Design and Recognition of Tactile Feedback Patterns for Snowboarding

Diploma Thesis at the
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I hereby affirm that I composed this work independently and used no other than the specified sources and tools and that I marked all quotes as such.

Hiermit versichere ich, diese Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt, sowie Zitate kenntlich gemacht zu haben.

Aachen, 31.10.2008

(Mareike Jacobs)

Contents

List of Figures

List of Tables

Abstract

Beside vision and hearing, touch is one of the most important human senses. It helps us to gather valuable information about the structure and composition of objects. But touch can also passively sense pressure and vibration that makes us aware of obstacles. The skin, covering the torso with its receptors, provides an extensive haptic space for presenting tactile information. As touch works independently from the other senses, it is an ideal communication channel in environments that are extremely noisy and where people are visually restricted or overloaded. Visually and auditive impaired people could benefit from tactile feedback as well.

Despite all these positive characteristics, tactile feedback is still not common in human-computer interaction (HCI). However, the research field of tactile feedback is more and more explored, especially in conjunction with wearable computing.

Joining this trend, we make use of a wearable feedback system in our work. We design vibrotactile feedback patterns, tailored to the snowboard domain, to communicate instructions for different posture corrections. These patterns are triggered at the corresponding body locations that need correction. The perception of the patterns is tested during cognitively and physically demanding tasks in the lab, and finally under realistic conditions in the indoor winter sports resort “SnowWorld” in Landgraaf.

Results show that our tactile feedback patterns are effective in triggering specific body movements and that they incite users to correct their body posture. Thus using full-body tactile feedback is a promising approach for teaching certain motion skills, e.g., sports.

Überblick

Neben Sehen und Hören ist der Tastsinn einer der wichtigsten menschlichen Sinne. Mit seiner Hilfe können wir wertvolle Informationen über die Struktur und Beschaffenheit von Objekten erhalten. Der Tastsinn kann aber auch passiv Druck und Vibrationen wahrnehmen, die uns auf Hindernisse aufmerksam machen können. Die Haut, die mit ihren Rezeptoren den Körper bedeckt, bietet eine ausgedehnte Fläche, um taktile Informationen zu vermitteln. Da der Tastsinn unabhängig von den anderen Sinnen arbeitet, ist er ein idealer Kommunikationskanal in Umgebungen, in denen ein extrem hoher Geräuschpegel herrscht und wo Menschen visuell eingeschränkt oder überlastet sind. Auch blinde und taube Menschen können von taktilem Feedback profitieren.

Trotz all dieser positiven Eigenschaften ist taktiles Feedback im Bereich der Mensch-Maschine-Interaktion immer noch nicht üblich. Das Forschungsgebiet des taktilen Feedbacks wird Schritt für Schritt weiter untersucht, speziell in Verbindung mit Wearable-Computing.

Diesem Trend schließen wir uns an und verwenden daher in unserer Arbeit ebenfalls ein tragbares Feedback System. Wir entwerfen Snowboard-spezifische Feedback-Patterns, um Anweisungen für verschiedene Korrekturen der Körperhaltung zu vermitteln. Diese Patterns werden an den entsprechenden Körperstellen ausgelöst, bei denen die Haltungskorrektur von nöten ist. Die Wahrnehmung der Patterns wird bei gleichzeitiger Bewältigung kognitiv und körperlich anspruchsvoller Aufgaben im Labor und schließlich auch unter realistischen Bedingungen im Indoor Winter Resort "SnowWorld" in Landgraaf getestet.

Die Resultate zeigen, dass taktile Feedback-Patterns spezielle Körperbewegungen effektiv auslösen können, und dass sie Benutzer dazu animieren, ihre Körperhaltung zu korrigieren. Daher stellt die Verwendung von taktilem Ganzkörperfeedback einen vielversprechenden Ansatz zum Lernen motorischer Fähigkeiten dar, z.B. beim Sport.

Acknowledgements

I express my gratitude to all people who supported me throughout the development process. Without their help this diploma thesis would not have been possible.

At first I would like to thank Prof. Dr. Borchers for sparking my interest in HCI. It was a pleasure to attend his inspiring lectures.

