate during a calculation task were measured. Additionally, two levels of environmental noise were given to evaluate it's effect. Results showed a 5% reduction of operation time in silent situations and 15% **reduction of operation time in noisy situations** when tactile feedback was given. Audio feedback did not have a beneficial effect.

Poupyrev et al. [Poupyrev et al., 2002] embedded a PDA with a piezo-based tactile actuator under the screen plate, thus providing vibrotactile feedback on the touching finger and to the grasping hand. In an evaluation with ten participants, the users had to tilt the device in order to scroll a list to a defined position. Tactile feedback was given in every step of the list. The experiment evaluated the effects of the feedback on completion time and overshoot. In total, tactile feedback resulted in 22% **faster task completion time** and also **reduced overshoot distance**. Interestingly, users stated the **preference of the users for the tactile feedback** in the device due to a better user experience: "Some suggested that emotionally it feels more comfortable and familiar" [Poupyrev et al., 2002].

Brewster et al. performed two experiments to evaluate the effect of tactile feedback during text input on mobile devices [Brewster et al., 2007]. In a laboratory study with 12 participants, they used a voice-coil actuator on the back of a PDA to provide tactile information on correct press-and-release of a button and on slips and tap errors. They found a **significant increase in the number of lines of entered text** when tactile feedback was given, a **significant decrease of made errors** and a **higher number of corrected errors** with tactile feedback. In order to evaluate their approach in a more realistic user scenario, they repeated the evaluation on a city underground train with six participants (see figure 3.10). Again, the number of corrected errors was significantly higher in the tactile condition. They did not find a significant difference in amount of text entered and total number of errors made. Measuring individual workload using a NASA TLX (Task Load Index) workload sheet [Hart and Wickens, 1990], **overall workload could significantly be reduced** (mental demand, physical demand, effort, frustration). Brewster et al. emphasize that audio feedback (e.g. affirmations, error messages) can have comparable benefits, but tactile feedback tends to help more in noisy and dynamic situations [Brewster, 2002].

Hoggan et al. [Hoggan et al., 2008a] also evaluated the effect of vibrotactile feedback during text input on mobile devices. In addition to tactile confirmation and slip messages, they created 'fingertip-over events' which occurs when a finger is over a button or moves between buttons. This way, the user can feel the virtual edges of the interactive elements comparable to the buttons of a real, physical keyboard (see figure 3.10). In their first evaluation with 12 participants

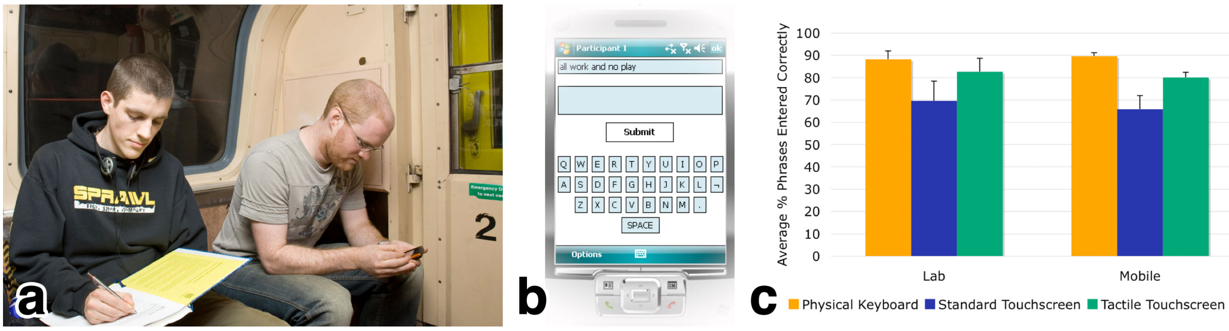


Figure 3.10: Measuring the benefits of tactile feedback on touch surfaces. a: Evaluation on an underground city train [Brewster et al., 2007], b: soft button keyboard on PDA with tactile feedback [Hoggan et al., 2008a], c: Average percentage of phrases entered correctly [Hoggan et al., 2008a]

they compared user performance on a standard mobile device without tactile feedback, a mobile touchscreen device with tactile feedback and the same touchscreen device without tactile feedback. Performing the study in both laboratory and underground train scenarios, they found **significant benefits for number of correct phrases** for both tactile and physical mobile device when compared to the touchscreen-only device (see figure 3.10). The same benefits were found for the **reduction of operation time and subjective workload**. In summary, the authors state that the addition of tactile feedback can bring touchscreen keyboards "close to the level of real, physical keyboards" [Hoggan et al., 2008a]. Furthermore, the authors point out that user performance can "be further improved by using multiple, specialized actuators which can provide localized feedback as opposed to a single standard actuator which vibrates the whole device" [Hoggan et al., 2008a].

Seungyon Lee et al. [Lee and Zhai, 2009] state the importance of synthetic feedback on touch surfaces in terms of effective speed and subjective user ratings. Additionally, they stress that both audio and vibrotactile cues boosts performance, but the combination of both do not have an additional beneficial effect. Ju-Hwan Lee et al. [Lee and Spence, 2008] provided combinations of visual, tactile and auditory feedback to the eight participants of their user study. Again, text input was performed on a mobile device in a dynamic scenario (driving simulation). In this evaluation, trimodal feedback (visual, auditory and tactile) had the most beneficial effect on both driving and input performance (in terms of **reduced response times**). The same holds true for subjective workload.

3.3.3 *HapTouch:* Tactile Feedback for In-Vehicle Touchscreens

The evaluations described above show the benefits of tactile feedback on mobile touchscreen devices regarding operation time and error rates. Noisy and dynamic scenarios involving movement and attention shifts such as a ride on the city subway train can create statistically significant quantitative effects. A similar situation is the interaction with direct-touch-based in-vehicle in-

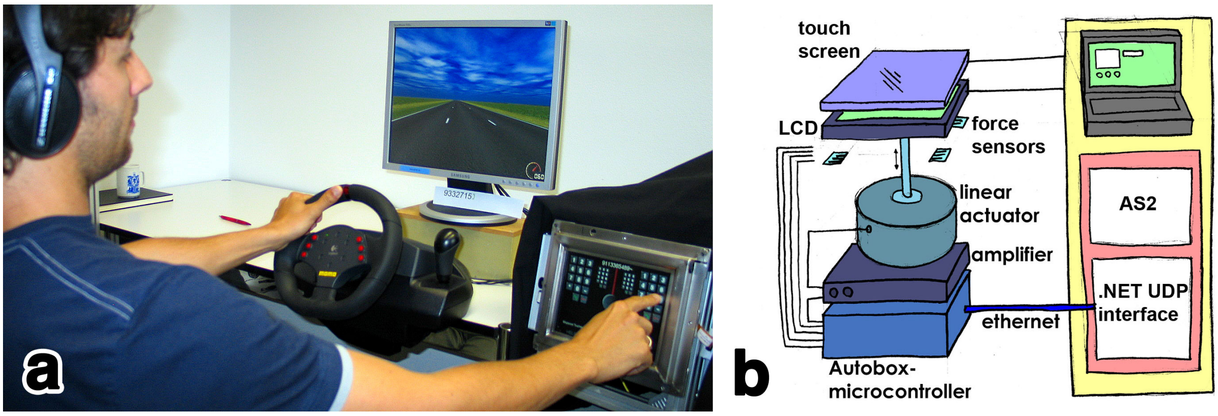


Figure 3.11: a: The *HapTouch* system in use. b: Schematic technical overview of the system (from [Richter et al., 2010]).

fotainment systems (IVIS) whilst driving. In [Richter et al., 2010], we present the *HapTouch* system, a force-sensitive touchscreen with tactile feedback allowing the user to manually explore and palpate interactive elements using the sense of touch (see figure 3.11). The project and publication is result of my Diploma Thesis, which was done in collaboration with BMW Research Munich[11]. In the project, results from a preliminary user study show reduced error rates and input time when tactile feedback is given. Design, implementation and evaluation of the *HapTouch* system is provided in brief in the following, please refer to our publication [Richter et al., 2010] for details.

The growing number of functionalities such as multimedia, navigation ad safety in today's cars can not be controlled by single mechanical buttons for every single functionality. Accordingly, car manufactures increasingly implement touchscreen interfaces for IVIS. However, due to the lack of tactile feedback, in-vehicle touchscreens demand significant visual attention [Burnett and Porter, 2001], which in turn results in potentially dangerous increased eyes-off-the-road time [Rydström et al., 2009]. Particularly, on touchscreens, the user has to visually control the finger's movement towards the interactive element on the screen. We proposed two methods to cope with these challenges:

- First, the system's pressure sensing abilities allow to approach the interactive element on the screen.
- Second, tactile feedback is given during this exploration on the screen, which helps to make buttons discriminable on touch and to provide acknowledgments after the interaction.

In order to to model the states of our pressure-sensitive touch device we expanded Buxton's three-state model of graphical interaction [Buxton, 1990]. We implemented 4 states (see figure 3.12).

Technically, the system is built up with a 8.4" color TFT display superimposed with a capacitive single-touch screen. Four force sensing resitors (FSR sensors) are mounted between corners of

[11] BMW Forschung und Technik GmbH

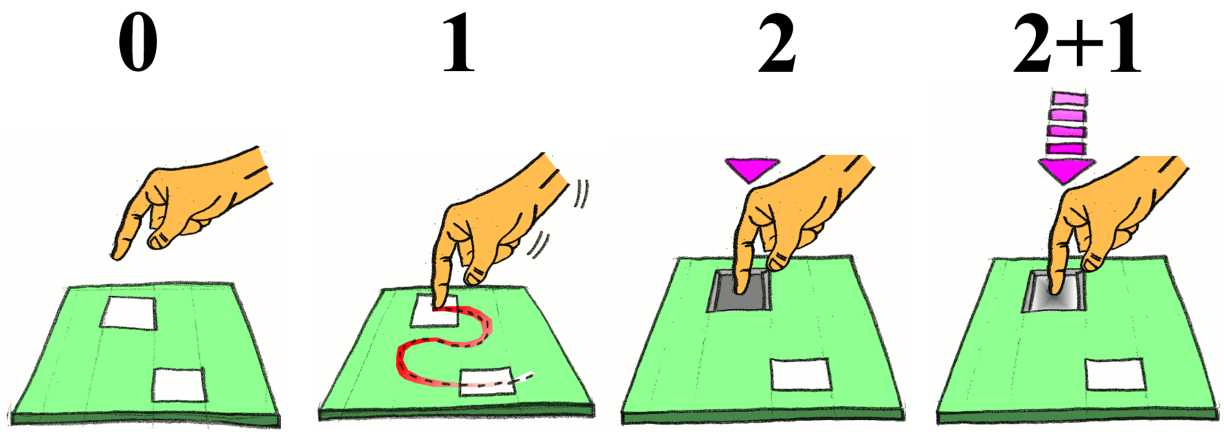


Figure 3.12: Four states of the interaction with the *HapTouch* system: **state 0:** The finger does not touch the screen. **state 1:** Manual exploration of the screen is possible, the finger is tracked and tactile feedback is given. However, no activation is performed. **state 2:** Elements and buttons are activated when pressure is applied, the tactile feedback communicates the mechanical 'snap' of buttons or 'clicks' of list elements. **state 2+1:** The additional variable pressure is introduced. The amount of force is mapped to interactions such as zooming and resizing and affects tactile parameters such as amplitude and frequency (from [Richter et al., 2010]).

the display and the casing. This assembly is mounted on linear bearings and connected to a high-performance voice coil actuator. Thus, tactile feedback can be applied to the touching fingertip in z-direction[12]. Both touchscreen and actuator system are controlled by a standard PC and an embedded microcontroller for signal generation (see figure 3.11). Tactile feedback can be given during all stages of an interaction with a virtual element: on direct touch of the element's surface, when rolling over the edge or when changing buttons.

The system was tested in a preliminary user study with 5 participants in a standardized dual-task driving simulation incorporating the Lane Change Test (LCT) as the primary driving task[13]. As a secondary task, users had to enter a sequence of numbers on a standard number pad on the tactile touchscreen.

The numberpad provided versatile tactile stimuli to the touching finger: on touch, the number buttons vibrate with frequencies that differ from those of the dialing button and the undo button. Additionally, when the fingers slips over the edge of a button (off the button or onto another one), a sharp 'snap' is given by the screen to illustrate the edge of a button. Based on these object-independent and object-related stimuli (see section 3.3.1) users could register their correct

[12] Available types of oscillation: sine, rectangle and sawtooth. Maximum of available amplitude: 28 mm. Maximum of available frequency: 20000 Hz.

[13] During the Lane Change Test, participants are presented with a simulated road [ISO, Geneva, Switzerland, 2007]. Appearing road signs order the participants to change lanes as fast and accurately as possible. The resulting driving performance is identified by the mean deviation (MDEV) between the position of the normative model and the actual driven course in meters.

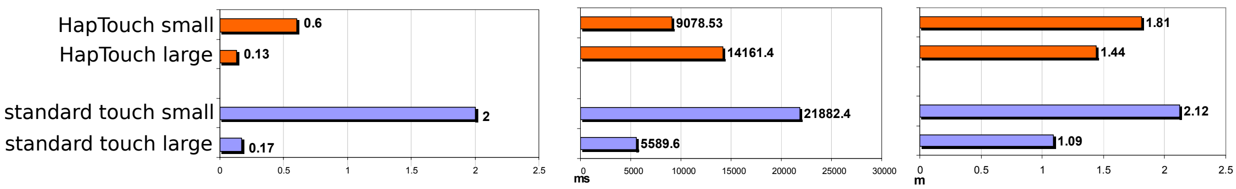


Figure 3.13: From left to right: Arithmetic mean values of errors per input, average total task time values and average mean deviation (MDEV) (n=5).

targeting of a button, the type of the button and the change onto another button non-visually (proactive feedback, feed-forward). On increased pressure onto the button, a confirming 'snap' was communicated as a feedback.

We implemented four versions of the touchscreen numberpad: two sizes (small/large) for each of the two feedback conditions (visual feedback with activation on touch vs. tactile-visual feedback with pressure sensitivity). This system variation was the independent variable, dependent variables were total task time, error rate and mean deviation (MDEV) in the Lane Change Test.

Due to the limited number of participants in the preliminary evaluation, no statistically resilient statements can be given. Nevertheless, we identified promising trends. Our results for error rates, total task time and MDEV are depicted in figure 3.13. In arithmetic mean, tactile feedback reduced the number of errors by 23.53% (large numberpad) and 70% (small numberpad). With tactile feedback on the smaller numberpad, we could reduce total task time by 58.51%. However, on the large numberpad, total task time was not reduced by tactile feedback. Also driving performance was improved when tactile feedback on the smaller numberpad was given: the average MDEV was reduced by 14.62%. Again, this effect was not found for tactile feedback on the larger numberpad.

With the *HapTouch* project, we had the intention to evaluate the technical feasibility of high-expressivity tactile feedback in a driving scenario. The *HapTouch* system represents a novel form of interaction with touch-sensitive surfaces. We separated manual tactile exploration and touch input and provided the users with proactive and reactive tactile feedback. In the dual-task scenario of a driving scene, these types of tactile feedback were especially helpful when using smaller GUI elements, which are error-prone on standard touchscreens due to occlusion and ambiguous input caused by the "fat finger problem" and the "Midas Effect" (see section 2.3). Obviously, tactile exploration takes time compared to simple touch: for total task time using the larger numberpads, *HapTouch*'s tactile feedback was not advantageous, which also resulted in decreased driving performance. In general, we can state that pressure sensing and tactile feedback helped to realize the finger's position on a button, supported the movement from one element to another based on the tactile perception of 'edges' and can allow for the non-visual acknowledgement of input. In this dual-task scenario, this helped to decrease total error rates for all GUI sizes and assisted with decreasing total task time and improving driving performance when using small GUI elements compared to standard touchscreens.

3.3.4 Implications

In summary, this sections demonstrates the potential of tactile feedback on touchscreens based on related work and own research. Tactile feedback can help to improve usability and user performance of an interactive system. This especially holds true for multitasking-scenarios with high visual load such as the use of mobile devices or driving environments. However, the mentioned results also show the importance of novel forms of touch interaction to apply the tactile feedback to the user's hand: on mobile devices, the tactile feedback is often additionally transferred to the grasping hand in order to make sure the feedback is perceived when the interacting finger has left the screen. With the *HapTouch* system, we tried to increase the amount of time during which tactile information is transferred by introducing a state of tactile exploration of virtual elements (similar to manual exploration of mechanical control elements). However, the presented richness of tactile stimulation on interactive surfaces is not comparable to the real world: with the whole screen area moving, we can not describe edges, roughness or forms that are palpable using both hands. 'Radical atoms' or reconfigurable screen elements which provide tactile stimuli are still a thing of the future. The following section shows the struggle of engineers and researchers to provide meaningful and rich tactile feedback on touch surfaces.

3.4 Surface Actuation: Concepts and Challenges

Designers and researchers of interactive displays implement various technical actuators into the display in order to address our tactile sense. Their goals range from the creation of artificial stimuli over the replication of the real world to increasing the general usability of the interactive system.

Technically, a vast number of different actuators technologies and forms is available: electromechanical, electrical, pneumatic, electrothermal, ultrasound or rheological actuators exist. Elaborate descriptions of tactile actuators exist (e.g. in [Chouvardas et al., 2008, Hayward and MacLean, 2007, Spirkovska, 2005]). Therefore, I will not give an exhaustive overview on actuator technology in this thesis. Actuators of tactile systems from related and own work will be described 'on the go' with references to appropriate literature. This approach allows to concentrate on overall concepts and the design of conceptual prototypes.

Technical concepts to provide tactile feedback for direct touch generally fall into one of three categories:

1. Actuating the screen or the device as a whole.
2. Segmenting the screen surface into individually movable tactile elements.
3. Adding electromechanical devices to create tactile stimuli.

The following chapter describes the three classes and provides examples from related work. Each of the three methods entails technical and conceptual benefits and challenges, depending on scenario of use, which are classified and discussed in this chapter.

3.4.1 Actuating the Screen's Surface or Encasing of Device

Electromechanical Actuation and Vibration: The most common way of haptically stimulating the touching fingertip or hand is the actuation of the device's screen or the device's body. Thus, tactile stimuli are transferred to the skin of the touching fingertip or the skin of the grasping hand. This principle is implemented in most of today's smartphones for alarms, incoming calls or typing feedback. Small flat or cylindrical pager motors rotate an eccentric mass. This movement results in vibrations around 200-300 Hz, which in turn activate the Pacinian corpuscles in the glabrous skin [Mortimer et al., 2007]. Vibrotactile stimuli are widely used in HCI, but can have disadvantageous effects such as mutual masking or creation of numbness over time [Mortimer et al., 2007, Luk et al., 2006].

Several system incorporate forms of vibrotactile feedback on touch surfaces. In 2001, Fukumoto et al. [Fukumoto and Sugimura, 2001] presented their *Active Click* system, where a voice-coil actuator[14] is mounted on the body or the touch panel of a PDA (see figure 3.14). Thus, users were receiving short vibrotactile bursts as acknowledgement of their input. Poupyrev et al. [Poupyrev and Maruyama, 2003] implemented the piezo-based[15] *TouchEngine* actuator in the frame of the device (see figure 3.14). In a case study, they provided clicks and pulses on touching and holding of interactive buttons. The *TouchEngine* was later implemented in a commercial product, the *Sony Navitus Remote Control*[16]. The principle of 'programmable friction' is also based on vibrating transparent surfaces atop the display [Levesque et al., 2011].

However, for larger touch surfaces such as tabletops or interactive walls, vibrotactile actuation does not scale: the electromechanical actuators have to be powerful and larger to move the full mass of the screen plate. Thus, operation noise such as humming or droning would occur. Additionally, due to flexing of the plane, spatial uniformity of tactile feedback is prohibited.

Electrovibration: Researchers try to incorporate the principle of electrovibration to cope with these challenges[17]. In 2010, Bau et al. presented the TeslaTouch system, an implementation of the electrovibration principle [Bau et al., 2010] (see figure 3.14). They performed evaluations of subjective opinion and of detection and discrimination thresholds and give guidelines and design recommendations of incoporating the principle into interface design. The principle has

[14] A cone is moved by a surrounding copper coil in a magnetic field when current is passing through. Voice coils are a basic component of audio speakers [Fukumoto and Sugimura, 2001].

[15] Piezoceramic materials shrink or expand based on the polarity of the applied voltage. Likewise, piezoceramic elements do emit voltage on mechanical deformation [Poupyrev et al., 2002].

[16] Sony Corporation: Navitus Remote Control
`http://ivanpoupyrev.com/products/navitus/RMNX7000_mksp.pdf` [cited 2012/11/12]

[17] The electrovibration principle is based on the interaction of skin layers and a current carrying conductor. The insulating dry outer skin forms the dielectric layer of a capacitor. Fluids in the inner skin layers and conductive surfaces or electrodes form two opposing conductor plates. Alternating voltage which is applied to the conductive surface results in an induced charge. This generates attraction forces between skin and touch surface, thus rendering friction to the moving fingertip. The feel of the friction can be modulated by altering the amount of applied voltage [Bau et al., 2010, Strong and Troxel, 1970, Grimnes, 1983]. In contrast to electrocutaneous approaches, no current is stimulating the nerve endings in electrovibration systems (see section 3.4.2).

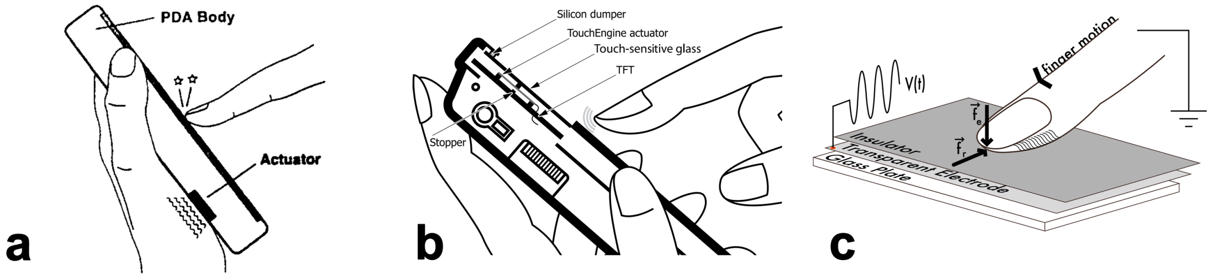


Figure 3.14: Methods for actuating the screen surface or device's encasing. a: The *Active Click* system is providing tactile feedback by actuating the device's encasing using voice-coil actuators [Fukumoto and Sugimura, 2001]. b: The *TouchEngine* moves the screen by integrated piezo actuators [Poupyrev and Maruyama, 2003]. c: The principle of electrovibration actuates the whole surface and can provide variable frictions to a single moving finger [Bau et al., 2010].

been adapted by vendors such as Senseq[18] for tablet computers, smart phones and larger touch surfaces. With electrovibration, several feelings of vibration or surface roughness can be incorporated. The principle does not entail the use of mechanical actuators and can be applied to larger interactive surfaces, when (transparent) electrodes and insulator layers are implemented.

However, the implementation of electrovibration for tactile feedback implicates several challenges for designers and engineers of touch interactions [Bau et al., 2010, Grimnes, 1983]:

- First, the alternating amounts of roughness can only be applied to the moving or sliding finger. The finger that is resting on an interactive element can not be provided with this form of tactile actuation.
- Second, the tactile feedback is limited to one stimulus per surface. Thus, only one type of tactile sensation can be created and is the same for every touching finger resulting in ambiguous feedback. An individual tactile sensation for every touching finger (e.g. on a multi-touch system) is not possible.
- Third, the sensation of the generated sensations tends to be weak and highly individual. When the fingers are wet, no sensation can be felt.

To increase the signal's intensity, Bau et al. [Bau et al., 2010] recommend to implement a grounding path by grounding the enclosure of the touch device, by wearing antistatic wristbands connected to electrical ground or by sitting or standing on a grounded pad. Recent work from 2012 shows the implementation of the electrovibration principle 'in reverse', where real objects touched by the user can be augmented with tactile feedback based on electrovibration created by a device worn by the user [Bau and Poupyrev, 2012].

Potentials and Challenges: In summary, the actuation of the screen surface or the device's encasing as a whole is the predominantly used method for tactile stimulation on touch surfaces. This approach includes electromechanical movement, vibration or electrical techniques such as

[18] `http://senseg.com/` [cited 2013/09/02]

electrovibration. This general approach can provide adequate and useful feedback for mobile devices or in-vehicle touchscreens (see the *HapTouch* system in section 3.3.3).

However, with regard to the development of non-flat, non-solid or deforming interactive surfaces, this form of tactile actuation also entails technical and conceptual drawbacks: First of all, the movement of the screen in z-direction can not create forms such as edges or surface structures, but emulates them by movement. The fingertip's ridges and bumps which are critical for the gathering of object information (see section 3.1.1) are not involved, as the screen's surface is still flat. Thus, the bandwidth and richness of communicated tactile information is limited. Second, a consequence of this form of actuation is the restriction to single touch. For both vibration and electrovibration, the screen can only communicate one single tactile sensation, which is the same for every touching finger. Although multiple fingers might touch the screen for multi-touch, gestural or even multi-person input, the tactile feedback is limited to one single stimulus. This results in ambiguity of feedback and hinders from manual exploration or input with multiple fingers or hands. Third, the presented principle of actuation suffers from limited scalability. For mechanical movement, an application to larger interactive surfaces such as tabletops or walls can result in bulky actuators and nonuniform actuation across screen dimensions and emitted noise.

3.4.2 Actuating Individual Screen Elements

Electromechanical 'tactile pixels': A second approach to superimpose visual and tactile displays with touch sensing surfaces is the segmentation of the touch surface in individually actuated elements, i.e. 'tactile pixels'. These individual elements can be moved electromechanically or can serve as individual electrodes for electrotactile stimulation. For electromechanic movement of elements, several examples from design and research exist:

In 2001, Iwata et al. [Iwata et al., 2001] present *FEELEX 1*, a deformable projected screen surface (24 x 24 cm) actuated with 36 linear actuators (6 x 6) (see figure 3.15). Each linear actuator includes a screw mechanism driven by a DC motor, force sensors on top of each rod sense the user's input. The authors propose palpation for medical examinations, 3D shape modeling and tactile touchscreens as applications for *FEELEX*. A similar shape display has been presented by Leithinger and Ishii in 2010 [Leithinger and Ishii, 2010, Leithinger et al., 2011]. This actuated tabletop display called *Relief* contains 120 motorized pins which are actuated by electric slide potentiometers which encode the user's input (pushing/pulling). Each potentiometer is driven by a dedicated DC motor, 32 controller boards for the system communicate with a computer. A flexible material can be attached to the pins, forming a continuous projection surface. The authors propose bimanual geospatial exploration as a first application. A similar system is the *TerrainTable* for topographical visualization, the system is commercially available[19]. However, only sparse information on tactile resolution and usage is given. The MIT's *Recompose* system is an actuated surface which technically and conceptually builds on *Relief* [Blackshaw et al., 2011].

[19] `http://www.is.northropgrumman.com/products/terraintable/assets/TerrainTable.pdf` [cited 2012/11/12]

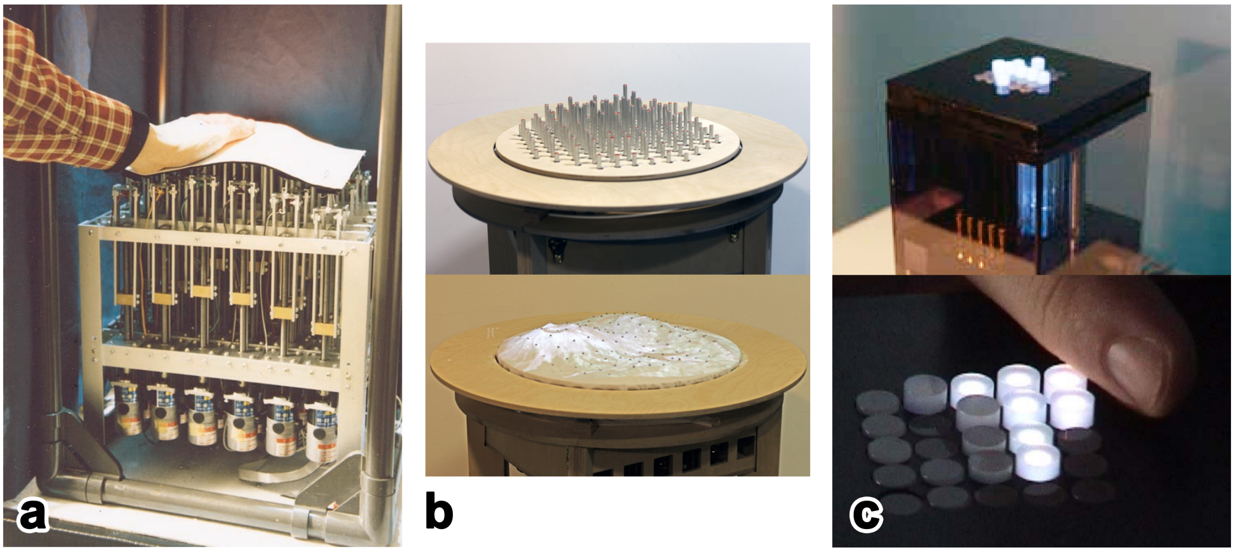


Figure 3.15: Electromechanical shape displays superimposing visual and tactile feedback. a: *FEELEX 1*, a deformable projected screen surface with 36 linear actuators [Iwata et al., 2001], b: *Relief* uses 120 motorized pins to display geospatial data (b-top), flexible latex can be attached to form a projection surface (b-bottom), c: *Lumen* is a 5 x 5 shape display with illuminated 'tactile pixels' [Poupyrev et al., 2004].

Other than *Relief*, *Recompose* also reacts to gestural input which is performed in mid-air over the shape display. The project *Lumen* by Poupyrev et al. [Poupyrev et al., 2004] follows a different approach for the visual display - every 'tactile pixel' contains an independent light source and sensing mechanism (see figure 3.15). This way, a resolution of 5 x 5 'pixels' on an area of approximately 5 x 5 cm is given (see figure 3.15). The system contains individual movable light guides which are moved up and down by individual strings made of shape memory alloy[20]. *Lumen* is used to present visual images and physical, moving shapes which can be manipulated with both hands.

Pneumatic, hydraulic, rheologic and electrical 'tactile pixels': Similar concepts base on different actuator technology. For example, in 2009 Harrison and Hudson use pneumatic actuation to create actuated screen elements [Harrison and Hudson, 2009]. Layering several specially cut pieces of acrylic with translucent latex, they form a semi-transparent surfaces containing individual air-chambers (see figure 3.16). Using small pumps, these individual air cells can be pressurized and deflated independently from each other. Multi-touch input can be realized using camera sensing of diffused infrared illumination and measuring changes of air pressure. Similarly, the commercial system *Tactus Tactile Layer Surface* incorporate fluids which are used to

[20] Shape memory alloy (SMA) can be deformed in low temperatures, but recovers its original shape when heated to a critical temperature (depending on specific materiality) [Otsuka and Wayman, 1998]. Typically, alloys such as Nitinol are heated by applying current [Nakamura, 2003].

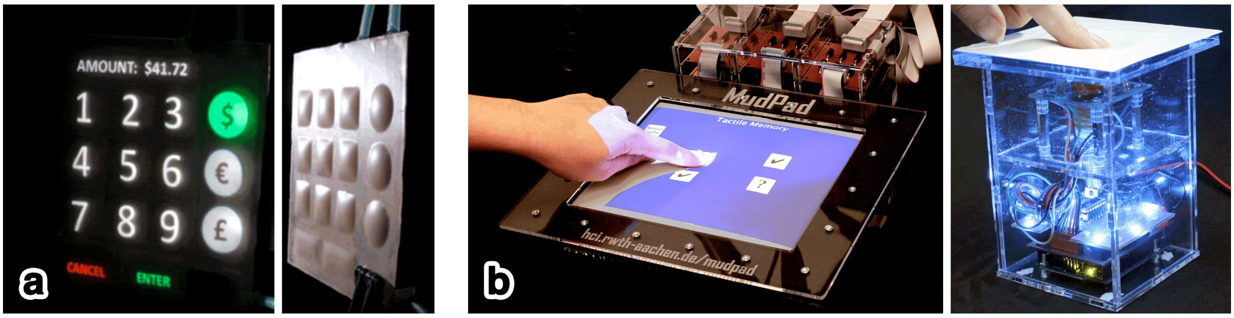


Figure 3.16: Pneumatic and rheologic shape displays: a: Actuating individual screen elements (left) by pumping air in latex chambers (right) [Harrison and Hudson, 2009], b: Changing the softness of screen areas (left) by applying magnetic forces to ferrofluid in a flexible container (Picture used with kind permission from Yvonne Jansen). A single actuator is depicted on the right [Jansen, 2010].

expand chambers in a layer of clear polymer on a touchscreen[21]. A first prototype was presented in 2012 which actuates the buttons of a QWERTY keyboard on a mobile device's touchscreen.

The *Mudpad* prototype [Jansen, 2010] incorporates an array of 84 individual electromagnets below a container of magnetorheological fluid[22] which is covered with flexible latex (see figure 3.16). Top projection can be used to depict GUI-elements on this device. By actuating the individual magnets under the container, 'passive haptic feedback' can be given: the viscosity of individual screen elements can be controlled. Non-continuous sensing of user input is performed using optical tracking through individual optical fibers in each individual element.

Another feasible solution to superimpose programmed visual and tactile information is the projection of a virtual scene on an electrotactile display [Chouvardas et al., 2008]. However, no systems which implement this notion are known to me.

Potentials and Challenges: The method of actuating individual screen elements produces fascinating and versatile prototypical systems. The dynamic shape displays can create non-flat forms and elevations which are palpable using multiple fingertips or hands. In contrast to the actuation of the screen 'as a whole', this approach can create rich tactile stimuli addressing several tactile modalities at the same time. Shape displays can produce levels of hardness, viscosity, roundness or vibration. In this way, shape display can be seen as a step towards effectively actuating every single visual pixel of a high-definition display and in this regard towards 'Radical Atoms' (see section 2).

However, current systems still have several characteristics which could be improved in implementations of the future: The foremost problem is the limited tactile resolution which results

[21] Tactus Technology: Taking Touch Screen Interfaces Into A New Dimension
`http://tactustechnology.com/documents/Tactus_Technology_White_Paper.pdf` [cited 2012/11/12]

[22] Magnetorheological fluid (aka ferromagnetic fluid) contains carbonyl iron powder dissolved in glycerin. The stiffness of the fluid is affected by the application of magnetic force. This effect is also used in shock absorbers or braking systems [Jansen, 2010].

from bulky technology used for actuating and sensing on every single 'tactile pixel'. As Yvonne Jansen, creator of *Mudpad*, points out: "Output accuracy for the haptic display depends on magnet size. As the magnets require a certain power to affect the fluid, their size cannot be reduced arbitrarily. The current prototype uses magnets about 1" (2.5cm) in diameter, which determines its resolution" [Jansen, 2010]. Thus, the tactile resolution and granularity can not keep up with the visual resolution and expressivity of today's displays. On the fingertip, we can discriminate two points which are separated only 2-4 mm (see section 3.1.1), today's tactile shape displays are still far away from this resolution. Another challenge is size, technical complexity and high price when a high number of tactile actuator elements is needed. This applies especially when different types of tactile actuators are implemented (e.g. for both motion and temperature). Electromechanical devices incorporate motors, cranks, guides and sensors, thus rendering the implementation in mobile devices impossible. Pneumatic and hydraulic solutions have been proposed. However, due to the fixed size and limited resolution of the individual expanding chambers, the flexibility of visual design on touchscreens is limited by the decreased tactile resolution. Additionally, numerous systems for compression and transport of air or liquid are needed. Despite all these challenges, the notion of 'tactile pixels' is the most promising and impressive form of tactile feedback on touch surfaces.

3.4.3 Actuating Additional Devices

Tactile pens and tangibles: A third method for the addition of tactile stimuli to direct-touch surfaces is the use of intermediate or auxiliary tactile devices atop the touch surface. Pens or styli have been used to interact with touch surfaces and can be attached with actuators for tactile feedback. Lee et al. [Lee et al., 2004] attached an electromagnetic solenoid on top of a stylus with pressure-sensitive tip. Thus, when the mass of the solenoid's iron core is rapidly accelerated away from the tip, the user holding the pen perceives a clicking sensation. The authors propose solenoid actions such as permanent lifts, hops (pulses with different durations to create sensations from clicks to thumps) and buzzes (see figure 3.17). An additional device is presented by Hemmert et al. [Hemmert et al., 2010], who use a pen-shaped device with a movable steel ball on the tip. The perceived friction of the ball pen on the interactive surface can be altered by applying braking forces to the steel ball using an electromagnetc coil (see figure 3.17).

Another type of intermediate actuated devices are used as both input device and more elaborate tactile emitter. The *Haptic Tabletop Puck* by Marquardt et al. [Marquardt et al., 2009] can render different levels of height, malleability and friction. The simple, yet powerful box-shaped prototype consists of two servo motors in a wooden encasing. The servo motors control a rubber brake on the bottom of the device and the movement of a wooden rod coming out the top of the device. The user moves the *Puck* on the interactive tabletop with the fingertip on the *Puck*'s rod, friction and rod movement is controlled by the computer. The rod is equipped with a force sensor, thus allowing for user input. As the wooden device occludes virtual elements underneath, a virtual pointer arrow is displayed as soon as the device is placed atop the tabletop (see figure 3.17). The authors propose applications such as tactually-enhanced painting, office-layouting and collaborative scenarios in which two *Pucks* are interconnected on a common interactive surface. As

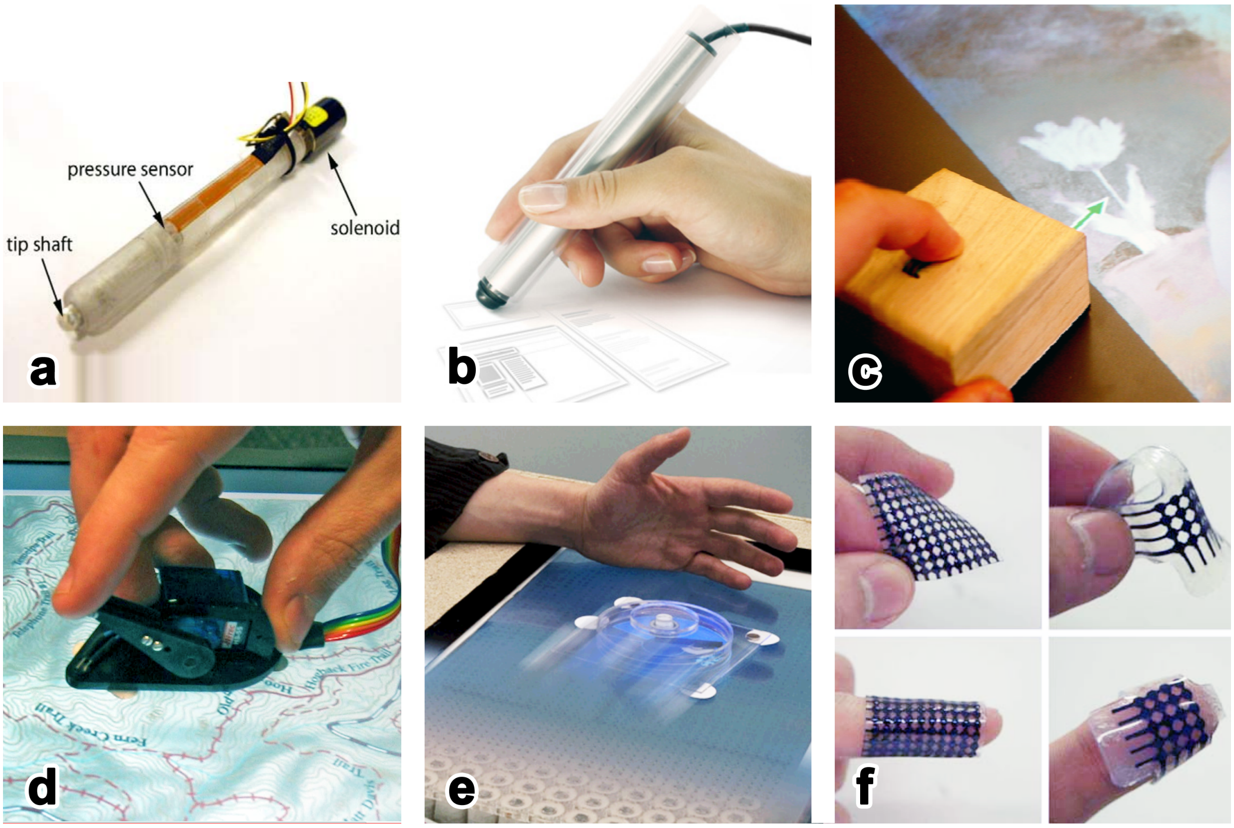


Figure 3.17: Actuated devices for tactile feedback on touch surfaces: a: Actuated input pen with clicking feedback caused by weight-shifting [Lee et al., 2004], b: Actuated pen with variable friction [Hemmert et al., 2010], c: *Haptic Tabletop Puck* device with virtual pointing arrow on tabletop [Marquardt et al., 2009], d: *formchaser* device on the tabletop raises and lowers the fingertip [Chang et al., 2008], e: Actuated widgets (*madgets*) on actuated workbench [Weiss et al., 2010], f: Wearable tactile actuator material [Koo et al., 2008]

the *Haptic Tabletop Puck* is both physical (tactile) embodiment and control device for its digital interpretation, it can be called a **'tactile tangible'**. A similar device is the MIT's *formchaser* [Chang et al., 2008], a simple finger-held mechanism which raises and lowers the fingertip depending on the virtual content on the touchsurface beneath the device (see figure 3.17). The device is used for tactile exploration only, no input can be performed[23].

Actuated widgets and thimbles: Weiss et al. [Weiss et al., 2010] present transparent widgets (i.e. *madgets*) for tabletop use, which are actuated by a matrix of electromagnets in the interactive surface. Permanent magnets on the bottom of the acrylic widgets allow for the programmable movement of the controls on the actuated workbench 3.17. The authors present several widgets which incorporate this principle: knob *madgets*, actuated radio buttons, actuated gear wheels and a magnetically triggered bell. Finally, wearable tactile actuators are a method to bring tactile feedback to any interactive surface. Koo et al. [Koo et al., 2008] present a flexible wearable

[23] Therefore, the *formchaser* can not be classified as 'tactile tangible'.

tactile display, e.g. for the fingertip. The surface of the material contains a matrix of cells with single actuator elements[24].

Potentials and Challenges: The notion of incorporating additional devices for both input on touch surfaces and output of tactile information is capable of creating rich and versatile tactile stimuli such as friction, movement, vibration or malleability. As the actuators are not implemented into the touch surface, this provides technical and conceptual freedom for design and implementation of both touch surface and tactile feedback device. For the touch surface, no potentially high number of individual actuators have to be implemented; this way, size and form of the interactive surface are not limited by the provision of tactile stimuli. For the touch device, tactile actuators do not have to be miniaturized and can be combined to form multiple tactile modalities (e.g. movement and friction [Marquardt et al., 2009]). Therefore, this approach is more scalable than actuating the whole surface or implementing matrices of actuators into the screen. Equally important, with additional tactile controls, more powerful interactions can be performed, designers and engineers can incorporate continuous pressure sensing and 'touch before activation' into the interaction. In so doing, a manual exploration of the interactive surface before activation is possible. Users can experience programmed surface structures and materialities of virtual elements on the interactive surface before activation. This supports non-visual interaction and results in more expressive and rich interactions.