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Special thanks go to my advisor Daniel Spelmezan and to Anke Hilgers for their valuable feedback and for assisting me in my work.

I would like to thank SnowWorld[1] for allowing us to conduct our pilot study in their indoor winter sport resort.

I also owe my gratitude to Nadine Zimmermann of the department for textile technologies of the RWTH Aachen University. The advice she gave us on smart textiles helped us in developing the wearable hardware of the snowboard assistant.

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Some special thanks go to my boyfriend Kilian, for his con-

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[1] www.snowworld.com

stant motivation and practical help, and to my sister Carina, who supported me in searching participants for our user studies.

I dedicate this work to my parents Wilhelm and Monika Jacobs, who always believed in me and made my studies possible. Without their financial support I would not have been able to pay the semestral tuition fees.

Finally I would like to thank all the patient participants of my user studies. Their valuable feedback helped me to improve my work.

Thank you!

Conventions

Throughout this thesis I will use the following conventions:

The plural "we" will be used throughout this thesis instead of the singular "I", even when referring to work that was primarily or solely done by the author.

Unidentified third persons are always described in male form. This is only done for purposes of readability.

The whole thesis is written in American English.

Definitions of tactile feedback patterns are set off in colored boxes, like the one below.

PATTERN X:

Pattern X: In pattern X some motors are vibrating.

Pattern X

Chapter 1

Introduction

Best way to learn sport techniques is with professional help

One way to learn new sport techniques is by self-teaching the basic skills. By doing so, students might quickly achieve first success. But most of the time, basic skills are not learned properly, so that students might reach a point where it is hard for them to make further improvements. In long-term view, it is better to let a professional teacher help you to learn the sport techniques. He corrects even smallest mistakes immediately, thus preventing the student from adopting false habits.

Instant feedback is an important teaching method

The best method to do this is by direct feedback. In sports like tennis and golf, the instructor can physically guide a student's arm to demonstrate correct techniques or to help adjust posture. In contrast to these domains, instant feedback is not feasible for snowboarding. While driving down the slope there is always a considerable distance between the beginner and the teacher that makes communication difficult. All the teacher can do is to give instructions before the descent (see figure 1.1), demonstrate the exercise, watch the student doing the exercise on his run, and give advice of improvement afterwards. During the exercise, the beginner has to rely on himself.

We believe that missing instant feedback slows down learning pace and leads to an increased number of mistakes. This condition can be very frustrating for the trainee. Gabriele Wulf [2007] conducted a user study that shows that

Figure 1.1: A snowboard teacher giving his students the instructions for the following exercise.

frequent concurrent feedback can be beneficial for learning new motor skills. Wearable automatic sports training systems that assess performance and provide feedback during exercises might solve the problem of missing instant feedback for snowboarding. With the help of these systems, snowboarding skills could be improved (see Chi et al. [2005]).

Audio and visual feedback are inappropriate for snowboarding

Automatic training systems can use different communication channels for giving feedback, i.e., audio, visual, and tactile channel. In the case of snowboarding, visual feedback is rather inappropriate. The snowboarder cannot constantly look at a certain object or trainer to receive instruction, as he needs to have an overview of the surrounding area. Auditive feedback is not a good solution either. Snowboarders depend on sound to become aware of other skiers who approach from behind. In addition, the sound produced by the own equipment while descending the slope is helpful, as it gives information about the pressure and edging angle of the board.

The *Snowboard Assistant* uses tactile feedback

Tactile feedback is mostly underused but promising alternative to the audio feedback channel. Therefore the Media Computing Group initiated a wearable computing project called *Snowboard Assistant*. The aim of this project is to develop a wearable system that detects wrong movements or bad postures of snowboarders by using different types of sensors. It also gives realtime feedback to make users aware of these mistakes, so that movements and posture can be corrected.

Aim of thesis: Designing tactile feedback patterns

This thesis aims at designing "tactile motion instructions", also called *tactile feedback pattern*, that will be triggered across the body and indicate how to adjust posture during the descent of the snowboarder. We conducted a qualitative study focusing on how people perceive and intuitively interpret vibrotactile cues triggered at different body locations. This study helped us designing a first set of motion instructions. We tested the perception of these motion instructions under cognitively and physically demanding tasks and compared them to audio instructions.