However, comparable to the two approaches mentioned before, also the incorporation of intermediate devices between touchscreen and user entails drawbacks regarding technical implementation and usability. First of all, most tactile intermediate devices are placed atop the screen. Depending on size, occlusion of virtual elements can happen, especially when multiple devices are used. The users do not touch their object of interest, but a control device, thus breaking the beneficial metaphor of 'direct manipulation' (see section 2.1). Additionally, gestural input using multiple fingertips or hands is limited when using tactile controls. Larger tactile devices incorporate wiring for power supply and control and are not mobile. The use of additional or wearable devices could be cumbersome, as they have to be retrieved also for short interactions on the screen or when in collaborative scenarios. Besides tactile pens, tactile controls can not be used on non-horizontal touchscreens or interactive walls, they would fall down when left atop the screen.

3.5 Summary

In the first half of this chapter on basics of haptic perception and its utilization in HCI, I show the versatility of the human sense of touch as a private and rich channel of information in our everyday world. Programmed haptic stimulation is widely used in addition to visual feedback or on its own in areas of application such as virtual reality, teleoperation or accessibility. The application

[24] The cells are embossed and contain dielectric elastomer, which is transformed when voltage (up to 3.5 V) is applied. The authors measured the displacement with a laser sensor, the cells can be displaced approximately by 384μm [Koo et al., 2008].

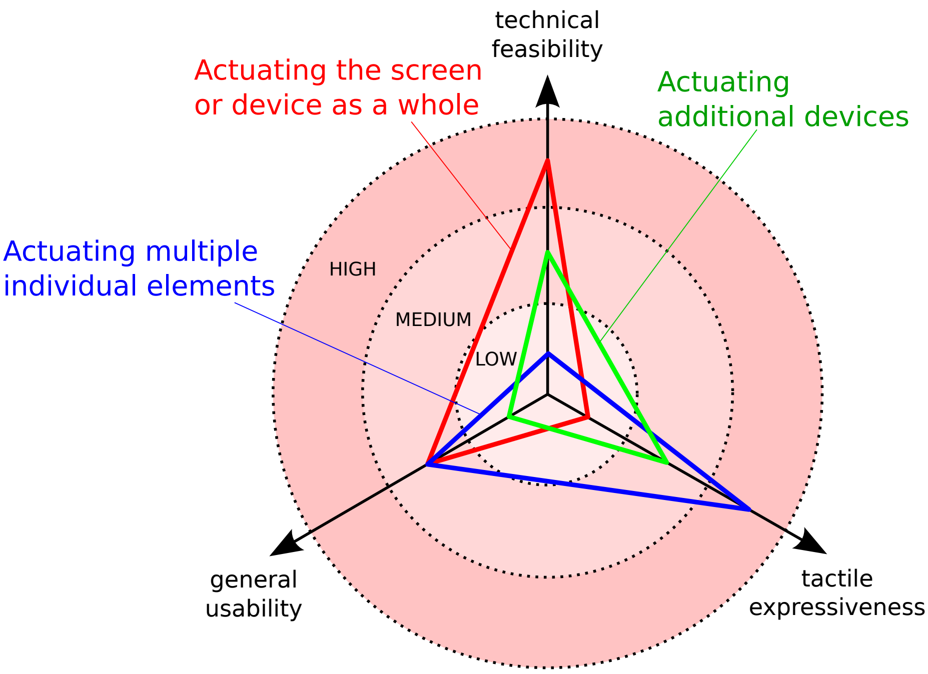


Figure 3.18: Taxonomy of methods to create tactile feedback on interactive surfaces. Details can be found in the text.

of crossmodal or multimodal tactile stimuli as channel of information on touch interfaces such as mobile devices or in-vehicle touchscreens has been shown to produce benefits regarding usability and personal appraisal of the interaction (see sections 3.3.2 and 3.3.3). Nevertheless, research on haptic interfaces is still a growing field.

Various concepts for the design of tactile actuator systems and feedback creation for touchscreens exist. In section 3.4, I presented three classes of methods:

1. actuating the screen or device as a whole
2. actuating multiple individual screen elements
3. actuating additional intermediary devices

Examples of prototypical systems and commercial products in each category are given. Each category entails potentials and challenges regarding **technical feasibility**, **tactile expressiveness** of the created stimuli and **general usability** of the resulting touchscreen interface.

In order to compare and discuss the characteristics of each approach, I arranged each method along these three dimensions[25] (see figure 3.18):

[25] Naturally, the figure represents a simplification and serves as a basis for the discussion and comparison of characteristics of very different technical approaches and design spaces. Additionally, the three dimensions are not completely separated, but can partly affect each other. For example, high technical complexity (with all negative effects such as high costs and limited scalability) can improve tactile expressiveness and general usability. On the other hand, even techniques with reduced complexity and tactile expressiveness can improve a system's usability (e.g. single-touch tactile feedback on in-vehicle touchscreens).

The **technical feasibility** characterizes the amount of complexity of the actuator technology:

1. When the screen or device is actuated as a whole, the technical complexity is low (i.e. high technical feasibility): a small number of simple actuators is used, e.g. for mobile phones simple rumble motors can serve as stimulators. The size of the actuators is not a predominating factor, as the tactile resolution is very low. This is true under the restrictions regarding size and form of the surface which were discussed in section 3.4.1.
2. For individual 'tactile pixels' on shape displays, the technical feasibility is very low (i.e. high complexity). This approach entails a high number of tactile actuators which have to be miniaturized in order to create high tactile resolution, especially for high resolution tactile feedback on smaller mobile devices where tactile feedback has to match high-resolution visual displays. For today, this results in increased costs for touch devices with desired high-resolution tactile feedback.
3. When additional actuator devices are placed atop the screen, the technical complexity is increased (depending on the desired complexity of tactile information). Nevertheless, the number of actuators is low and scalable towards larger surfaces, resulting in cost-effective devices.

The **tactile expressiveness** characterizes the versatility of the created tactile information:

1. For touchscreens or interfaces that are actuated in total, the tactile expressiveness is reduced. The palpation of reliefs or surface structures can only be emulated, because the flat surface of the screen is still the object which is presented to the touching fingertip. Additionally, the whole surface creates only one tactile stimulus in total.
2. The 'tactile pixels' approach however, creates impressive tactile representations of forms and surface structures with potentially high resolution. Sensations such as hardness, movement or viscosity can be combined. Similar to real world objects, the user can palpate and manipulate these shape displays using both hands.
3. The tactile expressiveness of additional devices moderate, depending on the type of the implemented actuators. Novel forms of tactile sensations can be created by combining electromechanical or electric actuator types. However, most systems in this class hinder the user from palpating actuated screen elements using the bare hands.

Finally, the **general usability** describes the quantitative effects and influences of the created tactile feedback on the usage of the touch interface:

1. Touch interfaces with actuated screens have been evaluated in mobile and multitasking scenarios (see section 3.3.2). In these scenarios, simple proactive and reactive non-visual information helps to decrease error-rates and increase interaction speed. On the contrary, this effect is not applicable on larger, non-flat, or deformable touch surfaces. Therefore, the general usability of interfaces implementing this principle can be valued as medium.
2. For individual 'tactile pixels' of shape displays, due to technical limitations, few evaluations in realistic usage scenarios have been performed yet. However, evaluations of comparable tactile displays such as braille-devices for visually impaired or blind users exist and have been shown to improve the usability of direct touch systems [Schmidt and Weber, 2009, Schiewe et al., 2009].

3. When additional actuator devices are placed atop the screen for tactile feedback, these devices can have increased technical complexity and size (depending on richness of tactile stimuli), thus being cumbersome to bring along. This approach also hinders from direct touch and manipulation of the screen surface. When multiple users want to interact with a common screen, collisions and occlusions are a problem. Additionally, this type of device often can not be used on non-horizontal surfaces. However, additional input devices such as styli or mice can greatly improve interaction speed and accuracy [Forlines et al., 2007, Balakrishnan and MacKenzie, 1997] .

With regard to the ongoing evolution of interactive surfaces to non-flat or non-solid forms, novel forms of touch interaction and tactile feedback are to be explored. Technically, methods of tactile actuation should be simple and cost-effective, to allow for fast prototyping and iterative evaluation of prototypical implementations. Nevertheless, tactile expressiveness should be high to create rich stimuli incorporating various tactile modalities such as temperature and deformation. When implementing new forms of tactile feedback, the general usability of the underlying touch systems should be increased in a degree that is equal or higher to existing technologies. The notion of direct manipulation should be preserved, the possibility for manual exploration before activation with proactive and reactive feedback should be maintained. Most importantly, the described developments of interactive surfaces call for more flexible and versatile methods for tactile feedback.

Therefore, my thesis describes a novel approach: the spatial separation of touch input location and location of tactile feedback. This concept of 'remote tactile feedback' can be seen as fourth method for the creation of tactile feedback on touch surfaces. The goal is to create technically feasible, understandable and rich tactile feedback to support the emerging forms of novel touch surfaces.

Chapter 4

Relocated Haptic Stimuli

At first, it may seem unnatural and intricate to link an ongoing touch interaction that is performed with fingertips or hands with tactile stimuli somewhere else on the body. However, this effect is omnipresent in the world around us. For example, musicians who play the violin, the piano or the drums use the tactile cues coming from the instrument as additional source of information: The movement of the bow on the violin's strings creates manifold vibrations and oscillations of the violin's body which are immediately transferred to the musician's neck. Thus, synchronized haptic sensations help the musician to recognize fine variations in the movement of the bow and allow for immediate fine-control of speed and angle of the shoulder, arm and wrist.

Moreover, this approach of relocated non-visual feedback is constantly applied in several research areas, namely: sensory substitution, accessibility and (to some extent) tabletop and mobile interaction. In this chapter, I will explain the theoretical basics and different specifications. The concept of remote tactile feedback heavily draws from sensory substitution on the conceptual and technical level.

4.1 Sensory Substitution

The term 'sensory substitution' refers to the translation of sensory information which is addressed to one sense to another sense. Thus sensory substitution can be described as a form of controlled synesthesia, as sensory stimulations dedicated to a certain sensory pathway are purposefully redirected to another sense [Hurley and Noë, 2003]. This translation mostly is performed by a technological system which is used to capture signals, to translate them and to deliver them to a sensory modality of a human.

A very early example of a such a system is the *Elektroftalm* by Noiszewski in 1897 [Spirkovska, 2005], a mobility aid for the blind: Here, a single selenium cell[1] placed on the

[1] Selenium is a photosensitive material which changes its conductivity depending on amount of impinging light.

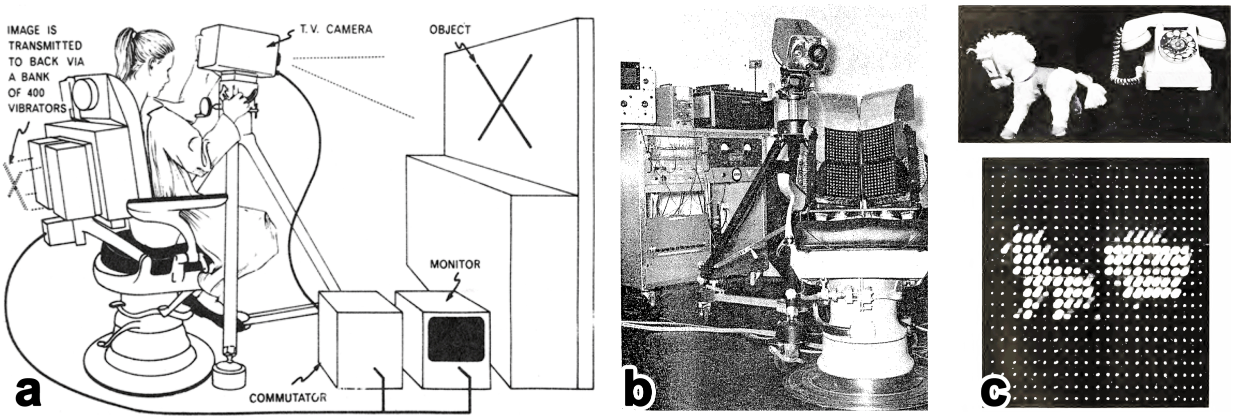


Figure 4.1: The*Tactile Vision Sensory Substitution System.* a: Structure of the system [White et al., 1970], b: the system without a user [Bach-y Rita et al., 1969], c: translation of camera images into a tactile representation [Bach-y Rita, 1972]

forehead controls the intensity of a sound source, thus supporting a blind person in distinguishing between light and dark (i.e. auditory vision). An early and well-known example is the *Tactile Vision Substitution System (TVSS)* by Bach-y-Rita [Bach-y Rita et al., 1969], a vision substitution system which uses an array of 20 x20 solenoid pins to 'haptically depict' an image coming from a camera on a person's back (i.e. tactile vision). Users are actively moving the camera to collect visual information which is then transferred onto their back (see figure 4.1). Various follow-up devices have been developed [Bach-y Rita, 1972]. Seeing impaired and blindfolded users had to undergo extensive training to discriminate and recognize objects[2].

Research on sensory substitution systems is highly interdisciplinary and incoporates research domains such as neuroscience, sensory prosthetics and human-computer interaction. Originally driven by the motivation to develop assistive systems for sensory impaired, it became relevant for research ares such as virtual reality and teleoperation.

4.1.1 Classification of Sensory Substitutions

Sensory substitution systems can be classified according to the sensory modalities which they interpret and communicate (see figure 4.2). For example, sensory substitution systems are used to substitute damaged receptor systems (such as the eyes or the optic nerve) by incorporating

[2] In the article from 1969, Paul Bach-y-Rita describes how blind users begin to incorporate this new sense of tactile seeing: First, they are trained to discriminate horizontal, vertical and curved lines. Then, they learn to recognize combinations of lines (squares, circles and triangles) and solid forms. This training takes about 1 hour. Afterwards, they learn a first vocabulary of common objects such as telephones or toy horses (see figure 4.1). Then subjects learn to deduce spatial relationships of two or more objects. Finally, subjects learn to discriminate individuals and to orient themselves in the room. After 10 hours or more hours of training, individuals were able to recognize familiar objects in 5-20 s [Bach-y Rita et al., 1969].

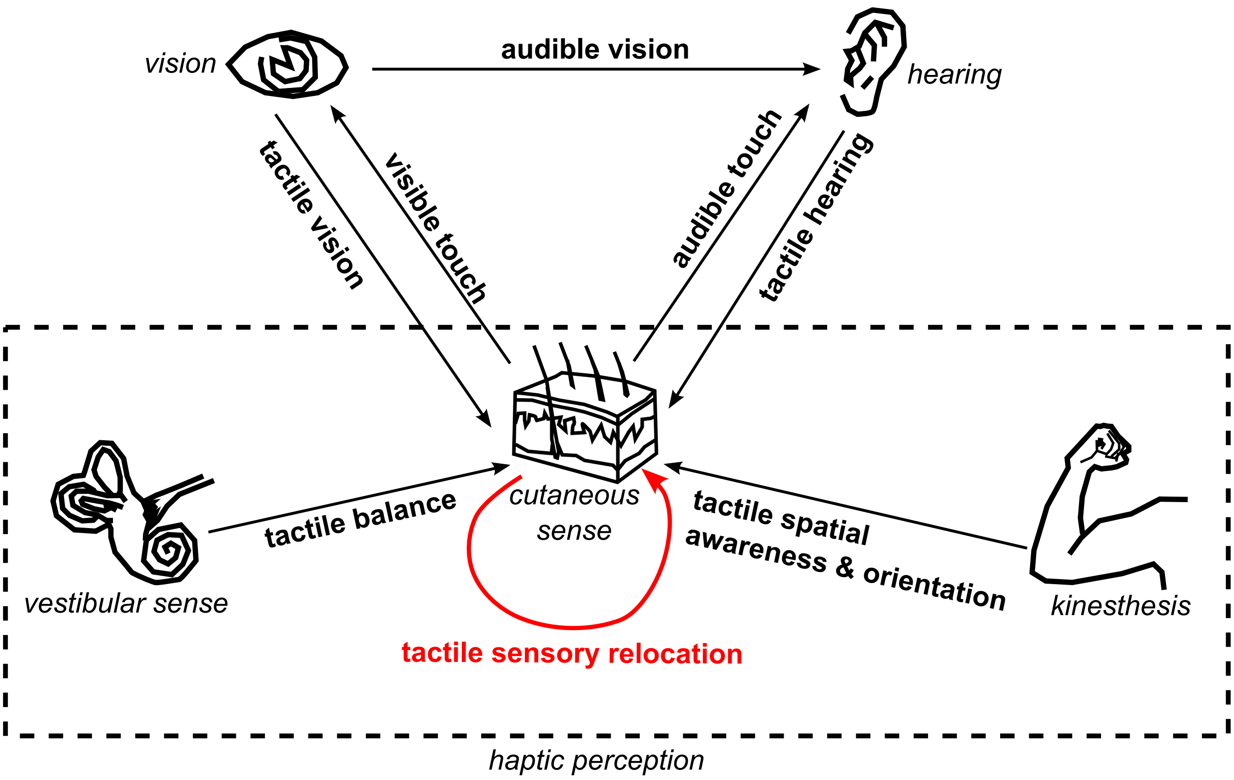


Figure 4.2: Classification of Sensory Substitution Systems. The arrows start at the modality which is substituted with the modality at the arrow's head. The majority of systems incorporate haptic perception as input or output modality. The concept of 'tactile sensory relocation' (marked in red) is closely related to remote tactile feedback.

devices which translate visual cues in audible information (e.g. the *vOICE* system[3] or Apple's *Voice Over* software[4]). As haptic perception has to perform diverse functions such as collecting tactile information, maintaining body balance or recording the body's posture (see section 3.1.1), many sensory substitution systems incorporate haptic perception as input or output modality.

The *OPTACON* (OPtical-to-TActile-CONnector) [Efron, 1977] is an example for a system enabling 'tactile vision'. It consists of a "small hand-held camera with an array of photocells (6 columns wide by 24 rows high), and a corresponding tactile display made up with a 6-by-24 array of pins measuring 1.1 by 2.7 cm" [Tan and Pentland, 1997] (see figure 4.4). Whenever a dark spot appears in the camera image, the corresponding pin on the tactile display vibrates. Thus, visual information is transferred in the tactile domain with typical reading rates of about 50 words per minute[5] [Craig and Sherrick, 1982].

[3] `http://www.seeingwithsound.com/` [cited 2013/09/02]

[4] `http://www.apple.com/accessibility/voiceover/` [cited 2013/02/09]

[5] Please note that this tactile representation is the only access to written information for the blind user. Other than tactile feedback, the tactile stimuli created by the *OPTACON* are allowing for reading solely based on tactile information.

4.1.2 Brain Plasticity and Sensory-Motor Coupling Devices

The ultimate condition for the working of sensory substitution systems is the ability of our nervous system to change structure and function in response to changes in functional demands - **brain plasticity** or **neuroplasticity** [Bach-y Rita, 1972]. Changes can affect the neurochemical, synaptic, receptor, and neuronal level [Bach-y Rita and Kercel, 2003]. The brain can be influenced by a lot of factors such as experience, learning, disease or stress [Kolb and Whishaw, 1998]. For example, when people learn new motor skills such as learning an instrument, plastic changes in the nervous structure have to occur, otherwise no learning can happen.

Our brain interprets the signals coming from our sensory organs depending on the specific location of the stimulated nerve cells (neurons) in the brain. For the brain, it is not necessary that these signals are presented in the same form as in natural sensory information systems [Bach-y Rita, 2004]. We 'see with the brain' [Bach-Y-Rita, 2003] as the visual image does not go beyond the retina but is translated into patterns of nerve impulses which in turn have to be recreated back into an internal representation of an image by the brain [Bach-y Rita, 2004].

When a peripheral sensory system such as an eye is missing from birth or due to an accident, the brain compensates with a greater activity in the remaining modalities and thus greater cerebral development in other areas. Furthermore, the brain does not lose the ability to see, the central mechanisms to process neural stimuli are retained [Bach-y Rita and Kercel, 2003]. Using an artificial peripheral sensory system as part of a sensory substitution system, the neural stimuli coming to the brain are processed in the underused brain segment. For example, blind users of the *Tactile Vision Sensory Substitution System* (desribed before) process and implement the tactile information coming from the device similarly to visual information (e.g. judging proportions of distant objects, recognizing individual persons and even performing anticipatory behaviors such as catching a ball [Bach-Y-Rita, 2003]). With training, the visual cortex can process the information coming from the sensory substitution device.

Figure 4.3 depicts the general structure and components of a sensory substitution system: Information about the environment is captured by sensors with modality A (e.g. visual information captured by a camera), the sensors can be both physical and virtual. The information is then transduced into a set of signals x(t), which are digitized and thus can be represented by data. This information is encoded into a set of signals y(t) which is understandable by the actuator system. The actuator system presents this information to a human sense of modality B (e.g. tactile information). The internal processing of the signals results in a reaction of the user, who in turn influences the sensory substitution device (typically by moving the sensors). This closing of the interaction loop is a crucial component of sensory substitution systems [Visell, 2009].

The importance of a closed feedback loop for the acquisition of sensorimotor experience has been emphasized by the majority of researchers in the field: As Lenay points out in [Lenay et al., 2003]: "No perception without action". A well-known example are in-voluntary rapid movements performed by the human eye (i.e. saccades): The constant movement of the retina results in permanent stimulation of the photoreceptor cells, which in turn deliver perma-

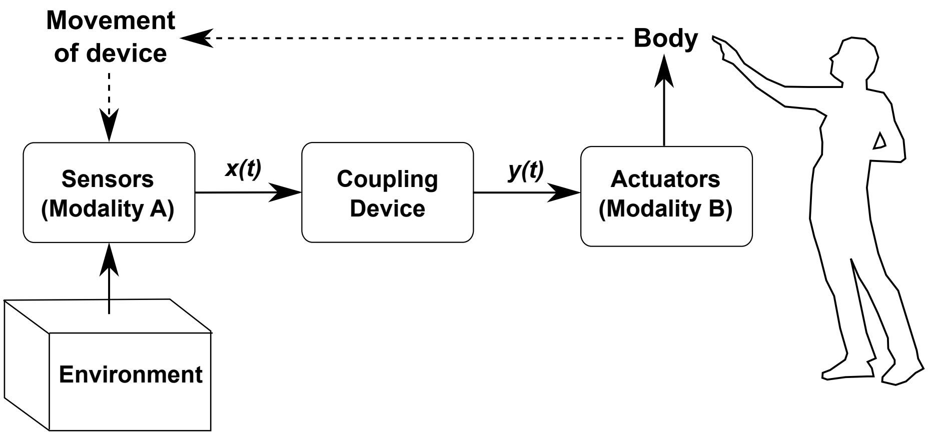


Figure 4.3: Technical structure of a sensory substitution system (adapted from [Visell, 2009]).

nent neural stimuli to the brain. This behavior helps the brain to form a coherent representation of the external world [Bach-y Rita, 1972]. If the user is given the possibility to modify the sensor of a sensory substitution system (e.g. by performing exploratory movements), the user learns to connect these exploratory movements with variations in the stimulus. This **proprioceptive-tactile perceptual feedback loop** helps the user to synthesize a spatial mental representation of the stimulus [Wall and Brewster, 2006]. This principle is crucial for learning and **exteriorisation** [Lenay et al., 1997]. Exteriorisation characterizes the effect in perceptive learning when the proximal stimulation is forgotten (e.g. tactile stimuli coming from the *TVSS*) and is integrated into the perception of stable objects in a certain distance [Lenay et al., 1997]. Finally, "sensory information is integrated with information from the "higher central nervous system" elements which mediate such functions as memory, thought, and decision-making" [Bach-y Rita, 1972].

4.1.3 Haptic Intrasensory Substitution

Several publications present an overview of sensory substitution systems (e.g. [Visell, 2009]), for this thesis, I will concentrate on systems which use haptic information as both input stimulus and output stimulus, a notion which I call **intrasensory substitution**. A first class of systems enables for tactile balance: For example, the electrotactile tongue display by Vuillerme et al. [Vuillerme et al., 2007] communicates pressure information coming from pressure sensors implemented in the clothing or shoe soles of persons to a wireless electrotactile display embedded in the person's mouth (see figure 4.4). Based on this biofeedback, older or disabled adults can change their posture to prevent pressure sores or to improve their walking balance. Several other systems allow for tactile situation awareness and spatial orientation. For example, the *Tactile Situation Awareness System (TSAS)* supports spatial orientation of aircraft pilots [McGrath et al., 2004]. Especially in situation with low visibility, sensory overload or heavy g-forces, the pilot may not rely on his spatial orientation. The vest-like system is connected to the aircraft's or helicopter's integrated navigation and altitude reference system. If the device recog-

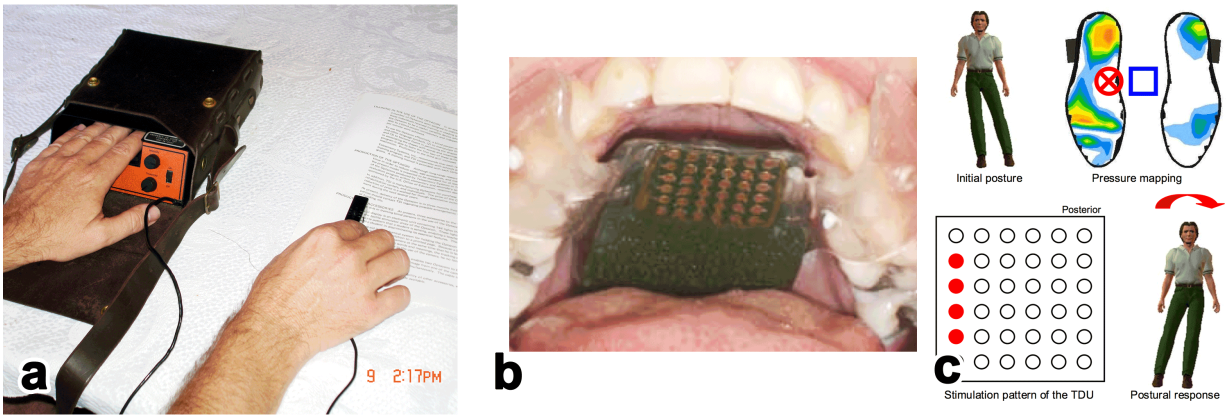


Figure 4.4: Systems for tactile sensory substitution. a: The *OPTACON* allows for 'tactile reading'[a], b: A wireless electrotactile display on the tongue [Vuillerme et al., 2007], c: Sensors in the soles of the shoes collect balance information which is transferred to the electrotactile tongue display. Based on this information, the user can correct the posture [Vuillerme et al., 2007].

[a] source: `http://upload.wikimedia.org/wikipedia/commons/7/72/Optacon.jpg` (public domain) [cited 2012/11/16]

nizes rapid or asymmetric movements, the pilot is informed by spatial vibrotactile information in the vest. Other systems use tactile headbands to increase situation awareness in hazardous environments (e.g. [Cassinelli et al., 2006]). In order to stress the importance of sensor-motor coupling, Lenay proposes the term "sensori-motor coupling devices" to address sensory substitution systems [Lenay et al., 1997].

4.2 Tactile Sensory Relocation

The intrasensory substitution interfaces presented above transform haptic stimuli such as head orientation or limb positions into other stimuli in the haptic domain such as tactile sensations. A subclass of these interfaces sense and communicate stimuli which stem solely from the tactile domain, this notion is called tactile sensory relocation.

4.2.1 Characteristics

Tactile sensory relocation is classified as a form sensory substitution. As Kurt Kaczmarek points out: "For the sense of touch, sensory substitution may also be the use of one area of skin to receive tactile information normally received at another location" [Kaczmarek et al., 1991]. Tactile sensory relocation systems transfer extracorporal tactile stimuli onto the user's skin. Also, tactile stimuli may been transferred from one location on the user's body surface to another. Either way, both sensor and actuator modality is tactile, e.g. comprises stimuli such as touch, pressure, skin deformation or vibration. Tactile sensory relocation is a conceptual simplification of sensory substitution, e.g. the sensor modality and actuator modality are identical (see figure 4.2).

Moreover, when the applied tactile stimulus is moved and relocated again, the user does not need an elaborate training to utilize the tactile information. Lenay describes this phenomenon with the *TVSS* as an example: When "one moves the tactile stimulator matrix from the chest to the back, or if one replaces the camera which was held in the subject's hands with a miniature camera fixed to the frame of a pair of glasses, the subject adapts almost immediately. In a few seconds, he recovers a distal perception in front of him" [Lenay et al., 1997]. Bach-y-rita states that "no relearning is necessary when the matrix is moved from one skin locus to another" [Bach-y Rita, 1972]. The ability to sense tactile stimuli depends on the characteristics of the mechanoreceptors in the skin of the used body location (see section 3.1.1).

4.2.2 Existing Implementations

We use the principle of tactile sensory relocation every day without technical devices: For example, a blind person can experience obstacles and unevenness on the ground using the white cane. This can serves as an sensory extension of the hand and the blind person "experiences the stimulation at the end of the cane rather than in the hand, where it occurs" [Auvray et al., 2005]. This effect is called exteriorisation and has been described above. Another example of this effect is given by Lenay, who states that "when riding a bicycle one forgets about the vibrations of the handlebar in one's hands and perceives instead the road under the wheels" [Lenay et al., 1997]. In general, we can state that when we use a tool, the tool serves as sensory extension of the body. We forget it and integrate its haptic behavior into our comprehensive bodily impression.

This principle and our ability to easily integrate these relocated tactile cues has been used in two ways (see figure 4.5): First, prostheses can serve as a form of 'sensory body extension' and relocate/transfer stimuli stemming from artificial limbs onto perceptive skin loci. This principle has been applied widely in prosthetic medicine. Second, our 'un-augmented' body can serve as a sensory device by itself (e.g. the fingertip), tactile stimuli resulting from a manipulation of this bodily sensory device can be applied somewhere else on the body. This principle has been applied in medicine before (e.g. when the tactile sense of a otherwise functioning limb is disabled). The notion of relocated tactile stimuli has also been explored in HCI (see section 4.2.2). Examples for both scenarios of use are given in the following.

Prosthetic Medicine and Accessibility

Numerous prosthetic systems (primarily artificial upper limbs and hands) have been presented which both lend the ability to grasp and manipulate objects as well as communicate tactile characteristics of these touched objects. In [Childress, 1980], Dudley Childress describes several patents and implementations of artificial limbs which also provide supplemental sensory feed-

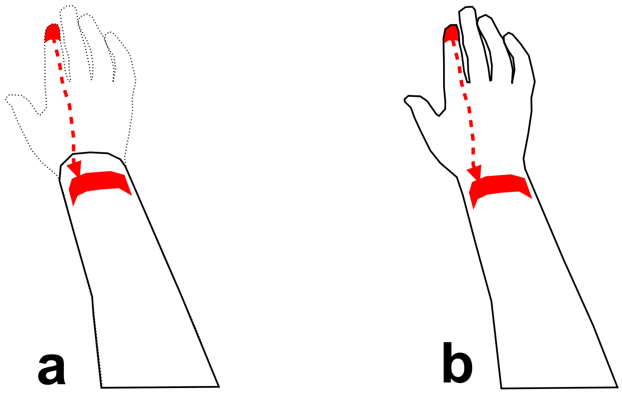


Figure 4.5: Two principles of tactile sensory relocation. a: Tactile information collected by an 'sensory body extension' (e.g. prosthesis) is relocated onto perceptive skin. b: The body can serve as sensory device and the tactile stimulus resulting from an action of the sensory device is transferred 'ex-situ', onto a different body location. Remote tactile feedback is the application of this principle for the interaction with touch surfaces.

back, artificial reflexes or control interface feedback[7]. The primarily used type of tactile information represents finger pressure, finger position and elbow position. Comparable to tactile actuators on interactive surfaces, diverse technical solutions for actuator devices have been proposed (electrocutaneous, vibrocutaneous and even transcutaneous methods) (see figure 4.6 for examples). Again, Childress stresses the importance of a closed loop, i.e. the direct sensory feedback resulting from a manipulation of the 'sensor' in order to avoid the feeling of "foreign appendages, not much related to the amputee's body image" [Childress, 1980].

However, this principle of tactile sensory relocation has been applied to people with existing limbs: Paul Bach-y-Rita describes an experiment with a person who had lost peripheral sensation in the hand due to leprosy [Bach-y Rita, 1995, Bach-y Rita and Kercel, 2003]. A sensor was implemented in a glove, tactile actuators were applied on the forehead of the person. After a phase of familiarizing with the relocated stimuli, the patient experienced the tactile stimuli as if they were applied on the fingertips and ignored the sensations on the forehead. All three crucial components of sensory substitution systems can be found in this example:

- **proprioceptive-tactile perceptual feedback loop:** The user is in control of the sensor (in this case: the hand).
- **brain plasticity:** The user adapts to the relocated stimulus based on feedback during the interaction.
- **exteriorisation:** Over time, the origin of the stimulus is ignored, the locus of the actuator spatially superimposes the locus of the sensor (in this case: the user perceives the tactile stimuli as if they were coming from the hand).

[7] Control interface feedback describes haptic stimuli which directly result from the input using the artificial limb such as cable controls and pressure demands.

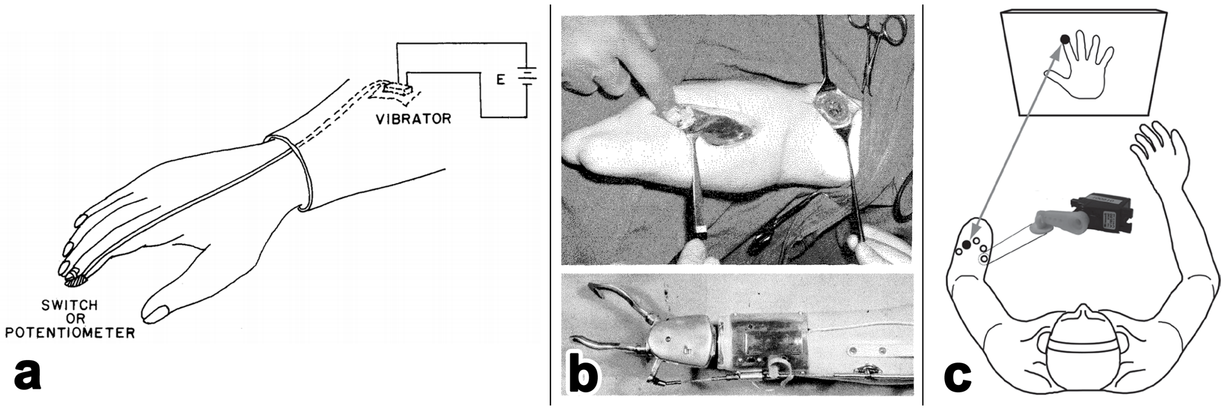


Figure 4.6: Example systems relocating exterior tactile stimuli onto the skin: a: Patented device for tactile sensory relocation [Conzelman et al., 1976], b: Electrotactile actuator and electrodes implemented into the forearm (top), arm prosthesis with hook and sensory electronics (bottom) [Clippinger, 1974], c: Input from a virtual hand depicted on a computer screen is transferred to a tactile display attached to the forearm [Antfolk et al., 2012]

Human-Computer Interaction

Relocated tactile stimuli have been rarely used in the communication of human and machine. Of course, general haptic feedback has a long tradition in HCI (see section 3.2), but this concept is very specific: manipulating a virtual or physical object by *touch* and receiving *tactile stimuli* coupled with this manipulation *spatially separated from the locus of operation*. Due to the importance of additional tactile stimuli on touch surfaces (see section 3.3), the field of touch interactions is a predominant application for relocated tactile stimuli. In the two following projects, the vibration motors in the user's personal mobile phone are used as tactile actuators for obvious reasons: the mobile phone often is in direct contact with the user (e.g. in the trouser pocket), no additional hardware is needed and the phone is a personal device which can not be modified by malicious persons.

De Luca et al. [De Luca et al., 2009] utilize this personal aspect of relocated tactile stimuli to increase the security during password input on ATMs: Here, the mobile phone is coupled to the ATM in a way that it can vibrate during the user's PIN input. "Every time the mobile device vibrates, the terminal indicates to the user that for the next input she should lie" [De Luca et al., 2009] (see figure 4.7). Using this 'lie overhead', observation attacks from malicious observers who want to steal the PIN are hindered. In the evaluation, observers were simulated using video cameras filming the keyboard and the users and with microphones to capture possible treacherous vibrations. Based on this data, it was analyzed how many PINs could be stolen. A lie overhead between 30% and 50% proves to be a useful trade-off between usability (error rate, interaction speed, user preferences) and security. In this case, the personal channel of (proactive) tactile information supports the transfer of sensitive information from machine to user.

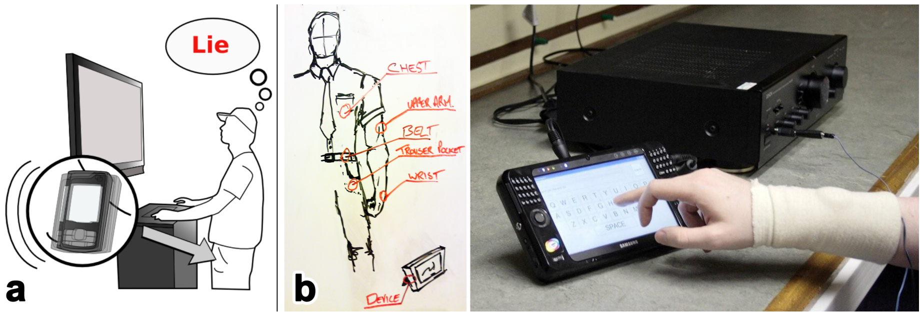


Figure 4.7: Relocated tactile stimuli synchronized with touch input: a: A vibrating mobile phone indicates when to lie during PIN input to avoid observation attacks [De Luca et al., 2009], b: Distal tactile feedback given on different locations of the body (left), text-input on mobile device with distal tactile feedback applied to the wrist (right) [McAdam and Brewster, 2009].

McAdam et al. have worked on 'distal tactile feedback' for text entry on mobile devices [McAdam and Brewster, 2009]. Extending their previous work on tactile feedback on mobile devices (e.g. [Hoggan et al., 2008a]), they evaluated the effect of tactile feedback given by a vibrating actuator[8] applied on different locations of the body. Different keyboard events such as fingertip-over, fingertip-click and fingertip-slide were synchronized with tactile stimuli (see figure 4.7). In an evaluation, they asked sixteen participants to enter remembered phrases of previously given text and measured the number of correctly entered phrases (accuracy), keystrokes per character (error rate), words per minute (input speed) and subjective workload. Feedback conditions were: no tactile feedback, feedback on the touchscreen and feedback on wrist, upper arm, chest, belt and front trouser pocket. In the results, type and location of tactile feedback did not have an effect on accuracy, error rate and subjective workload. However significant effects of feedback location on text entry rate were found: in general, users with tactile feedback given on wrist and upper arm performed best. The authors consider the relatively large size of the keypads and the non-dynamic scenario as reasons for the small effect of the given feedback. In a similar evaluation with 21 participants [McAdam and Brewster, 2011], 3 forms of tactile feedback (none, simple, elaborate) was given at two locations (pocket and wrist) using a vibrating actuator. Dependent variables were speed and keystrokes per character. In terms of text entry rates, significant effects were found for both sets of feedback (e.g. around 15% speed increase for elaborate feedback), but not for the location of feedback.

4.3 Towards Remote Tactile Feedback

Remote tactile feedback on touch surfaces is a form of tactile sensory relocation and thus a form of sensory substitution. However, the amount of necessary learning and adaption is greatly reduced, as the substitution is intrasensory, i.e. no translation of sensory information into another

[8] C2 Actuator from Engineering Acoustics Inc. [Chouvardas et al., 2008]

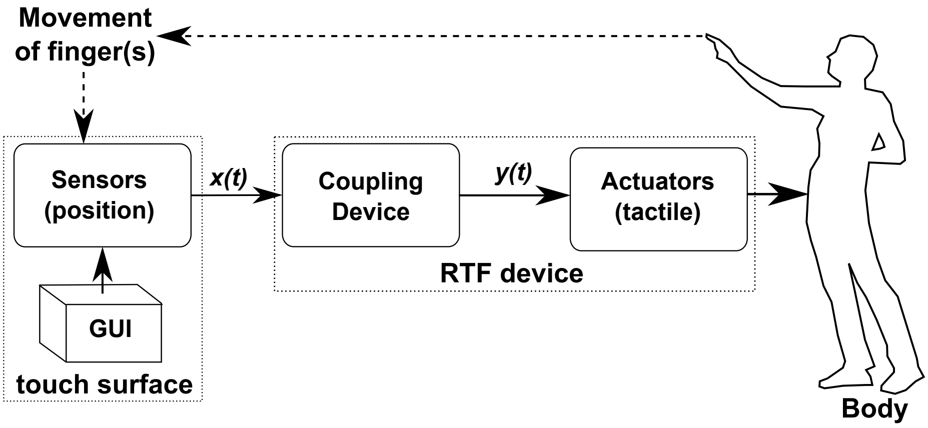


Figure 4.8: Structure of an interactive surface incorporating remote tactile feedback.

modality is necessary. Underlying concepts of sensory substitution also apply to remote tactile feedback systems:

- neurological mechanisms (e.g. brain plasticity, exteriorisation)
- psychological principles (e.g. tactile-sensomotory feedback loop)

Therefore, an interactive surface with remote tactile feedback can be structurally described as a sensory substitution system (see figure 4.8): Information on the position of the finger in relation to the GUI depicted on the touch surface is captured by the touch surface's sensors. The information is transduced to a set of signals x(t) and encoded into a set of messages for the tactile actuators which are part of the device. Then, the information is presented to the body of the user. The feedback loop is closed when the user moves his finger on the surface and thus alters the resulting tactile stimuli. When designing touch systems incorporating this principle of feedback, the basics of sensory substitution have to be taken into account.

In summary, the notion of sensory substitution helps to augment the capacities of humans by enriching available sensory channels and by creating novel forms of stimuli. Furthermore, remote tactile feedback can be seen as a form of sensory supplementation, facilitating novel forms of perceptions and bringing new ways of coupling with our environment [Lenay et al., 2003]. This concept is a fundamental part of my research.

Chapter 5

Remote Tactile Feedback on Interactive Surfaces

In the previous chapters, I identified challenges of direct touch human-computer interaction which have been addressed by the integration of programmed tactile stimuli. Various technical concepts to create and utilize cutaneous feedback on touch surfaces exist. Evaluations of tactile touchscreens have shown improved usability and user performance. In this and the next chapter, the concept of remote tactile feedback is presented as a valid alternative solution for tactile augmentation of touch surfaces with additional beneficial characteristics.

5.1 Definition and Problem Space

The term 'remote tactile feedback' describes the spatial dislocation of cutaneous stimuli which are synchronized with an interaction with direct touch surfaces onto parts of the user's skin which are not in contact with the screen. Tactile transducers form an output mechanism whose signals are synchronized with the user's input on the interactive surface, thus creating a tactile-sensomotory feedback loop. Based on this synchronism of stimuli, users integrate the remote tactile cues, visual feedback and auditory stimuli coming from the screen into an overall multimodal sensation. Figure 5.1 depicts four principles of providing the users of interactive surfaces with remote tactile stimuli. In order to maintain continuous contact of the actuators with the user, actuators could be part of wearable interfaces, can be integrated into the user's clothing or embedded into the user's direct environment (e.g. the frame of the interactive surface or the seat of the user).