1.1 DIA-Cycle

We followed an iterative design approach, the *DIA-cycle*

In the process of designing the tactile feedback patterns we followed an iterative design approach, the *DIA-cycle*. The DIA-cycle consists of three different phases: **D**esign, **I**mplementation, and **A**nalysis. One usually starts with the design phase where first ideas are collected. These ideas are then processed to a simple storyboard as an initial implementation. After the conduction of the associated user survey, the results can be analyzed and used to refine the initial design. Usually many iterations of the DIA-cycle are needed to improve usability and react to the users' needs. A sketch of the structure of the DIA-cycle is shown in figure 1.2.

At first we determined the thresholds for minimal- and maximal-perceivable vibration strength. After this, we conducted several tests to find out how people intuitively interpret vibrotactile cues, and how users perceive and process the tactile feedback patterns under cognitively and physically demanding tasks. In the end we compared tactile instructions to audio instructions under real-world conditions.

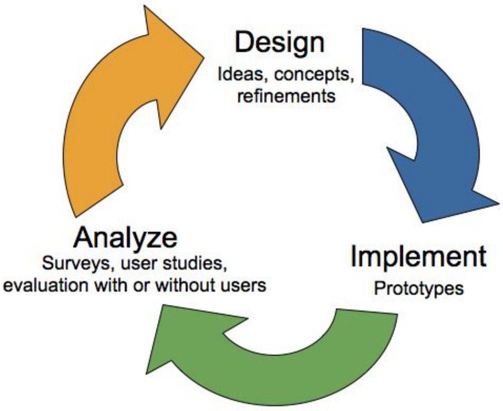

Figure 1.2: The DIA-cycle: one iteration consisting of design, implementation, and analysis.

1.2 Thesis Structure

This thesis is organized as follows:

Chapter 2—"Background" gives an overview of basic topics that are important for this diploma thesis. Special terms from the psychological and physical domain are explained here.

Chapter 3—"Related work" discusses research work that has to do with vibrotactile feedback, haptic perception, and wearable computing.

Chapter 4—"Designing the Tactile Feedback Patterns" describes the Hardware setup, the test to determine thresholds of vibration perception, and documents the finding of the first tactile feedback patterns.

Chapter 5—"Natural Interpretation of Tactile Feedback Patterns" takes a closer look at how people perceive and intuitively interpret the tactile feedback patterns, described in the chapter before.

Chapter 6—"Learnability of Patterns and Influence of Cognitive Load" provides information about the user study, in which we investigated the learnability of the patterns and the influence of cognitive load on identification performance.

Chapter 7—"Testing Patterns Under Realistic Conditions" takes a closer look at how the system works under realistic conditions. After all the tests that took place in the lab we now tested our final vibrotactile feedback patterns on the slope.

Chapter 8—"Summary and Future Work" sums up the results of the previous chapters. It also gives some methodical recommendations and refers to new interesting research topics in the field of wearable systems and vibrotactile feedback.

Chapter 2

Background

Humans have five different senses of human perception: vision, hearing, touch, taste, and smell. As we are designing vibrotactile feedback patterns in this work, we are only interested in one: touch.

Five human senses

2.1 The Somatosensory System

The human somatosensory system is a part of the nervous system and provides information about the processes taking place on and in our skin. It comprises the receptors and nervous centers that produce the sensory modality of touch. The sensory receptors, covering the skin, muscles, bones, and joints, are responsible for receiving and conveying stimuli that are later processed in the nervous centers.

The somatosensory system senses touch

2.2 The Sense of Touch

The somatosensory system can be divided into two subsystems: the kinesthetic and the cutaneous (or tactile) sensory system. The kinesthetic sensory system receives and processes information about movement and the relative position of adjacent parts of the body. The receptors sensing this

Kinesthetic sensory system

information are located in the muscles, tendons, and joints.

Cutaneous sensory system

In contrast to that, the cutaneous sensory system refers to the sensations arising from the skin. It can process sensations of pressure, vibration, temperature, and pain. For an overview of all definitions mentioned before, see table 2.1. As our work deals with with vibrational stimulation, and the kinesthetic sensory system is not involved in the perception of vibration, we will focus on the cutaneous sense in this chapter. For further information on the kinesthetic sensory system, see Goldstein [2002].

Term	Definition
Haptic	Relating to the sense of touch, active feeling of size, surface structure, etc., of an object.
Kinesthetic	Meaning the feeling of motion. Relating to sensations originating in muscles, tendons and joints.
Cutaneous	Pertaining to the skin itself or the skin as a sense organ. Includes sensation of pressure, vibration, temperature, and pain.
Tactile	Pertaining to the cutaneous sense, but focussing on pressure and vibration.

Table 2.1: Haptic Terminology. (adapted from Oakley et al. [2000])

As mentioned before, the term "tactile" pertains the cutaneous sense, but it also focusses slightly on sensations of pressure and vibration. Amongst other things, we use vibrational information to determine the roughness of an object's surface. Because we are mainly interested in vibrational stimulations in this work, we will refer to the tactile sense in the following chapters.

2.3 Skin Anatomy and Sensor Physiology

The structure of the skin

This skin is a complex organ that protects us from harmful micro-organisms and damage and regulates heat. It has two major appearances: glabrous skin at the palms and the soles of the feet, and hairy skin. The skin comprises the dermis, epidermis, and the subcutaneous tissue. The different receptors belonging to the cutaneous sensory system spread throughout these layers. The general structure of the skin can be seen in figure 2.1.

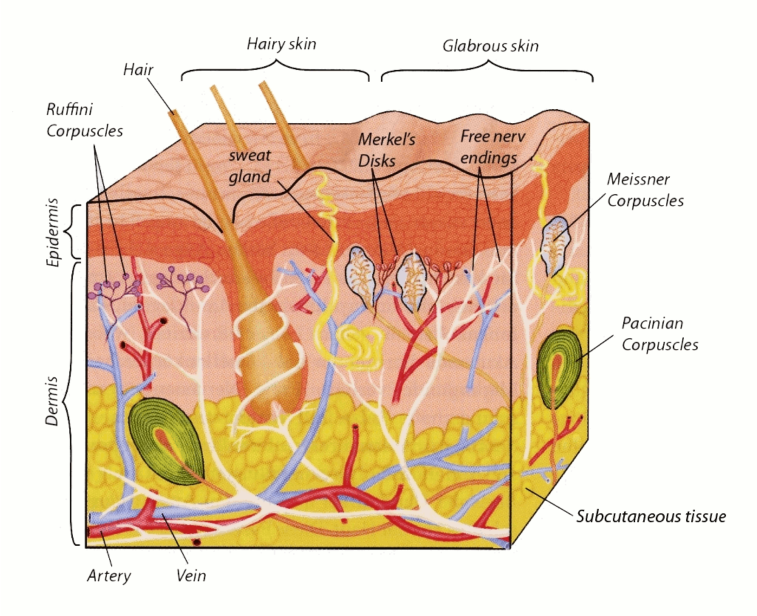

Figure 2.1: Mechanoreceptors and their location in the skin. (taken from Carlson [2004])

Four different types of mechanoreceptors

Mechanoreceptors are responsible for tactile sensations. There exist four types of them, located in and between the two skin layers epidermis and dermis. These four mechanoreceptors are called:

- Meissner Corpuscles,
- Merkel's Disks,
- Pacinian Corpuscles and
- Ruffini Corpuscles.

Rapidly and slowly adapting mechanoreceptors

The four mechanoreceptors mentioned before can be divided into two categories: rapidly adapting and slowly adapting mechanoreceptors. The Meissner and the Pacinian corpuscles belong to the rapidly adapting mechanoreceptors. As the name implies, these receptors quickly react to an onset or offset of tactile stimuli, but will also rapidly adapt to sustained stimulation.

The Merkel's Disks and Ruffini Corpuscles belong to the slowly adapting mechanoreceptors. In contrast to the others, they slowly react to the onset or offset of stimuli but also slowly adapt to sustained stimulation.

Mechanoreceptors can be categorized also by other attributes

Beside the rate of adaptation, mechanoreceptors can be categorized further according to the sizes of their reception fields. A summary of all mechanoreceptors and their properties can be found in table 2.2. Most relevant for our work are the Pacinian corpuscles, as these rapidly adapting mechanoreceptors are responsible for the perception of vibration.