In our everyday world, we actively palpate and manipulate unknown objects with our hands. In combination with other sensory cues, we thereby form a coherent internal representation of the physical object and its characteristics in our brain. This concept has been transferred to the

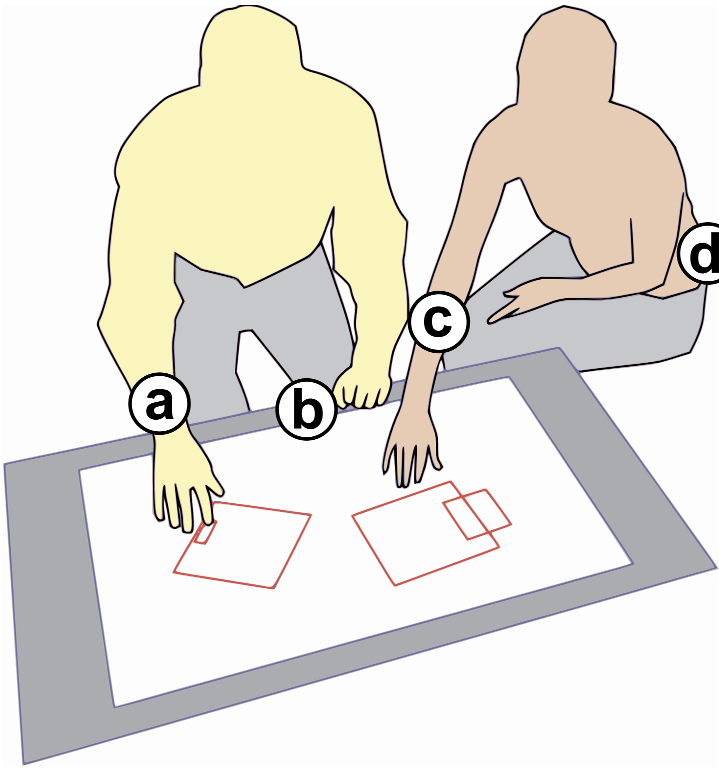


Figure 5.1: Alternative methods of integrating tactile actuators into the user's direct environment. a: wearable interfaces, b: actuators embedded into the touch display's frame, c: actuated clothing, d: actuators embedded into the user's seat.

interaction with non-physical or digital information: The concept of direct manipulation also relies on the "continuous representation of the object of interest" [Shneiderman, 1984] and actions which resemble those from the physical world. The "coincidence of input and output space" [Ishii, 2008] and "realtime response" [Ishii, 2008] also are a fundamental requirement for the concept of TUIs. Here, tangible and intangible representations are 'perceptually coupled' to achieve a 'seamless interface' [Ishii, 2008].

The concept of remote tactile feedback clearly follows this argumentation. Input and output space are perceptually coupled, the communication of sensory cues and responses happens in realtime. The non-physical object of interest is continuously present and the input mechanisms resemble those from the 'real world'. However, the output space is extended onto the whole body surface of the interacting person. This spatial expansion also conceptually expands the concept of touch interactions and entails more versatile and creative possibilities.

The notion of remote tactile feedback accommodates ongoing technical and social developments. Taken into account are the growing pervasiveness of touch surfaces, the evolution of interactive surfaces towards non-planar, non-solid and flexible forms (see section 2) and the necessity for additional tactile feedback (whose beneficial effects on user performance have been shown before, see section 3.3.2).

Remote tactile feedback has inherent characteristics which make it useful to implement this approach as an alternative to conventional methods of tactile feedback (see section 3.4): technical feasibility to support rapid prototyping of interfaces and haptic stimuli, proactive and reactive feedback to support manual exploration with reduced visual load, high expressiveness and versatility of tactile stimuli and tactile feedback for multi-touch input.

These inherent benefits of remote tactile feedback must not be utilized at the expense of the benefits of direct tactile feedback, namely decreased operation time, reduced error rates and subjective decrease of workload (see section 3.3.2). When exploiting the unique benefits of the novel concept, we have to make sure that we maintain the positive effects of programmed cutaneous stimuli during direct touch interactions.

Therefore, we conducted three consecutive user studies pursuing three purposes: First, we formally compared the effects of both direct and remote tactile feedback and visual-only feedback on accuracy, total task time and input errors as well as user preference. Second, we evaluated the effects of the locus of remote tactile feedback on interaction speed and error rate. Third, we measured the influence of additional cognitive load on the interaction speed and the influence of the location of the stimulus.

The user studies were carried out on different forms of interactive surfaces. In the first study, we used a purpose-built dual display to directly compare direct and remote tactile stimuli. For the second and third evaluation, we used an interactive tabletop display. Sizes and form factors of the displays also condition form and position of the tactile actuators: When comparing direct and tactile feedback, we used the same body location and stimulus design for both settings. For the studies on the tabletop, we designed a simple wrist-worn actuator system providing vibrotactile signals. The results of the three consecutive evaluations were published in [Richter et al., 2012b]. The three experiments and the resulting findings are presented in the following.

5.2 Comparing Direct and Remote Tactile Feedback

In the first evaluation, we had the intention to compare the effects of remote tactile feedback, direct tactile feedback and visual-only feedback on the user performance during text input on interactive surfaces[1]. In order to guarantee the validity and reliability of our measurements, we developed a touchscreen setup exclusively for the evaluation. Thus, we made sure that the notion of direct tactile feedback is comparable to remote tactile feedback: for both settings, we used the same *locus of application* (tip of index finger) and same *actuator system* for tactile feedback. In the evaluation, we tested the effects of the general concept of remote tactile feedback, locus and type of feedback is optimized in later projects (see chapter 6).

[1] This work was part of Florian Weinhart's Bachelor's thesis [Weinhart, 2011]

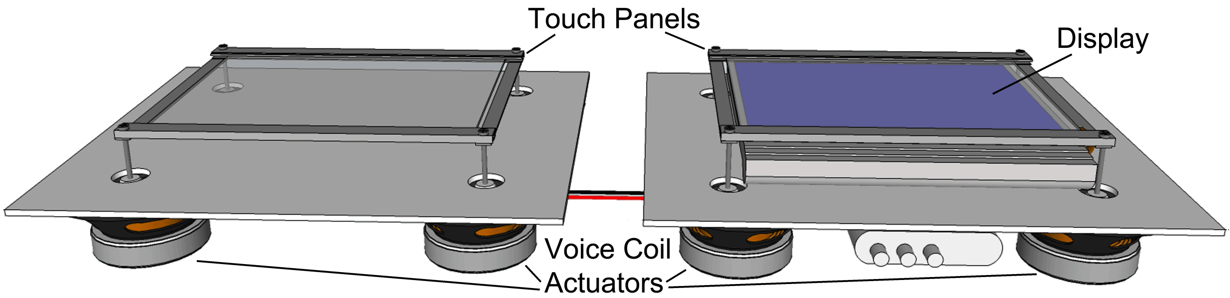


Figure 5.2: Schematic drawing of the dual screen prototype used in the evaluation (from [Richter et al., 2012b]).

5.2.1 Prototype

The purpose-built prototype can be described according to the classification established in chapter 3.4. There are several reasons for the design and implementation of own prototypes instead of the application of commercial systems, e.g. technical flexibility, price, control of stimuli and additional insights for future remote tactile interfaces. In this prototype, the direct tactile feedback follows the basic method of actuating the screen surface in vertical direction. Accordingly, the same principle was used for the remote actuator.

Hardware

The low-cost prototype is a dual touchscreen with vibrotactile feedback (approximately 80x40x20 cm (WxLxH))). An overview of the system is given in figure 5.2. In general, the prototype consist of two parts: One half contains a touchscreen with spatially superimposed capacitive sensing and direct vibrotactile feedback. The user interacts with the fingertip of the index finger on the dominant hand. The second half of the device is for remote actuation only: the user rests the fingertip of the non-dominant hand on the actuated glass plate. In the following, the technical structure of the prototype is described according to the structure of a remote tactile feedback interface (see figure 4.8).

Sensors: The user's input is sensed using a transparent capacitive touch panel[2] mounted atop a 15" TFT screen[3]. The screen is depicting the GUI and is connected to a PC via USB. The other half of the device has neither sensing abilities nor visual output.

Coupling Device: The GUI, the processing of user input and the creation of tactile stimuli is done on a PC using the Processing programming language[4,5]. The PC's audio output is connected to

[2] 3M MicroTouch SCT3250EX 15.68" Surface capacitive USB Touch System

[3] Eizo FlexScan L367

[4] Processing is an open source programming object-oriented programming language with an integrated IDE for the creation of images, animations and interactions. The Processing syntax is closely following the Java language, every Processing sketch is a Java PApplet [Casey Reas, 2007].

[5] `http://processing.org` [cited 2013/02/09]

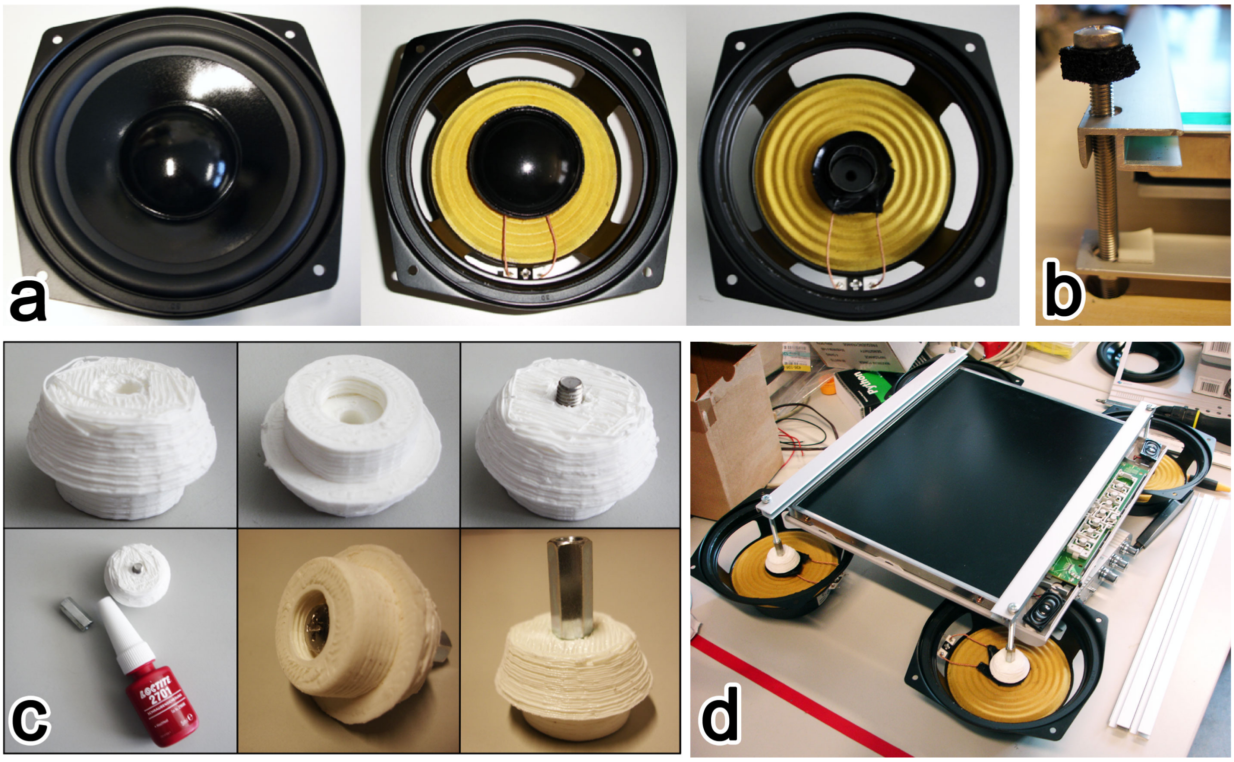


Figure 5.3: Construction of the actuator system: A loudspeaker's membrane was removed (a) and in order to connect it to the leading rods which are attached to the screen glass (b), adapters were 3D-printed and attached to the cone of the speakers (c). (d) shows the finished actuators without the wooden attachment plate (images from [Weinhart, 2011]).

an amplifier[6] which is attached to the wooden encasing of the prototype. The audio amplifier drives eight loudspeakers attached to the corners of both feedback units.

Actuators: The prototype follows the principle of vibrotactile actuation with voice coils. The membranes of the eight loudspeakers[7] were removed to avoid the generation of noise. The speakers are attached to the corners of the 2 connected feedback units, threaded rods coming from the center of the speakers stick out of holes in the wooden panels. The leading rods are attached to aluminum profiles which in turn form holding frames for the sensor panel and the glass panel. All leading rods are free to move vertically (see figure 5.3). Thus, sound which is generated on the PC is transduced into oscillations of the touch surface. This way, the glass plate over the screen and the second glass plate move in the same way and can produce the exact same type of tactile stimulation.

[6] Lepai LP-808, 12 V, 2x15 W

[7] Dynavox DY-166-9A, 4 Ohm, 80 W, resonance frequency 50 Hz

Tactile Signal Design

With remote tactile feedback and an actuator which is constantly in contact with the user's skin, it would be possible to provide feedback before, during and after the contact of the user's finger with the screen. This is not possible with direct tactile feedback on non-mobile devices. In order to avoid disadvantages for the direct feedback setting, we implemented the "lift-off-metaphor" as a means for text input [Potter et al., 1988] on a keyboard (see section 5.2.2). Object-related stimuli were given when the user's finger crosses an edge of a virtual element (see 3.3.1): For the standard keys, a rectangle wave with amplitude 1.0[8], 1 Hz and length of 10 ms was multiplied with a sine wave of amplitude 0.5, 170 Hz and 40 ms. The signals were cut off after the given number of milliseconds. Thus a short 'snap' was perceived when crossing the edge of an element, followed by a 'buzz'. In accordance with related evaluations such as [Hoggan et al., 2008a], we added 'home keys' which feel different. Home keys are used on physical keyboards to allow for touch typing. On QWERTY keyboards, the letters 'F' and 'J' have little bumps and can thus be distinguished from the neighboring buttons. For these home-keys, we multiplied a square wave (amplitude 1.0, 1 Hz, cut off after 10 ms) with a saw wave (amplitude 0.5, 70 Hz, cut off after 80 ms).

5.2.2 Evaluation

We assumed that the addition of remote tactile feedback entails usability benefits which are comparable to those created by direct tactile feedback. In order to validate our assumptions, we conducted a laboratory evaluation using our prototype.

Participants: Twelve participants (five female) with an average age of 22 years took part in the evaluation. All participants were right-handed and had used touchscreen devices before. Most of the participants were students or department staff.

Task: Figure 5.4 depicts a screenshot of the GUI used in the evaluation and the two settings. The task was to enter text phrases using the on-screen keyboard. Size and form of the GUI were designed as a reduced version of the iPad virtual keyboard. The phrases to be entered were depicted at the top of the screen. For generalizability, we used 9 phrases (plus 1 training phrase) out of the established 500 phrase set proposed by MacKenzie et al. [MacKenzie and Soukoreff, 2003]. Text input was designed as a drag-and-lift-off task, similar to the lift-off-technique [Potter et al., 1988] and the Swype-input technology on smart-phones[9]. Additionally, dragging is a common task on interactive surfaces, an increased amount of tactile information can be transferred during the long contact with the surface.

In order to enter a character, the user puts the finger on the start area in the center of the lower half of the screen. A letter was entered by dragging the finger towards the corresponding key, then lifting the finger off when over the key. The entered letter appeared in the text field below

[8] The amplitude was fixed, we did not measure the displacement of the screen.

[9] `http://www.swype.com/` [cited 2013/02/09]

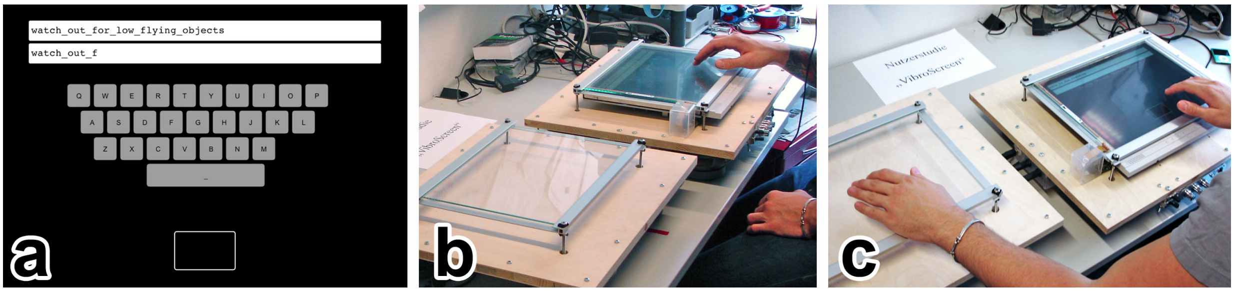


Figure 5.4: Setup of the comparison evaluation. a: screenshot of the text input task, b: setup for the conditions visual-only feedback and direct tactile feedback, c: setup for the remote tactile feedback condition.

the depicted phrase. In order to ensure that erroneous inputs have no effect on total task time, error correction was not possible. Participants were instructed to enter 'the correct letter at the correct position' and as fast and accurately as possible. Furthermore, they should continue with entering the next letter when they made a mistake.

Conditions: In total, three feedback conditions existed, i.e. the factor feedback had three levels: visual-only feedback, direct-tactile feedback and remote tactile feedback. The conditions were presented in a counterbalanced order to avoid unwanted training and learning effects.

Design: The evaluation had a within-subject repeated measures design.

Apparatus: All users were seated during the evaluation and wore headphones with music to mask unwanted environmental noise and sounds coming from the actuator prototype which could give unwanted auditory feedback for the user's interaction. The setup used for the different conditions is depicted in 5.4. For visual-only and direct tactile feedback, the user used the dominant hand for input on the interactive screen. For remote tactile feedback, the user rested the index finger's tip of the non-dominant hand on the second glass plate. The interaction is performed with the index finger of the dominant hand.

Procedure: In the beginning, the users performed a training with the input method and all three feedback conditions. During the training, three phrases were entered using the drag-and-lift-off text entry method. After the training, the study was performed starting with one of the three feedback modalities in a counterbalanced order. After entering 9 phrases under the given tactile conditions, the users were asked to fill out a questionnaire on their subjective evaluation of realism of the stimuli, information transfer and estimation of usability. Finally, the participants were asked to rate the three modalities according to their personal preference.

Independent and Dependent Variables: Both quantitative and qualitative data was collected. We quantitatively measured the *accuracy of input* (number of characters entered correctly divided by the overall length of the phrases entered), the *total task time* (time needed for entering 9 phrases per modality, measured from first touch to final letter) and the *number of missed keys*

	Accuracy Ratio	Total Task Time (s)	Number of Missed Keys
Visual-Only Feedback:	M=0.941 (SD=0.060)	M=338.091 (SD=81.404)	M=15.083 (SD=9.986)
Direct Tactile Feedback:	M=0.910 (SD=0.070)	M=367.270 (SD=73.009)	M=15.000 (SD=10.946)
Remote Tactile Feedback:	M=0.934 (SD=0.049)	M=344.036 (SD=86.003)	M=12.250 (SD=10.420)

Table 5.1: Quantitative results (means and standard deviations) for the three modalities.

(number of lift-offs outside of a button). Subjective estimation of the tactile conditions were collected using an adapted AttrakDiff questionnaire[10].

Hypotheses: We assumed that the addition of both direct and remote tactile feedback has a positive effect on the user performance and the subjective estimation of the interaction. Therefore, we had the following hypotheses:

H1: Accuracy is higher with tactile feedback than with visual-only feedback.
H2: Total task time is lower with tactile feedback than with visual-only feedback.
H3: Fewer keys are missed when typing with tactile feedback than with visual-only feedback.
H4: Users will prefer interactions with tactile feedback to interactions without tactile feedback.

Results

An overview of the quantitative results is given in table 5.1, the results are shown in figure 5.5.

Accuracy: In general, a very low number of false characters was entered. The highest accuracy (number of correctly entered characters divided by the overall length of the phrases) was achieved when no tactile feedback was given (M=0.941, SD=0.060), the lowest accuracy was achieved with direct tactile feedback (M=0.910, SD=0.070). A one-way repeated measures ANOVA showed no significant influence of the type of feedback on the accuracy ratio ($F(2, 33) = 0.87$, $p = 0.428$). Hence, hypothesis 1 has to be rejected.

Total Task Time: Entering all nine phrases took more than 300 seconds in every modality. On average, participants were fastest when remote tactile feedback was given (M=344.036 s, SD=86.003) and slowest with direct tactile feedback (M=367.270 s, SD=73.009). Participants needed about 2.9 seconds less task time per phrase when the tactile feedback was applied remotely and not directly. However, a one-way repeated measures ANOVA showed no significant influence of feedback modality on total task time ($F(2,33)=0.442$, 0.646). Therefore, also hypothesis 2 can be rejected.

Number of missed keys: On average, participants missed the fewest keys with remote tactile feedback (M=12.250, SD=10.420) during input of the 9 phrases. Most false lift-offs occurred when no tactile feedback was given (M=15.083 , SD=9.986). However, a one-way repeated measures ANOVA showed no effects of feedback on total task time ($F(2,33)=0.285$, 0.754). Hence, we rejected hypotheses 3.

[10] AttrakDiff is a questionnaire-based evaluation for determining subjective perceptions of quality, pragmatic and hedonic qualities and emotional consequences of an interaction with a product. In our experiment, participants rated the stimuli on a 5-point scale of semantic differentials, i.e. pairs of opposing adjectives. The method originates from user experience research [Hassenzahl et al., 2003].

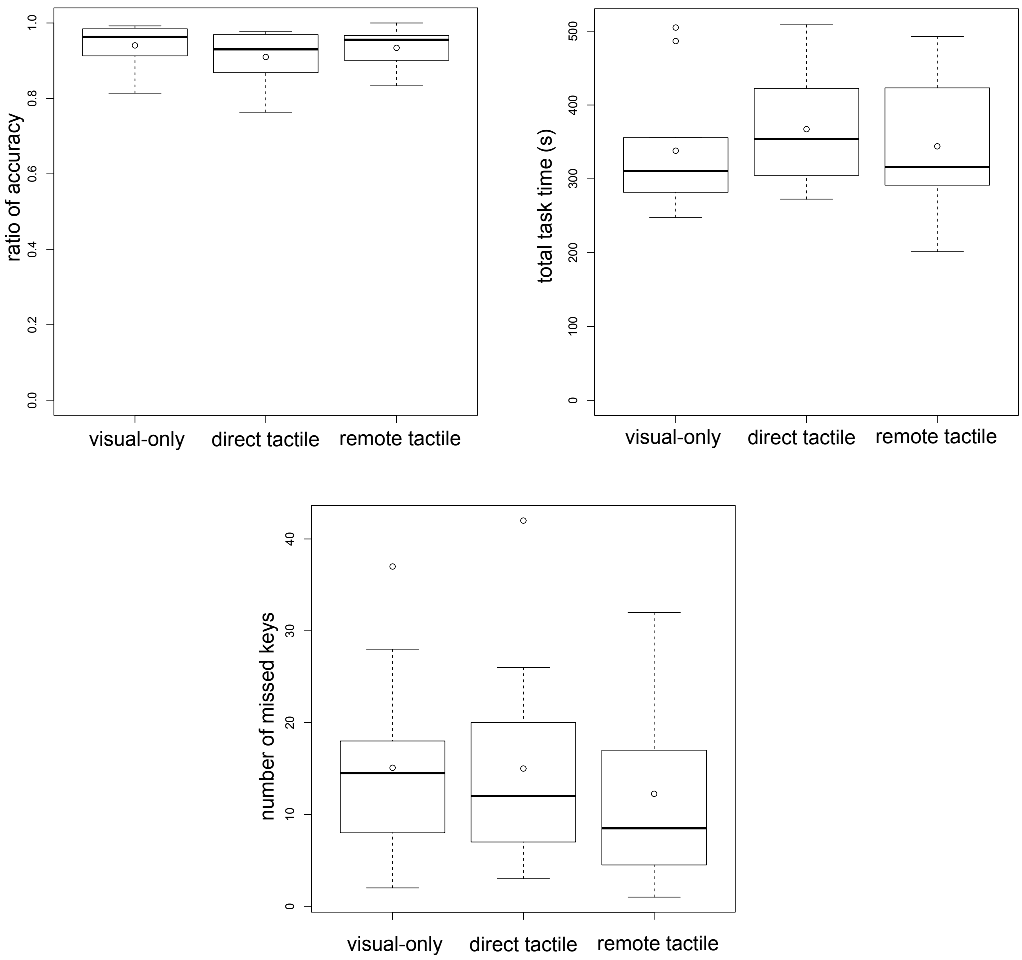


Figure 5.5: The average ratio of accuracy (top left), the total task time in seconds (top right) and the number of missed keys (bottom) for the three modalities. The boxplots in this thesis depict the median as solid line and the mean as empty circle inside of the box. Outliers are represented by empty circles outside of the box.

Subjective Evaluation: A modified AttrakDiff questionnaire was used to assess subjective opinions on three general dimensions of the tactile stimuli: degree of realism, design of tactile stimuli and bandwidth of information. The results are shown in figure 5.6. For both direct and remote tactile feedback, subjective results were positive, especially for understandability and simplicity of transduced information. Again, we found no strong difference between the values for direct and remote tactile stimuli. Furthermore, direct tactile feedback was rated as favorite by 7 out of 12 people, remote tactile feedback was rated as favorite by 4 people and the visual-only feedback condition by 1 person. The results of the subjective rankings of modalities are depicted in figure 5.7. Half of the participants rated visual-only feedback as least popular.

In summary, users preferred interactions with tactile feedback (direct or remote) to interactions without tactile feedback. Hence, we can confirm hypotheses 4.

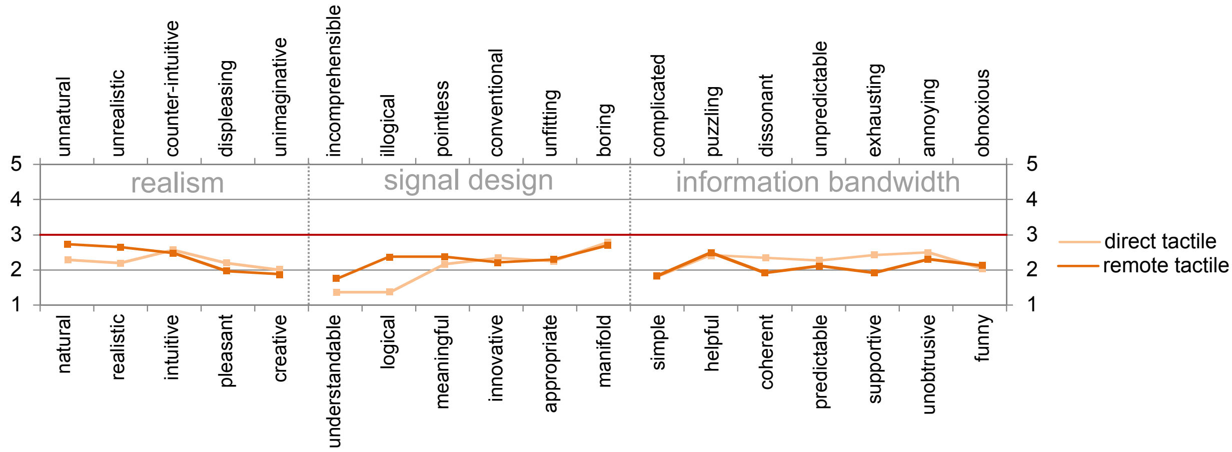


Figure 5.6: Subjective ratings of direct and remote tactile stimuli. Discrete values are connected for readability.

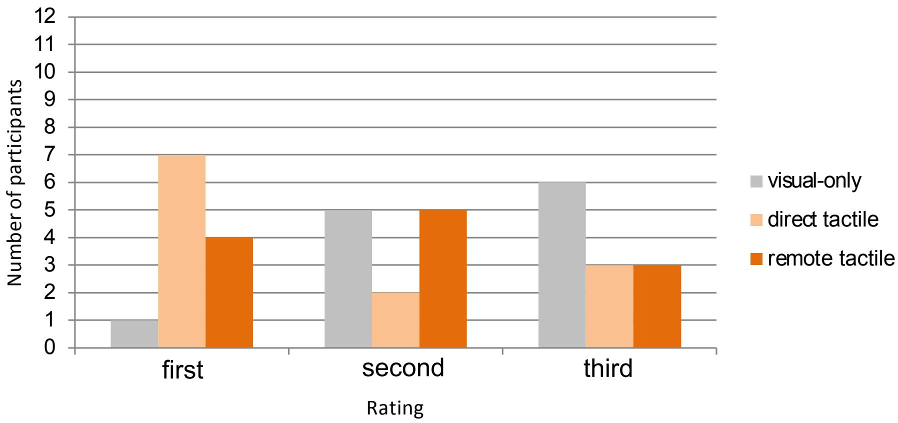


Figure 5.7: Subjective rankings of the three modalities.

5.2.3 Interpretation and Discussion

Our assumption that both direct and remote tactile feedback during drag-and-lift-off text input have beneficial effects on accuracy, time needed and number of missed keys could not be confirmed by the results. The type of feedback did not have an effect on the users' performance. Thus, the hypotheses 1, 2 and 3 had to be rejected. Several factors may have led to these results and are discussed below.

A first reason for the missing effects of the provided tactile stimuli could be the **technical drawbacks** of the purpose-built prototype. The prototype and the tactile stimuli were designed and implemented solely for this evaluation. We chose not to use commercial tactile touchscreen products such as Immersion's TouchSense system[11], due to the fact that these systems can not be used in remote tactile configurations. A secondary goal of the evaluation was to gain insights on potential actuators for remote tactile interfaces. However, the approach of using voice coils or modified loudspeakers resulted in two main problems: latency and mechanical instability. The system was not able to provide instantaneous tactile feedback in under 100 ms[12], the dynamic of the modified electromagnetic magnetic coils was too low. Interestingly, several users stated that 'buttons with tactile feedback are harder to press'. This subjective perception may result from the phenomenon that longer latencies of tactile feedback can create feelings of harder buttons. As Kaaresoja et al. suggest, "different latencies can be used to represent tactile weight in touchscreen interaction" [Kaaresoja et al., 2011]. Additionally, the movable assembly of the touch panels led to unwanted horizontal motion of the glass when users dragged their fingers across the screen.

A second cause of the missing effects of additional non-visual feedback can be found in the **study design** and the **context of use**. Previous evaluations of tactile touchscreens were often performed in dynamic multi-tasking scenarios such as mobile or driving settings (see section 3.3.2). In contrast, our evaluation was performed in the lab, where participants had no added visual and cognitive load. Additionally, the keyboard buttons on the prototype were much larger than soft buttons on a mobile device. Thus, users could additionally use their vision to control the position of their fingers and accidental slips off the button occurred only rarely. This observation was also made by McAdam et al. who state that the big size of their virtual keys made them "so easy to hit that the tactile feedback was not needed" [McAdam and Brewster, 2009].

Interestingly, the subjective evaluation of both forms of tactile stimuli was very positive. This is an important finding and corresponds to the results of similar evaluations. However, these results can be seen with skepticism for two reasons: First, the users were presented with an exploratory prototype which is fun to use. Most participants were technophilic or have a scientific background. The participants dealt with a novel system and evaluate it positively, this estimation could change after prolonged use (**novelty effect**). Second, a certain 'interviewer effect' could have led to the positive results: in the questionnaire, participants might hesitate to judge too negatively.

The main reason for the lack of effects could be found in the very **artificial study setting**. The evaluation tried to create same conditions for both direct and remote tactile feedback (same locus of stimulus, same type of feedback, etc.). This created several problems: We had to create a purpose-built system solely for the comparison. Resting the non-dominant finger on a glass plate for remote tactile feedback during an interaction is fatiguing and non-ergonomic. Thus, the usability of the system was greatly reduced. This location of the stimulus (fingertip) and method of application would never be used in touch interfaces which are used more regularly. Therefore, the results of this evaluation do only partly imply consequences for future applications of the

[11] `http://www.immersion.com/products/touchsense-tactile-feedback/` [cited 2012/11/30]

[12] This time-range (100 ms to 200 ms) has found wide acceptance with designers of interactive systems as the threshold of human perception to recognize a change in a system. Reactions to a user's input below this level are perceived as instantaneous [Dabrowski and Munson, 2001]. Due to the versatility and high individual nature of tactile perception, we adapted this value for the design of our prototypes.

concept. In summary, we state that formally comparing the effects of direct and remote tactile feedback is extremely difficult when the same locus of stimuli is used for both modalities.

As a consequence, we updated the research agenda for the following two evaluations. We compared the effects of visual-only feedback and the effects of remote tactile feedback on the user performance. A different type of remote tactile actuator was used to reduce latency and to relocate the stimuli to a less inconvenient body location. Also, a more standard interactive surface was used. In order to gain insights for the design of future interfaces with remote tactile feedback, we evaluated the effect of the location of application. Additionally, a higher number of participants had to take part in the evaluation. Our main intention behind this decision is to ensure a broader generalizability of the results.

5.3 Evaluating Remote Feedback on the Tabletop

The design of the second evaluation resulted from the insights gained from the study presented above. The goal was to analyze the effects of remote tactile feedback in comparison to visual-only feedback on user performance during a touch interaction[13]. Additionally, we measured the influence of the location of stimulus application by placing vibrotactile actuators on the dominant and non-dominant wrist.

5.3.1 Prototype

The evaluation was performed on an existing interactive tabletop system instead of a mobile device. The effects of tactile feedback have been widely evaluated on mobile touch devices, which is not the case for tabletops mainly due to technical difficulties. Moreover, tactile feedback as an additional form of crossmodal information has many potentials on multi-user tabletop systems as it is a more personal and individual channel of information. The description of the prototype follows the structure presented in section 4.3.

Hardware

Sensors: The interactive GUI was presented on an interactive tabletop system (see figure 5.8). The tabletop has the dimensions 99x74x89 cm (WxLxH). The sensing is based on the FTIR technology (described in section 2.2.2). Due to the necessary infrared lighting and cameras inside the tabletop, the device is designed for standing users only. The camera is connected to a PC system which recognizes the touch input.

[13] This work was part of Sebastian Löhmann's Diploma thesis [Löhmann, 2011a]

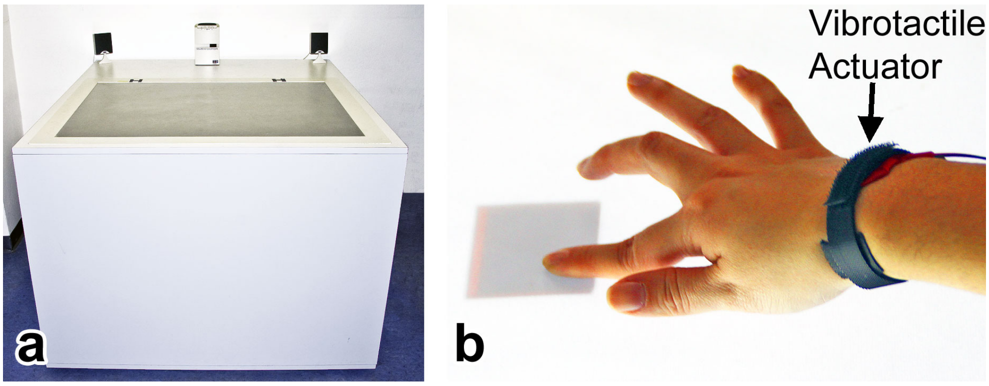


Figure 5.8: Apparatus of the user study: a: Interactive tabletop system, b: wrist-worn vibrotactile actuator.

Coupling Device: The input information was processed on a PC and communicated onto an Arduino[14,15] board via a virtual COM-port. The Arduino was powered by the PC.

Actuators: Two vibration motors connected to the Arduino served as communicators of remote tactile stimuli. VibeBoards by LilyPad[16] were used to ensure the comparability with similar evaluations of tactile interface prototypes (e.g. [Bird et al., 2009]). Amplitude and frequency of the vibration can not be controlled separately, as the increase of voltage increases the rotational speed which results in stronger vibrations with higher frequency. The actuators are placed on the outer side of both wrists, following recommendations by McAdam et al. [McAdam and Brewster, 2009]. The wearable actuators thus form augmented jewelry or tactile watches which could inspire future implementations. The actuator system is depicted in figure 5.8.

Tactile Stimulus Design

The actuators were designed to emit diffuse vibrations around 250 Hz in order to address the vibration-sensing Pacinian corpuscles in an optimal fashion (see section 3.1.1). The LilyPads were applied with a fixed voltage of 5 V. Two simple types of vibrotactile stimuli could be given on the wrist: A vibration with a fixed length of 130 ms or a continuous vibration which has to be stopped by the software. The duration of 130 ms was chosen based on results from Kaaresoja et al. [Kaaresoja and Linjama, 2005] who state that "that the optimal duration of the control signal should be between 50 and 200 ms" in order to be reliably recognized but not irritating. During the drag-and-drop task, vibrotactile feedback - a 130 ms vibrotactile impulse - was given when the dragged virtual element superimposed the target area.

[14] `http://www.arduino.cc/` [cited 2013/02/09]

[15] The term Arduino describes a class of open-source single-board microcontrollers with a central Atmel AVR processor and integrated input/output support. Programming is done using IDE in Processing-based JAVA. GCC is used as a compiler, the data is transferred onto the board via USB and uploaded via bootloader [Mellis et al., 2007].

[16] `http://lilypadarduino.org/?p=514` [cited 2012/11/30]

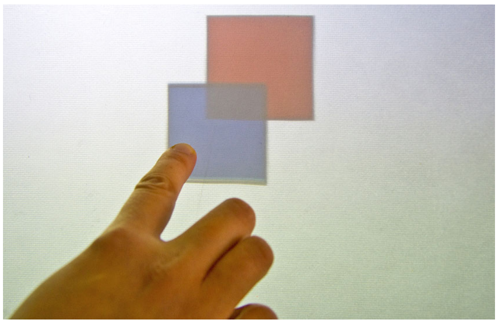


Figure 5.9: The task was to drag the blue square onto the red target square.

5.3.2 Evaluation

We assumed that the addition of remote tactile feedback using wearable actuators has beneficial effects on the user performance regarding the number of input errors and the speed of the interaction. Furthermore, we assumed that the relocation of tactile stimuli onto the contralateral wrist (i.e. the non-dominant side of the body, which is not used for manual input) does not have a negative influence on the user performance.

Participants: Eighteen participants (six female, average age 28 years, three left-handed) took part in the evaluation. Twelve participants had a technological background (e.g. students, staff of the computer science department). Participants were asked to rate their personal experience with interactive surfaces, vibrotactile stimuli and surfaces with vibrotactile feedback on a scale from 1 to 5 (1='no experience', 5='very experienced'). On average, the participants rated 3.61 for their experience with touch surfaces, 3.44 for the experience with vibrotactile stimuli and 1.9 for the experience with touch surfaces providing tactile feedback.

Task: The given task was to drag a virtual blue square onto a virtual red square using the tip of the dominant index finger (see figure 5.9). The size of the blue square was 50x50 mm, the size of the red target square was 54x54 mm, both squares were approximately 50 cm apart. As soon as the squares superimposed, the users had to lift-off the finger in order to complete the task. After a successful dragging, both squares disappeared and two new squares were depicted on different locations on the table with the same distance. When both squares did not superimpose on lift-off, the user had to fine-correct the input. The participants were asked to perform the drag-and-drop task as 'fast and accurately as possible'.

Conditions: In total, three feedback conditions existed, i.e. the factor feedback had three levels: visual-only feedback, remote tactile feedback given on the dominant wrist and remote tactile feedback given on the non-dominant wrist.

Design: The evaluation had a within-subject repeated measures design.

Apparatus: Participants were constantly wearing two wristbands, however, only one or none was activated depending on the current task condition. All participants were standing next to the tabletop and wore no headphones as the actuator system did not produce audible noise. The

	Total Task Time (ms)	Number of Errors
Visual-Only Feedback:	M=2602 (SD=755)	M=3.78 (SD=3.23)
RTF dominant wrist:	M=2364 (SD=420)	M=3.72 (SD=2.54)
RTF non-dominant wrist:	M=2344 (SD=447)	M=3.39 (SD=1.82)

Table 5.2: Quantitative results (means and standard deviations) for the three modalities.

wrist-bands were connected to the microcontroller with one cable each. The participants were free to decide where to put their non-dominant hand (but not allowed to use it for input on the tabletop).

Procedure: At the beginning, the participants were informed about the functionality of both actuators and tabletop. The drag-and-drop task was performed three times with each modality in order to avoid unwanted training effects during the evaluation. In the following evaluation, the participants were asked to perform 30 trials per condition, resulting in 90 drag-and-drops. The conditions were presented in a fully counterbalanced order. Finally, participants were doing a guided interview on their subjective evaluation of the effects of remote tactile feedback, and their personal recommendations for future implementations.

Independent and Dependent Variables: The first dependent variable was the *total task time* per trial. The measurement started when the participants first touched the blue square and ended on a successful drop. If the user had to manually correct her/his input, the measurement continued. The second dependent variable was the number of *input errors*, describing the number of lift-offs when the square does not superimpose the target-square correctly. Thus, a higher number of input errors results in extended total task time. Independent variable was the feedback modality (visual-only, RTF dominant, RTF non-dominant).

Hypotheses On the one hand, we assumed beneficial effects for the remote tactile feedback in general. On the other hand, we assumed that the relocation of the feedback away from the interacting hand does not result in reduced user performance.

- **H1:** Remote tactile feedback increases the interaction speed and reduces the number of input errors.
- **H2:** The relocation of the remote tactile feedback has no negative effect on interaction speed and number of input errors.

Results

An overview of the quantitative results is given in table 5.2, the results are shown in figure 5.10. Extreme values caused by technical drawbacks of the interactive table were removed before the analysis (discussed in section 5.3.3).

Total Task Time: The fastest mean user performance was achieved with remote tactile feedback on the non-dominant wrist (M=2344 ms, SD=447). On the contrary, user dragged-and-dropped the slowest when no tactile feedback was given (M=2602 ms, SD=755). Despite this trend, a one-way repeated measures ANOVA showed no significant influence of the type of feedback on task time ($F(2,51)= 1.172$, $p=0.318$). Hence, the first part of hypotheses 1 has to be rejected.

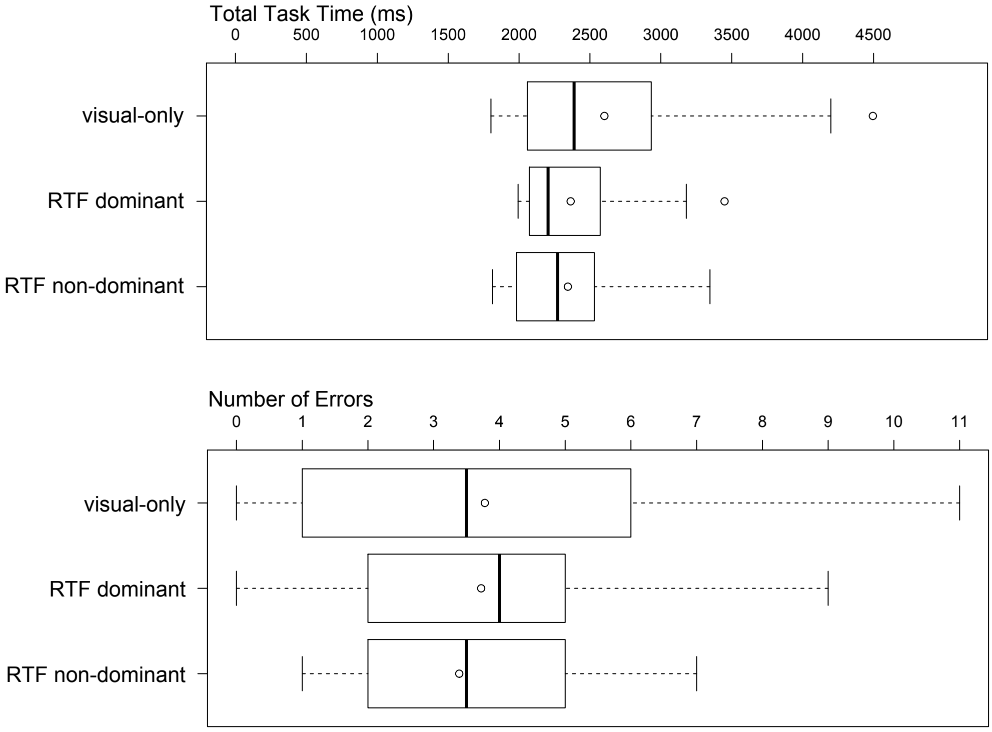


Figure 5.10: Average total task times (top) and number of missed keys (bottom) for the three modalities.

Error rate: Participants rarely lifted off their finger before they superimposed both squares. On average, most erroneous lift-offs per 10 trials were performed with visual-only feedback (M=3.78, SD=3.23). The fewest errors happened with remote tactile feedback on the non-dominant hand (M=3.39, SD=1.82). Again, the trend indicates benefits resulting from remote tactile feedback on the non-dominant hand. However, a one-way repeated measures ANOVA showed no significant influence of the type of feedback on the number of errors (F(2,51)=0.118, p=0.889). Consequently, we have to reject hypotheses 1 in total.

However, the results clearly confirm hypothesis 2: the relocation of the tactile feedback to the non-dominant hand had no negative effect on interaction speed and number of input errors. In general, tactile feedback had no disadvantageous effect on user performance. On average, both interaction speed and rate of correct input were not decreased when tactile feedback was given. On average, the values for task time and number of errors were even lower when the remote tactile feedback was moved to the non-interacting hand.

Interview results: During the guided interviews, the participants were asked about their personal liking of the signals, the perceived benefits of the tactile feedback and the subjective differences resulting from the application on the dominant or non-dominant wrist (see figure 5.11 for the results). Nine out of 18 participants (50%) stated that the feedback was pleasant and comfortable, 6 participants stated their opinion as 'neutral' and 3 found it (partly) uncomfortable. Seven participants assumed that the tactile feedback helped to reduce the error rate, 9 participants considered it helpful to increase interaction speed. When asked about the difference between the two

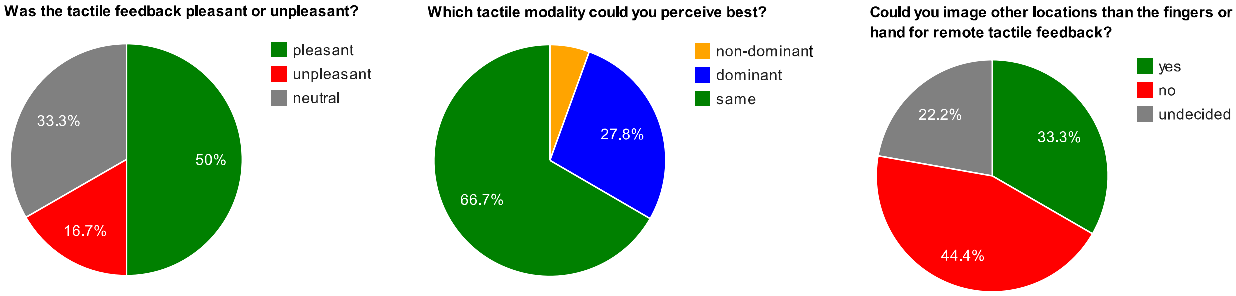


Figure 5.11: Summary of answers from the guided interviews.

locations of tactile stimuli, 12 out of 18 (66.7%) stated that both locations are well perceivable. Fourteen participants (77.8%) stated that both locations are equally comfortable, 3 even found the remote application more comfortable. When asked about their opinion on tactile feedback on other locations of the body, the opinions were divided: 6 participants could image to have tactile feedback on the arm, the leg or on other locations on the body. Eight users stated the feedback has to be "on the hand", "on the finger" or "close to the active place". One participant stated that he/she would be afraid of tactile feedback on the corpus. Finally, no participant perceived fatigue caused by the tactile stimuli.

5.3.3 Interpretation and Discussion

Both forms of remote tactile feedback did not have a significant influence on the user performance. Mean values showed trends towards a reduction of total task time, these effects were even stronger when tactile feedback was given at the non-dominant wrist. However, analyses of variance did not show significant effects. The tactile stimuli indicated the moment when the users accomplished the goal of their interaction - the overlapping of both virtual elements. Thus, the participants received this acknowledgement in both visual and tactile form, the rapid nature of haptic perception might have resulted in faster task completion. This effect could be more effective on the hand which is not involved in the interaction, because the tactile mechanoreceptors are not irritated by movement of the interacting hand. However, the use of simple and high-latency vibrotactile actuators[17] might have diluted potential effects of remote tactile feedback. However, the reduction of total task time can improve the directness of an interface and support the user in the achievement of her/his goals when using a specific interaction. Therefore, the increase of interaction speed is an objective of the third user study.

The second evaluation was partly influenced by technical difficulties with the interactive tabletop such as unrecognized input and high latency. Extreme values of task time and error rate were identified using boxplot visualizations and excluded from the statistical analysis.

[17] The vibration motors take ramp-up times of around 50 ms to reach the full vibration speed and the highest intensity of stimulation [Kaaresoja and Linjama, 2005].

As a second main result, we could show that the relocation of the remote tactile feedback to locations farther from the interaction had no negative effect on interaction speed and number of input errors. Users seemed not to be irritated by the dislocated stimuli. This observation is also supported by the qualitative results, e.g. two third of the participants stated that they perceived tactile stimuli equally well on both locations. One third of the participants even could imagine other locations for cutaneous signals than the fingertip or hand without any former experience with this novel type of interface. These results encouraged us to use different locations of the skin for the application of remote tactile feedback (such as the back, see section 6.2.2).

Based on these results, we once more updated our research agenda for the third evaluation of the effects of remote tactile feedback on user performance. In order to support the reliability of input, we chose to elaborate on the improvement of interaction speed. Furthermore, we decided to use less artificial tasks in a more realistic scenario.

5.4 Evaluating Multi-Touch Remote Tactile Feedback under Cognitive Load

The results from the two aforementioned evaluations showed positive subjective responses to both direct and remote tactile feedback and no negative effects on the system's usability caused by the relocation of tactile stimuli. However, we could not recreate significant quantitative effects of (direct and remote) tactile stimuli on touch surfaces. Consequently, the identification of interaction tasks and usage scenarios in which users benefit the most from remote tactile feedback is crucial for the development and for future applications of remote tactile feedback interfaces.

Therefore, we conducted a third evaluation that was designed based on the findings from the preceding user studies. We wanted to assure a transferability of our results towards remote tactile feedback systems used under real-life conditions (e.g. in the car) with increased cognitive load. Accordingly, we changed the design of the third user study in the following ways:

1. We added cognitive load to replicate more life-like usage conditions.
2. We allowed for multi-touch and gestural input.
3. We designed the input task as a combination of standard input methods on tabletops (scaling, rotation and drag-and-drop of virtual elements).

5.4.1 Prototype

Again, the evaluation was performed on the interactive tabletop system with the same types of wrist-worn vibrotactile actuators (see figure 5.8). Due to the tabletop's former problems with latency and failing detection of input, we exchanged the tabeltop's semi-transparent surface in order to improve the FTIR sensing. Despite the described latency problems of vibration-motor-based tactile actuators, we decided to incorporate them again due to their simplicity of implementation, cost-efficiency and frequent use in similar tactile feedback systems.

The tactile actuators were applied on the same positions of the participants wrist: on the hairy skin on the lateral side of the hand (opposing the palm). Also the design of tactile acknowledgments wasn't changed, we used vibrations of 250 Hz with a duration of 130 ms and a fixed voltage of 5 V, following recommendations from related work [Kaaresoja and Linjama, 2005]. The feedback was given as object-independent simultaneous acknowledgments of the successful completion of the given task (see section 3.3.1). Moreover, this information was given crossmodally on both the visual and tactile channel.

5.4.2 Evaluation

We assumed that remote tactile feedback results in decreased total task time needed for a set of gestural and multi-touch interactions on a tabletop. The participants could know from the additional tactile acknowledgement when to correct their input and when to start with the next task. We also wanted to back our findings that the relocation of the stimuli to body-parts not involved with the interaction has no negative effects on the total task time and preserves the beneficial effects. Finally, we assumed that under additional cognitive load, the application of remote tactile feedback will further reduce total task time.

Participants: Eighteen participants (five female, average age 28 years, all right-handed) took part in the evaluation as paid participants. Again, the participants were asked to rate their personal experience with interactive surfaces and vibrotactile stimuli on a scale from 1 to 5 (1='no experience', 5='very experienced'). The results were similar to those of the former evaluation (average value of 3.78 for the experience with touch surfaces, 3.23 for the experience with vibrotactile stimuli). All but one participant had used mobile devices with vibrotactile feedback before.

Task: The given task was to perform a set of common tabletop interactions: scaling, rotation and drag-and-drop (see figure 5.12). At the beginning, a gray square (5x5 cm) had to be scaled using both hands by performing a outward dragging gesture touching two opposing corners. During scaling input, the square turned red. On reaching the correct size (10x10 cm with a threshold of 4 pixels), the square changed its color to green. In the tactile conditions, a 130 ms 'buzz' was provided as acknowledgement. An 'overshoot' was possible when the square was scaled too much, which had to be corrected. After completion of a correct scaling (green square), the square had to be rotated by 180° in clockwise direction. Participants were allowed to use both hands. The square could only be rotated by 360°. In accordance to the scaling task, visual feedback (green square) and tactile feedback (130 ms signal) were given when the square had been rotated correctly. Finally, a target area (10.4x10.4 cm) appeared, in which the square had to be dragged. Again, change of color and (in the tactile conditions) haptic feedback were used as acknowledgement for correctly performed input. Participants were asked to perform the input task as quick and accurate as possible.

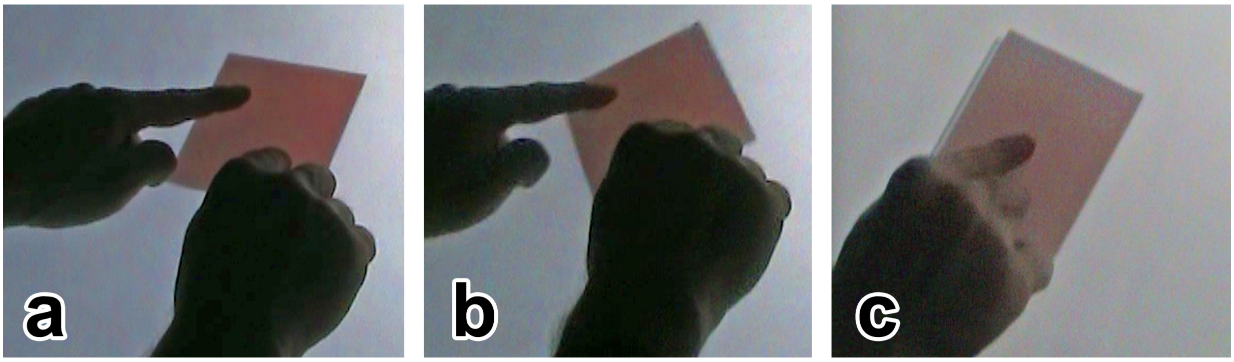


Figure 5.12: A set of three interactions had to be performed in the evaluation. a: Two-handed scaling, b: two-handed rotating, c: single-handed dragging (all three are video stills [Löhmann, 2011a]).

Cognitive load for the participants was produced by incorporating an auditory task proposed by Leung et al. [Leung et al., 2007]. We chose a solely auditory additional task to minimize potential interferences with the tactile and visual modality. In the conditions with added cognitive load, the participants were listening to random sequences of spoken characters. The sequences could contain eight letters from 'O' to 'V'. The task was to identify occurrences of three succeeding identical letters (e.g. 'PPP') and to indicate this by saying "Now!". A sequence of three succeeding identical letters was given five times per minute in varying intervals. Participants were asked to perform the auditory task as accurately as possible, even if the input task would take longer. This additional cognitive load makes the laboratory study more comparable to dynamic multitasking scenarios (e.g. multi-person interaction on the tabletop, cooperative work, taking part in a conversation during input).

Conditions: In total, we had two factors: the application of the remote tactile feedback and the addition of the cognitive load. The independent variable feedback had three levels: visual-only feedback, remote tactile feedback given on the dominant wrist and remote tactile feedback given on the non-dominant wrist. The independent variable cognitive load had two levels: added cognitive load and no added cognitive load.

Design: The evaluation had a within-subject repeated measures design.

Apparatus: The participants were standing next to the tabletop wearing two wristbands independent from the given condition. Loudspeakers on the tabletop were used to give the sequences of letters for cognitive load. The participants could freely position their non-dominant hand; for scaling and rotating, both index-fingers had to be used for input. However, only one or no wristband was giving tactile stimuli at a time[18].

Procedure: At the beginning, participants were allowed to test all three interactions and the tactile feedback. Afterwards, the additional auditory task was introduced. The actual evaluation consisted of six parts, i.e. every combination of the three feedback conditions with both degrees

[18] Remote multi-haptic feedback (two distinct tactile stimuli synchronized with two points of contact with the surface) will be discussed in section 6.4.

	Total Task Time (ms) NACL	Total Task Time (ms) ACL
Visual-Only Feedback:	M=10062 (SD=1857)	M=11023 (SD=2501)
RTF dominant wrist:	M= 9807 (SD=2010)	M=10692 (SD=2267)
RTF non-dominant wrist:	M=9946 (SD=1764)	M=11305 (SD=2747)

Table 5.3: Quantitative results for total task time (means and standard deviations) without cognitive load (no additional cognitive load - NACL) and with additional cognitive load (additional cognitive load - ACL).

of cognitive load were applied. The order of conditions was fully counterbalanced. The set of the three consecutive interactions was performed 10 times in each combination.

Independent and Dependent Variables: We measured the time needed for every single input task and the duration of the three consecutive input tasks for every condition (starting at the first touch, stopping measurement at the successful completion of the last task). Additionally, we measured the number of times the participants were able to identify the consecutive letters in the auditory task. Thus, we could comprehend and compare the degree of cognitive load.

Hypotheses: In total, we formulated three hypotheses:

H1: Remote tactile feedback increases the interaction speed when performing gestural and multi-touch input on the tabletop.
H2: The relocation of the remote tactile feedback does not decrease the beneficial effects.
H3: Under additional cognitive load, remote tactile feedback additionally increases the interaction speed when performing gestural and multi-touch input on the tabletop.

Results

An overview of the quantitative results is given in table 5.3, the results are shown in figure 5.13.

Total Task Time and Effect of Additional Auditory Task: Without the additional auditory task, the fastest user performance over all three tasks was achieved with remote tactile feedback on the dominant wrist (M=9807 ms, SD=2010). Users were the slowest when no tactile feedback was given (M=10062 ms,SD=1857). Under added cognitive load caused by the auditory task, remote tactile feedback on the dominant wrist was the most helpful again (M=10692 ms, SD=2267). Users performed the slowest when remote tactile feedback was given on the non-dominant wrist (M=11305 ms, SD=2747). On average, the addition of an auditory task caused increased total task time of 10.7% over all three modalities. However, one-way repeated measures ANOVAs showed no significant effects of the type of feedback on total task time: ($F(2,51)=0.083$, $p=0.92$) without added cognitive load and ($F(2,51)=0.268$, $p=9.766$) with added cognitive load.

Scaling Task Time: Figure 5.14 shows the average task times for the individual sub-tasks. For the scaling task *without added cognitive load*, users performed faster with remote tactile feedback on the dominant hand (M=2516 ms, SD=516) compared to the visual-only feedback condition (M=2831 ms, SD=501). The type of tactile feedback had a significant effect on the time needed for scaling ($F(2,51)=3.926$, $p=0.0259$). Tukey's HSD tests were carried out on the data. The results show a significant difference ($p=0.05$) between mean scaling times when remote tactile

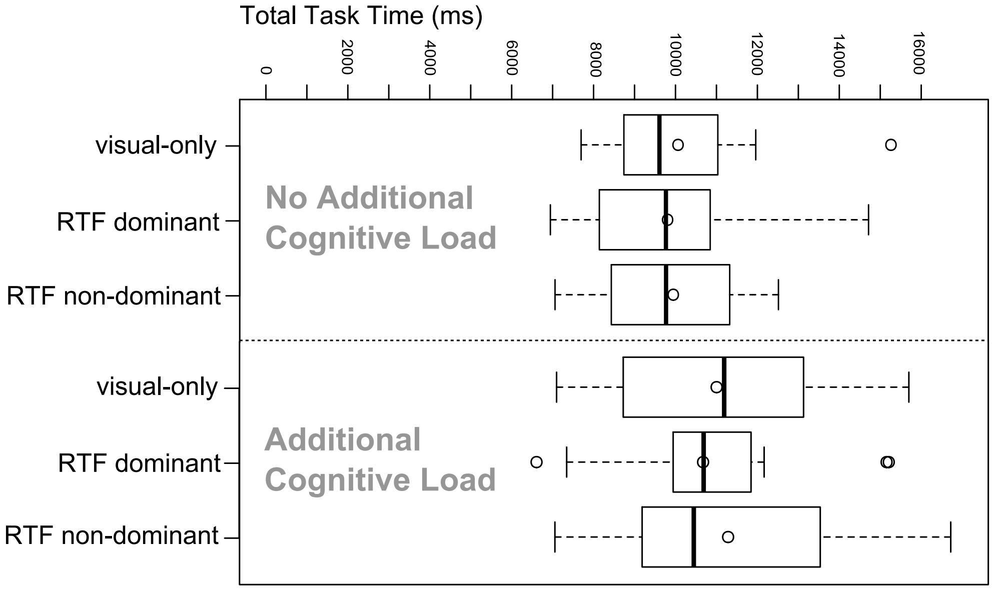


Figure 5.13: Average total task times without additional cognitive load (top) and with additional cognitive load (bottom) for the three modalities.

feedback was given on the dominant hand compared to visual feedback only (no differences between the other two conditions). **In other words, during the scaling-task, the participants were significantly faster when remote tactile feedback was given on the dominant hand compared to the setting with only visual feedback.**

For all other sub-tasks, no form of remote tactile feedback had a significant effect on the interaction speed. Thus, we consider the effect of remote tactile feedback on task time during the scaling task as an exception which needs further examination. This exception has no effect on our general hypotheses: Remote tactile feedback did not increase the interaction speed, thus we reject hypothesis 1. However, the relocation of the remote tactile feedback to the non-dominant hand did not significantly decrease the measured values, therefore, we can accept hypothesis 2. Finally, remote tactile feedback did not show an increased beneficial effect under additional cognitive load. Therefore, we also have to reject hypothesis 3.

5.4.3 Interpretation and Discussion

As a first result, we stated that the additional auditory task created cognitive load for the participants which had a negative influence on the interaction speed in all three sub-tasks. The detection of consecutive audible characters resembles a conversation whilst performing touch input. However, in contrast to results from related work, the additional non-visual feedback did not show benefits in this type of multi-tasking environment.

In order to create a more lifelike scenario on the tabletop, one could introduce additional visual load or attention shifts. Additional tactile feedback might have a stronger effect in these scenar-

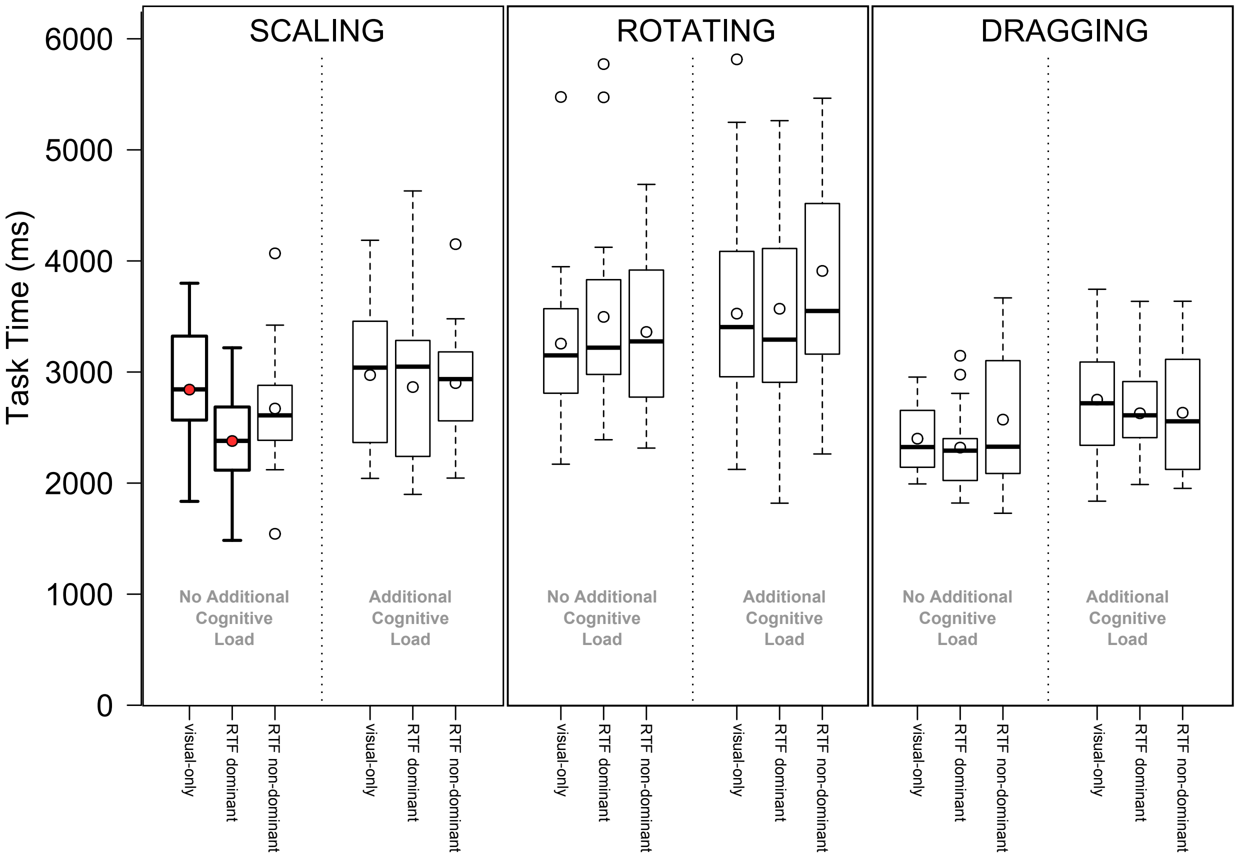


Figure 5.14: Average task times for the individual sub-tasks without and with additional cognitive load. Significant differences were found between the scaling times with visual-only feedback and remote tactile feedback on the dominant hand without additional cognitive load.

ios. In our study, the information on the complete interaction was given crossmodally: the same information was presented both visually and tactile. When frequent attention shifts and glances to secondary tasks are necessary, the parallel transmission of non-visual cues might create more distinct benefits.

Significant beneficial effects were found when remote tactile feedback was given on the dominant hand during the scaling task. We were not sure why this is the case in this condition, further evaluations could be performed to clarify this effect.

Comparable to the previous evaluation, the relocation of remote tactile stimuli onto the non-dominant wrist did not cause negative effects. The tactile acknowledgments were simple and non-ambiguous and do not directly refer to the movement of the hand. Therefore, the position of this abstract tactile notification might not be crucial. Depending on the type of tactile stimulus, this finding could be used to explore the creation of remote tactile interfaces for various body locations.

5.5 Summary

In this thesis, I propose remote tactile feedback as an alternative approach to provide haptic stimuli on touch surfaces. Remote tactile feedback is applicable on non-planar interactive surfaces and can be combined with input mechanisms such as pressure sensing. This novel approach contains inherent characteristics which can not be achieved with common methods to provide tactile feedback on touch surfaces. Nevertheless, remote tactile feedback has to keep up with direct tactile feedback when it comes to creating its previously verified benefits: Direct tactile feedback has been shown to be advantageous in multi-tasking scenarios with increased visual and cognitive load. Typically, evaluations have been performed as text-input tasks. With the three evaluations, we wanted to evaluate if the effects of remote tactile feedback on the user's performance are comparable to those of direct tactile feedback.

Therefore, we conducted detailed user studies evaluating quantitative effects (accuracy, total task time, key misses, input errors) and subjective ratings of this approach. In the three evaluations, we used two types of horizontal interactive surfaces: a smaller purpose-built device and an interactive tabletop. We chose not to include mobile platforms, as similar research has been performed on this class of devices and our results are transferable to the mobile sector (see section 7.2). We applied common technical methods to create tactile stimuli: high-frequent vertical movement of the screen surface as well as wearable vibrotactile actuators. We implemented both forms of tactile stimuli: object-related stimuli indicating the position of a key in the first evaluation and object-independent stimuli indicating the correct execution of the task in the other two evaluations. Finally, common tasks on interactive surfaces were implemented: a form of text-input in the first evaluation and dragging, scaling and rotation of virtual elements in the second and third study. Table 5.15 shows our hypotheses in the three evaluations and whether we could accept or reject them.

In the first evaluation, we did not find significant effects of both forms of either direct or remote tactile feedback on the user's performance. Likewise, both forms of haptic signals did not have a negative effect on accuracy, interaction speed and number of missed keys. We could identify a strong preference of the users for tactile feedback, regardless of its form of application: both direct and remote stimuli were rated highly positive in terms of realism, signal design and information content. People clearly preferred tactile feedback to visual-only information.

The results of the second evaluation show the flexibility of remote tactile stimuli: although we could not identify significant effects of remote tactile feedback on interaction speed and number of input errors, we gained similar subjective ratings for tactile feedback on the dominant and non-dominant hand. Although we used simple vibrotactile actuators, half of the participant stated the haptic stimuli to be pleasant. Moreover, two third of the interviewees stated that they could perceive the stimuli on both positions equally well. This supports our assumption that body locations more distant from the interacting hand can be used for the application of haptic signals coupled with the interaction.

The third evaluation included additional cognitive load and a wider variety of touch interactions. We could show that the additional auditory effect had a negative effect on the user's performance.

#	HYPOTHESIS	
H1.1	Accuracy is higher with tactile feedback than with visual-only feedback.	rejected
H1.2	Total task time is lower with tactile feedback than with visual-only feedback.	rejected
H1.3	Fewer keys are missed when typing with tactile feedback than with visual-only feedback.	rejected
H1.4	Users will prefer interactions with tactile feedback to interactions without tactile feedback.	**accepted**
H2.1	Remote tactile feedback increases the interaction speed and reduces the number of input errors.	rejected
H2.2	The relocation of the remote tactile feedback has no negative effect on interaction speed and number of input errors.	**accepted**
H3.1	Remote tactile feedback increases the interaction speed when performing gestural and multi-touch input on the tabletop.	**rejected (with exception)**
H3.2	The relocation of the remote tactile feedback does not decrease the beneficial effects.	**accepted**
H3.3	Under additional cognitive load, remote tactile feedback additionally increases the interaction speed when performing gestural and multi-touch input on the tabletop.	rejected

Figure 5.15: Hypotheses and results of the three consecutive evaluations. Notable results are marked in bold.

However, remote tactile feedback could not fully compensate for this disadvantage. With additional non-visual feedback, the users performance did not change. Still, we found that people performed significantly faster when remote tactile feedback was given on the dominant wrist during the scaling task without additional cognitive load compared to visual-only feedback. Again, the relocation of the remote tactile feedback had no negative effect on interaction speed and number of input errors.

In summary, we can state that in order to identify further quantitative effects of remote tactile feedback on user performance, one should incorporate more carefully designed tactile stimuli using tactile actuators with lower latency. Tactile feedback has been shown to be especially helpful in environments with high *visual* load, which we did not recreate in our evaluations. Additionally, a higher number of participants would create statistically more resilient results.

Still, we could not identify measurable differences between the effects caused by direct tactile feedback and different locations of remote tactile stimuli. Furthermore, our evaluations have shown a highly positive subjective rating of tactile feedback in general and - in one case - a significant improvement of interaction speed when remote tactile feedback was given.

These results corroborate my approach of further exploring the notion of remote tactile feedback. The next step is to analyze its inherent characteristics. My research on this novel topic is broad in scope, therefore I developed conceptual prototypes incorporating diverse actuator technologies and forms of proactive, reactive and detached tactile feedback on various body locations. My research on inherent characteristics of remote tactile feedback is presented in the next chapter.

Chapter 6

Inherent Characteristics of Remote Tactile Feedback

The concept of combining a touch input with distal cutaneous stimuli has several characteristics that are not included in common approaches of creating tactile feedback. This can help to take on challenges of existing tactile feedback concepts for touch surfaces such as restricted scalability due to high mechanical complexity and size, limited versatility of the created stimuli or the difficult application on non-flat interactive surfaces (see also section 3.4). Furthermore, the novel concept can accommodate for more flexible input methods such as force sensing, bimanual and gestural input.

The following main part of the thesis identifies and analyzes four of these idiosyncratic benefits, namely:

1. The simplification of the integration of cutaneous stimuli.
2. The transmission of proactive, reactive and detached feedback.
3. The increased versatility of tactile sensations.
4. The provision of haptic feedback for multi-touch input.

For every part, prototypical interfaces have been implemented to demonstrate the feasibility of the approach.

Each section describes the technical aspects of the implemented prototype which helps designers and researchers to easily recreate and extend the concept. Most of the presented prototypes have been part of an evaluation, the results demonstrate the feasibility of the approach and expose its limitations. Furthermore, the chapter highlights possible usage scenarios for remote tactile interfaces such as the car or environments with a tabletop.

6.1 Simplification

Section 3.4 has identified three main concepts for the generation of cutaneous stimuli on touch surfaces: (1) actuating the screen's surface or encasing of device, (2) actuating individual tactile pixels and (3) incorporating additional actuated devices. For every class, the expressiveness of the created tactile stimuli comes at the expense of technical complexity and limited scalability.

The two following projects address several aspects of this problem: the *PhantomStation* implements psychophysical illusions to reduce the number of individual actuators which are needed to create continuous sensations of movement on the skin. The results of an evaluation demonstrate that simple vibrotactile actuators can create stable tactile illusions, possible applications of the concept are presented. The *EdgeMatrix* prototype is used to explore the feasibility of distal tactile shape displays. Thus, more complex forms such as edges or lines can be communicated non-visually.

Both projects demonstrate a main beneficial aspects of remote tactile feedback: no electrical or electromechanical tactile actuators have to be integrated into the touch surface. This allows for interactive surfaces of arbitrary forms and materials, the touch panels can remain transparent (e.g. for back-projection) and the concept is applicable to larger touch areas.

6.1.1 *PhantomStation*: Remote Tactile Phantom Sensations

In the following, I describe our[1] approach to utilize the psychophysical Phantom Sensation to present tactile sensations of linear movements to the forearm of a user of an interactive surface. The project was published in [Richter et al., 2011a] and [Richter et al., 2011b].

Terminology and Related Work

The term *Phantom Sensation* describes a class of psychophysical effects based on temporal and amplitude inhibitions[2]. David Alles provides a definition: "Two equally loud stimuli presented simultaneously to adjacent locations on the skin are not felt separately but rather combine to form a sensation midway between the two stimulators. This phantom sensation is affected by the separation of the stimuli, their relative amplitudes, and their temporal order" [Alles, 1970].

The position of the created stimulus can smoothly be adjusted between the actuators using two 'funneling methods': Either by varying the intensities of the two stimuli (*amplitude inhibition*) or by changing the inter-stimulus time interval (*temporal inhibition*) between the two adjacent actuators [Kato et al., 2010]. Increases of the inter-stimulus interval result in the perception that

[1] This work was part of Benedikt Blaha's Diploma thesis [Blaha, 2011]

[2] The effect is closely related to phenomena such as Cutaneous Saltation (perception of intermediate sensations between repeatedly stimulated locations), the Funneling Illusion (perceived fusioning of multiple sequential sensations into one) and Apparent Movement (continuous movement of a tactile sensation between changing stimuli with changing amplitudes) [Eimer et al., 2005, Bekesy, 1958, Rahal et al., 2009].

the position of the sensation moves towards the earlier stimulus. With an inter-stimulus interval over 8-10 ms, two individual sensations are perceived at the positions of the two actuators [Bekesy, 1958]. If the relative amplitude or 'loudness' of the stimuli is varied, the phantom stimulus will appear closer to the louder one. A combination of both temporal inhibition and amplitude inhibition does only sightly improve the effect [Alles, 1970].

This tactile illusion has been analyzed and recreated by psychologists and perceptual researchers since the 1950s [Bekesy, 1958]. Other, more recent implementations have proposed the use of tactile illusions for moving sensations on two-dimensional tactile displays [Israr and Poupyrev, 2011] or hint at the possibility to reduce the number of stimulators in wearable interfaces [Kato et al., 2010]. However, only limited material on technical aspects of reproducing this effect and utilizing it for touch interfaces exists.

Therefore, we implemented a technical prototype to test the feasibility of utilizing this illusion for remote tactile feedback. The goal was to create a phantom sensation which is reliably perceived and movable with a high resolution. Thus, we could support touch input with the sensation of directional tactile movement. Using only two actuators, a form of sensation could be created which usually requires several actuators which are arranged in a row or matrix form (such as shape displays, see section 3.4.2).

To allow for simple prototyping and easy recreation of the effect, we used off-the-shelf materials for the prototype. At first, we compared combinations of standard actuator technologies (solenoids, vibration motors, voice coils) and inhibition modes (amplitude inhibition, temporal inhibition) in a user study. In the next step, we designed several widgets on touch surfaces which can be supported using this illusion-based form of remote tactile feedback. Our course of action is described in the following.

Prototype

The *PhantomStation* prototype is depicted in figure 6.1. The wooden encasing had the dimensions of 34x14x9.5 cm (LxWxH). We chose the inner side of the forearm as the body location for the application of the stimuli for several reasons: First, mechanoreceptors in the skin of the forearm are evenly distributed and have known characteristics [Bekesy, 1958, Cholewiak and Collins, 2003]. The forearm has been used for the application of phantom stimuli before, which could support the comparability of our approach. With regards to future implementations of the principle, we chose the forearm as this location could be used for wearable interfaces and does not affect the user's privacy too much. Furthermore, our decision for this position was supported by an observation by Ryall et al. [Ryall et al., 2006]: During the interaction with tabletop surfaces, people were found to lean on the surface and rest their non-active arm on the frame of the device or even the screen. Therefore, we consider the implementation of actuators in the tabletop's frame as a feasible approach. All three pairs of actuators are 8 cm apart, this value has been identified to create the most stable sensation for this skin area [Alles, 1970, Rahal et al., 2009].

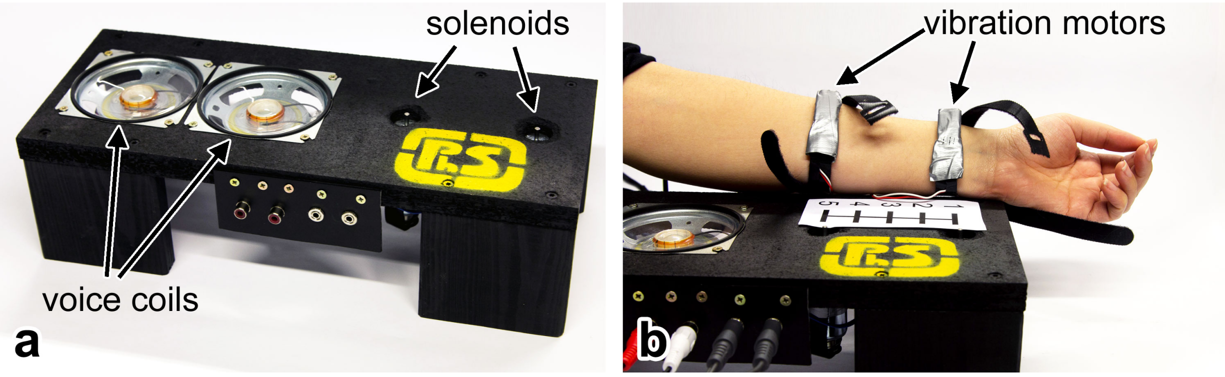


Figure 6.1: The *PhantomStation* prototype and the position of the three incorporated actuator types. a: System overview, b: User with attached wearable vibration actuators.

We chose the following three actuator types for three reasons: All three are commonly used in the field of research on tactile feedback, they are readily commercially available at a low price and they differ in the characteristics of created stimuli (see figure 6.2).

Vibration motors: As in the studies described in sections 5.2 and 5.4, we used Lily Pad Vibe boards for vibrotactile actuation. The pancake-shaped motors were included in an adaptable arm-sleeve to maintain the fixed distance of 8 cm. Vibration motors are limited in their controllability: both vibration amplitude and frequency are altered by applying different driving voltages. Both parameters can't be controlled separately. Latency can also be an issue, vibration motors have ramp-up times of around 50 ms. The stimulation is diffuse and can affect larger skin areas than the other two types of actuators. Prolonged usage also can overload the mechanoreceptors, leading to fatigue and displeasing sensations.

Linear solenoids: For punctual tactile stimulation, we used electromagnetic solenoids[3]. A solenoid consist of a ferrous plunger which is moved in one direction by activating a magnetic coil. Thus, a solenoid can switch between two states: fully drawn in and fully extended. As solenoids can't create variable amplitudes, they can not be used for the amplitude inhibition mode. The solenoids were attached to the prototype's wooden encasing, the stroke width was 8 mm. Solenoids of this type have a latency of about 25 ms to reach full extension[4]. This type of actuator creates a snapping noise when extended.

Voice coil actuators: We used voice coil speakers as third actuator technology[5]. This type forms a hybrid between vibration motors and solenoids: A copper coil in a magnetic coil reacts to a current passing through and moves a cone in vertical direction. Thus, high-frequent vibrations in a spatially limited skin area can be created. Thereby, amplitude and frequency can be controlled separately.

[3] Black Knight tubular push solenoid, 12 V

[4] `http://www.maccon.de/fileadmin/FTPROOT/tubular_solenoid_320.pdf` [cited 2012/12/17]

[5] Visaton SL 87 XA Speakers

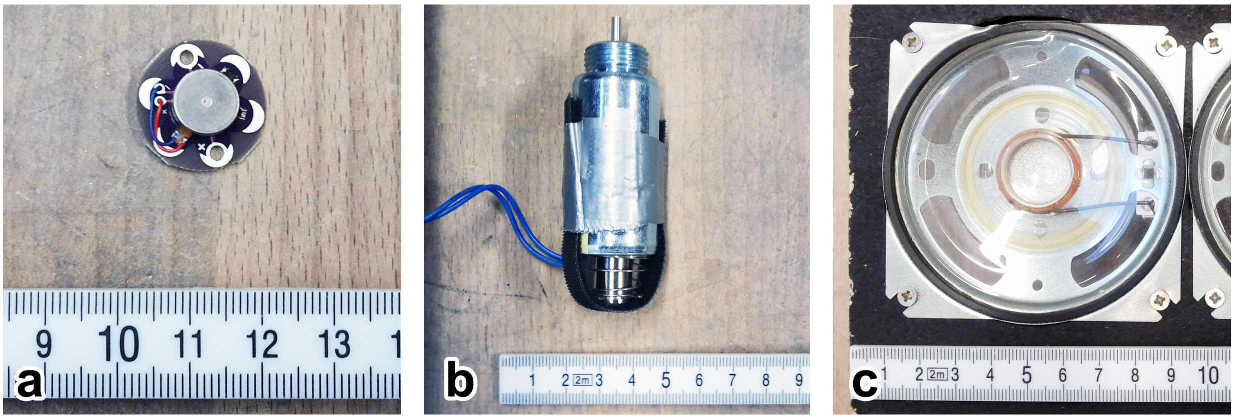


Figure 6.2: The three actuator types of the *PhantomStation*. a: vibration motor, b: linear solenoid, c: voice coil actuator

Evaluation

The described setup was utilized in an evaluation to identify the actuator technology which creates the most stable phantom sensation. Fifteen computer literate persons (5 male, average age 35 years) took part in the evaluation. All of them were right-handed and rated their technical experience with a median of 4 on a scale of 1 ('very low') to 7 ('very high'). We decided to ask participants with no dedicated technical background, i.e. no students of the computer science department in order to minimize positive bias caused by the novelty effect (also discussed in section 5.2.3).

Using a within-subject repeated measures design, all participants were presented with all five combinations of actuator technology and funneling mode. The order of these AFM-combinations was fully counterbalanced using a non-balanced Latin Square. During the task, the participants were seated with their non-dominant forearm resting on the device. Depending on the type of stimulation, the participants were asked to rest their arm on a pair of actuators. For vibrotactile stimulation, users were asked to wear an arm sleeve which contained the pair of actuators (still, the arm rested on the wooden encasing). A scale from 1 to 5 was depicted next to the user's arm to provide a spatial orientation for the location of the created phantom stimulus. The position 1 represented the distal actuator near the wrist, position 5 identified the proximal actuator near the elbow (see also figure 6.3). We decided to use this form of discrete positioning in order to be more consistent with related research (e.g. [Barghout et al., 2009]) and to make measurement more exact, future implementations should allow for a continuous positioning.

After a short training phase with each AFM-combination, users were presented with located stimuli and were asked to indicate the perceived position on the visual scale. Every stimulus was presented only once. If more than one stimulus was perceived, the participants were asked to indicate the position of the stronger one. Within one of the 5 combinations, each of the 5 positions was tested 3 times. The order of the positions within each AFM-combination was randomized. When the actuator technology was changed, the prototype was turned around. After each AFM-combination, the participants were asked to fill in a questionnaire containing questions on the

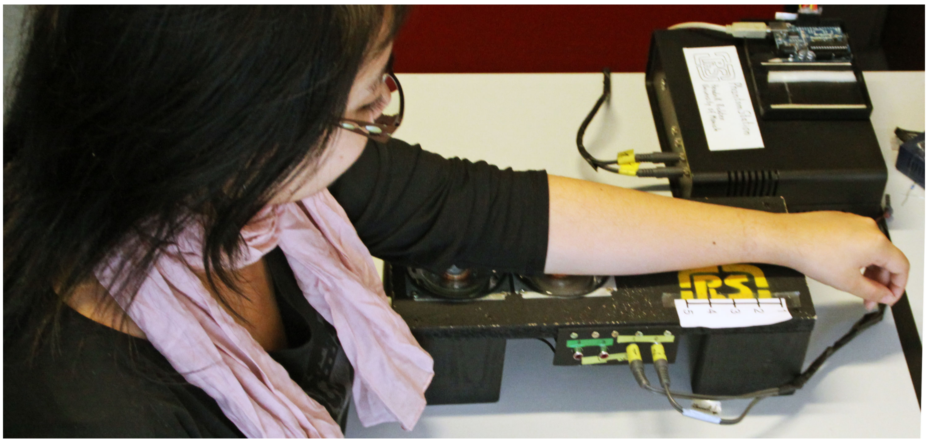


Figure 6.3: Study setup during the evaluation with the *PhantomStation*. The participant uses the solenoid actuators.

acceptance of the prototype, the comfort of the stimuli and the recognizability of the created phantom sensation.

Results

In total, each position was tested 225 times (15 participants, 5 AFM-combinations, 3 repetitions). In order to evaluate the general correctness of our method, we measured the frequency of occurrence for each perceived position. The results show a median of 3 and a mean of 3.09 (SD=1.43), proving that each (phantom) position was picked equally often across all combinations. The results for the perceived positions for each AFM-combination depicted in figure 6.4 shows the occurrence of phantom sensations for all modalities[6]. The AFM combination 'vibrotactile actuator with amplitude inhibition mode' shows the most stable Phantom Sensation wit the least spatial deviation.