Receptors	**Meissner Corpuscles**	**Merkel's Disks**	**Pacinian Corpuscles**	**Ruffini Corpuscles**
Location	Dermis	Epidermis	Dermis	Epidermis, Dermis
Adaption	Rapid	Slow	Rapid	Slow
Spatial range	Small 12 mm	Small 12 mm	Large 100 mm	Large 60 mm
Function	Movement, Velocity	Vibrations, Pressure	Vibrations, Pressure	Pressure, Skin shear, Thermal changes
Frequency	20–100 Hz	0–10 Hz	100 Hz–1 kHz	0-10 Hz

Table 2.2: Characteristics of the four types of mechanoreceptors responsible for perceiving tactile sensations.

2.4 Perception of Vibrotactile Stimuli

Four attributes characterizing tactile stimuli

Tactile stimuli can be characterized by four attributes: the modality, intensity, duration and location of a stimulus. In the following paragraphs we will take a closer look at these attributes.

Modality: Modality denotes the type of a stimulus, i.e., cutaneous, body position (proprioceptive), pain (nociceptive), and the thermal stimulus. The modality is primarily determined by the type of sensor, e.g., mechanoreceptors perceive cutaneous stimuli.

Intensity: By intensity, the strength or magnitude of a stimulus is meant. It is measured in Decibel, relatively to a detection threshold. Geldard [1960] describes that humans can identify three absolute levels of stimulus intensity.

Duration: Duration denotes the length of tactile stimulus, measured in milliseconds. In the past, researchers have determined many different threshold values concerning tactile stimulation. More on this in chapter 2.4.1

Location: Mechanoreceptors sense tactile stimuli. The brain can then locate the site of stimulation by determining the receptor's locations. The accuracy depends on various parameters that are discussed in 2.4.2.

2.4.1 Temporal Order

Important factor for tactile feedback design: Inter-burst interval

Our ability to distinguish two stimuli depends on the length of the time interval between them. Hirsh and Sherrick [1961] determined the threshold for distinguishing two brief stimuli, which is 20 ms. But with an increasing number of consecutive stimuli a longer inter-burst interval (IBI) is needed to distinguish them. The authors stated that for a sequence of five or six stimuli, the IBI might have to be as long as 500 ms.

Burst duration

Another time span that is important is the burst duration (BD) of a stimulus. Geldard [1960] indicates that a BD between 0.1 and two seconds is reasonable. He argues that BDs shorter than 0.1 seconds are perceived as annoying poke, whereas BDs that are longer than two seconds slow down the communication via vibrotactile stimuli. In other

Body part	Two-point threshold
Tongue tip	1.1 mm
Finger (inside)	1–2 mm
Palm	10 mm
Upper arm	39 mm
Thigh	45 mm
Middle of the neck	67 mm

Table 2.3: The two-point thresholds for different parts of the body.

experiments, Geldard and Sherrick [1972] used a BD of 2 ms and Jones et al. [2007] a BD of 500 ms.

2.4.2 Vibrotactile Patterns

Tactile feedback patterns are temporal sequences of tactile stimuli

The main goal of this work is to design tactile feedback patterns. These are temporal sequences of tactile stimuli that can be varied by changing the attributes frequency, amplitude, waveform, inter-burst interval, burst duration, location, and relative order. Changes in the first three attributes are mainly used for patterns delivered to the fingertips. Other regions of the human body are less sensitive than the fingertips, because of a lower receptor density. Therefore, the perception of the three attributes is not accurate enough at these regions. We do not address fingertips by our feedback patterns, and the motors used by us do not allow to control frequency and amplitude independently. Therefore, we neglected the attributes frequency, amplitude, and waveform during the design process of our feedback patterns. Later we will try to find out beneficial attributes, so that the associated tactile feedback patterns will incite people to change their body posture in a certain way.