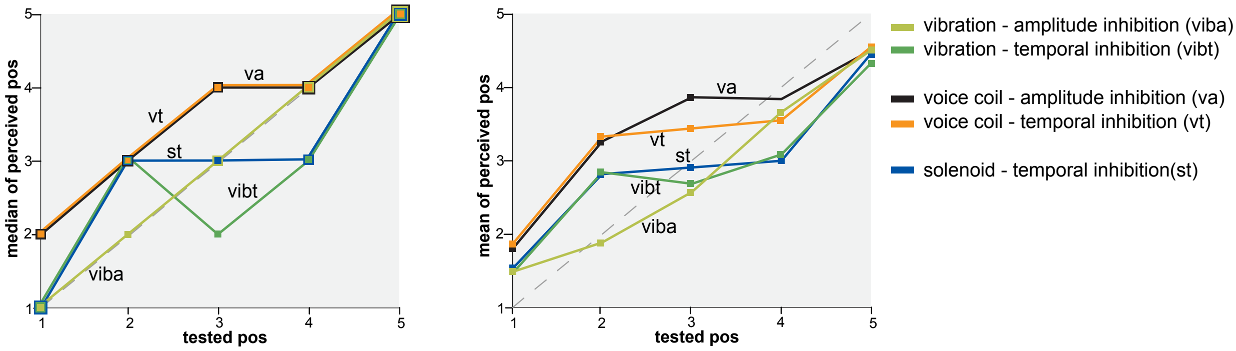


Figure 6.4: Medians and means for the values of the perceived position of a phantom sensation. Discrete values are connected for readability.

[6] Depicted are both medians and means for an overview although the data is measured on a nominal scale.

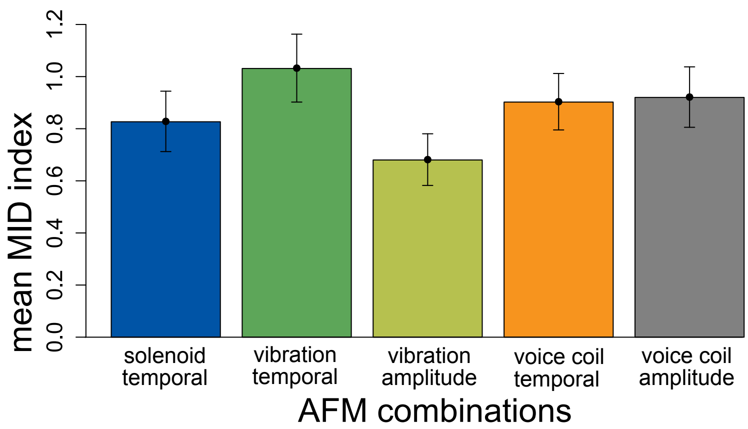


Figure 6.5: Means of the Mean Input Deviation (MID) index for each AFM combination. Error bars represent 95% confidence intervals.

In order to identify the most effective AFM-combination, we aggregated the data and created a mean input deviation (MID) index. This mean of spatial deviation is the average of the difference between tested position and the position that was perceived by the participants for each AFM-combination (see figure 6.5). The lower the MID index value, the more distinct is the created phantom sensation. Both the lowest and highest level of accuracy was created with the vibrotactile actuators, depending on the inhibition mode: amplitude inhibition resulted in a mean of 0.68 (SD=0.76) and temporal inhibition in a mean of 1.03 (SD=1.00).

Using one-way repeated measures ANOVA, we found that the type of AFM-combination had a significant effect on the MID index ($F(4,56)=8.45$, $p<0.001$). Based on the resulting values and the answers given in the questionnaire, we identified the vibrotactile actuators using amplitude inhibition as most distinct and stable technology to create phantom sensations. The stimuli created by this combination also were rated as being least disturbing, least intimidating and most comfortable. More detailed results can be found in [Blaha, 2011].

Applications

After identifying the most effective simple actuator technology to create this tactile illusion, we incorporated this form of tactile stimulus as remote tactile feedback on touch surfaces. Vibrotactile actuators are small, light and easy to control, this makes it possible to use them in a form of wearable interface. Therefore, we decided to use an actuator-equipped arm-sleeve to explore possible widgets which could be equipped with this form of remote tactile feedback. Following our classification of tactile stimuli into object-related and object-independent forms (see section 3.3.1), we propose several examples: The moving phantom stimulus could convey abstract information such as a current zooming level (e.g. 'closer to the wrist' means 'zoomed in') or the state of a progress (e.g. 'the download is finished when the sensation arrives at the wrist'). For object-related stimuli, we can imagine the phantom sensation to communicate the amount of pressure which is applied to the screen (e.g. 'with more pressure, the stimulus approaches the elbow').

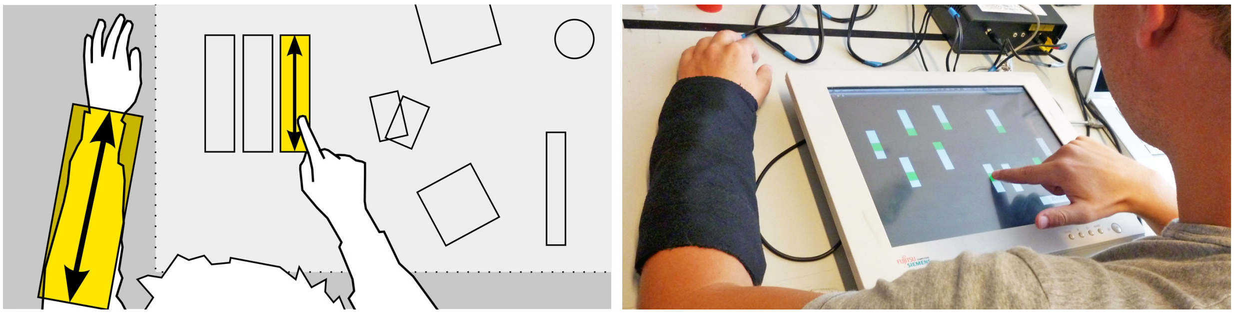


Figure 6.6: Coupling the remote phantom sensation with touch input, the picture shows the concept and a possible implementation.

An almost obvious concept is the coupling of phantom sensation and a fader widget as depicted in figure 6.6.

Here, the position of the moving phantom stimulus crossmodally conveys the current position of the widget's slider. This information is also available in visual form. The fader's interactive area is mapped onto the user's forearm. Depending on the size of the fader widget on the screen, the tactile resolution could be higher than the visual resolution. This could support the user's accuracy of positioning the fader and decrease the effects of the fat finger problem. In a preliminary user study, we explored this potential by measuring the accuracy with which participants could position the slider of faders with different sizes when given remote tactile (phantom) feedback. However, we could not find a significant effect caused by the tactile feedback on the accuracy of the users. An interview with the participants revealed several possible reasons. Most users stated that they concentrated on the visual feedback only, which was sufficient to complete the task, so they could ignore the tactile feedback. The phantom stimulus was clearly perceivable, but is also a highly individual effect. In order to integrate this form of phantom stimulus into a coherent visual-tactile feedback, a certain amount of cognitive effort seems to be required. A participant performed the task with closed eyes and stated afterwards: "Yes, now I can imagine, I am feeling it now!" People tended not to incorporate the phantom stimuli when the visual feedback was sufficient.

Discussion and Conclusions

In summary, we explored phantom stimuli as a means to create both stable tactile feedback and support direct touch interactions. Thus, no actuator technology has to be implemented into the touch surface and the number of individual actuators can be reduced. We identified vibrotactile feedback with amplitude inhibition as an effective technology for the creation of stable phantom sensations. We proposed several touchscreen widgets which could be coupled with this form of one-dimensional moving stimulus. A first wearable implementation of the principle for fader widgets did not show a significant effect of the feedback.

Using phantom-based illusions on touch surfaces is an exploratory, but powerful idea. This effect provides a special form of feedback, our preliminary evaluation hinted at a possible practicability in scenarios with increased visual load. However, the effect is perceived differently from person

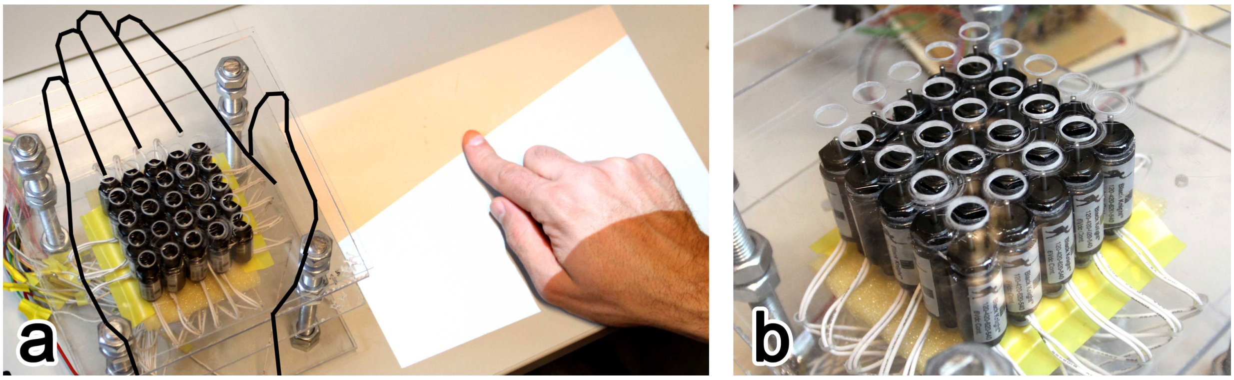


Figure 6.7: Overview and actuator technology of the *EdgeMatrix* prototype. a: The user explores lines, edges and forms of virtual objects on a touch surface with the dominant hand, the resulting programmed tactile information is provided by a shape display on the user's non-dominant palm. b: Detail view of the solenoid actuator matrix.

to person, making the effect more unstable. Therefore, we decided not to implement and test further widgets with remote tactile phantom illusions.

6.1.2 *EdgeMatrix*: A Remote Tactile Shape Display

A **large number** of **very small** individual actuators is ultimate basis of the vision of 'tactile pixels'. Up to today, the mechanical complexity needed for sensing and actuation in every single component results in bulky actuators. Thus, the haptic resolution of today's shape displays can not keep up with the great number of visual pixels in each dimension. The aforementioned *PhantomStation* prototype explored a method to decrease the number of single actuators which are needed to generate tactile stimuli on interactive surfaces. The *EdgeMatrix* prototype presented in this section is a remote tactile shape display with which we enlarge the haptic resolution by increasing the number of remote tactile actuators. Thus, a very small sensor area (e.g. fingertip) can be coupled with programmed high resolution shape information (see also [Richter, 2011]).

For the *EdgeMatrix*, we[7] adapted the concept of shape displays (see section 3.4.2) and utilized it as an remote tactile actuator system. Shape displays are a very versatile form of stimulator, as they can dynamically display palpable forms, reliefs, edges and surface structures. This supports the human's ability to become acquainted with an object's form, orientation and materiality by performing exploratory hand movements [Lederman, 1987]. The *EdgeMatrix* is another functional prototype to explore and formally evaluate our concept. An overview of the system is depicted in figure 6.7.

[7] This work was part of Kadri Januzaj's Diploma thesis [Januzaj, 2010].

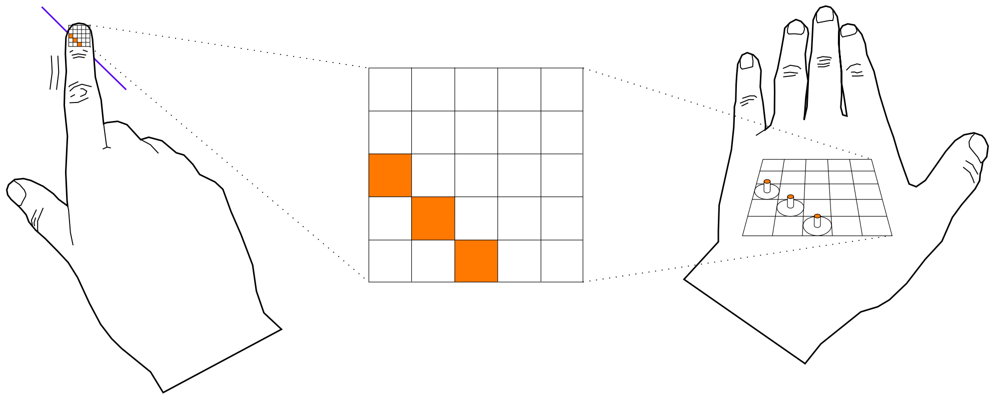


Figure 6.8: The closed interaction loop of the *EdgeMatrix*. Details in the text.

Prototype

We used the prototype to transfer a two-dimensional 5x5 raster corresponding to the virtual information under the dominant fingertip onto the contralateral palm. The decision to use this position was based on the well-known characteristics of the mechanoreceptive units in this glabrous skin area. We used electromagnetic solenoid units again, as we found very low latency with this form of actuator during our work with the *PhantomStation*. However, we had collected negative opinions on the strength of the stimulus when using larger actuators, so we decided to use weaker solenoids. Again, solenoids only have two states: fully extended or fully retracted. Thus, no slopes can be represented by the *EdgeMatrix*. The interaction process with the system is depicted in figure 6.8. The prototype is following the general concept of a closed loop sensory substitution system (see section 4.3): The user moves his finger on the touch surface. Constantly, an (invisible) 5x5 matrix with the dimensions 10x10 mm is attached to the location of this touch like a mouse-pointer. This virtual element serves as a sensor matrix, as soon as the user crosses a virtual line or edge, each of the 25 matrix elements perform a hit-test. If a matrix element is in contact with the virtual object, this information is transferred onto the tactile shape display. The corresponding number of single solenoids are actuated on the *EdgeMatrix* and push against the user's palm. This sensation is constantly changing due to the movement of the dominant finger. Thus, the interaction loop is closed and manual exploration is tightly coupled with tactile sensations.

Technically, the interactive surface is projected onto a table. An infrared LED is attached to the interacting hand and tracked using a camera. We also could recognize the horizontal rotation angle of the user's finger by putting two LEDs on the finger (one on the nail, the other one closer to the knuckle). This information is not available when using standard touchscreens. The hit-test information of the virtual sensor matrix is transferred to an Arduino Mega 2560 which in turn activates the individual solenoids in the tactile matrix. We used off-the-shelf solenoids for industrial use[8].

[8] Black Knight tubular push solenoid, 5 V

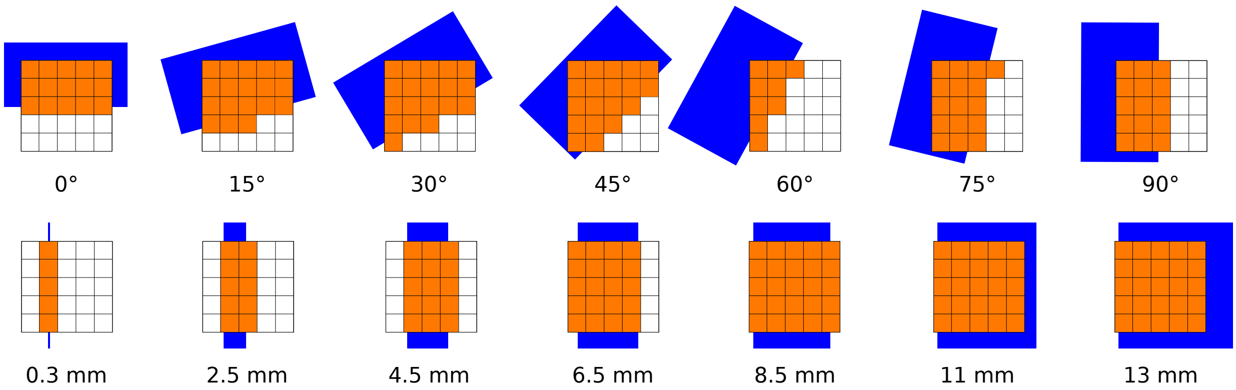


Figure 6.9: Different object angles and line widths during the *EdgeMatrix* evaluation and the corresponding representations in the virtual sensor matrix.

The total size and resolution of the active area was designed based on the two-point-discrimination threshold in the human palm: here, two distinct tactile stimuli can be distinguished if they have a distance of 12.5 mm or more. Therefore, the solenoids' rods (aperture: 1.6 mm) have a distance of 13 mm and the active area is 50 mm^2 in total. On the contrary, the two-point-discrimination value on the human fingertip is about 5 times smaller. Therefore, we defined the size of the virtual sensor matrix as 10 mm^2. Similar to the *Relief* prototype presented in [Leithinger and Ishii, 2010], a transparent membrane can be put atop the active area of the *EdgeMatrix*, thus merging the stimuli into sensations of moving forms.

Evaluation

Our goal is to provide high resolution shape information using simple remote tactile feedback. We were interested in how people utilize this form of remote tactile information to identify virtual objects and forms. Based on previous studies, where people did not integrate the remote tactile feedback when visual information was sufficient, we decided to allow for non-visual object exploration only. In the evaluation, we tested the participant's ability to identify the orientation of virtual objects and the width of virtual lines using remote tactile stimuli.

Twenty-eight participants (14 female, average age 26 years) took part in the evaluation which had a within-subject repeated measures design. There were two tasks (see figure 6.9): First, the participants were asked to identify the orientation angle of seven virtual planes. Second, the participants were asked to detect the width of seven virtual lines. Both the planes and the lines were not visible on the interactive surface, but could be explored using the dominant hand, remote tactile feedback was given at all times. The participants were free to explore the virtual objects as long as they wanted before giving a value. The sequence of the two tasks and the sequence of line widths and angle grades was fully counterbalanced over all 28 participants[9]. For the angle identification tasks, participants were provided with a picture of an angle meter and the information on the seven existing angles. For the line width task, participants had the possibility

[9] For this evaluation, the orientation (rotation) of the interacting finger was not tracked and the virtual sensor matrix was not rotating to maintain a transferability of the concept onto other common touch surfaces.

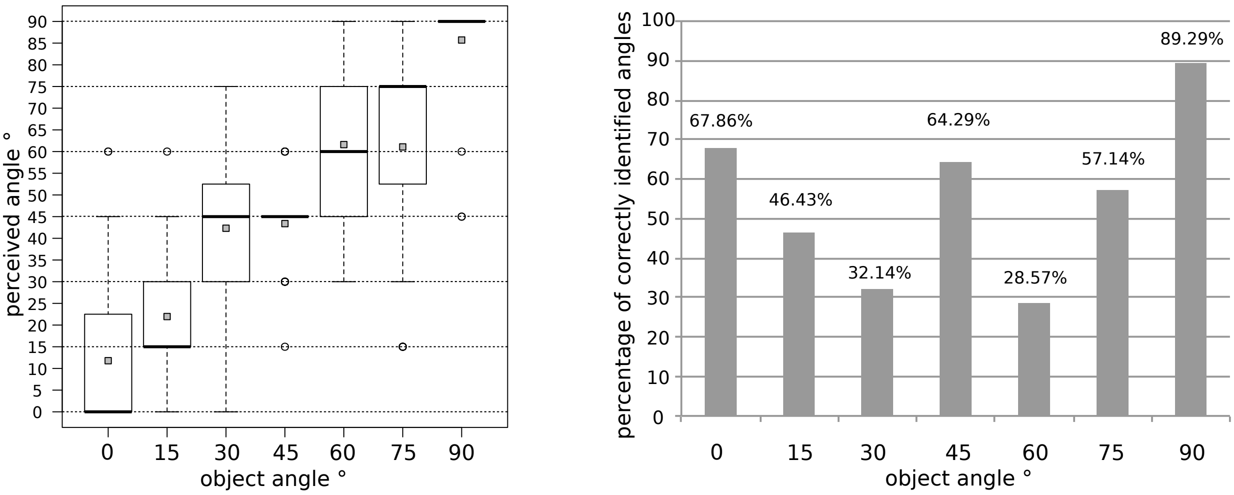


Figure 6.10: Results for *EdgeMatrix* angle task: Perceived angle for the presented virtual edges' angles (left). Rate of correctly identified angles for the virtual edges' angles (right).

to look at a ruler, but were free to decide on the millimeter value. Finally, all participants were asked to fill in a questionnaire on perceptibility of the stimuli, their ability to integrate the remote sensations and their feeling of 'touching virtual objects'.

Results

The results show a high rate of correctly identified angles and line widths. Figure 6.10 shows the results for the exploration of virtual object angles: For six out of the seven angles, people were able to identify the correct degree (according to the measured medians). Angles of 0° and 45° were identified correctly with a percentage over 60%, 90° was identified in almost 90% of the cases. All other angles were identified with stable rates of over twice the chance level.

For the task in which participants were asked to feel out a line width solely based on remote tactile feedback of the 5x5 matrix, the results are depicted in figure 6.11. The results indicate a stable rate of width-identification for virtual lines. However, we observed an offset of about 6 millimeters between the actual line width and the median line which was experienced with the *EdgeMatrix* by the participants.

Discussion and Conclusions

Our goal with the simple prototype *EdgeMatrix* was to evaluate the feasibility of remote tactile shape information. With this notion, future implementations can simplify the integration of this form of tactile actuation, as the number of individual stimulators is greatly reduced, no actuators have to be integrated into the surface and a large number of single pin actuators render the information under the user's fingertip. Our evaluation with the basic interface shows the ability of the participants to utilize this form of haptic information to analyze and identify virtual objects, when no visual parameters are provided. We were surprised by the participants' performance who did not have previous experiences and extended learning phases with the system.

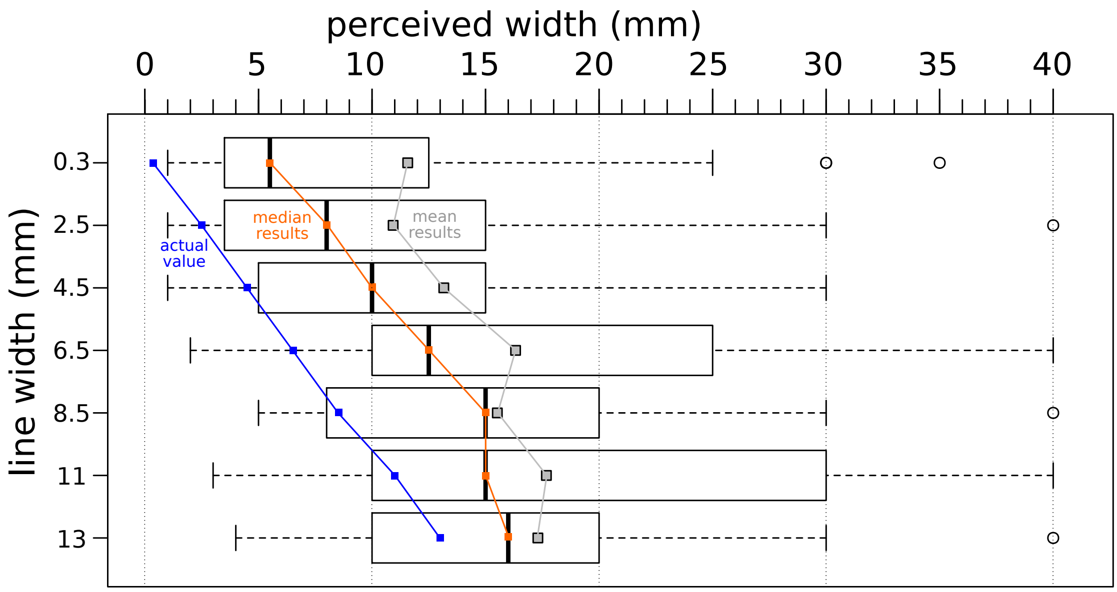


Figure 6.11: Results for *EdgeMatrix* line task: Perceived line widths for the presented virtual lines.

The participants' answer in the questionnaire helped us to further refine our results: Two third of the participants stated that they were 'never' or 'rarely' irritated by the relocated stimuli. Interestingly, over half of the participants said that they 'sometimes' or 'often' had the feeling, they were really 'touching' the virtual objects. Moreover, twenty percent stated that they 'always' could palpate the elements. Negative remarks were given on three aspects of the interface which helped us to further refine the concept: First, the positioning of the *EdgeMatrix* was found to be cumbersome, people were forced to rest their non-dominant hand on the device. Second, several participants noted that the matrix should adapt to the user's body surface like a second skin. The palm is curved, every pin applies a different force on the skin. A more adaptable interface could help to equalize the sensations coming from each actuator. Third, people were irritated by the noise coming from the ventilation and the activated electromagnetic solenoids. This should be minimized in future implementations. These three technical enhancement were incorporated when we designed the matrix-based remote tactile feedback in the car described in section 6.2.2.

In summary, the *EdgeMatrix* reinforces the practicability of remote tactile feedback. By closing a tight interaction loop, the very basic tactile information coming from the 5x5 matrix was integrated into a coherent overall sensation. Manual exploration is a crucial concept of tactile interaction, its implementation is facilitated and technically simplified by the use of remote tactile feedback.

6.2 Proactive, Reactive and Detached Tactile Feedback

In section 2.3, unintended activation (also known as the 'Midas-Effect') was identified as a conceptual challenge of interactive surfaces. This challenge has been addressed before by the addition of pressure sensing: The user can explore the interactive surface by touch, additional pressure activates a virtual element. Tactile feedback can be given during these proactive and reactive phases (e.g. in [Richter et al., 2010]). This helps to prevent mode errors and to support interactions which do not interfere with concurrent tasks (such as driving a car).

The concept of tactile stimuli before, during and after input is omnipresent in real-world input elements such as mechanical push buttons. Here, we can feel the button's form and position before and after activation which informs non-visually about function and state of the element and the progress of our interaction with it. The prototype *TacSnap* transfers this rich and meaningful tactile information on touch surfaces using remote tactile feedback and avoids the need to implement force sensing technology into the screen.

Another method for proactive and reactive feedback is the provision of sensations before and after the finger is in contact with the screen. Naturally, this concept is not practicable when the screen itself is actuated. Therefore, we implemented two remote tactile feedback systems which track the user's finger before, during and after touch input: We implemented a matrix of pneumatic remote tactile actuators in the seat of a vehicle to support the driver's input on a touch-based in-vehicle-information system. An elaborate field study with the system evaluates its potential to improve the usability of in-vehicle touch interfaces and to reduce the mental load for the user. Finally, the *Interactive Watzmann* explores tactile feedback above non-planar interactive surfaces. The prototype haptically augments gestural interactions over the surface. The tactile stimuli are spatially and conceptually detached from the non-planar surface.

The three projects demonstrate that remote tactile feedback provides flexibility in three ways: First, more complex forms of actuation can be applied, but do not have to be implemented into the touch surface. Second, tactile feedback can be given in mid-air before and after the actual touch. Third, the tactile feedback is independent from form and material of the interactive surface.

6.2.1 *TacSnap*: Push Button Behavior on Touch Surfaces

With the *TacSnap* project, we[10] present our twofold approach to transfer the multimodal characteristics of push buttons onto interactive surfaces: First, we analyzed the force-path-characteristics of physical buttons and deduced a descriptive model which substitutes input force with input dwell time. Second, we implemented the concept using a remote tactile feedback interface. Subjective opinions on the concept and the perception of the stimuli were collected in a preliminary evaluation. This work was also published in [Richter and Schmidmaier, 2012].

[10] This work was part of Matthias Schmidmaier's Project thesis [Schmidmaier, 2011].

Mechanical Push Buttons for Interactive Surfaces

The activation of a mechanical push button is a multimodal experience which has five phases:

1. Taking aim and reaching towards the button with the hand in the air.
2. Touching the element collecting haptic cues which immediately inform us about the button's function and current status.
3. Pressing of the button; varying forces and displacements give feedback during this reversible process towards activation.
4. Activation; a confirming 'snap' can be felt or heard. Subsequently, the user's finger reduces the pressure and the button moves back to the starting position.
5. Finally, the touching finger leaves the button's surface.

This 5-step process can be performed rapidly, depending on the mechanical characteristics of the button. Multimodal feedback is given throughout all stages.

These rich sensory cues continuously convey the button's location, form and the state of our interaction with it. Therefore, the manipulation of mechanical buttons demands very little visual and cognitive attention; their feedback allows for typing on a computer keyboard or turning the in-car ventilation knob fast and precisely. According to Abigail Sellen's classification of sensory feedback [Sellen et al., 1992], this information can be characterized by the time it happens. Reactive feedback helps to acknowledge an action whereas proactive feedback can help to determine the current mode *before* taking action. For interactions with digital information, Sellen states that "by providing sensory feedback, a common class of error (mode errors) can be significantly reduced for both novices and experts" and that combined visual/tactile feedback can "significantly improve performance" [Sellen et al., 1992]. However, this form of sensory information is very limited on today's touchscreens, as the (programmed) non-visual feedback is reduced to a short 'buzz' or 'click' *after* touching the on-screen keyboard. Sellen describes tactile feedback as being 'sustained, demanding, and actively maintained'. This salience of tactile feedback increases its efficiency in preventing mode errors. Our *TacSnap* protyotype can provide remote tactile feedback coupled with a multi-step push button input on a touch surface.

Physical push buttons directly transfer the forces coming from the user's finger into mechanical movement. On touchscreens, the user's pressure has to be measured and processed in order to utilize it as a form of input mechanism. Force sensing on touchscreens can be done directly by implementing force sensors into the touch surface or into individual segments of the screen. A method of indirectly estimating the amount of applied pressure is to analyze the size of the contact area between fingertip and screen using capacitive or optical sensing [Benko et al., 2006]. The size of the contact area grows with the amount of applied force. However, this value differs for every single finger of the hand and for multiple users. In 2003, Nashel et al. [Nashel and Razzaque, 2003] suggested the use of linger or dwell time during touch input for the estimation of pressure on touch devices. The longer the finger stays on an element, the harder a button is pushed. However, they did not formalize or generalize this notion. This interesting idea is backed by findings from Kaaresoja et al. [Kaaresoja et al., 2011] who found that users perceive buttons with longer feedback delays as heavier and harder to press. In order to prevent from the need to implement force sensing technology into interactive surfaces, we

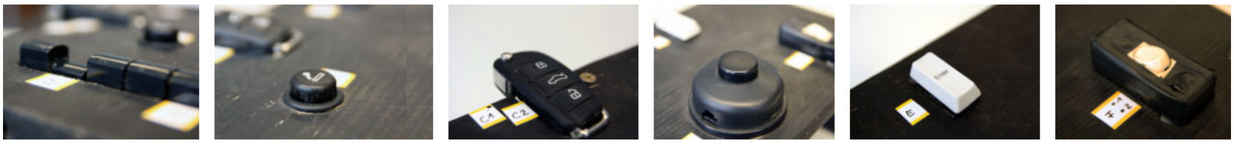


Figure 6.12: Examples for mechanical push buttons.

developed a substitution model which formalizes the connection of input force and input dwell time.

Substitution Model

The basic principle of our substitution model can be described as follows: The substitution of input force with input dwell time can be deduced from the movement speed of the button during the phases of interaction: The more force is needed, the slower the movement of the button. If we disregard the actual displacement during input (which can not be recreated on solid touchscreens), we may substitute the force of input with the speed of input (which also affects the speed of output/feedback).

In an initial analysis, we measured the ratio of input force and displacement for different physical push buttons (see figure 6.12). We applied two measurement techniques: The first one was a mechanism consisting of a stepper motor and a Force Sensing Resistor[11]. The button was pushed automatically, the applied force was measured for each step. This method resembled the (more elaborate) test-rig developed by Nagurka et al. [Nagurka and Marklin, 2005]. As our collected force and displacement data lacked resolution, we implemented a second method to measure the buttons' characteristics. With an FSR sensor mounted to the fingertip, each button was pressed several times. We averaged the resulting ratios for each button and translated the values in Newton using the sensor's resistance-force curve.

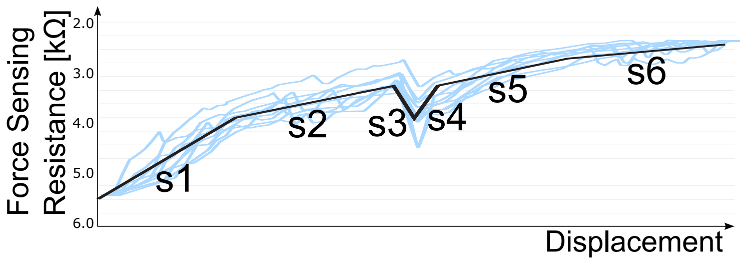


Figure 6.13: Overlay of measured force-path-behaviors of a basic push button and separation into six linear sections. The segments are described in the text [Richter and Schmidmaier, 2012].

The resulting force diagrams of the measured buttons have several key components forming the tactile characteristics of the button (see figure 6.13). These characteristic sections can be defined

[11] FSR type IEEFSR-150NS

by strong changes in the curve's gradient. We averaged the FSR vales for the start and the end of each section and determined fixed ratios between force and displacement.

Figure 6.14 depicts the resulting schematic for a force profile with six sections a to f: For section a, a higher amount of input force Δf is needed to achieve the corresponding displacement Δd. Following our substitution model, this higher amount of needed force would be emulated with an increased amount of input dwell time, resulting in slow feedback. The opposite holds true for section c: A low amount of input force is needed to pass through the section, resulting in a reduced time that is needed to pass through the section caused by short dwell times and fast feedback. For most push buttons, the activation happens in this section. In general, our approach allows for a user-defined accuracy of approximation: The more individual section are defined or known from measurement, the more detailed the force profile can be recreated [Richter and Schmidmaier, 2012]. The formula in figure 6.15 describes our substitution model for each distinct section more formally.

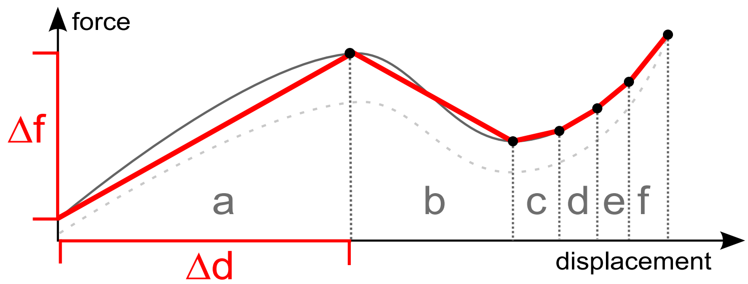


Figure 6.14: Schematic example for the segmentation of force-path behaviors. The dotted line represents the button's mechanical behavior during the return phase [Richter and Schmidmaier, 2012].

This way, we accentuate the strong and defining aspects of a button's mechanic behavior. A button which is harder to press takes longer to activate on a touchscreen. A button with a defining 'snap' during activation can be replicated as this defining characteristic is replicated by the rapid change of feedback on the touchscreen. The action is reversible before the actual activation of the button. Following this model, we can recreate visual, auditory and tactile cues of push buttons on touch surfaces without pressure sensing. In the following, I present our implementation of this principle with a remote tactile interface.

$\text{dwellTime}_{section}$ = (Δforce + forceStart) * delayFactor	
$\text{dwellTime}_{section}$	duration of section [msec]
Δforce	amount of force for this section [N]
forceStart	force needed to start the button's movement [N]
delayFactor	describes the relation between force and dwellTime

Figure 6.15: The formula describes the substitution of input force with input dwell time for a single section in the force-path-behavior of a push button [Richter and Schmidmaier, 2012].

Figure 6.16: The *TacSnap* prototype is applied to the ball of the thumb during use [Richter and Schmidmaier, 2012].

Prototype

In order to implement the principle for tactile feedback on touch surfaces, we developed the simple feedback device depicted in figure 6.16. The device consist of a high-torque servo motor[12] and a linkage system which moves a pin up and down, similar to the *FEELEX*'s piston crank system [Iwata et al., 2001]. The mechanism could be applied to different locations of the body, such as the back (when implemented in the chair) or the wrist (when using a small-scale wearable implementation). The user is resting the non-dominant hand on the device. When the dominant fingertip touches a virtual push-button on the screen, the pin pushes against the ball of the user's other thumb.

The functional principle of the system is depicted in figure 6.17. The virtual button's tactile characteristics during its activation are transferred to the non-dominant hand in upward direction. Thus, we recreate the deformation of the skin which is happening when our fingertip presses a mechanical button: The harder we press a physical button, the stronger the skin is deformed. This deformation is reproduced on the non-dominant hand. For each section of the virtual button's force-path-behavior, we apply our substitution model, i.e. harder sections take longer to pass through. Consequently, the movement speed of the tactile pin varies for each section[13]. After complete activation of a button, the contact pin retreats into the encasing.

Preliminary Evaluation

In a preliminary evaluation with nine participants, we wanted to optimize our model and collect first user feedback. Our first goal was to optimize the force-to-speed substitution by identifying a general value for the force-to-speed-substitution ratio (i.e. *delayFactor*). Therefore, we depicted three virtual representations of three physical buttons on the touchscreen. When touched, the

[12] Modelcraft MC-630 MG

[13] The servomotor moves the pin in small discrete steps of 0.25 mm. By varying the delay between each of these steps, we could define the movement speed.

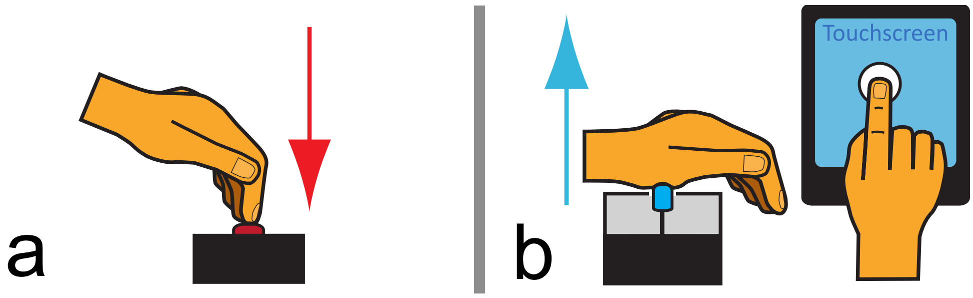


Figure 6.17: Functional principle of the *TacSnap* prototype: a: A physical button is pushed down which results in a deformation of the skin on the fingertip. b: This deformation of skin is recreated remotely by the upward movement of the interface's pin when a virtual push button is pressed [Schmidmaier, 2011].

visual representation (e.g. height, color, brightness) changed according to the model, the tactile information was given using the prototype. Participants were allowed to freely try the physical and virtual version. Meanwhile, the participants were asked to adjust the replay speed of the virtual buttons to make the feedback similar to the stimuli coming from the mechanical buttons. We assumed a similar speed ratio across all participants. However, the value was highly variant and differed greatly from participant to participant. This topic needs further attention in future evaluations.

In guided interviews, we asked the participants about their opinion on several topics such as: the relocation of the stimulus, other possible areas for application, potentials of the system and the difference between virtual buttons with and without remote tactile feedback. All but one participant (who was 'irritated by the relocation') stated that the *TacSnap* feedback felt 'good' or 'interesting' and the relocation was 'forgotten' after a 'short time'. The nine participants perceived great variances in the quality of the stimuli ('too slow', 'missing sounds'), but could easily discriminate between the virtual buttons due to the feedback. When presented with the virtual buttons with visual-only feedback, 7 out of nine participants stated that they preferred the tactile virtual buttons, because they are more 'distinguishable', 'pleasant' and one feels more 'connected to them'.

Discussion and Conclusions

The *TacSnap* concept is an exploration of the potential of recreating the rich proactive and reactive multimodal characteristics of mechanical push buttons. We presented a model which substitutes input force with input speed, thus avoiding the necessity to implement force sensing on touch surfaces. Using a remote tactile interface, we exemplify the principle of feedback with dynamic speed changes. In a preliminary user study, we collected positive user responses on the feeling of the created stimulus and the feasibility of the relocation. Furthermore, the augmented buttons were perceived as highly discriminable and involving.

The concept presented here is clearly a work-in-progress, future implementations and evaluations are necessary to strengthen our first positive results: Future implementations should consider other, more practical locations of application. The maximum displacement and size of the pin should be adapted accordingly. Also, the force feedback is a trade-off between rich stimuli and interaction speed: The harder a button is to press, the longer the activation is taking which might be undesired or unnecessary in situations with sufficient visual feedback. This concept is very basic research, I can not recommend a clear usage scenario yet. However, participants in the study could imagine to have buttons on touchscreens which are 'harder to press' because they activate important functions. Others embraced the 'finer control' and the distinguishability of the buttons.

In summary, the *TacSnap* principle demonstrates that remote tactile stimuli can provide elaborate proactive and reactive feedback. This work concentrated on the substitution of input force with input speed, resulting in dynamic feedback speed. This concept can be applied to visual, auditory and tactile feedback to create more lifelike and distinguishable digital control elements. Furthermore, special widgets with no physical representation can be created by applying the substitution.

6.2.2 *AutomotiveRTF*: Remote Tactile Feedback in the Car

The development and the implementation of the *AutomotiveRTF* project are the result of lessons learned from related research and own research projects: First of all, tactile feedback has been proven to be most helpful in terms of improving the usability of an interactive system in scenarios with increased visual or cognitive load or multitasking (see section 3.3.2). With the *HapTouch* project (presented in section 3.3.3), we have already identified tactile feedback as beneficial for touch-based interactions with in-vehicle infotainment-systems. Next, we implemented several prototypical systems for remote tactile feedback which were used in laboratory user studies. In these evaluations, the tactile stimuli were applied on the non-dominant hand or forearm, mainly due to the well known characteristics of tactile mechanoreceptors in these areas and to maintain the generalization of the results. However, we should also examine tactile feedback on other locations of the human body to allow for more versatile and practical future implementations of the concept. With the *EdgeMatrix* prototype, we showed that low-resolution actuator matrices can communicate meaningful tactile information such as virtual objects' orientation, location and contour. Finally, the concept of remote tactile feedback has not been evaluated before in a realistic usage scenario or in-the-wild.

For all these reasons, the *AutomotiveRTF* project was developed in collaboration with BMW Research Munich[14]: We[15] implemented the system in a car by customizing components from the serial production. The driver is in permanent contact with several elements of the car interior, we chose to to implement a matrix of pneumatic actuators in the back of the seat. Thus, we could utilize the location of the stimulus on the user's back as another parameter of tactile feedback design. Finally, the system was tested in an on-the-road field study.

[14] BMW Forschung und Technik GmbH

[15] This work was part of Michael Schmidmaier's Diploma thesis [Schmidmaier, 2012].

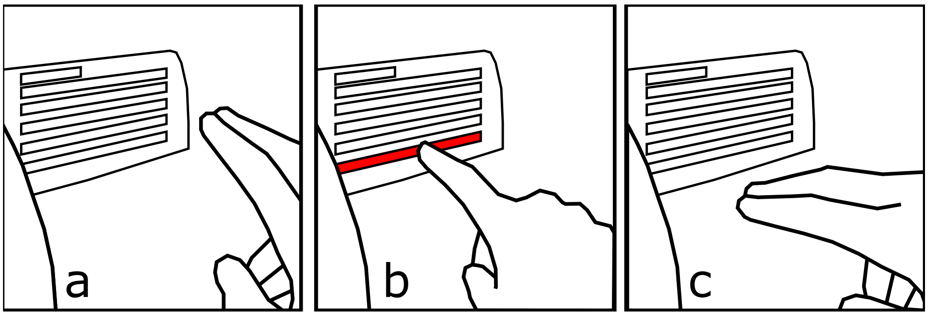


Figure 6.18: Remote Tactile Feedback can support phases (a) before, (b) during and (c) after a direct-touch interaction (from [Richter and Wiethoff, 2011]).

I consider this project as one main contribution of this thesis. Still, the description of the work on the *AutmotiveRTF* system is integrated in this chapter on proactive and reactive feedback, as this is one of the essential characteristics of the general 'remote tactile feedback' concept. A patent is applied for the system. Therefore, it has not been presented in more detail in a scientific paper yet. The basic principle for remote tactile feedback in the car has been proposed in [Richter and Wiethoff, 2011].