2.4.3 Tactile Acuity

Tactile acuity

As mentioned before, tactile feedback patterns are not only

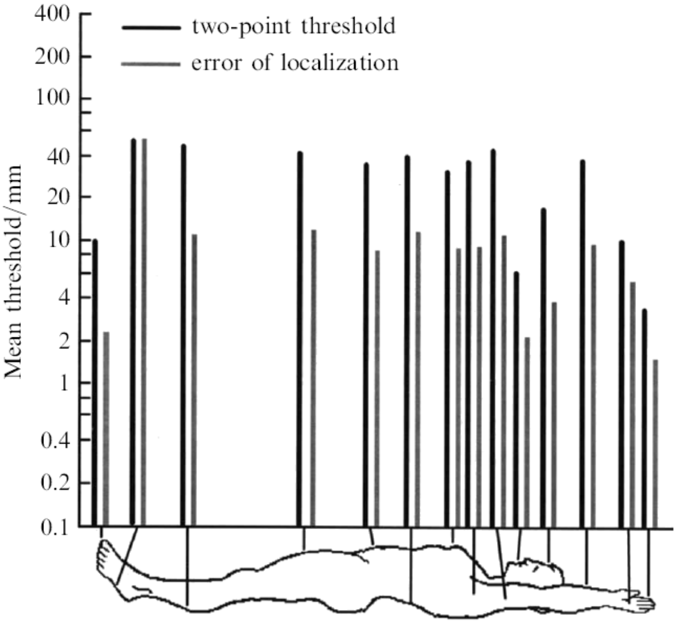

Figure 2.2: Comparison of the accuracy of the two-point threshold and error of localization. (taken from Cholewiak [1999])

defined by temporal attributes like inter-burst interval and burst duration, but also by the location of each stimulus of the pattern. It is important that people can determine the location of the stimuli to be able to identify a certain tactile feedback pattern. The level of precision for locating stimuli is defined as spatial resolution, or tactile acuity. It can vary depending on the type of stimulus and the area of the body where it is applied.

Two-point threshold

In this context the so-called "two-point threshold" plays a decisive role. It is defined as "the smallest separation at which two points applied simultaneously to the skin can be clearly distinguished from a single point." (see Colman [2006]) The two-point threshold is linked to the spacing of the different types of mechanoreceptors in the skin and thus varies for different parts of the body. Colman [2006] also states that the two-point threshold ranges from 1 to 60 mm. The two-point thresholds for different parts of the body are listed in table 2.3.

Error of localization

The error of localization is another possibility to measure tactile acuity. It measures whether the same point on the skin was touched twice or whether two different points were touched successively. Cholewiak [1999] states that the error of localization is generally lower or equal to the two-point threshold. Figure 2.2 outlines the relation between the two-point threshold and the error of localization.

Somatosensory cortex and the sensory homunculus

The reason for the different spatial resolutions of the body parts lies within the somatosensory cortex. The body parts occupy different amounts of space of the somatosensory cortex, which are independent from the actual size of the body part. More neurons are responsible for cutaneous sensations from the lips, hands, and feet than for other parts of the body, e.g., upper arms or chest. This mapping of space of the somatosensory cortex on the different parts of the body is often visualized by the so-called sensory homunculus, which can be seen in figure 2.3

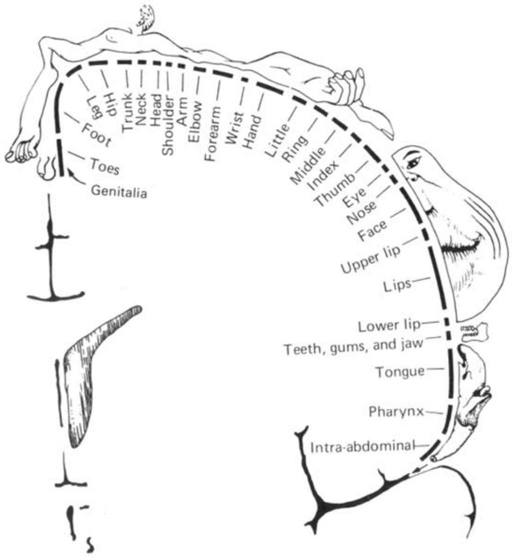

Figure 2.3: Sensory homunculus: the distorted human figure above the brain hemisphere reflects the mapping of the different body parts to areas of the sensory cortex. Body parts that occupy more relative space of the sensory cortex are bigger than other parts occupying less space. (taken from Penfield and Rasmussen [1950])

2.4.4 Tactile Illusions

Misinterpretations can happen with the tactile sense

We all know from the visual sensory system that we sometimes misinterpret what we perceive. Fata morganas are one famous example. Misinterpretations can also happen with tactile stimuli, thus leading to tactile illusions.