Prerequisites for In-Vehicle Interaction

Due to the increasing functionality of in-vehicle-infotainment systems, touchscreens are more and more used as the primary interface [Pitts et al., 2010]. Physical controls for distinct functions are not appropriate, as the space on the car's dashboard is limited. The concept of 'one button per function' has had its day. Manufacturers have also relied on haptically enabled controllers (e.g. BMW's iDrive or Audi's MMI), but these can have disadvantages in terms of usability [Rydström et al., 2005] and increased (but interruptible) interaction times [Ecker et al., 2009]. Touchscreens provide simple direct manipulation and are robust enough to be deployed in a car. Still, the missing tactile information has been identified as a disadvantage in this scenario. Several evaluations show that haptic feedback can compensate for increased visual workload, especially when visual feedback is restricted [Pitts et al., 2010].

Driving a vehicle while trying to glance at a map, using the in-vehicle-infotainment system or having a conversation with the fellow passengers is a mentally demanding (multi-)task. In order to understand human performance in such scenarios, Wicken's multiple resources theory (MRT) describes interference between two tasks which share sensory modalities [Wickens, 2008]. According to this model, human resources are limited and the performance of a certain task decreases, if other tasks require the same resource simultaneously. In the car, the occurring interactions may be classified into three categories: The primary task is the driving task which requires the most visual attention. It includes the control of the car and the observation of the environment. The secondary task directly supports the primary task and ensures road safety. Examples are the setting of turning signals or the control of lights. The tertiary task is used to address functions of entertainment and comfort. The use of the touchscreen falls in this third category. Therefore, mental and visual load should be minimized when the touchscreen is used in order to minimize

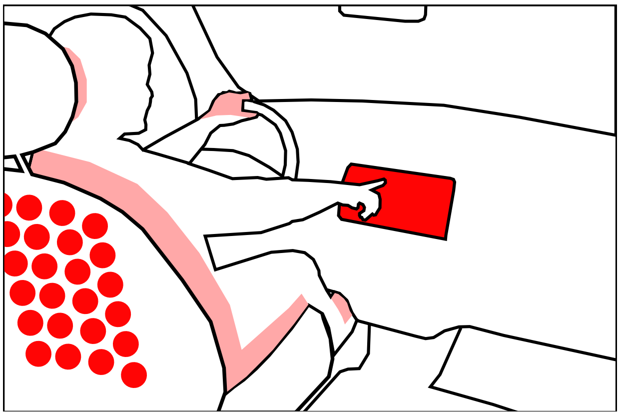


Figure 6.19: Various parts of the driver's body are in permanent contact with the car's interior and thus can be used to communicate remote tactile stimuli. The *AutomotiveRTF* system uses a matrix of pneumatic elements implemented in the backrest to provide remote tactile feedback.

interference with the safety-relevant primary and secondary task. Switching to the haptic channel as feedback information can further increase usability and safety.

In order to minimize visual and cognitive load caused by in-vehicle user interfaces, several general requirements for their design and behavior have been defined and standardized [ISO, Geneva, Switzerland, 2003a, ISO, Geneva, Switzerland, 2003b]. Among others, the input should require as little visual attention as possible, the interaction has to be possible without the simultaneous use of both hands and no explicit learning phase should be required.

The *TacSnap* prototype addresses these challenges: tactile feedback is introduced to allow for interaction with reduced visual load. Furthermore, we provided proactive and reactive feedback. Tactile feedback is given before, during and after the interaction - similar to an interaction with physical controls. The user is informed on the position and type of the interactive element under his fingertip before actually touching the screen surface (see figure 6.18). The system tracks the user's finger in mid-air and thus can provide programmed tactile information coming from the backrest during this phase of manual targeting and exploration. Also, the user is informed about the consequences of the interaction non-visually and can return to the primary task without the need to check for visual acknowledgments on the screen.

Implementation

Following the general structure of an interactive feedback device, the system can be described as having three main components: a touchscreen and a tracking apparatus to capture the finger's position in the proximity of the screen and on the screen. An embedded micro-controller and PC serving as coupling device between sensor and actuator system. Finally, a matrix of individual pneumatic actuators in the backrest serve as remote tactile feedback system to provide localized stimuli.

Touchscreen and Tracking: The tracking above the 10.4” touchscreen which is positioned in the dashboard is performed using a Microsoft Kinect[16]. In the final prototype which was embedded in the car, the depth-sensor is mounted over the windshield in a distance of 60 cm to the screen. The Kinect is mounted almost perpendicular to the touchscreen, capturing an area of about 50 cm x 37 cm with a resolution of 640 x 480 pixels. The touchscreen is part of this viewing window and a tracking area with a resolution of 50 x 18 quadratic fields is defined. Following BMW’s guidelines for the minimum size of widget elements (1.15 cm^2), the resulting side length of 0.575 cm for each ’tracking pixel’ is sufficient for high resolution tracking. To further boost performance, we implemented a resolution of 21 x 7 fields for the prototype which was used in the evaluation. In z-direction, a ’hover space’ of 20 mm was defined, allowing for a resolution of 10 steps (the Kinect has a depth resolution of about 2 mm in a distance under 100 cm). The tracking application is based on two assumptions: The user is positioned to the left of the touchscreen and interacts with the right hand. Also, the system estimates the position of the tip of a single stretched finger, with the fingertip closest to the screen.

Coupling Device: A PC[17] serves as a coupling device: it is used to display the touchscreen GUI and to handle the tracking data. The tracking application is written in C++, using the *OpenNI*[18] framework and the *PrimeSense NiTE Middleware*[19]. The calculated tracking data is transferred to the user application (written in *Actionscript 3*) over a socket connection. The PC is connected to an Arduino Mega over USB using the *as3Glue v2.0 library*[20] in combination with *Serial Proxy v0.1.4* and the Firmata protocol v2.3.2 [21].

Actuator System: Main component of the actuator system is a modified pneumatic massage system, which is available as optional equipment for the rear seat. The original back massage mat consists of 12 individual cells, we separated 6 pairs of cells resulting in a total number of 18 individually controllable air cells (see figure 6.20). The decision to modify this equipment and utilize it as actuator is based on several reasons, such as:

- Unobtrusive implementation in the backrest.
- Amplitude of movement freely controllable.
- Designed to ensure perceivable stimulation for 95% of users.
- No audible operation noise.
- Low energy consumption.
- Robust close-to-production hardware for continuous use.

The physiologic characteristics of tactile mechanoreceptors in the human back have been taken into account: As described in section 3.1.1, the two point discrimination value on the back averages 40 mm, the distances between the individual cells of the mat exceed this value. Furthermore,

[16] `http://www.microsoft.com/en-us/kinectforwindows/` [cited 2013/02/09]

[17] EliteBook 8730w, Windows7

[18] `http://www.openni.org/` [cited 2013/02/09]

[19] `http://www.primesense.com` [cited 2013/02/09]

[20] `http://code.google.com/p/as3glue/` [cited 2013/02/09]

[21] `http://firmata.org/wiki/` [cited 2013/02/09]

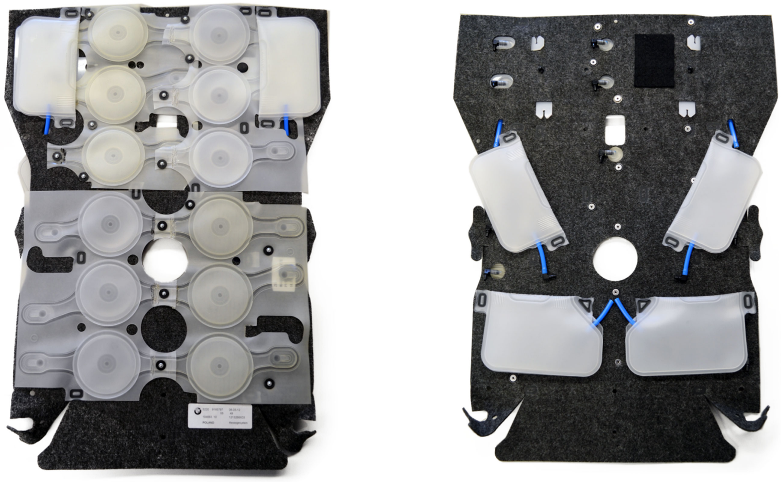


Figure 6.20: The modified air cell pad of BMW's pneumatic massage mat: The front view (left) shows 14 individual cells, the back side (right) contains four larger air cells (from [Schmidmaier, 2012]).

the back is highly sensitive to pressure changes (see figure 3.5), which makes it a adequate location to apply different levels of force. Moreover, the back has been used as a body location for tactile stimulation before[22].

Two air pumps[23] are part of the system: one for inflation and one for venting. Both pumps are serial components of the BMW massage mat. Each air cell is connected to these two pumps by individual tubing. A controllable valve is inserted into in each channel. Filling and drawing the air is performed by opening or closing the valves, the pumps are continuously activated. Each valve can be activated individually by the Arduino, the duration of filling and venting determines the size of the cell and thus the tactile stimulus.

The cells are prefilled to allow for fast and low-latency tactile feedback. The times needed for an empty cell to be filled to the minimum extent which is perceived by a participant were identified in a preliminary evaluation with six participants. The resulting prefill-values varied between 76 ms (small cells) and 224 ms (largest cells). This prefill procedure allows for small latency: the system can react to the user's input in under 150 ms. For single small cells, even fill or evacuation intervals of 20 ms are perceivable. Simple tactile patterns such as push, pull, pulse, horizontal alternating patterns, directional swipes and push-button-like behavior have been implemented. The resulting actuator system is depicted in figure 6.21.

[22] Additionally, we performed evaluations to measure the pressure distribution on a chair and consulted information from seat manufacturers.

[23] MAPU PY50936-G U13V

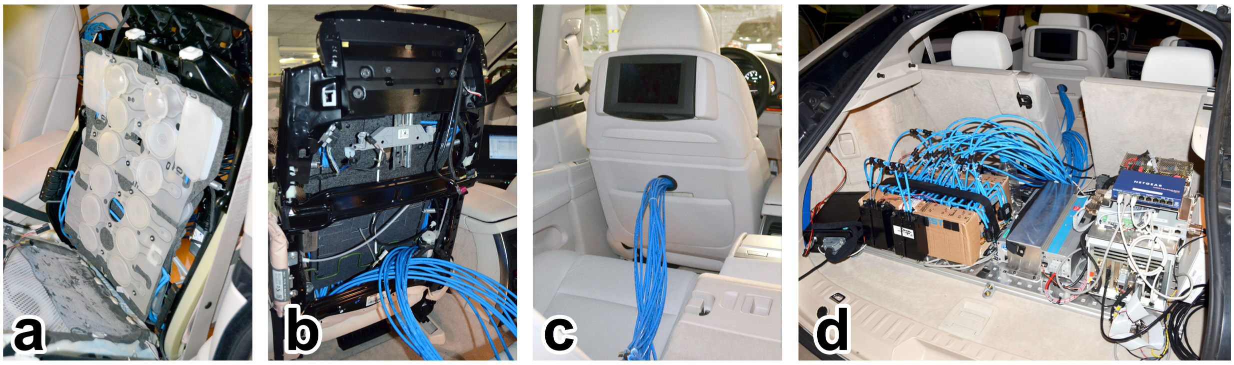


Figure 6.21: In-vehicle installation of the actuator system. a: The air cell matrix is placed underneath the backrest upholstery (padding removed for photo), b and c: Tubing runs to the pneumatic hardware in the trunk. d: Pneumatic hardware and control PC is placed on the left, the hardware on the right is not part of the system (from [Schmidmaier, 2012]).

Field Study

The development of a robust and versatile technical platform to evaluate the potentials of remote tactile feedback in the car was the primary goal of the *AutomotiveRTF* project so far. We analyzed the concept and the effects of the feedback in a field-study with 24 participants (four female, average age 35 years).

We implemented three tasks which are common on in-vehicle infotainment systems and also are part of BMW's current GUI (see figure 6.22). All three widgets follow BMW's standardized requirements for size and position. Each widget has two conditions, tactile and visual feedback or visual feedback only[24].

- **Dialing:** The user has to enter a number shown on the right of the screen. Remote tactile feedback is provided on hovering and activation. Single air cells on the lower back are used and alternate left and right when the user alternates between buttons.
- **List Selection:** The user has to select a given name from a list. A single air cell provides remote tactile feedback on touch, release and transition. Another air cell is activated when the list category is changed via the scroll bar. Further, a sequence of vertical cells are activated to indicate the scrolling and the absolute position in the list.
- **Targeting:** The user has to touch icons which successively appear on the screen. Remote tactile feedback using a single cell is given on hover, touch and release.

The study had a within-subject, repeated measures design and was conducted on public streets in the north of Munich. The route had a total length of 23 km and consisted of two-lane highways and inner-city roads with varying speed limits between 50 km/h and 100 km/h. The route had several traffic lights. Evaluations took place during the day and outside of rush-hour phases. The participants were asked to adjust the seat position according to their needs. After an introduction and training phase, participants were asked to primarily regard road safety and traffic regulations,

[24] Due to the limited space, an elaborate description of the tactile parameters such as fill time, position of air cell or activation sequence can't be given here. This information can be found in [Schmidmaier, 2012]

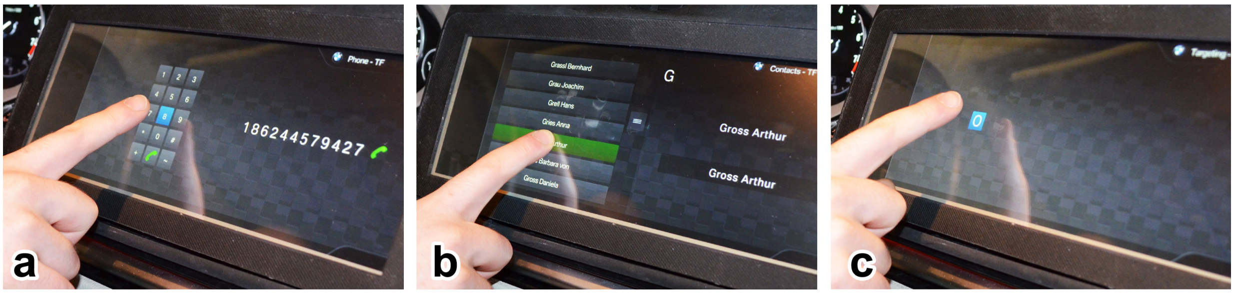


Figure 6.22: The three tasks of the field-study. a: Dialing, b: List Selection, c: Targeting (from [Schmidmaier, 2012])

to drive on the right lane and to follow the traffic flow. Eventually, the tasks were started manually by the examiner in a moderate traffic situation without traffic lights or lane-changing vehicles ahead. The order of tasks and modalities was fully counterbalanced. Each modality was repeated 5 times, the full evaluation took about 90 minutes per participant.

Several dependent variables existed: **Task completion time** was measured in all three tasks. The measurement started when the finger first touched the screen. The **number of missed buttons** was measured during the dialing and targeting task. The **number of scroll steps** was measured in the list selection task. Next, the **subjective mental workload** was collected after each task using a modified version of the Driving Activity Load Index (DALI) [Pauzié and Manzano, 2007], a tool similar to the established NASA Task Load index (NASA TLX) [Hart, 2006]. Using a questionnaire, subjective ratings on six dimensions of mental workload are captured: effort of attention, visual demand, tactile demand, interference with the driving task, temporal demand and frustration. Finally, a questionnaire consisting of five-point Likert scales and open questions were handed out after all tasks to measure **subjective quality and effects** of the remote tactile patterns.

Results

The results comprise both quantitative data and subjective ratings:

Dialing Task: The quantitative results for the dialing task are shown in table 6.1. A Wilcoxon test revealed a **significant increase of task completion time** by 13.7% when remote tactile feedback was given ($p<0.05$). No significant effects were found for the number of input errors and the number of missed buttons. The application of remote tactile feedback resulted in a **significant reduction of visual load** by 11.3% (see figure 6.23). This shift to the tactile caused a **significant increase of the tactile demand** by 62.2%.

List Selection Task: Quantitative results for the list selection task are shown in table 6.2. No significant effects were found for task completion time and the number of scroll steps. Again, the subjective workload ratings showed a clear preference for the visual-tactile feedback modality (see figure 6.23). All means (except for tactile demand) showed decreased levels of subjective workload, frustration and effort. A **significant reduction of visual load** by 10.6% was found using a Wilcoxon test ($p<0.05$).

	Task completion time (ms)	Number of input errors	Number of missed buttons
Visual-Only Feedback:	M=21090 (SD=7615)	M=1.4 (SD=1.9)	M=2.7 (SD=2.7)
Visual-Tactile Feedback:	M=23980 (SD=10955)	M=1.7 (SD=2.8)	M=3.3 (SD=3.3)

Table 6.1: Quantitative results for the dialing task.

	Task completion time (ms)	No. of scrolls steps
Visual-Only Feedback:	M=11590 (SD=9123)	M=2.9 (SD=6.9)
Visual-Tactile Feedback:	M=10930 (SD=5903)	M=2.5 (SD=6.6)

Table 6.2: Quantitative results for the list selection task.

Targeting Task: Table 6.3 depicts the measured results for the targeting task. No significant effects were found for task completion time and the number of missed buttons. Subjective workload ratings (see figure 6.23) showed decreased values for visual and temporal demand, when remote tactile feedback was given. However, a **significant increase of tactile demand** by 15.4% was found using a Wilcoxon test ($p<0.05$) for the visual-tactile modality.

Further Subjective Ratings: When asked how well they could associate the tactile feedback on the back with the interaction on the screen, 20.83% of the participants stated 'very well' and 37.5% 'well'. No participant could not associate interaction and feedback. For all three tasks, the tactile patterns were perceived rather or very distinctively: the answer 'rather well' or 'very well' was given by 67% (targeting), 62.5% (list selection) and 62.5% (dialing task).

However, the patterns were found to be not easily discriminable. Participants stated that they could not really identify different patterns for hover, touch and acknowledgement. The majority of participants could 'not at all' or 'hardly' discriminate the different feedback stimuli: 62.5% (targeting), 54.2% (list selection) and 62.5% (dialing).

Interpretation

The remote tactile feedback interface deployed in this field study for the first time. For a start, we implemented three very different widgets which also differed in their (makeshift) design of the corresponding tactile feedback: proactive stimuli were given during the hovering over the dialing keys and the target icons, but not on for the list widget. On the other hand, the list widget gave localized feedback and indicated the current position in the list by positioned stimuli on the user's back. We expected very diverse results regarding objective and subjective measurements for the three tasks.

However, we found three main effects common for all widgets: First, the remote tactile feedback did not have an effect on the number of input errors and (mostly) total task time. For the dialing

	Task completion time (ms)	Number of missed buttons
Visual-Only Feedback:	M=22370 (SD=8194)	M=5.8 (SD=5.2)
Visual-Tactile Feedback:	M=22970 (SD=8544)	M=5.6 (SD=5.2)

Table 6.3: Quantitative results for the targeting task.

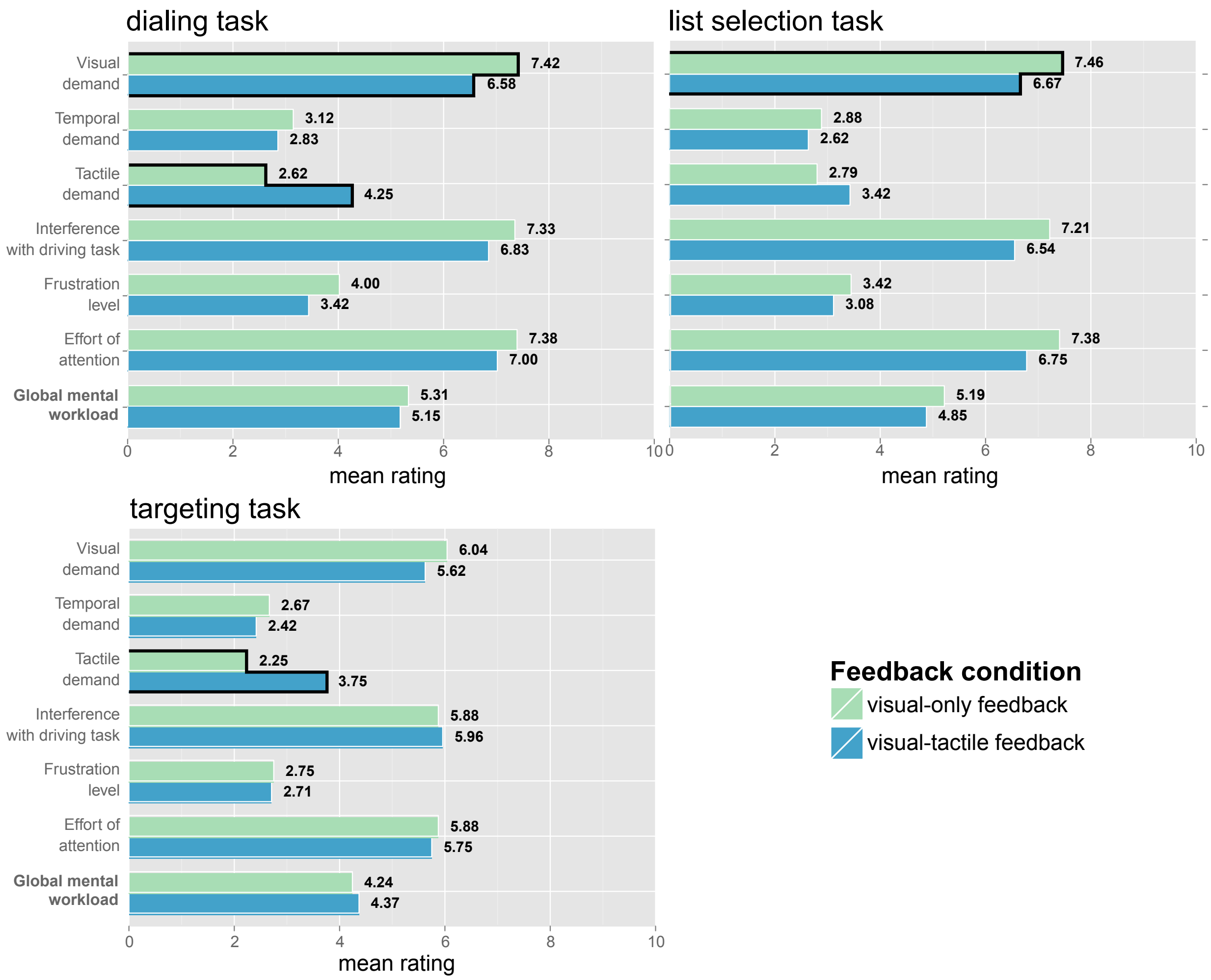


Figure 6.23: Subjective workload ratings fro the three tasks (0 (low) to 10 (high)), N=24. Significant differences are marked (adapted from [Schmidmaier, 2012]).

task, the total task time was increased by the addition of remote stimuli. Interestingly, the users seemed to utilize the rather complex proactive and simultaneous feedback, which resulted in a significantly reduced subjective visual load over 10%. In the in-vehicle context, the decrease of visual load may have a higher priority than an increase of total task time. Second, remote tactile feedback could significantly reduce the subjective visual load for two out of three tasks (dialing and list selection). It can be assumed that the more elaborate design of tactile stimuli may be the reason (as only one air cell was active during the targeting task). Third, the subjective estimations of the remote tactile feedback concept and the stimulus design were similar for all three tasks: First of all, participants clearly could associate their interaction with the feedback on the back. Next, tactile feedback increased the tactile demand, which indicates a shift from the visual to the tactile modality. Then, the pneumatic actuator system created clearly perceivable stimuli. Finally, the tactile stimuli during hover, touch and release were hardly discriminable. Unintended motions of the hand in the moving car resulted in too much tactile information, especially during the dialing tasks, were the buttons were close together. The tactile hover effect may be useful for rough localization of elements more apart from each other.

In general, the proactive tactile hover effect should be used sparingly (especially in the car) to prevent tactile information overload. The reactive feedback, however, was stated to be well suited for acknowledgments when the finger has left the screen. Also during continuous interactions such as list scrolling, remote tactile feedback was found helpful. More elaborate stimulus design and the intensified incorporation of location as an additional stimulus parameter should be used to strengthen our first positive effects,

Discussion and Conclusions

The *AutomotiveRTF* project is the first implementation of the remote tactile feedback concept in an automotive environment. It also demonstrates proactive and reactive feedback as distinctive feature of this novel approach. The pneumatic actuator matrix is designed to provide more elaborate tactile stimuli in the future. Future implementations should improve the pump system to allow for faster actuation and should utilize pressure sensing to ensure more stable tactile pattern design. Future evaluations of the system should incorporate eye tracking to support our positive findings on the reduction of visual load. Most of all, more work has to go into the design of tactile stimuli and the interrelations of visual and tactile representations of the GUI elements. A stronger exploitation of the localized stimuli based on physiologic characteristics and user centered design could help to improve the beneficial effects for usability and driving performance. Furthermore, this could help to establish additional usages of the system, e.g. the tactile support of gestural interactions in the car[25].

In summary, with the *AutomotiveRTF* project we showed that participants are able to integrate remote tactile stimuli in a supportive manner. The subjective visual load caused by the interaction with a touch-based in-vehicle infotainment system whilst driving was significantly decreased in two out of three cases. I assume that more elaborate design of tactile patterns will strengthen this effect.

6.2.3 *Interactive Watzmann*: Tactile Exploration in 3D

The project *Interactive Watzmann* is an experimental setup to explore and demonstrate the possibility to provide remote tactile feedback for an interaction above an interactive surface. The wrist-worn vibrotactile actuator matrix provides remote haptic stimuli to a user exploring the space above a surface. Thus, the interaction and the feedback are both spatially detached from the surface. The surface is not interactive per se, but does provide a reference frame for gestural interactions above it. We[26] used the *Interactive Watzmann* to haptically render direction and height of thermal winds over a paper maché model of the Watzmann, a mountain in the Bavarian

[25] These challenges are currently addressed in another master's thesis [Polleti, 2012]. However, its results are not available at this point.

[26] This work was part of Miriam Kranz's Diploma thesis [Kranz, 2011]

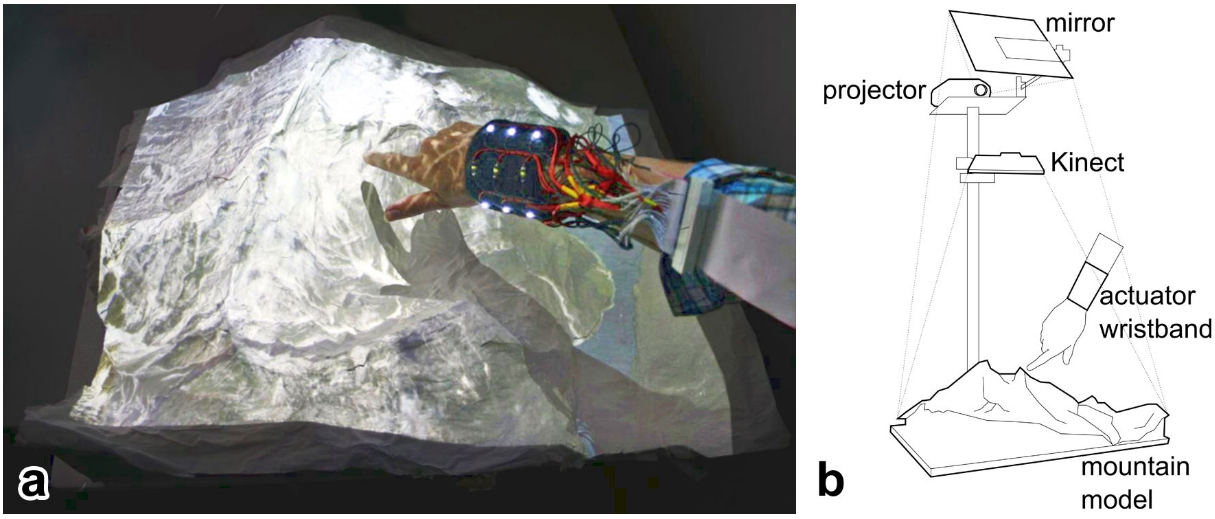


Figure 6.24: The *Interactive Watzmann* prototype. a: The user of the system manually explores the space above a paper maché model of the Watzmann. A wrist worn matrix of vibrotactile actuators communicates strength and direction of virtual thermal winds. b: Technical setup of the system.

Alps south of the village of Berchtesgaden (see figure 6.24). The system was deployed in an office of the German Alpine Club[27] for three days in order to collect user opinions and observe the use of this experimental prototype in the field.

The human wrist has been analyzed and used as a position for the application of tactile stimuli before. This location is socially acceptable and we are used to discretely wear small electronic devices there (e.g. wrist watches). This makes it an appropriate location for wearable tactile actuators to support the interaction with mobile or gestural interfaces. Wearable vibrotactile actuators have been used to provide navigation information for pedestrians [Bosman et al., 2003], collision feedback for virtual reality scenarios [Schätzle et al., 2011] or non-visual alerts [Lee and Starner, 2010]. Furthermore, matrices of vibrotactile actuators have been used to analyze the tactile sensitivity and the ability of stimulus localization. The forearm and wrist has been shown to be not suitable for stimuli which have to be localized exactly [Cholewiak and Collins, 2003]. This holds true for both the dorsal and palmar wrist side [Chen et al., 2008]. However, the wrist is a suitable location for directional tactile patterns [Piateski and Jones, 2005]. Additionally, these patterns are more easily identified when they move sideways (i.e. around the wrist rather than between elbow and wrist) [Chen et al., 2008]. These findings and the two-point threshold of up to 40 mm on the forearm (see 3.6) have been taken into account for the design of the *Interactive Watzmann*'s actuator system and tactile stimuli.

[27] `http://www.alpenverein-muenchen-oberland.de` [cited 2013/02/09]

The model of the Watzmann was designed in a scale of 1:10000 and build on the basis of maps and contour curves. A satellite image of the region is projected[28] onto the model. Manual interactions in the space above the model are detected using a Microsoft Kinect [29], the GUI is written in C++ and uses the *OpenNI*[30] framework for tracking and *OpenCV*[31] to process images. A mobile aluminum rack holds both projector and Kinect. Finally, a wristband (width: 8 cm) with 18 vibration motors (Lilypad's vibe boards) serves as remote tactile actuator. The tactile signals describe position and strength for virtual thermal winds on the interacting user's fingertip[32]. The upward wind was depicted by activating the columns of vibration motors for 200 ms sequentially from the lowest to the uppermost, with the vibration running around the wrist. We implemented two levels of intensity by doubling the amplitude and halving the inter-stimulus interval.

We deployed the prototype in an office of the German Alpine Club for three days, altogether 35 people interacted with the prototype. Twenty-five persons were willing to take part in the guided interview and to answer questions on the interaction, the relocation of stimuli and their ideas on future uses of the concept[33]. As a training, the participants were made familiar with the interaction and the resulting feedback. The results are summarized in the following:

Positive adjectives were used to describe the experience of the **interaction**, such as 'exciting', 'mystical' or 'surprising'. Seven of the 25 participants said the interaction was 'unusual'. Two participants stated that the interaction in mid-air was 'more hygienic' than touch. Two participants stated that the interaction 'could be tiring after a while'. Eleven of the 25 people had difficulties to distinguish the different **tactile stimuli** or to recognize the direction of the tactile stimuli. Three people clearly preferred the stimuli on the wrist, six people would have liked to perceive it at the fingertip. Others wished for additional visual feedback. Eleven people used adjectives such as 'good', 'non-problematic' or 'OK' to describe the **sensory relocation**. Interestingly, two participants were reminded of a sleeve for the measurement of blood pressure by the actuator system. In summary, a majority of 21 participants described the novel **interactive system** with positive adjectives such as 'simple', 'intuitive', 'cool', 'coherent', 'exciting' or 'useful'. The observed **hand postures** of the users were very diverse. However, most of the people used slow exploratory movements to detect active areas. Very few users touched the model.

With the system, we tested a novel form of interface and a novel form of sensory feedback. The ratings are very basic and describe the users' experience of 10 minute use. Still, we identified three main findings:

- The **relocation of tactile** stimuli was understandable and did not pose a problem to the majority of users.

[28] projector ASK M3

[29] `http://www.microsoft.com/en-us/kinectforwindows/` [cited 2013/02/09]

[30] `http://www.openni.org/` [cited 2013/02/09]

[31] `http://opencv.willowgarage.com/wiki/` [cited 2013/02/09]

[32] The actual wind data was taken from `http://www.xcskies.com/maps` [cited 2013/02/09]

[33] We did not ask the participants for demographic data in order to make them more willing to answer the questions.

- The **scenario** was understood and accepted by the participants. We assume that the users had no expectations in the device and no comparable system was known to them. Therefore, we received positive responses.
- The poorly designed **tactile stimuli** were criticized the most. We chose structured vibrotactile feedback to communicate the (non-visual) information. We assume that the vibrations caused a masking effect for the surrounding area on the wrist, which made it harder to distinguish the moving tactile patterns.

In summary, I consider the *Interactive Watzmann* a basic platform to collect first user responses to relocated tactile feedback which is detached from a touch surface. The findings from our deployment are moderate, but back the results from previous evaluations: First, the concept of remote tactile feedback is accepted, as long as the interaction loop is tightly closed. Second, the tactile stimuli themselves have to be designed carefully to communicate intended information. Vibrations are very popular in tactile research, due to their simplicity and strength of stimulation (see section 3.1.2). However, we found that vibrotactile actuation can lead to masking effects and can result in indistinct tactile patterns for moving stimuli or different levels of stimulation. In the next chapter, I address the potential of remote tactile feedback to provide more versatile tactile feedback by combining different types of actuators on the body or by using novel tactile media.

6.3 Increased Versatility of Tactile Stimuli

The previous sections described two applications of remote tactile feedback: The first goal was to **simplify** the technical integration of cutaneous feedback into touch interactions. Phantom Sensations are a method to reduce the number of individual actuators. Also, a remote tactile display was used to demonstrate that no actuators have to be implemented into the touch surface in order to communicate the orientation and width of virtual objects. Second, I demonstrated **proactive, reactive and detached remote feedback** as a method to extend the time frame for tactile feedback and thus to support the touch interaction. We could create discriminable virtual elements by replicating tactile stimuli from mechanical push buttons. The concept of remote tactile feedback was implemented in a vehicle and helped to decrease the subjective visual load during driving. With the next prototype, we collected first user responses on remote cutaneous feedback for gestural interactions.

In this section, I describe my work on a third application of remote tactile feedback which emerged from previous findings: the **design of more versatile stimuli**. As seen in our previous evaluations, indistinct tactile feedback will frustrate and irritate the user. More versatile stimuli can help in two ways: It can increase the information bandwidth by presenting more discriminable tactile signals. Also, it can increase the expressiveness of non-visual communication by utilizing the richness of our tactile perception in the everyday world.

The *HapticArmrest* combines different typical actuators into one simple remote tactile interface. Thus, this project exemplifies the potential of creating more versatile stimuli by applying diverse remote actuators on the user's skin. A preliminary experiment shows that a reliable discrimination of virtual elements is possible solely based on their tactile representation. The *ThermalTouch* utilizes thermal cues as carriers of information during a touch interaction. I present the technical prototype and the results of our evaluation which show that the created thermal cues help to discriminate virtual materials on the touchscreen. Finally, with the *LiquiTouch* system, we explore liquid as a versatile tangible medium for tactile communication. Liquids combine rich tactile characteristics such as pressure, temperature and viscosity. In this section, I present an implementation for remote water feedback.

6.3.1 *HapticArmrest*: Actuator Fusion

In section 3.4, I have described conventional approaches to bring versatile tactile feedback to interactive surfaces. Most conventional approaches of actuation generate a single haptic modality such as vibration, movement or levels of softness. In order to combine tactile actuators for more diverse or rich feedback, a combination of different actuators would have to be implemented into the touch interface. This results in increased technical complexity, space issues due to the (potentially) large number of actuators and increased price. Consequently, additional actuated tangible devices which have to be moved around on the depicted virtual elements can be utilized. However, this approach results in problems such as occlusion, the loss of direct manipulation

Figure 6.25: Overview of the *HapticArmrest* prototype. The system can be seen as the actuated frame of an interactive surface (from [Richter et al., 2011c]).

and impracticality on vertical surfaces. Therefore, I propose to utilize another inherent characteristic of remote tactile feedback: the possibility to combine several cheap and simple actuator technologies for meaningful and rich tactile feedback and reduced complexity at the same time.

With the *HapticArmrest* prototype, I present a first simple remote tactile interface to provide two different touch sensations (see figure 6.25 for an overview): We[34] used haptic stimuli and tactile signals to render both object-related and object-independent information. Specifically, individual fingers are moved to indicate the features of virtual edges, individual fingertips are stimulated by vibrations to render the type of a virtual element. Based on these stimuli, participants in an evaluation were able to reliably discriminate visually identical interactive elements. Furthermore, we assessed the hedonic and pragmatic quality of the conveyed tactile stimuli in order to improve future implementations. The work was published in [Richter et al., 2011c].

Prototype

As the name *HapticArmrest* implies, the prototype is a wooden object[35] designed in the length of an adult's forearm. The decision to develop this form of interface was influenced by an observation made by Ryall et al. [Ryall et al., 2006]: During long-term interactions with interactive tabletops, people tend to lean on the surface with their non-interacting hand or arm. This can result in accidental inputs and erroneous system behavior. Thus, the prototype can be seen as the actuated frame of an interactive tabletop. For a start, the user of the interface is asked to place the non-interacting hand on the front of the interface. For future implementations, in order to avoid the necessity to place the hand on a predefined area, not only the hand but alternatively also the wrist or forearm could be stimulated. In contrast to wearable actuators, the *HapticArmrest* delivers optional additional tactile information which can be cut out easily by lifting the arm off the actuators. This also distinguishes this approach from additional actuated input devices, which are necessary to interact at all.

[34] This work was part of Sebastian Löhmann's Project thesis [Löhmann, 2011b].

[35] dimensions: 60x14x9.5 cm (LxWxH)

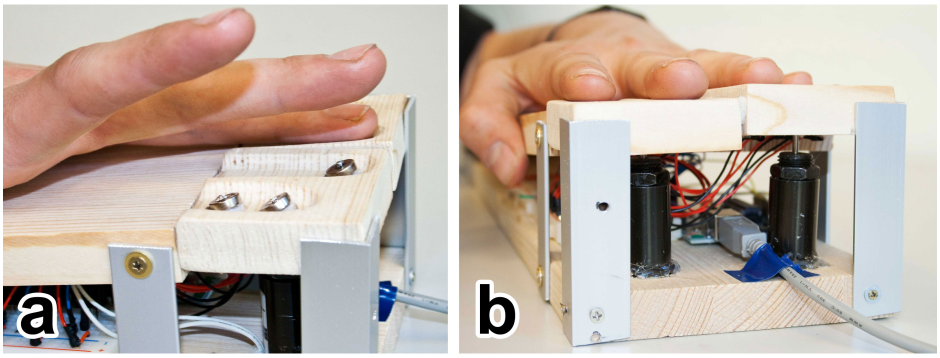


Figure 6.26: Actuators of the *HapticArmrest* prototype. a: eccentric vibration motors, b: linear solenoids (from [Richter et al., 2011c])

The prototype incorporates two forms of simple actuators which provide different stimuli (see figure 6.26): Altogether, six **vibration motors**[36] have been installed. These motors are positioned under the user's fingertips[37] and can be activated separately. Stimulus parameters are position and duration of stimulus, which can be combined into more complex tactons (e.g. stimulating several fingers at once or in moving patterns). In addition, we implemented two **linear solenoids**[38] which can lift two individual wooden pads by 4 mm. This feedback can be considered as being 'haptic', as the receptors in the finger's joints are stimulated rather than the skin. Again, the two signal parameters are the position and the duration of a stimulus. In total, we designed 12 distinct feedback patterns for each type of actuation. The actuators are controlled by an Arduino which is in turn connected to a tablet PC[39] which displays the GUI.

Evaluation

In the evaluation, we wanted to analyze the ability of the users to integrate the versatile remote stimuli as additional source of information when interacting with virtual objects. Additionally, we evaluated the subjective hedonic and emotional quality of the signal, as this aspect plays a major role in the acceptance of this form of feedback [Salminen et al., 2008]. We created a task in which 6 visually identical rectangles were presented on the touchscreen (see figure 6.27). Two of these 6 elements shared a common tactile characteristic which could be experienced by manually exploring the element. Haptic feedback from the solenoids was given when the edge of an element was crossed. On touch of an element's inner zone, a vibrotactile pattern was given. Either solenoid or vibrotactile feedback were presented. The task was to identify the pair of virtual elements with the common tactile representation. Twelve volunteers (6 female, all right-handed) took part in the evaluation and wore earmuffs to reduce unwanted noise coming from the actuators. After an introduction and training phase, each participant was asked to perform 6

[36] '10 mm diameter pancake 3 V' for mobile phones

[37] We added 2 motors to support left-handed users during whose use the prototype is switched and to allow for stimulation of smaller little fingers.

[38] Black Knight tubular push solenoid, 24 V

[39] PaceBlade SlimBook P120

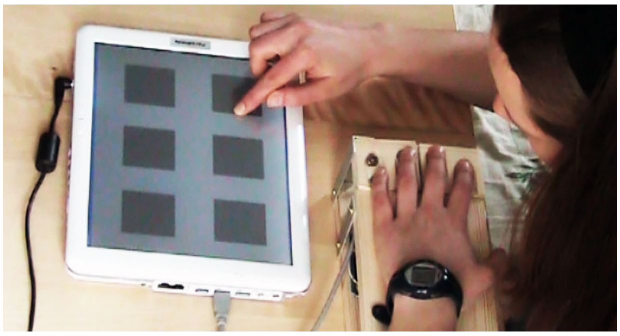


Figure 6.27: The usage of the *HapticArmrest* during the evaluation (videostill) [Löhmann, 2011b].

trials (three solenoid, three vibrotactile). The participants did not experience the same stimulus twice and were free to manually explore the touchscreen. In total, we logged 72 selections of haptically identical pairs.

Remote tactile stimuli and the combination of different tactile modalities is a novel form of feedback. The users' subjective connotations form an integral part of a subjective experience. Therefore, this time we wanted to analyze the emotional and hedonic impact of the resulting signals instead of evaluating the effects on the system's usability (see section 5.2). We conducted an evaluation based on the AttrakDiff method. The method is used to evaluate the interactive product's capability to fulfill the user's needs for 'stimulation' and 'identification' [Hassenzahl et al., 2003]. Pairs of opposing adjectives (semantic differentials) are presented to the participant who is then asked to rate the system on a scale from -3 to +3 between these adjectives. Instead of comparing two systems, we evaluated our two signal types.

The resulting rates for the identification of matching pairs depend on the type of tactile feedback:

- **Vibrotactile feedback:** All pairs of virtual elements with identical vibrotactile feedback could be identified by the participants, resulting in a identification rate of 100%.
- **Solenoid feedback:** In six out of 36 trials, participants were not able to correctly identify the matching pair of virtual objects. This results in a identification rate of 83.33%.

These results indicate that the unlimited time to explore the virtual elements and the lab situation without external disturbances supported the participants in their task. The high number of design parameters for each tactile modality seems to result in highly discriminable stimuli.

The results of the AttrakDiff questionnaire are shown in figure 6.28. Overall, the ratings for both types of tactile stimulation are very similar (i.e. no mean differences above 1.0) and show a tendency towards adjectives with a positive connotation. Two experiences in the ratings of technical quality form an exception: Both vibrotactile and movement feedback are perceived as rather *technical* and somewhat *unpredictable*. We assume that the prototypical nature of the system entailing noise, latency or rough design of the encasing resulted in the rather negative ratings of the pragmatic quality. The strongest tendencies were found in the ratings of hedonic quality or quality of stimulation of the feedback: Both signal types were described as being *creative*, *innovative* and *novel*. Both stimuli are generally perceived as *good*. The strongest

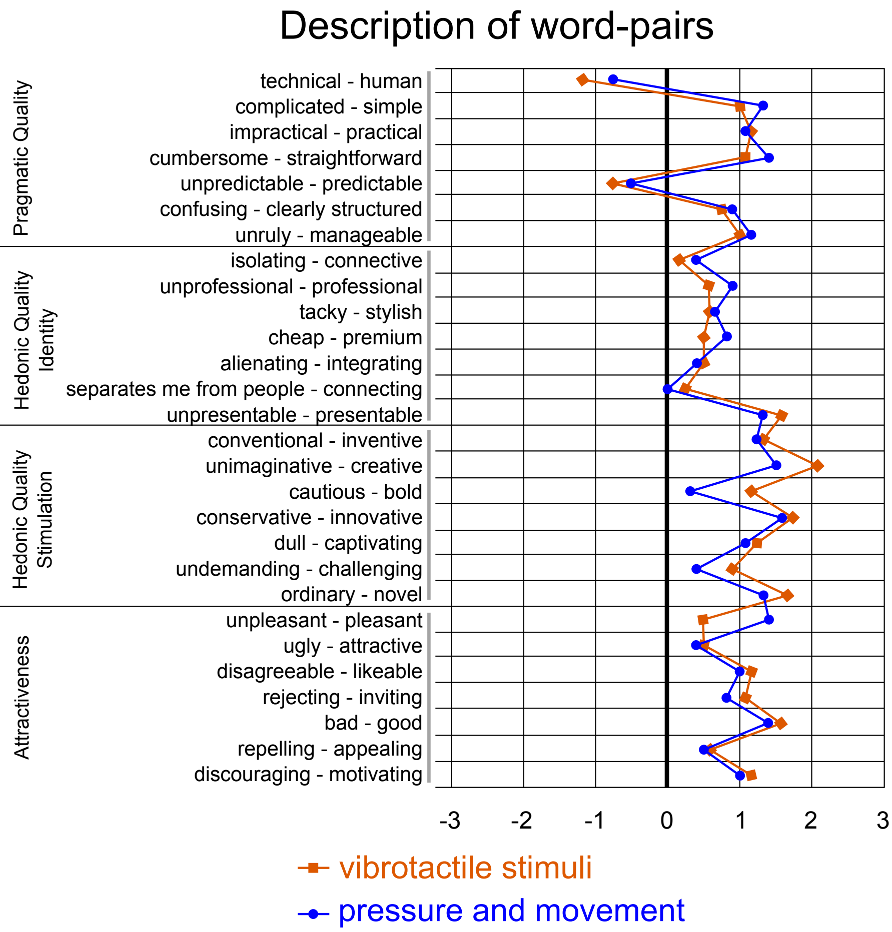


Figure 6.28: The results from the AttrakDiff method. Discrete values are connected for comparability (from [Richter et al., 2011c]).

differences show that vibrotactile feedback is perceived as more *bold* than the stimuli coming from the solenoids. However, the moving platform were described as being more *pleasant* than the vibrating motors. This result is consistent with my criticism of vibrotactile feedback. In general, both forms of stimulation are rated positively and are utilized as information source to identify matching pairs of virtual elements.

In addition to this project, we used an adapted version of the AttrakDiff method before to compare two more different forms of stimulation: direct and remote tactile feedback (see section 5.2). Still, also in that setting, no strong differences between both modalities were found. Therefore, the AttrakDiff method as a means to identify disparities between forms of stimulation (rather than systems) should be taken with a pinch of salt. However, we still lack standards to evaluate novel forms of sensory feedback. Additionally, we gained minor findings in the *HapticArmrest* project for pragmatic and hedonic qualities of feedback. Therefore, we used an adapted version of this method again for the system presented in section 6.3.2.

Discussion and Conclusions

In summary, the *HapticArmrest* is a simple system to explore the use of remote tactile feedback in order to create novel tactile stimuli which complement each other. Participants in our user study were able to utilize the stimuli for the discrimination of virtual objects. This work is a first step towards the creation of more versatile and distinctive tactile signals. Here, we used moving platforms and additional design parameters such as location-encoded rhythmic patterns. However, we did not combine the two types of stimulation to form novel sensations. We refer to this notion as **actuator fusion**. This principle is feasible when different actuators on different body locations simultaneously provide synchronized feedback for a touch interaction. The multiple resulting stimuli melt together forming potentially rich haptic representations. Again, this approach is unique for the concept of spatially separating touch and resulting feedback.

6.3.2 *ThermalTouch*: Thermal Material Characteristics

In our everyday life, non-visual cues such as texture, malleability or temperature help us to identify and discriminate objects on touch. If we touch items with the same surface characteristics, such as metal or hard-plastic keys, the change of temperature in our fingertips is the primary source of object information. Additionally, thermal stimulation can be a highly emotion-evoking sensation: e.g. warm clothing or a hot bath result in relaxation and satisfaction, whereas direct contact with a hot oven plate results in an immediate retreat of the hand. These connotations have become part of our everyday language, e.g. when we talk about a cold-hearted person or a heated discussion. However, this additional perceptive non-visual channel is still underused on interactive surfaces. Programmed thermal cues could be particularly helpful on interactive surfaces to allow for a non-visual discrimination of virtual materials or (in combination with other tactile modalities) to simulate or create virtual materials. Two main reasons for the neglect of these sensations exist: First, thermal stimulation is subtle, whereas other tactile modalities such as vibrotactile sensations deliver stronger and more immediate signals. Second, to allow for a thermal actuation of the surface, larger or numerous actuators would be needed to be integrated into the touch interface (see also section 6.1). This leads to technical problems, e.g. mutual interferences of the actuators which heat and cool each other. This makes programmed thermal stimuli hard to use and to combine with other modalities to create more useful tactile feedback.

With the *ThermalTouch* project, we[40] address these challenges. Using a remote thermal interface, we could present temperature profiles of 5 different materials. In a user study, we evaluated how well participants could discriminate virtual objects based on these programmed thermal patterns. We compared two deployments: The interface as a stand-alone device without touch interaction versus the interface used as a supplemental (i.e. remote) thermal feedback actuator for direct touch interaction. Our results show that the 5 materials are highly discriminable in both settings.

Thermal sensation is a tactile modality which has not been discussed before in this thesis. Therefore, I will give a brief introduction into the basics of thermal perception and related work. In the

[40] This work was part of Sven Osterwald's Bachelor's thesis [Osterwald, 2011].

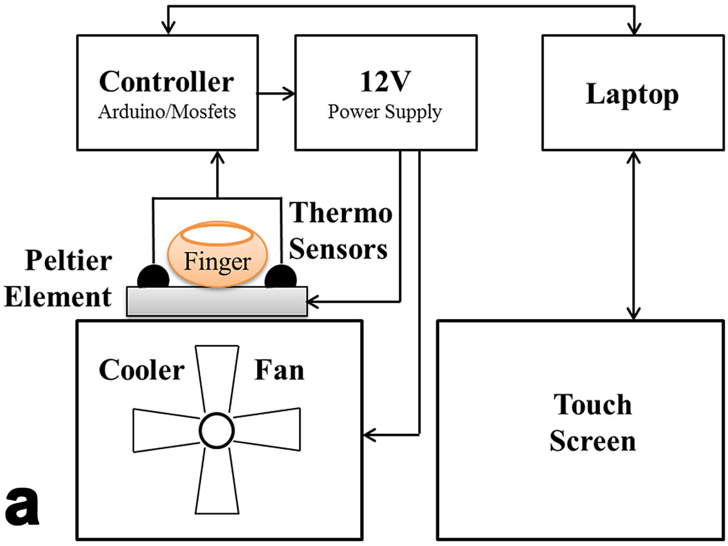
following, I will present the prototype, describe our evaluation and its results and propose future applications of the concept. Additional information can be found in [Richter et al., 2012a], this section is based on this publication.

Basics and Related Work

Thermal Perception: Thermal perception is based on either constant (static) or altering (dynamic) skin temperature. For *static temperatures* in a range between 30-36°C, no temperature cues are perceived due to adaption. Therefore, this range is often called neutral zone or physiological zero [Lederman and Klatzky, 1998]. Static temperatures outside of this zone (below 30°C and above 36°C) create a constant sensation of coldness or warmth. Finally, static temperatures below 18°C and above 45°C do not result in adaption and do not create a sensation of temperature: the thermal sensation is replaced by pain [Schepers and Ringkamp, 2009]. On the other hand, *dynamic temperatures* outside the neutral zone create the perception of increasing or decreasing coolness or warmth [Lederman and Klatzky, 1998]. Interestingly, dynamic temperatures **inside** the neutral zone are perceived as static sensations of cold and warmth [Wilson et al., 2011]. These rapid rapid increases and decreases of temperatures inside the neutral zone are the basis of our perception of a material's thermal characteristic.

Material Discrimination: During daily activity, our skin temperature varies between 20°C and 40°C with a center usually between 32°C and 35°C [Jones and Berris, 2002]. As a consequence, the temperature of our body surface is higher than the temperature of most surrounding objects. Therefore, an object transfers heat away from the skin in our fingertips when we touch it. These dynamic temperature changes are perceived as different static sensations of cold, depending on the thermal conductivity, heat capacity, and initial temperatures of both skin and material [Ho and Jones, 2004]. To be perceivable, the temperature changes have to occur at a rate of over 0.5°/minute [Jones and Berris, 2002]. In general, a material's thermal characteristic is only part of its entire tactile representation, which also comprises cues such as texture, profile or hardness [Caldwell and Gosney, 1993].

Thermal Sensations in HCI: Programmed thermal sensations have been used before in various fields of human-computer interaction. Hereby, the thermal cues are often combined with other tactile modalities and with visual and auditory cues. In the field of virtual reality, thermal cues were utilized to support the training of physicians during the diagnosis on a virtual patient [Kron and Schmidt, 2003]. Other projects incorporate versatile temperature stimuli in virtual scenarios using heating devices, infrared lamps and ventilators [Dionisio, 1997]. For telepresence, multiple tactile stimuli "from contact pressure/force, to hardness, texture, temperature, slip, surface profile/shape and thermal conductivity" [Caldwell and Gosney, 1993] were implemented in instrumented fingers to communicate tactile cues from a robot-device to the operator. More structured thermal notifications have been tested on mobile devices [Wilson et al., 2011]. In order to further elaborate on the use of thermal cues for the simulation of materials, several research projects incorporate psychophysical experiments. Utilizing the well-known characteristics of human thermal perception (at least in the hand), they envision the use of more versatile temperature feedback in virtual reality and telepresence scenarios [Ino et al., 1993, Ho and Jones, 2004].



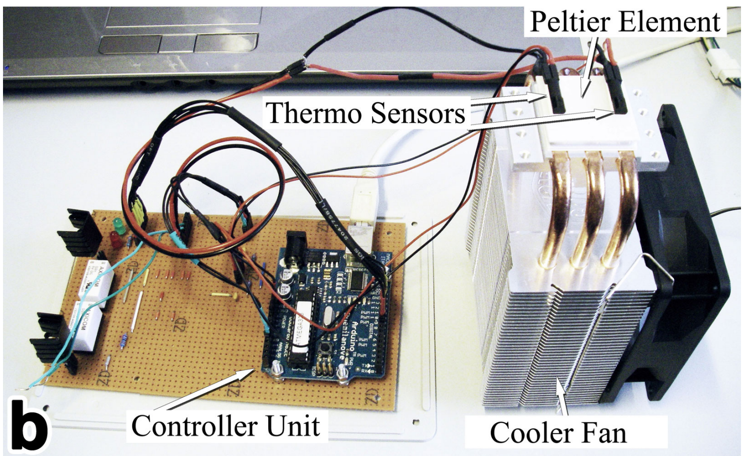
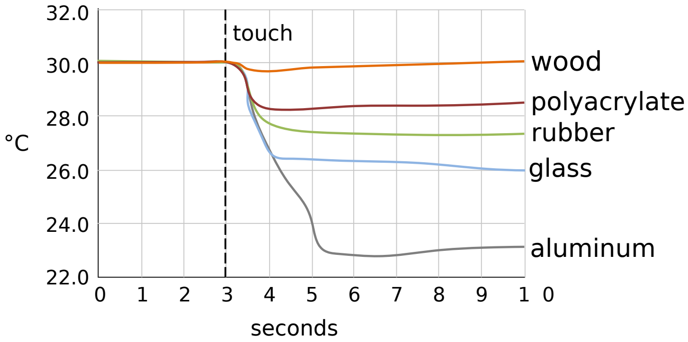


Figure 6.29: The *ThermalTouch* system: a: Technical structure, b: The actuator system (touchscreen not depicted here) (from [Richter et al., 2012a]).

Here, stand-alone thermal displays are used to simulate the heat flux behavior of touched objects. Remarkably, thermal information has not been added to touch surfaces yet. Tactile modalities such as vibration, movement or electrocutaneous stimulation could be combined with thermal stimuli to create more discriminable, versatile, interesting or (if wanted) lifelike feedback. The *ThermalTouch* is a first step in this direction.

Prototype

The aforementioned projects provided us with valuable technical information on the design of both prototype and stimuli. Particularly, we adopted the results obtained by Ino et al. [Ino et al., 1993]: First, they measured the temperature changes occurring on a human fingertip which touches the five materials aluminum, glass, rubber, polyacrylate and wood. Then, they presented these thermal profiles to the fingertips of participants in a user study and measured the



material	ΔT (°C)	cooling time (ms)
wood	-0.1	500
polyacrylate	-1.7	600
rubber	-2.6	1000
glass	-3.1	1200
aluminum	-6.9	3200

Figure 6.30: Each of the five materials has an individual temperature profile with defined temperature decreases (ΔT) and cooling times. The depicted temperature profiles represent measurements of the *ThermalTouch*'s behavior.

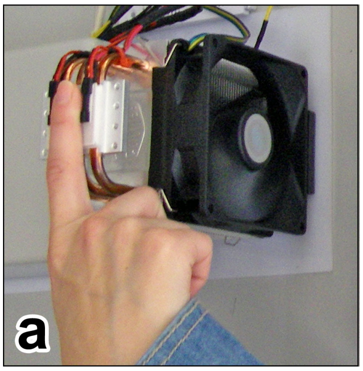
rate of correctly identified (virtual) materials. The *ThermalTouch* project extends this work both conceptually and technically. The system is described here in short, more detail can be found in [Osterwald, 2011].

Actuator System: The structure of the prototypical remote thermal system is depicted in figure 6.29. The user is interacting with his dominant hand on a touchscreen. On touch of virtual elements, predefined thermal events can be displayed on the index finger's tip resting on the cooling device. The actuator consists of a Peltier element[41] (29.5x29.5x4.1 mm (LxWxH)) connected to a 12V cooling fan over heat conducting film. Two analog temperature sensors[42] are attached to the Peltier element to constantly control the heat pump's status. The intensity and direction of the current driving the cooling device is managed by an Arduino. This setup results in a maximum speed of cooling of 6.2°C/s and heating of 5.5°C/s.

Thermal Stimuli: The temperature profiles of the five materials which are presented by the prototype are depicted in figure 6.30. When looking at the curves, one can see that to simulate the heat capacity characteristics of wood, a small temperature decrease of -0.1°C is needed and can be provided by the device in 500 ms. Aluminum, which is the coldest of the materials, has a temperature decrease of -6.9°C. The prototype can provide this stimulus in 3200 ms when cooling down from the starting temperature of 30°C. This cooling process was preprogrammed for each virtual material.

[41] Peltier cells are thermoelectric heat pumps and consist of two dissimilar conductors. Depending on the direction and amount of the applied current, one conductor is emitting heat whereas the other is cooling. This effect can be increased by actively transferring away heat with a cooler fan. Peltier elements are widely used for thermal actuation.
`http://www.electronics-cooling.com/1996/09/an-introduction-to-thermoelectric-coolers/` [cited 2013/01/15]

[42] KTY81-210



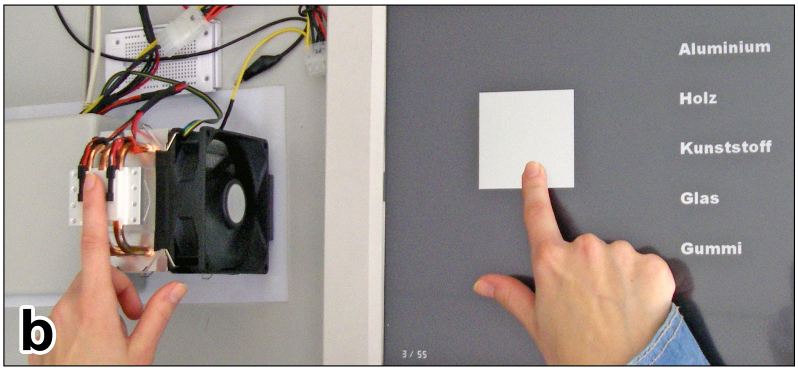


Figure 6.31: The two uses of the thermal display during the evaluation: a: stand-alone device, b: remote thermal feedback (from [Richter et al., 2012a]).

Evaluation

In related work, similar thermal actuator devices have been used as stand-alone device to simulate thermal material characteristics. In the evaluation by Ino et al. [Ino et al., 1993], the participants were informed beforehand that only five materials will be presented (wood, polyacrylate, rubber, glass, aluminum). Thus, the task is not an identification of a material, but rather a discrimination of several thermal profiles. We recreated Ino's evaluation and transferred the approach to remote tactile feedback. We assume that a discrimination of thermal characteristics of virtual elements on a touchscreen is also possible when the actuator is used as supplemental or remote interface. We formulated several research questions:

- Can participants discriminate virtual materials on the stand-alone *ThermalTouch*?
- Can participants discriminate virtual materials on a touchscreen with remote thermal stimuli from the *ThermalTouch*?
- How do participants subjectively rate realism, signal design and information bandwidth of both setups?

In total, 20 participants (nine female, average age 24 years) took part in the study. Two subjects declared to be left-handed. As shown in figure 6.31, we had two conditions:

- **Stand-Alone:** Thermal cues are presented to the the dominant index finger without an interaction by the user. Upon touch of the actuator, the subject was given one of the 5 thermal profiles. Subsequently, the participants had to indicate the perceived materials by checking a list on a touchscreen. A two-second break allowed the actuator to reheat back to the starting temperature of 30°C.
- **Supplemental/Remote:** Thermal cues are presented to the non-dominant index finger as a reaction to the dominant index-finger's touch of virtual objects on a touchscreen. Upon touch of a white rectangle on the touchscreen, one of the 5 thermal profiles was applied to the other hand's finger. Again, the participants selected the perceived signal from a list on the same touchscreen. The actuator heated back to 30°C as soon as the users had lifted their finger from the touchscreen.

	wood	polyacrylate	rubber	glass	aluminum
	stand-alone feedback				
wood	**33.0**	28.5	37.0	1.0	0.5
polyacrylate	31.0	**36.5**	24.0	6.0	2.5
rubber	21.0	36.5	**14.0**	21.0	7.5
glass	16.0	23.0	11.0	**39.0**	11.0
aluminum	0.5	0.5	1.5	32.0	**65.5**
	supplemental feedback				
wood	**43.5**	30.0	22.5	3.0	1.0
polyacrylate	18.5	**45.5**	17.5	14.0	4.5
rubber	12.5	36.5	**10.0**	33.0	8.0
glass	10.5	21.0	9.0	**45.5**	14.0
aluminum	0.5	2.5	5.0	21.5	**70.5**

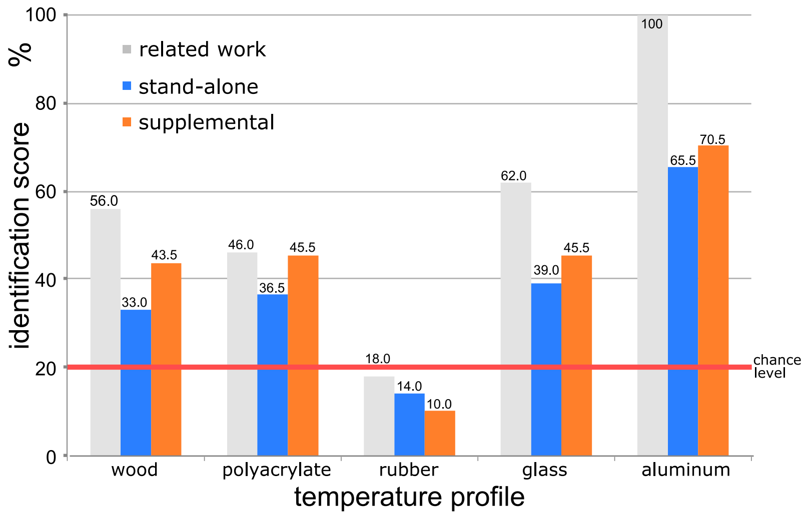


Figure 6.32: The percentage of correct identifications for each material in the two settings (from [Richter et al., 2012a]).

We used a within-subject repeated measures design, with the independent variables being feedback location and applied thermal profile. Dependent variable was the user's choice of a material. Before the tasks started, participants were informed about the five available materials and were asked to rate them from cold to warm according to their personal experience. After a training sequence of five materials, every material was given eleven times in a randomized sequence for each subject. The sequence of setups was fully counterbalanced across subjects. After the completion of the task in each setup, participants were asked to fill out a questionnaire. As in the evaluation described in section 5.2, we used an adapted AttrakDiff form to collect the users' opinions on the signals in the two very different settings.

Results

Figure 6.32 shows the percentage of correct identifications for each material in the two settings. In both the stand-alone and the supplemental setup, aluminum was identified correctly in 65.5% and 70.5% of the trials. Nearly equal identification rates can be found for glass (39.0% and 45.5%), polyacrylate (36.5% and 45.4%) and wood (33.0% and 43.5%). Rubber was identified correctly in only 14% or 10% of the cases in both settings. All other materials were identified correctly with rates clearly above the chance level of 20%. The percentage of correct identifications measured by Ino et al. [Ino et al., 1993] exceeds our results. However, we assume that their smaller sample size of only 5 subjects (we used 20) might be a reason. Still, the order of identification rates is the same in both evaluations.

In section 6.3.1, I already discussed the trouble we had to identify differences between the subjective ratings of two forms of tactile stimulation using the AttrakDiff method. We failed to detect disparities between the two tactile sensations. Therefore, we adapted the AttrakDiff for the *ThermalTouch* project and introduced oppositional adjectives which are more suitable to describe sensory sensations. We loosely classified these adjectives into the categories realism, signal de-

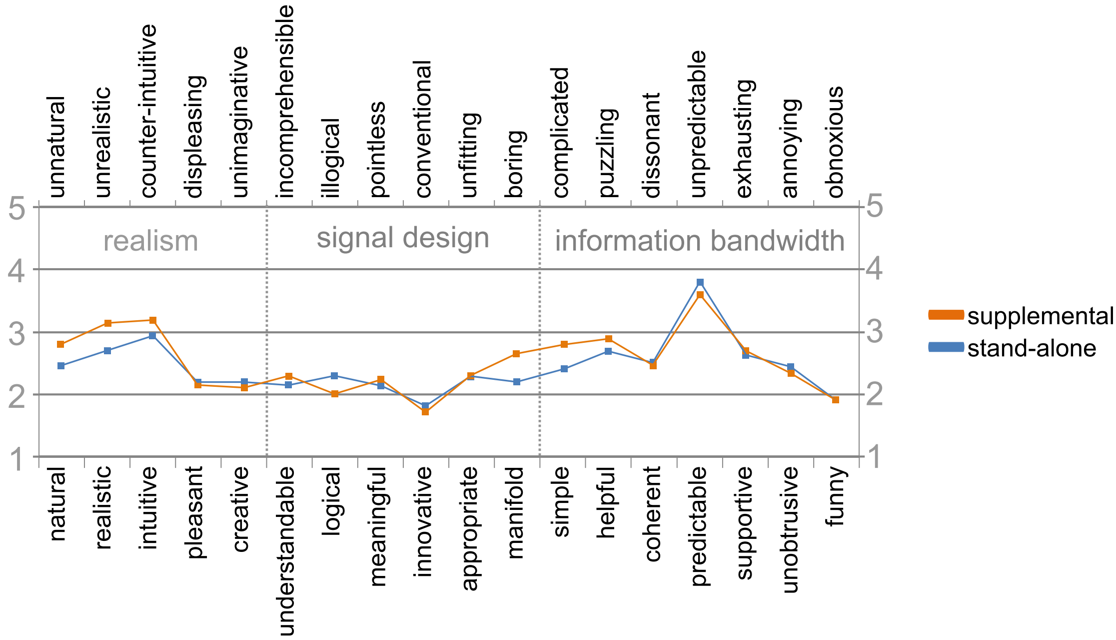


Figure 6.33: Subjective ratings of stand-alone and supplemental thermal stimuli. Discrete values are connected for readability.

sign and information bandwidth. The results for both stand-alone and supplemental application are presented in figure 6.33.

In general, both feedback designs were perceived similarly. Still, the remotely applied stimuli during touchscreen use were rated as being a little less natural, realistic and intuitive. However, the remote stimuli were perceived as more logical than the stimuli on the stand-alone setting. More differences could be found for signal design and information bandwidth: The remote stimuli were rated as being less manifold and simple. Both forms of stimulation had the connotation of being funny and innovative, but somewhat unpredictable.

Interpretation and Discussion

The remote application of thermal stimuli allowed for a stable rate of discrimination and identification of virtual materials which are touched at the same time. With the exception of rubber, all materials were recognized clearly above chance level. Our results coincide with those from related work. Additionally, the adapted form of the AttrakDiff questionnaire helped to identify qualities of the stimuli (e.g. innovative, funny) and differences between both settings (e.g. realistic, simple).

Interestingly, we can see a strong effect on the results when we take the individual subjective perception of material temperatures into account. At the beginning of the evaluation, we asked the participants to order the five materials from cold to warm based on their real-life experience. It became obvious that most users expected an ordering which differs from the presented. Looking at the individual orderings, we detected two groups of materials which are either cold (aluminum,

	stand-alone feedback		
order	used	investigated	individual
wood	33.0	37.0	44.5
polyacrylate	36.5	31.0	40.5
rubber	14.0	36.5	48.0
glass	39.0	39.0	45.0
aluminum	65.5	65.5	78.0
average	**37.6**	**41.8**	**51.2**

	supplemental feedback		
order	used	investigated	individual
wood	43.5	22.5	32.0
polyacrylate	45.5	18.5	33.5
rubber	10.0	36.5	42.5
glass	45.5	45.5	54.5
aluminum	70.5	70.5	78.5
average	**43.0**	**38.7**	**48.2**

Figure 6.34: The percentage of correct identifications with underlying subjective orderings.

glass) or warm (polyacrylate, wood). People individually reordered the materials inside of these groups, but never mixed cold and warm materials. When these personal orderings are integrated into the results, all but one identification scores increase. Figure 6.34 shows the results for the order we used in the evaluation (i.e. 'used') , an average of all individual orders (i.e. 'investigated') and the individual orderings (i.e. 'individual'). This observation shows the highly individual nature of thermal perception.

Future Applications and Conclusions

The *ThermalTouch* project is a first step towards the use of thermal cues on touch surfaces without the need to implement numerous actuators into the screen. In the next step, one should consider implementing more powerful power supplies and more than one actuator to allow for a faster change between heating and cooling. Furthermore, we only used a controlled cooling effect yet, active heating should be considered, too. Future embodiments of the concept could utilize wearable actuators or instrumented furniture to convey the stimuli. In contrast to mechanical sensations such as force or vibration, thermal stimuli can easily be communicated 'over a distance', e.g. using warm or cold jets of air or liquid[43].

Three future applications of the concept of remote thermal stimuli come to mind:

- **Material simulation:** Thermal cues could be used to make virtual elements more discriminable, which could be especially helpful in dynamic scenarios. Due to the subtle and slow thermal stimulation, I recommend to use a combination of diverse tactile sensations (e.g. vibration, temperature, force) to create rich and redundant non-visual feedback. Additional visual cues would help to create the experience of more 'real' textures.
- **Object-independent information:** Thermal cues could communicate abstract information such as importance, function or state of a virtual element. For example, important buttons could be hot (e.g. 'Buy ticket?'). Visual representations of data could feel cold when not used for a long time. Additionally, the remote nature of the thermal stimuli forms a personal and private channel of information between human and machine or human and human. Thus, (with user identification) a virtual object could feel different for different users.

[43] I realized this notion with the *LiquiTouch* prototype which is described in section 6.3.3.

- **Thermons:** Following Brewster concept of structured, abstract tactile messages or icons called 'Tactons' [Brewster and Brown, 2004], I propose the term 'thermons' for structured thermal messages. They could support users of stationary and mobile interfaces as well as sensory impaired persons. Parameters could be absolute temperature, rate of temperature change or duration of stimulus.

In summary, our results show that remote thermal stimuli can help to make virtual elements on a touch surface discriminable and identifiable. To a certain extent, a simulation of material characteristics is possible (e.g. when the available materials are known to the user).

6.3.3 *LiquiTouch*: Liquid Tactile Feedback

The aforementioned projects used two methods to create more versatile tactile stimuli: First, different actuators on different body locations create more than one tactile modality and can potentially form a coherent new stimulus. Second, remotely applied thermal stimuli are a subtle, but powerful source of object information and emotive effects. The project *LiquiTouch*, which is presented in this section, is a conceptual result of these previous projects. Again, several tactile modalities are unified. However, instead of using several actuators, *LiquiTouch* incorporates fluid matter as a novel medium if tactile communication. As a consequence, the project utilizes the notion of tactile stimuli 'over a distance'. The created tactile feedback is remote, but relocated only a few millimeters. Still, no actuators are implemented into the interactive surface.

LiquiTouch is a work-in-progress and can be described as a technical platform to explore the versatility of liquid matter to communicate tactile information[44]. In the following, I introduce the interface prototype, describe the numerous available parameters for liquid tactile stimulus design, discuss the potentials and limitations of the concept and present potential scenarios of use and the ongoing work on the project. The basic concept has been published in [Richter et al., 2013].

Liquid Input, Liquid Output

We get in contact with manifold fluids in our everyday life. Liquid is a medium which communicates versatile sensory stimuli for all five senses. This especially holds true for haptic sensations: "The warm water washing around our feet at the beach, the power of a waterfall, the slippery edge of a swimming pool or the stickiness of honey are but a few examples" [Richter et al., 2013]. However, common actuator systems fail to recreate these diverse sensations as they are mostly designed to create only a single type of stimulus (e.g. force or vibration). The use of liquids can overcome this limitation as it creates the whole range of haptic cues such as warmth, coolness, rigidness, pressure, movement or force. Moreover, liquids can "evoke strong emotional effects such as surprise or relaxation, e.g. when having a water balloon fight or a warm bath after a long day" [Richter et al., 2013]. Designers and researchers in the field of tangible interaction and physical computing try to incorporate these effects to blur the barrier between digital and physical world.

[44] This work was part of Moriel Serors's and Felix Manke's Bachelor's theses [Seror, 2011, Manke, 2011].

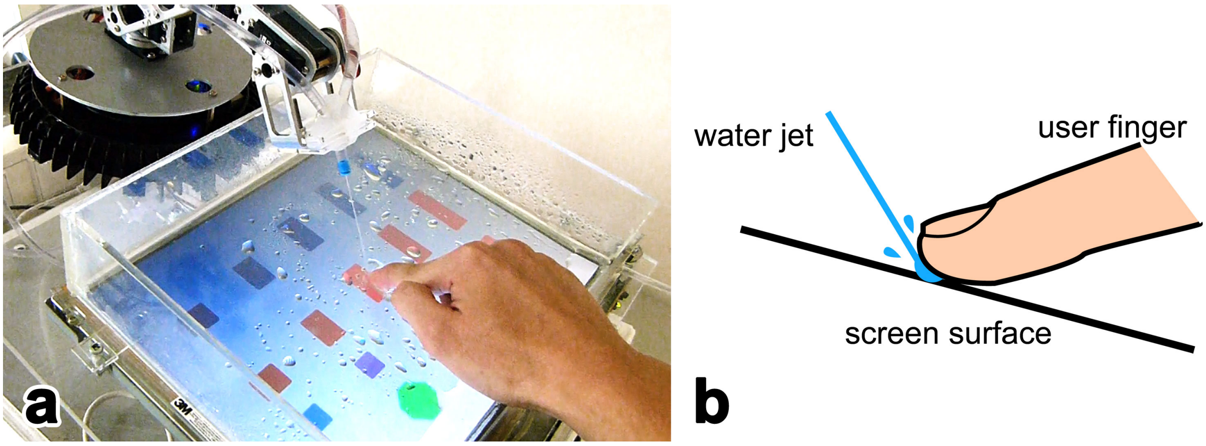


Figure 6.35: The *LiquiTouch* prototype uses directional water jets which are sprayed between the touchscreen and the finger to communicate tactile properties of GUI elements.

Liquid matter has been used as a **input** medium for playful virtual reality applications and creates interesting psychological effects such as a feeling of relation and curiosity [Pier and Goldberg, 2005, Yabu et al., 2005]. Other projects describe the creation of more 'organic' input such as gestures using water-filled bowls [Geurts and Abeele, 2012] or with semi-fluid materials such as mud [Gerhardt, 2009]. A very special form of liquid input can be performed with interactive urinals [Maynes-Aminzade and Raffle, 2003].

The *Hydraulophones* by Steve Mann [Mann et al., 2006] are a well-known example of fluid-based instruments with water as medium for both input and **output**. When these organ-like instruments are played, tactile information is communicated bidirectionally: The musician covers or even closes the holes in the instruments with the fingers, thus hindering or stopping the water from flowing and thereby altering the sound. Furthermore, this input is coupled with an immediate tactile output. This concept is the same with analogue instruments such as the violin or the guitar: the emitted subtle tactile cues support the musician to play the instrument and to establish an emotional, multimodal connection to the instrument and the resulting work of art. Other systems create non-solid feedback and thus allow for tactile communication 'over a distance'. For example, directed ultrasound waves can be used to form palpable objects in mid-air [Iwamoto et al., 2008]. Fog-displays are non-solid projection canvases which create 'floating images'. As a consequence, these images can be touched or entered by the user and are haptically perceivable as cold vapor.

Prototype

The *LiquiTouch* prototype is a touchscreen system coupled with a robot arm sitting next to the screen. The robot arm is constantly pointing at the position of a touch input. On touch of interactive virtual elements, a directed water jet with versatile programmable tactile characteristics can be shot from the arm's tip onto the contact point of finger and glass surface (see figure 6.35).

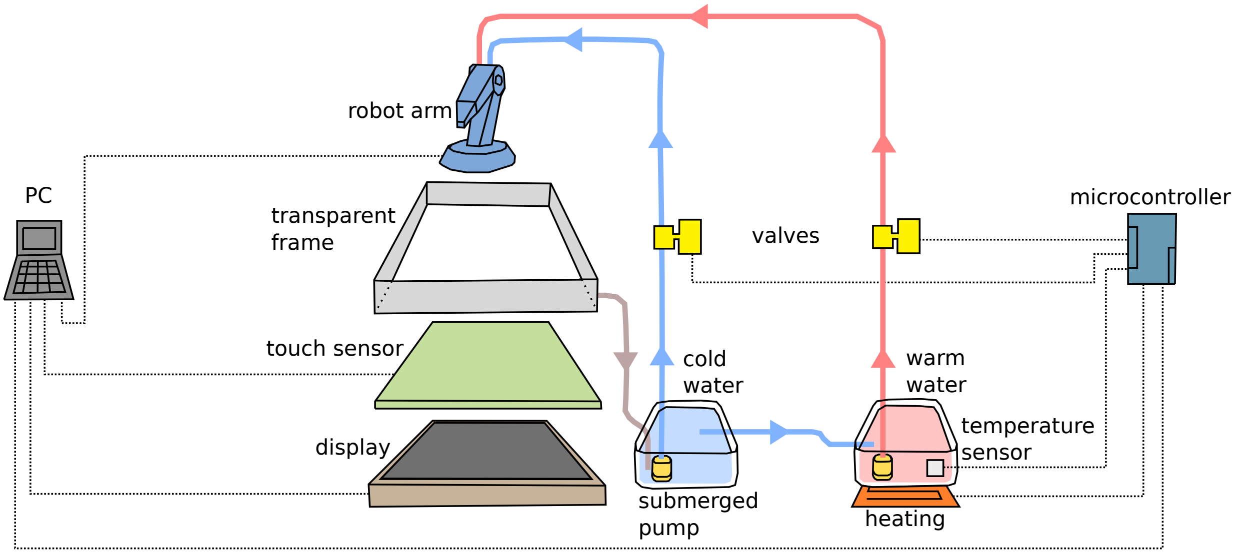


Figure 6.36: Technical components of the *LiquiTouch* prototype.

Hardware: The current[45] technical conception of the prototype can be seen in figure 6.36[46]: A standard 15" TFT displays shows a GUI and is superimposed with a transparent surface capacitive touch overlay. The user's interactions are registered by a PC. Meanwhile, two pumps submerged in canisters filled with cold and warm distilled water[47] are constantly activated and transport water to two closed valves. An Arduino microcontroller regulates the warm water's temperature by constantly measuring and reheating it. We are working on a maximum temperature of 50°C to avoid too hot or painful stimulation. When a virtual element on the screen is touched, the pre-programmed tactile stimuli are transferred: The robot arm is equipped with a nozzle - stemming from a water pistol - and constantly points at the user's finger on the screen. At this moment, a structured jet of tempered water is shot under the user's fingertip. For that, the Arduino rapidly opens and closes both valves independently which results in tactile stimuli with various pressures, rhythms and temperatures. Finally, a frame made of acrylic glass around the inclined touch area collects the emitted water and a tubing carries the water back into the cold-water container. The current spatial resolution of the feedback is 0.5 cm with a total latency of approximately 200 ms.

Signal Design: At the moment, we actively control the activation and deactivation of the valves and thereby can create and combine four parameters for liquid tactile stimuli:

- **Pressure:** The valves can be opened and closed in very short intervals, thus creating a form of pulse-width modulation. The ratio of on-periods versus off-periods controls the amount of flowing particles. We implemented this principle to be able to dynamically adjust the pressure of the water jet on the fingertip.

[45] February 2013

[46] Technical details as well as component names can be found in [Richter et al., 2013]

[47] Non-distilled water would interfere with the surface capacitive touchscreen as it transports electrical loads.

- **Frequency:** We can adapt the on-off periods of the valves to create distinct water droplets and to regulate the frequency of the single droplet pulses.
- **Rhythm:** To create more complex rhythmic sensations, we combine both pressure (i.e. amplitude), duration and frequency of the stimuli.
- **Temperature:** A change of the water jet's temperature can be performed by individually activating and deactivating the valves in the hot and cold water tubing. Thereby, we can dynamically create temperatures and thermal patterns. At the moment, the water coming from the two tubing systems mixes in the nozzle on the robot arm.

The potential design space for liquid stimuli is much larger, we can think of controllable parameters such as the size and target of the jet, the color or viscosity of the liquid and additional modalities such as smell or sound. The notion of combination is an integral part of designing with liquid tactile feedback: fluid matter as a medium combines tactile modalities which usually need individual actuators to be created. Furthermore, we recommend to combine liquids with different temperatures (as we did) or viscosity. Finally, liquid tactile feedback also could be combined with common tactile feedback technologies or deformable or organic interactive surfaces.

Discussion and Conclusions

Apparently, the use of liquids in combination with electronics poses inherent difficulties and risks. Additionally, fluid matter is hard to control and its use entails bulky systems with pumps, containers and tubing. This greatly limits feasible usage scenarios. Still, the general concept is intended to encourage practitioners to explore novel media for the creation of tactile stimuli. Therefore, we can think of several deployments: A large scale implementation in an outdoor scenario could allow for multiple persons to interact with the system. Playful scenarios such as swimming pools, playgrounds or theme parks might be feasible. Future versions of the system could be presented in an artistic public context (comparable to Mann's *Hydraulophones*).

As a next step, the prototype should be improved technically (e.g. active cooling, temperature measurement of the generated jet, improvement of resolution). In the future, we want to use the prototype to identify general guidelines for the design with liquid tactile stimuli. Therefore, our research agenda has two main points:

- First, we want to perform psychophysical measurements to further elaborate the stimulus design. Therefore, we intend to measure both perceivable differences in temperature, pressure and frequency as well as perceptional thresholds (e.g. using JND experiments)., The transferability of the results onto other liquid feedback interfaces might be limited. However, they can serve as a basis for future experiments with the prototype.
- Second, we want to measure the subjective appraisal of this special form of tactile feedback. As seen before, the qualitative evaluation of tactile stimuli is still a problem. Therefore, we are working on a classification of measurement methods from user experience, workload assessment and usability research and analyze their adaptability to measure subjective effects of sensory stimuli.

In summary, the ongoing *LiquiTouch* project aims at the increase of the versatility and expressiveness of tactile information using the rich sensory characteristics of liquid matter. I present it as part of my thesis on remote tactile feedback, although the stimuli are only relocated a few millimeters. Still, the drops and "spills that are coming from this non-sterile form of feedback could be described and used as unstructured particles of tangible bits" [Richter et al., 2013]. Liquid tactile feedback has the potential to make digital information tangible, to bridge the gap between virtual and physical world and to improve the flow of information between computing technology and its users.

6.4 Remote Tactile Feedback for Multi-Touch

Multi-touch input has become a de-facto standard for the interaction with touch-sensitive surfaces in the recent years. Multi-touch technology has been available since the 1970s, researchers such as Bill Buxton[48] focus on multi-touch as an approach to go beyond simple pointing, to adopt the various specialized possibilities we have with real-world tools and to increase our gestural vocabulary when we interact with digital information. Evaluations have shown increased selections speeds when two or more fingers are involved compared to single-finger or mouse interactions [Kin et al., 2009]. Furthermore, in the context of future interactive surfaces which are deformable or even transforming, multi-touch is an essential component of the interaction to increase the available degrees of freedom for the user and to make tasks accomplishable in manifold ways.

However, the provision of tactile feedback is an issue, even for simple single-point interactions on touchscreens. When it comes to multi-point input or even multi-touch input including parameters such as pressure or the size of the touch area, matching programmed tactile feedback dedicated to multiple contacts (described by my term *Multi-Haptics*) is completely missing. Common approaches to provide tactile feedback fail when transferred onto multi-touch systems (i.e. actuation of the device or screen area, utilizing additional devices), as they often result in problems such as ambiguous tactile stimuli, occlusion and space issues. These challenges have already been discussed in section 3.4. Therefore, when researching novel forms of tactile feedback on touch surfaces, one has to incorporate multi-touch interaction.

This thesis introduces the concept of remote tactile feedback and presents evaluations in which this notion is analyzed for single-point interactions. My decision to exclude multi-touch input for most parts of my research is based on the fact that I follow a structured bottom-up approach: I started to analyze the concept in a reduced complexity setting (single-touch interactions) and explored several inherent characteristics, assuming that the findings are in parts transferable to multi-touch and multi-user interactions. Additionally, single-touch still is the most prevalent form of touch interaction today. However, I am of the opinion that a thesis on tactile feedback on interactive surfaces is not complete when multi-touch interactions are left out completely.

Therefore, we[49] ran an experiment to analyze the feasibility of remote tactile feedback for bimanual interactions on a tabletop. Two individual actuators in the left and right seating area of a chair provided dedicated feedback for the user's input with the left and right hand, respectively. The participants performed both synchronized and sequential interactions with both hands. We found significantly decreased rates of input errors when remote tactile feedback was given. Interestingly, this was also the case when the left actuator supported the right hand's action, and vice versa. These findings support our assumption that the temporal association between multi-touch interaction and feedback is more important than the spatial association, thus allowing for

[48] `www.billbuxton.com/multitouchOverview.html` [cited 2013/01/21]

[49] This work was part of Tobias Stockinger's Master's thesis [Stockinger, 2012]. Intermediate results have been published in [Stockinger and Richter, 2012].

the more flexible design of future remote tactile interfaces. The evaluation, its results and the implications for multi-touch and multi-user interactions are summarized in the following.

6.4.1 *Multi-Haptics*: Bimanual Remote Tactile Feedback

Most of our manual everyday activities rely on the control of objects using more than one finger or even both hands. Such simple tasks as tying the laces of our shoes involve manifold concurrent or serial actions. This also holds true for the interaction with mechanical control elements, driving a car is an example of such a complex and fluid bimanual interaction in which also the feet are involved. But when we interact with modern graphical interfaces on a touchscreen, we mostly are "stripped of our dexterity, and are left poking clumsily at the digital world with the single index finger" [Moscovich, 2006].

Classifications of Multi-Touch

The introduction of single-hand/ multi-finger gestures such as pinch to zoom or rotate on smaller touchscreen devices allows for the control of additional parameters without the need for clear interaction points. However, these gestures need to be learned before they can be used effectively. On larger interactive surfaces such as tabletops or interactive walls, multi-hand interaction using single or multiple fingers on each hand can be inspired by real-life interactions such as swiping [Rekimoto, 2002] or stretching [Hilliges, 2009]. Additionally, multi-touch input can also include the interaction of multiple persons on a shared touch display[50].

According to Yves Guiard [Guiard, 1987], the two hands can be considered as two abstract motors cooperating and acting together to achieve a goal. In this regard, both hands work in a coordinated fashion with different hierarchical roles. These two manual motors work together in series, thus forming a kinematic chain. Activities can be termed symmetric when both hands play the same role, either in phase (e.g. rope skipping) or out of phase (e.g. keyboard input), or asymmetric when both hands play very different roles (e.g. playing the guitar).

Evaluation

Following these classifications, our evaluation scenario had the following characteristics:

- bimanual single-finger interaction on a tabletop
- symmetric activity, both in phase and out of phase
- dedicated remote tactile feedback for left and right hand

As our evaluation is constructed as a lab-study, we reduced the complexity to control the influencing variables. However, the interaction resembles feasible tasks that can be performed on a touch surfaces such as moving the sliders on a virtual mixing desk.

[50] The implications of remote tactile feedback in this scenario are discussed in section 6.4.2

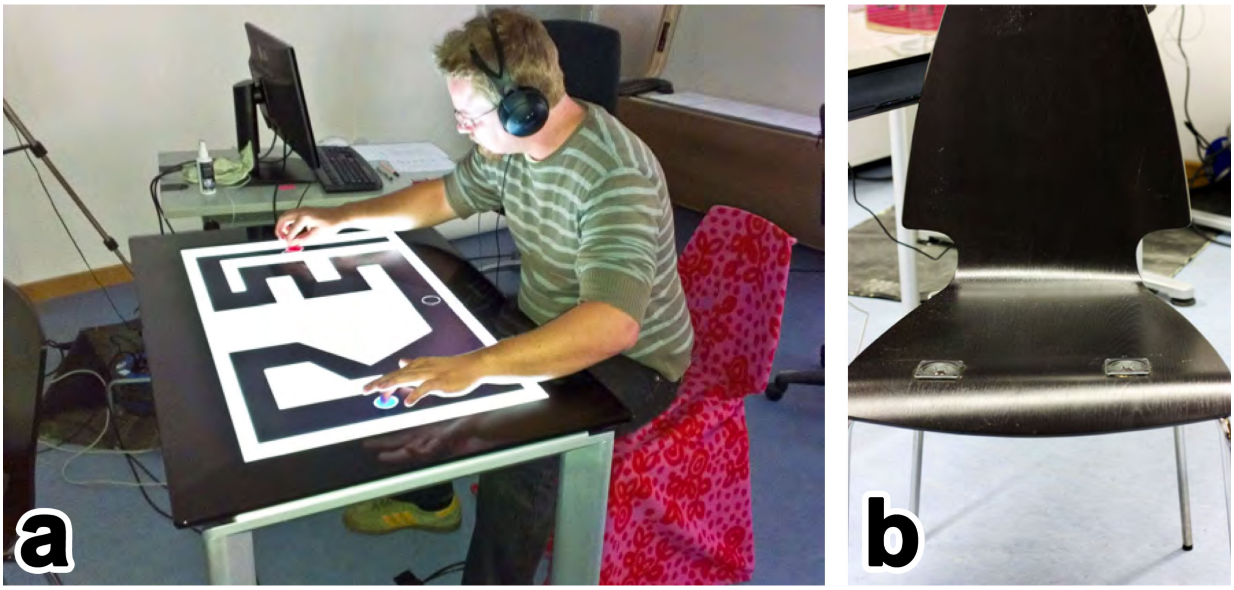


Figure 6.37: Evaluating bimanual remote tactile feedback. a: Participant performing the task on the Microsoft Surface, b: Actuated Chair (from [Stockinger, 2012]).

With the evaluation, we wanted to analyze the effects of multiple instances of remote tactile stimuli synchronized with the actions of left and right hand on error rate and interaction speed. Furthermore, we were interested in the effects of spatial correlation: Are the effects caused by a remote actuator on the right half of the body which is coupled with the action of the right hand (i.e. *parallel*) different from the effects caused by this right actuator when coupled with the actions of the left hand (i.e. *crossed*)? Additionally, we held a guided interview to evaluate if the participants recognized the feedback, could discriminate the different occurrences or did notice that the correlation was crossed sometimes.

In total, 32 participants took part in the study (14 female, average age 24 years). The setting is depicted in figure 6.37: The task was to drag two circles through an asymmetric tunnel from the outer lower corners of the screen onto the target area in the lower center of the screen 'as fast and accurately as possible' without touching the walls. The evaluation had a within-subject, repeated measures design and three dependent variables were defined:

- **Total task time:** starting at the first touch of a circle and ending when both circles have been dropped onto the target.
- **Number of errors:** defined as the number of times a circle touched the virtual wall of the tunnel.
- **Duration of error:** the time spent with a circle touching the wall.

The independent variable **type of feedback** had three levels: visual-only, tactile-parallel and tactile-crossed. The task had to be performed six times and both sequentially and simultaneously in each condition. The asymmetric tunnel was switched horizontally for half of these trials.

The input performed with each hand was synchronized with a dedicated tactile actuator[51] in the seat of the chair (see figure 6.37). The actuators were covered in order to hinder the participants from recognizing their number and location. Individual remote tactile feedback was given at three points of an interaction: On touch of a circle, a continuous vibration of 80 Hz was played. On contact of a circle with a wall (i.e. error) a pulsation with 12.5 Hz is communicated, as long as the circle touches the wall. Finally, when a circle is moved onto the target area, a 'snap-in' stimulus of low frequency is played. In order to cover unwanted noise, users had to wear headphones with music during the trials. As the skin adapts to tactile stimulation and might become insensitive, participants were asked to stand up after two conditions and take a short break.

Results

We found significant quantitative effects of the tactile feedback in both the simultaneous (i.e. both hand acting at the same time) and the sequential (i.e both hands act consecutively) setting:

In the simultaneous setting, we found that the **provision of remote tactile feedback for both hands significantly reduced the number of errors** (significant by Friedmann's ANOVA ($\mathscr{X}^2$=7.54, $p<0.05$)). A post-hoc-test with Bonferroni corrections revealed significant differences between the visual-only (13.8, SD=9.32) and tactile-parallel feedback (10.01, SD=6.19) as well as visual-only and tactile-crossed feedback (9.85, SD=5.9) ($p<0.167$). In other words, the provision of parallel remote tactile feedback and crossed remote tactile feedback resulted in a reduction of the average numbers of errors of 23% and 24%, respectively. This effect came at the expense of a **slightly increased total task time**: We found a significant effect of tactile feedback using a one-way repeated measures ANOVA ($F(2,58)=6.07$, $p<0.01$). The post-hoc-test with Bonferroni corrections showed significant differences between the visual-only (19.9 s, SD=7.1) and tactile-parallel condition (21.5s, SD=7.2) as well as visual-only and tactile-crossed condition (21.7 s, SD=6.4) ($p<0.167$). This means that people needed more time when a form of tactile feedback was given (3.6% for parallel and 6.2% for crossed feedback). No effect of the feedback on was found on the duration of the errors.

Also in the setting with sequential interaction, **both forms of remote tactile feedback could significantly decrease the number of errors made** (Friedmann's ANOVA ($\mathscr{X}^2$=9.17, $p<0.01$)): Again, a post-hoc-test with Bonferroni corrections revealed a significant difference between the visual-only (8.82, SD=6.91) and tactile-parallel setting (6.37, SD=4.13) as well as between the visual-only and tactile-crossed condition (6.15, SD=4.28) ($p<0.167$). This is a reduction of 27% of average error rates with parallel tactile feedback and even 30% when the correlation of the input sides and the feedback location was crossed. Furthermore, the provision of remote tactile feedback did not result in significantly reduced total task time. No effect was found regarding for the duration of the errors.

When asked in the guided interview, if they realized that tactile feedback was provided, **only 3 out of 32 people didn't notice the tactile feedback at all**. The participants were asked in which situation they noticed tactile feedback, 88% noticed it when they hit a wall (error), 78%

[51] Visaton FRWS 5 voice coil

realized the feedback when they had completed the task ('snap-in'). However, only 9% realized the vibration on touch of a circle. Interestingly, the answers revealed that **users tended to over-interpret the signals**: 8 people had the feeling of signals which vary in intensity, depending on their number of errors. One participant felt that the error pulses increased in frequency when the circle was not moved away from the wall fast enough.

A majority of **20 out of 32 recognized the tactile stimuli as two separate sensations**. Five people recognized only on stimulus, four recognized three and 3 were 'not sure' about the number of stimuli. It is notable, that **only two of the participants recognized that the correlation of left/right hand and left/right stimulus was inverted in half of the trials**.

Discussion and Conclusions

The notion of bimanual remote tactile feedback is far from being fully exploited yet. However, I see the approach as a possibility to provide tactile feedback on larger interactive surfaces where different points of interaction are augmented with dedicated non-visual feedback. This is not possible with most of the common methods for tactile feedback on touch surfaces (see section 3.4).

Bimanual remote tactile feedback could significantly reduce the number of input errors, although the feedback was reactive, i.e. informed the user when an error had already happened. The reasons could be found in the users' adapted usage strategies and a form of more self-reflective behavior during the interaction: The participants relied on the tactile feedback, some even assumed helpful stimuli which weren't there. As one participant put it: "you don't have to concentrate on both hands, you can look over to the hand that makes a mistake only when you need to". I speculate that the 12 persons who did not recognize separate signals could have performed better, one participant noted that if she/he "had known, that there are two feedback locations", she/he would have utilized the signals to a higher degree. The spatially separate stimuli are easily recognizable, maybe due to their application on two different limbs which may have resulted in less signal overlap.

Comparable to the *AutomotiveRTF* study in section 6.2.2, we experienced a slight increase of total task time, when feedback was given. Again, I think that this effect is rather small in comparison to benefits such as decreased visual load or (as seen here) reduced error rates.

Most interestingly, over 90% of the participants did not realize that left and right interaction has been connected with the right and left actuator (i.e. crossed) half of the time. This supports the findings from sensory substitution (see section 4.1): As long as the sensory-motor loop is tightly closed, the position of a stimulus is less important. In other words: the temporal association between interaction and stimulus is more defining for the usability of a system than the spatial association between both. This important finding supports the design of more versatile bimanual remote tactile interfaces in the future: As long as the two actuators are apart far enough to excess psychophysical thresholds, a spatial correlation between hand and actuator is unnecessary. This results in the assumption that multiple actuators for multiple hands could be integrated into one actuated wrist band or vertically into the backrest of a chair. This potential needs greater attention in future evaluations.

However, I think that the transferability of our results has its limits: depending on use-case, type and location of actuators or even the participants' clothing, the results might be different. Future evaluations should also analyze a potential effect of this form of feedback on the participants' use of both hands: Results from related work [Terrenghi et al., 2007] indicate a connection between physical feedback and bimanual input. Furthermore, a physicality of feedback might result in reduced total task times. This effect should be analyzed for bimanual remote tactile feedback.

Future manifestations of bimanual remote tactile feedback should definitely analyze the possibility to extrapolate the concept: Does the correlation of input and feedback work for more than two points of contact? Is this concept also feasible for not only 'points of contact' but also different forms and sizes of contact with the interactive surface (i.e. palm of the hand, forearm)?

6.4.2 Outlook: Multi-User Remote Tactile Feedback

The notion of multiple remote tactile stimuli for multiple contacts with the interactive surface can easily be extended towards a scenario in which multiple people interact simultaneously on multiple interactive surfaces. The size and character of the interactive surfaces as well as the social scenarios they are used in have implications for the additional remote tactile feedback. In the following, I briefly address questions which are raised when thinking about the vision of remote feedback in multi-user scenarios. The thoughts are merely speculations, their feasibility should be addressed in future research projects.

Spatial Conditions: With remote tactile feedback, multiple persons can freely and directly interact with a larger shared interactive screen and still receive tactile stimuli. No additional actuated devices such as pens or pucks are necessary on the surface. However, also the underlying concept of direct manipulation and (for TUIs) a spatial 'coincidence of input and output' [Ishii, 2008] comes to an end when numerous persons want to physically interact with an entity of limited size. In other words, space is an issue when it comes to multi-user direct manipulation of virtual objects on interactive surfaces. In section 2.2.4, I described the vision of future interactive surfaces which are deformable and transforming to allow for universal input and output facilities. In order to avoid cramped conditions on these surfaces caused by multiple persons simultaneously touching it, interactions 'over a distance' might be used (e.g. mouse- or laser-pointer-like devices or gestures). As indicated in section 6.2.2, remote tactile feedback could support these direct and indirect input methods.

Individualization and Transfer: Every user of a shared interactive surface could receive *individual* dedicated remote tactile stimuli depending on the user's role in the interaction or on the manipulated data. For example, the same virtual element could feel cold for one user, rough for the next user and could lack tactile stimuli for the last user. This highly individual nature of remote tactile feedback can be controlled by using different types of actuators on different locations of the several users' bodies and result in different tactile information content. On the contrary, the *same* form of tactile actuation can be achieved on very different forms of interactive surfaces. For example, by wearing an actuated arm sleeve for remote tactile feedback, a user could touch a virtual element on a tabletop first and then on a mobile touch device. Both virtual elements can have the same tactile representation.

Personalization: In addition to individualized or generalized stimuli, the concept of remote tactile feedback might help to *personalize* the haptic sensations coming from the interface. According to Alan Dix, supporting the flexibility of a system is a means of increasing its usability [Dix et al., 2004a]. Customizability is a principle of this flexibility, the user interface and its multimodal appearance should be modifiable by the user (adaptability). The principle of remote tactile feedback can in parts fulfill this need: For example, users could change the way the interface behaves for them by wearing or not wearing an actuated wristband. Users could control their personal level of stimulus intensity by resting their back on an actuated seat with less or more pressure. Furthermore, a system could provide customizing features to individually alter the level and type of tactile experiences for the users to allow for more efficient use of the tactile stimuli[52].

Communication: As already described in section 6.2, the provision of remote tactile feedback is not restricted to the moment of contact with an interactive entity. When in contact with the human body, the tactile actuators can be used to convey structured non-visual messages in manifold situations. These *tactons* [Brewster and Brown, 2004] could be used as alerts (e.g. when someone else is interacting with a digital entity which is associated with the receiver of the tactile message) or as carrier of emotions (e.g. [Park et al., 2010]). This channel of information could also be used between a number of persons in a larger group or over a distance. The concept allows for a transition between tactile feedback for touch feedback and communication.

Privacy: The universal principle of tactile stimuli fluently utilized to support interactions and to facilitate communication has an additional characteristic: haptic cues are discreet and form a personal and private channel of information between human and machine or between human and human.

6.5 Summary

In this chapter, I identified four classes of inherent characteristics which are entailed with the utilization of the concept of remote tactile feedback: technical simplification, proactive/reactive/detached tactile feedback, increased versatility of stimuli and multi-touch haptic feedback. These characteristics can help to avoid general challenges of tactile feedback on today's touchscreens and allow for a more versatile usage of tactile feedback on future forms of interactive surfaces.

When utilizing this principle, the tactile output is not superimposed with the visual output. We exploited this characteristic for the **technical simplification** of tactile feedback in two ways:

[52] This idea is backed from our findings with the *ThermalTouch* prototype in section 6.3.2: When taking the persons' individual experiences with tactile stimulation in the everyday world into account, we could greatly increase discrimination rates.

First, remote psychophysical illusions were used to reduce the number of individual actuators needed to create localized cutaneous stimuli. An evaluation showed that these phantom sensations can be created using simple vibrotactile actuators with amplitude inhibition. However, a certain amount of cognitive effort is needed to utilize this form of phantom feedback for a touch interaction. When visual feedback is sufficient, users tend to dismiss the phantom sensations. Second, we showed that high resolution tactile feedback is possible for a single point of contact with the screen by externalizing a pin matrix under the non-dominant hand. With a tightly closed sensory-motor loop, persons were able to identify orientations and sizes of virtual objects based on their programmed tactile representations. Interestingly, this is possible with no previous learning and without any visual representation of the virtual object on the touchscreen.

In the next step, we showed that remote tactile feedback can be **proactive, reactive and detached** and utilized this characteristic for three reasons: First, we can extend the time window of tactile communication when the finger is on the screen. Therefore, I presented a model to substitute input force with input speed to avoid the need for pressure sensing mechanisms. This model is applicable for visual, auditory and tactile cues. Implementing the model, we recreated multimodal cues of mechanical push buttons using remote tactile feedback coupled with a touch surface. The results of the preliminary evaluation show that the relocation is forgotten by the users after a short time. In accordance with the previous evaluations, the users preferred the tactile-visual feedback over the visual-only setting. The remote application of proactive and reactive stimuli resulted in more distinguishable and 'involving' virtual elements. Second, we supported the phase when the finger is in the air before (targeting) and after an interaction. The chapter presented an elaborate technical implementation of the concept as a pneumatic actuator matrix in the car. A field-study with the system revealed a significant reduction of subjective visual load in two out of three cases. Again, the participants' responses indicated an easy association between touch and remote feedback. However, the proactive stimuli given when the finger is in mid-air often resulted in confusion, whereas the reactive stimuli gained highly positive responses. Third, I presented an experimental setup to augment mid-air gestures which are detached from a non-flat surface with remote tactile feedback using a wearable actuator system. Again, the internal association between interaction and feedback was described as easy by users. However, the evaluations showed problems with the discriminability of the tactile stimuli.

As a result, the focus of the next section was set on the **increase of versatility and expressiveness** of the remote tactile stimuli in order to increase the information bandwidth and to allow for more discriminable stimuli. Hence, the evaluation ob subjective responses on the hedonic and pragmatic qualities of the stimuli played a major role. First, we incorporated several different types of tactile actuators and location as tactile design parameter to allow for more distinct stimuli. Second, we incorporated novel tactile modalities and showed that it is possible to create discriminable virtual materials on touchscreens based on remote thermal profiles. Furthermore, the results indicate a high influence of individual sensory experiences on the subjective perception and the effectiveness of the programmed stimuli. Third, I described the implications of liquid as a novel medium for tactile communication. This part also describes the technical prerequisites and stresses the importance of combination (e.g. of tactile modalities and technologies) as essential to increase the versatility and expressiveness of the stimuli.

Finally, this chapter described our analysis of dedicated remote tactile feedback for more than one hand, a concept we termed **multi-haptic feedback**. The results of the evaluation showed a significant reduction of the number of input errors when multi-haptic feedback was provided. This corroborates the beneficial effects of tactile feedback in more dynamic scenarios. Most interestingly, the beneficial effects were also found when the left actuator represents the right arm's actions and vice versa: These findings show the importance of a closed sensory-motor loop and backs the general concept of remote tactile feedback. Temporal association turned out to be more relevant than spatial association between manual action and sensory reaction. Multi-person touch interactions coupled with remote tactile feedback is identified as a promising field of future research.

Chapter 7

Conclusions and Future Work

The work of this thesis covers a field which draws from many disciplines. Following Alan Dix' definition, the main part of my work lies in the field of human-computer interaction, i.e. the design, implementation and evaluation of interactive systems in the context of the user's task and work [Dix et al., 2004b]. My research deals with the physical characteristics of machines and the effect on the user's performance. Working on the boundary between the physical and digital world, the field can be denominated 'physical computer science'. Specifically, digital information is stored, accessed and utilized in the form of programmed tactile stimuli. Still, a very important part of this thesis lies 'outside the box', as I heavily borrow and rely on information from physiology (i.e. how our body recognizes and transforms sensory cues) and psychology (see chapter 4).

In this thesis, I also try to identify and support ongoing developments in the field: The direct manipulation of interactive surfaces has become an omnipresent standard for the interaction with digital information and is a subject to constant change. I describe this process in chapter 2. Designers, researchers and developers struggle to expand the physical mechanisms for input and output to allow for easier and more flexible interactions. This trend is illustrated by the heterogeneous sizes of current devices (see section 2.2). The thesis endorses ongoing developments in the field towards more organic interactive surfaces: In other words, touch surfaces will exist which are non-flat, "transformable and flexible, naturally adaptable and evolvable, while extremely resilient and reliable at the same time" [Vertegaal and Poupyrev, 2008]. I illustrated this trend in section 2.2.4. The goal is to develop devices which are adaptable to the user's needs and provide flexibility in the means to fulfill set goals. In this regard, the lack of appropriate and meaningful tactile feedback has been identified as one main drawback of current systems which often results in increased visual load, decreased accuracy and limited user satisfaction (see 3).

7.1 Contributions

With my work, I introduce the notion of remote tactile feedback on interactive surfaces as a novel field of research and a valid alternative for existing techniques. As described in the introduction (see section 1.4), this dissertation has four contributions which are relevant to researchers and practitioners:

- First, the dissertation defines the **framework of remote tactile feedback** and motivates and substantiates the approach with applied concepts and techniques from physiology and sensory substitution. Thus, the dissertation structures the design space. Additionally, it proposes a taxonomy to compare methods for tactile feedback on interactive surfaces.
- Second, the dissertation describes the design and the technical implementation of diverse **prototypical remote tactile interfaces**. This information can help researchers and practitioners to rapidly build their own and to adapt the concept of remote tactile feedback. These prototypes were utilized in diverse evaluations and observations in order to answer the two posed research questions.
- Third, the potential of the approach to **improve the usability of touch surfaces** was in the center of RQ1. The dissertation shows that remote tactile feedback can improve the user's performance in a way similar to direct tactile feedback.
- Fourth, the dissertation analyzes possible future directions of interactive surfaces and current challenges of methods to provide tactile feedback. Consequently, RQ2 was about the identification of unique features of the approach which make **tactile feedback on interactive surfaces more versatile and simpler to integrate**. Furthermore, remote tactile feedback can support the user on non-flat interactive surfaces or during multi-touch or gestural input. These characteristics were analyzed in diverse user studies with purpose-built prototypes.

In chapter 1, I formulated the two research questions to structure the work in this thesis. The main empirical findings were summarized within the chapters 5 and 6. In the following, I will synthesize these findings to answer the research questions and to discuss the approach of remote tactile feedback as a valid alternative for the creation of cutaneous stimuli on touch surfaces.

7.1.1 Improved Direct Touch Interactions

Research Question 1:
Does remote tactile feedback improve the direct touch interaction in terms of reduced error rates, increased interaction speed, decreased distraction and better subjective ratings?

The examination of this first research question was the main focus of chapter 5 in which I presented three consecutive user studies. In these evaluations, we compared the quantitative effects of direct and remote tactile feedback and measured the impact of non-visual stimuli which were applied on different locations on the users' bodies. My motivation behind this approach was to analyze if the beneficial effects of remote tactile feedback are comparable to those of direct tactile feedback (known from related work). Thus, when utilizing the approach's unique virtues (subject matter of RQ2), the known general advantages of additional tactile feedback must be preserved. A direct comparison of both the direct and remote application of stimuli as we performed it in 5.2 is somewhat artificial, as we used the fingertip (dominant and non-dominant hand) in both cases. This location is not practicable for future implementations of the approach. Nevertheless, we gained valuable insights regarding stimulus location and signal design. In general, the beneficial effects of additional remote tactile feedback are visible throughout the majority of the presented projects of both the chapters 5 and 6.

A significant **reduction of error rates** was found in the evaluation of multi-haptic feedback in section 6.4. In this situation, the users were asked to interact on a tabletop using two hands in a rather complex task. This imposed a certain amount of *cognitive and visual load* on the users. The *simple reactive tactile stimuli* were designed as object-independent warnings and acknowledgments and were drawing the user's attention to the hand which performed a more difficult task at this moment. However, this significant effect came at the expense of a significantly increased total task time, as users tended to concentrate more and perform slower when tactile feedback was given.

However, we did find a significant **increase of interaction speed** caused by remote tactile feedback in one evaluation (see section 5.4). *Simple reactive tactile stimuli* on the dominant wrist were used which helped the users to know when they had finished the bimanual scaling task. This time, no additional visual or cognitive load was present. It can be assumed that the *simplicity and low latency* of the stimuli did not tempt the users to explore and 'feel out' this novel form of acknowledgement.

The strongest decrease of distraction was found when we measured the effect of remote tactile feedback on the subjective visual load during touch interactions of a driver (see section 6.2.2). We observed a transfer of subjective workload from the visual to the tactile channel. This resulted in a significant **decrease of subjective visual load** of around 10% for two out of three tasks. This time, we designed more *elaborate cutaneous stimuli* which also had parameters such as body location and different amplitudes. These remote stimuli communicated object-independent information concerning the status of the interaction (e.g. position in the list) and acknowledgments (e.g. activation of button). Again, this came at the expense of significantly increased total task time in one task, as users tended to experience the tactile stimuli for a prolonged time.

We found that tactile feedback in general greatly influences the **subjective evaluation** of an interactive system, this finding is in accordance with related work (e.g. [Brewster et al., 2007]). In the evaluation presented in section 5.2, both forms of tactile feedback (direct and remote) were preferred over visual-only feedback. Accordingly, both forms of cutaneous stimulation gained comparable subjective ratings. In general, the provision of cutaneous stimuli had strong subjective effects: people stated that they were able to 'feel the virtual objects' (*EdgeMatrix* project in section 6.1.2), perceived emotions such as 'connection' and 'involvement' (*TacSnap* project in section 6.2.1) and often stated the interaction to be 'exciting' (the *Interactive Watzmann* in section 6.2.3) or 'creative', 'innovative' and 'novel' (*HapticArmrest* in section 6.3.1).

In summary, I can give a positive answer to the first research question. Under cognitive or visual load, simple forms of reactive remote stimuli can help to reduce the numbers of input errors and to decrease subjective workload. These effects are comparable to those of direct tactile feedback. On the other hand, more elaborate cutaneous feedback which also communicates surface characteristics or forms of virtual objects can have a highly positive effect on the user's rating of an interaction, but may result in increased task times as users tend to explore this novel form of feedback[1].

7.1.2 Versatile Feedback and Simple Integration

Research Question 2:
Does remote tactile feedback provide additional inherent characteristics which are beneficial for direct-touch interactions?

The positive quantitative results of the evaluations presented in chapter 5 encouraged me to address the technical and conceptual features which result from the use of remote tactile feedback. I consider the answering of this research question the main contribution of my thesis, as it takes on limitations of common approaches for haptic feedback and current tendencies in the development of interactive surfaces. The broad and experimental approach to explore and analyze the inherent effects of remote cutaneous feedback (i.e. simplification, proactive/reactive/detached feedback, increased versatility of tactile stimuli and multi-haptics) have been presented in chapter 6. The main findings were summarized in section 6.5.

The work on this research question can be considered basic research as it opens up a novel concept of non-visual feedback and identifies conceptual correlations which do not exist for other approaches of tactile feedback on touch surfaces. Therefore, this research heavily relies on purpose-built prototypes which often are used in a single evaluation to analyze a single aspect of the approach. Still, the distinct characteristics of remote tactile feedback were evaluated with prototypes on different levels, from experimental to close to product maturity. Accordingly, the findings can also be classified according to the type of the underlying prototypes and devices:

The majority of prototypes had an exploratory character and were used to highlight specific aspects of the concept in single evaluations[2]:

- **Simplification:** The *EdgeMatrix* and the *PhantomStation* were used to demonstrate methods to technically simplify the integration of tactile feedback by reducing the numbers of actuators and to increase tactile resolution without the need to integrate numerous actuators into the touch surface.
- **Proactive, Reactive and Detached Tactile Feedback:** The *TacSnap* prototype was used to generate tactile stimuli which resemble those of mechanical control elements on a standard touchscreen. Thereby, we could create more distinguishable and 'involving' stimuli.

[1] This novelty effect can decrease over time [Benko et al., 2009].

[2] Future manifestations of these specific concepts might use other locations of application or smaller form factors.

- **Increased Versatility of Tactile Stimuli:** With the *HapticArmrest* and the *ThermalTouch* prototype, we highlighted the use of remote tactile feedback to create more versatile tactile stimuli by implementing diverse actuators and by integrating thermal stimuli.

Another class of prototypes was also used to exemplify and discuss the approach, to observe long-term effects or to serve as a basis for consecutive steps of research:

- **Proactive, Reactive and Detached Tactile Feedback:** The *InteractiveWatzmann* is an experimental setup which was deployed in a longer evaluation to observe the effects of remote tactile feedback during gestural input in mid-air.
- **Increased Versatility of Tactile Stimuli:** The *LiquiTouch* prototype is intended to inspire designers and practitioners to consider novel media for tactile communication and new forms of tactile feedback.
- **Bimanual Remote Tactile Feedback:** With the concept of *Multi-Haptics*, we entered the domain of multi-touch interactions with corresponding tactile feedback and gained positive results regarding error reduction and design guidelines for future actuators.

Finally, one project was implemented in a context which can be considered closer to product maturity:

- **Proactive, Reactive and Detached Tactile Feedback:** In the *AutomotiveRTF* prototype, we utilized devices from serial production in a standard car. The field-study with the system revealed a significant reduction of subjective visual load.

In summary, I can give a clear positive answer to the second research question. Furthermore, the diverse evaluations pose implications for future uses of the concept. These implications are discussed in the following.

7.1.3 Valid Alternative Concept

Section 3.5 outlined the three common methods to provide tactile feedback on touch surfaces and compared the characteristics of these methods along the three dimensions *technical feasibility*, *tactile expressiveness* and *general usability*. Remote tactile feedback forms an alternative option.

This concept also corresponds with the underlying findings from sensory substitution and tactile sensory relocation (see chapter 7). Here, the user has to be 'in control' and moves her/his body to navigate a sensor[3] on the object of interest. This connection is temporal, i.e. the feedback has to come in realtime to close the proprioceptive-tactile perceptual feedback loop. Temporal coincidence is more important for a functioning manipulation of the environment than a spatial coincidence. This fact corresponds with our findings: a relocation or interchange of actuators does not affect the interaction or is not even realized by the interacting person (see sections 5.2 and 6.4). Users reported an almost immediate connection between interaction, visual stimulus and remote tactile sensation. Hence, this main finding opens up vast possibilities for the design of future remote actuator systems, which were addressed in chapter 6.

[3] The mechanoreceptors in the skin are also 'sensors'.

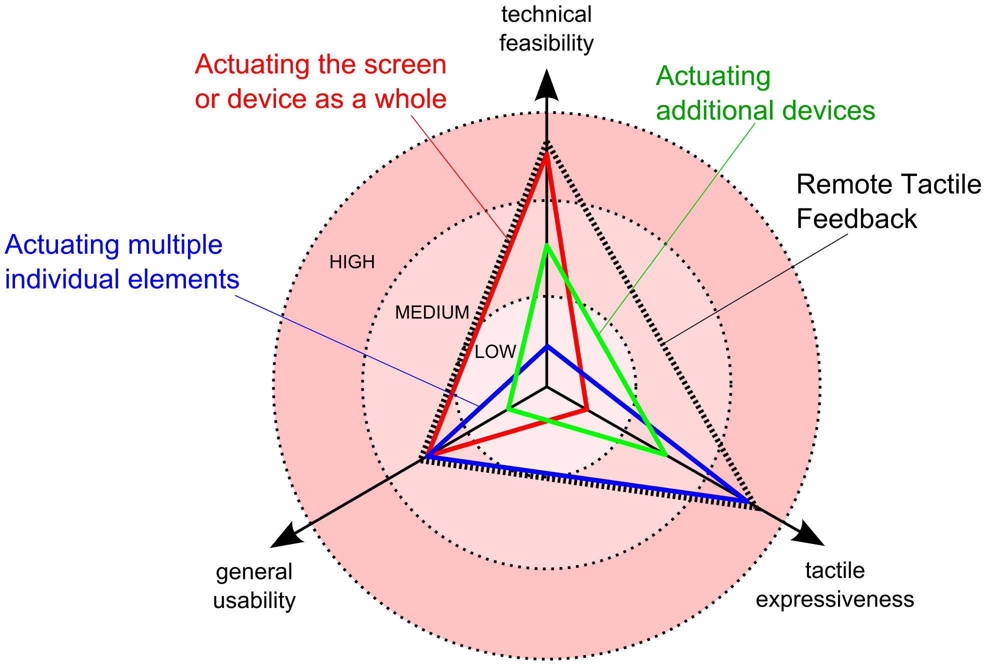


Figure 7.1: Remote tactile feedback included into the taxonomy of methods to create tactile feedback on interactive surfaces. Details in the text.

In figure 7.1, the characteristics of remote tactile feedback are classified accordingly. In the following, I extrapolate the findings from the evaluations in chapter 6 in order to compare all four methods [4].

Technical feasibility: The technical feasibility of remote tactile feedback can be considered high. High resolution shape information can be transferred (see section 6.1.2), no actuators or fixed buttons have to be integrated into the screen. Thus, the concept is easily scalable towards larger, non-flat or non-solid interactive surfaces without the need to implement a high number of stimulators (see section 6.1.1). In contrast to the use of additional actuated pointing devices, the touchscreen is the only means of input.

Tactile expressiveness: The tactile expressiveness of remote tactile signals can reach the high level of cutaneous signals created by 'tactile pixels'. Edges, surface structures, thermal stimuli or moving sensations can be presented (see sections 6.1.2, 6.3.2, 6.2.2). The whole human body with versatile psychological and physiological characteristics can be utilized to apply cutaneous sensations[5]. Furthermore, I stress the importance of combination of sensations to create more versatile and meaningful tactile sensations (see section 6.3.3). However, for simple tactile acknowledgments (e.g. on mobile devices), the approach of 'actuating the device as a whole' might be sufficient to decrease workload and error rate (see section 3.3.2). Remote tactile sensations

[4] As this thesis describes basic research in a novel field, individual claims may be speculative and represent subjective estimations.

[5] Cultural differences and emotional effects of mediated touch have to be taken into account. The discussion of these aspects can be found in section 7.3 (future work).

can allow for multi-haptic feedback (see section 6.4). However, actuated devices could be used in scenarios which require more exact input, but no multi-touch.

General usability: The approach presented in this thesis allows for multi-touch tactile feedback without occluding the screen with additional devices. The crucial concept of direct manipulation is preserved. The concept of remote tactile feedback depends on a steady contact of the actuators with the user's skin. This challenge is discussed in section 7.2. However, the user thereby can modify the quality of the experienced stimuli by relocating or taking off the actuators (see section 6.4.2). In summary, I consider the general usability of the approach comparable to the actuation of the screen or device.

7.2 Limitations

This thesis presents a novel concept, provides findings from fundamental research and exemplifies the feasibility of the approach. This form of research highlights limitations and open questions which have to be addressed and analyzed in future implementations. This section follows Buxton's axiom that "Everything is best for something and worst for something else. The trick is knowing what is what, for what, when, for whom, where, and most importantly, why"[6]. Therefore, I discuss the challenges of remote tactile feedback regarding the *scalability of the approach*, the *placement of tactile actuators* and feasible *scenarios of use*.

Scalability of the approach: The scalability of the approach is limited in two dimensions: *size* of the touchscreen and *number* of simultaneous users. First, for very small touch interfaces which are often used in dynamic or mobile scenarios, the addition of tactile feedback has been shown to be highly beneficial (see section 3.3.2). However, for this kind of touch interface, the separation between 'actuating the whole device in the holding hand' and providing remote tactile feedback is blurry. It can be said that remote tactile feedback already exists on mobile devices, as the feedback is often provided to the holding hand and not to the touching finger. Furthermore, unique characteristics of remote tactile feedback such as the provision of multi-haptic feedback might not be important on small screens, as users mostly do not interact with multiple separate points of input[7]. Still, inherent potentials of remote tactile feedback such as more versatile stimuli should be considered for mobile devices. The findings of the thesis in this domain are transferable onto smaller screens. Second, in a scenario with a multitude of users on one or several interactive surfaces, an additional remote feedback device (which has to communicate with the touch system) for each of these users can be as complicated as multiple actuators on the surface. In other words: Larger shape displays with 'tactile pixels' might be preferable when numerous users (e.g. more than 10) want to interact for a short time.

[6] Bill Buxton: Multi-Touch Systems that I Have Known and Loved
`http://billbuxton.com/multitouchOverview.html` [cited 2012/08/31]

[7] Gestures such as 'pinch' are performed with multiple fingers, but do not represent different information for the two points of contact.

Actuator Placement and Size: Current developments in the field of interactive surfaces show that Mark Weiser's vision becomes reality (see chapter 2): "The most profound technologies are those that disappear" [Weiser, 1991]. Consequently, the concept of remote tactile feedback should follow this notion of systems that "fit the human environment instead of forcing humans to enter theirs" [Weiser, 1991]. The prototypes presented in this thesis are far from fulfilling this vision: They are primarily used in evaluations and often are made of off-the-shelf components (e.g. wooden encasing, industrial solenoids). Users often had to hold their arms in certain uncomfortable positions to reach the sometimes non-aesthetic actuators (e.g. finger on the *ThermalTouch* in section 6.3.2). Nevertheless, the prototypes demonstrated possibilities for feasible implementations in the future and took the differing spatiotemporal resolutions on different body areas into account: On the one hand, we used wearable interfaces (see section 5.3) and implemented methods which might be realized in the future with 'active clothing' (see section 6.2.3). Implementing these wearable solutions allows the user to move around freely and to use the actuators for more than one device. On the other hand, we envisioned remote tactile actuators in the user's direct environment such as the frame of the interactive table (e.g. *PhantomStation*, *TacSnap*, *HapticArmrest*) or the seat (e.g. *AutomotiveRTF*, *Multi-Haptics* project). Thus, many versatile actuators can be flexibly positioned. However, it is important to ensure the permanent contact with the user's skin to communicate tactile information[8]. Smaller actuator systems are available today and will be even smaller in the future. This trend of miniaturization will simplify the integration of remote tactile technology.

Scenarios of Use: The systems presented in this thesis oscillate between 'interactive sketches' and 'prototypes': According to Greenberg and Buxton [Greenberg and Buxton, 2008], sketches are used to "illustrate the essence of an idea, but have many rough and/or undeveloped aspects to it". Sketches are evocative and explore a novel design space. On the other hand, the systems in this thesis serve as prototypes, which are used to evaluate an idea or resolve certain questions. Both authors state that "Consequently, premature usability evaluation of the sketch as prototype could, unsurprisingly, find significant problems that could kill the design outright, especially if a novel design is compared to one that is more conservative" [Greenberg and Buxton, 2008]. Therefore, I tried to implement the notion of remote tactile feedback on several levels of fidelity. In human-centered development, the performance of a novel system has to be improved first until it is 'good enough' to fulfill the user's needs [Norman, 1998]. Therefore, the concept of remote tactile feedback has not been implemented in more concrete or long-term usage scenarios. However, the implementation of the concept in a car (see the *AutmotiveRTF* project in section 6.2.2) shows a promising direction.

[8] Please note that remote tactile feedback is mostly used in addition to visual feedback and is not the only channel of sensory information, which makes continuous contact with the actuators less crucial.

7.3 Ongoing and Future Work

The presented basic research is a first step and included three aspects: We analyzed and identified locations of the human body where remote tactile feedback can be applied. With projects such as *ThermalTouch*, *HapticArmrest* or *EgdeMatrix*, we demonstrated possibilities for the design of remote tactile stimuli. Finally, we tested and compared a multitude of actuation principles and technologies (e.g. in the *PhantomStation* project). I believe that ongoing and future work can build on these foundations and should include two parts: First, the ongoing evaluation of the technology and its effect on the user's perceptions and emotions is important. Second, the deployment of the concept into real-life and long-term settings can provide valuable insights. Both parts complement each other and form an iterative process.

At the moment, I am working on evolving my research methods to "encompass the need to evaluate next generation socially situated ubiquitous technologies" [Barkhuus and Rode, 2007]. On the one hand, I am using psychophysical measurements to collect characteristics such as the 'just noticeable difference' of a stimulus (e.g. the minimum difference between remotely applied thermal cues which can be perceived by the users) and the effect of the location of application on the perceptibility of the sensation. Here, I also want to incorporate social and cultural influences which affect the usage of tactile stimuli between humans and technology or humans and humans (the second aspect is part of 'proxemics' [Hall, 1966]). The goal is to provide more formal guidelines for the design of remote tactile stimuli. On the other hand, it is important to combine methods to analyze user experience, workload or usability (such as AttrakDiff, NASA TLX or SUS) with biometric sensors (e.g. heart rate measurements, galvanic skin response) to gain deeper insights into the emotional effects and experiences with this form of stimulation.

This approach requires interdisciplinary research: Future PhD students working on the concept could be psychologists or neurologists to provide more substantial proof of the subjective effects and to create 'crossmodally congruent' stimuli for the visual, tactile and auditory domain (see section 3.3.2). This research work should be paralleled with the main part of the future research agenda: the implementation of the concept into realistic usage scenarios with advanced actuator technology.

Projects in this thesis such as the *AutomotiveRTF* highlighted suitable usage-scenarios for remote tactile feedback. Others include tabletop or multi-user scenarios, as they also are dynamic scenarios with increased visual and cognitive load. Smaller and more efficient actuators should be used which could 'vanish in the background'. In the process, actuators could be radio-controlled and equipped with integrated circuit control (instead of using microcontroller units) to allow for mobile use or the dynamic coupling with multiple interactive surfaces. These usage-scenarios should last several days or weeks. Thereby, one could minimize the effect of the novelty bias (which could result in increased quantitative benefits) and test the acceptance and adequacy of the technology in the specific scenario.

7.4 Closing Remarks

Our sense of touch contributes to a rich internal representation of the world we live in. This collection of information comes from both unconscious behavior and an active exploration and manipulation of our environment. However, we usually can not *ertasten* the physical nature of digital content on today's interactive surfaces. The presented thesis works on this challenge and describes alternative ways to use our body's skin as a bridge between non-physical matter and ourselves.

With remote tactile feedback, this thesis presents an alternative approach to create haptic sensations synchronized with a manipulation of digital information on touch surfaces. This novel principle is exemplified and analyzed using technical prototypes. Remote tactile feedback is shown to be beneficial in terms of reducing the number of input errors, increasing the interaction speed and improving the subjective appraisal of a system. Furthermore, the thesis highlights inherent characteristics of the principle which simplify, diversify and expand the use of non-visual stimuli during touch-based interactions.

I think that haptics in computation will move beyond special purpose applications in the near future. Haptic sensations which augment our interaction with digital information will be more than just 'clicks' and 'buzzes' and will convey content which is not already visible on the screen. We will touch interactive surfaces that are non-flat, non-solid, transformable and transforming. Furthermore, these interfaces will be seamlessly interwoven into the world around us. This development demands for more flexible and versatile means of communication with technology.
I hope that the concept of remote tactile feedback can support this dialogue.

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Eidesstattliche Versicherung

(Siehe Promotionsordnung vom 12.07.11, § 8, Abs. 2 Pkt. .5.)

Hiermit erkläre ich an Eides statt, dass die Dissertation von mir selbstständig und ohne unerlaubte Beihilfe angefertigt wurde.

München, den 21. Februar 2013

Hendrik Richter