Tau effect

Two well-known tactile illusions are the tau effect and kappa effect. The tau effect says that "the more rapidly traversed of two equal distances defined by three stimuli is perceived as shorter" (see Goldreich [2007]). Let's assume your arm is stimulated successively at three locations L1–L3 on your arm, and the distance between L1 and L2 is the same as the distance between L2 and L3. If the distance L1–L2 is traversed faster than distance L2–L3, the first one is perceived as shorter. The tau effect is illustrated in figure 2.4.

Kappa effect

The kappa effect states that "the perceived time between stimuli dilates as the distance between stimuli is increased" (see Goldreich [2007]). This means that an inter-burst interval will appear longer between successively triggered stim-

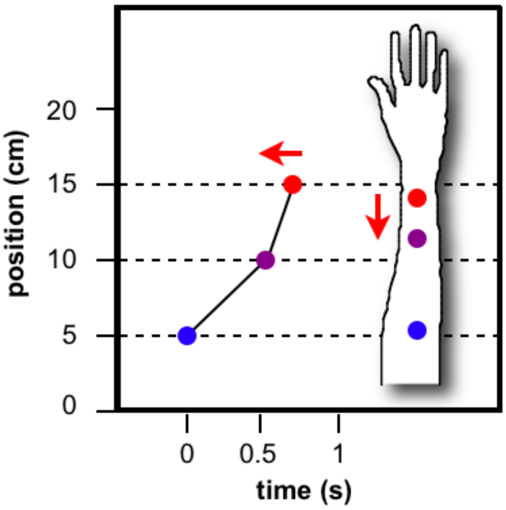

Figure 2.4: Tau effect: The more rapidly traversed of two equal distances is perceived as shorter. (taken from Goldreich [2007])

uli separated by a larger distance than more closely situated stimuli, even though they take an equal amount of time.An illustration of the Kappa effect is shown in figure 2.5.

Sensory saltation, also called "cutaneous rabbit"

Another tactile illusion that is interesting for us is sensory saltation , also called "cutaneous rabbit" . It was first discovered in 1972 by psychologist Frank Geldard (see Geldard and Sherrick [1972]). The phenomenon of sensory saltation can be produced when presenting three taps on spatially separated points on the skin. Instead of being perceived as individual taps at discrete locations, they are felt as a continuous movement between the two points, as if a rabbit was hopping along the arm. Sensory saltation is visualized in figure 2.6.

The cutaneous rabbit illusion was extensively studied by scientists since 1972. Eimer et al. [2005] discovered that sensory saltation applies equally to various parts of the body. It is of great interest for the exploration of tactile feedback. Gerald found out that the inter-burst intervals between the taps can vary within intervals between 25 and 200 ms. The distance between two tapping points can be changed within a range of 2 and 35 cm.

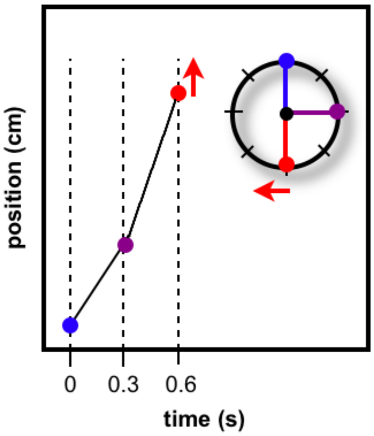

Figure 2.5: Kappa effect: When inter-stimulus distance is increased at fixed inter-stimulus time, inter-burst interval will appear longer. The clock top right indicates the subjective estimation of time.(taken from Goldreich [2007])

2.5 Summary

Extensive and innumerable literature is available on the human haptic sense, its physiological requirements, and its capabilities.

We presented the basic physiological and perceptive principles that are relevant for designing vibrotactile feedback patterns. These principles have to be understood in order to generate vibrotactile feedback patterns that are easy to map to desired posture corrections.

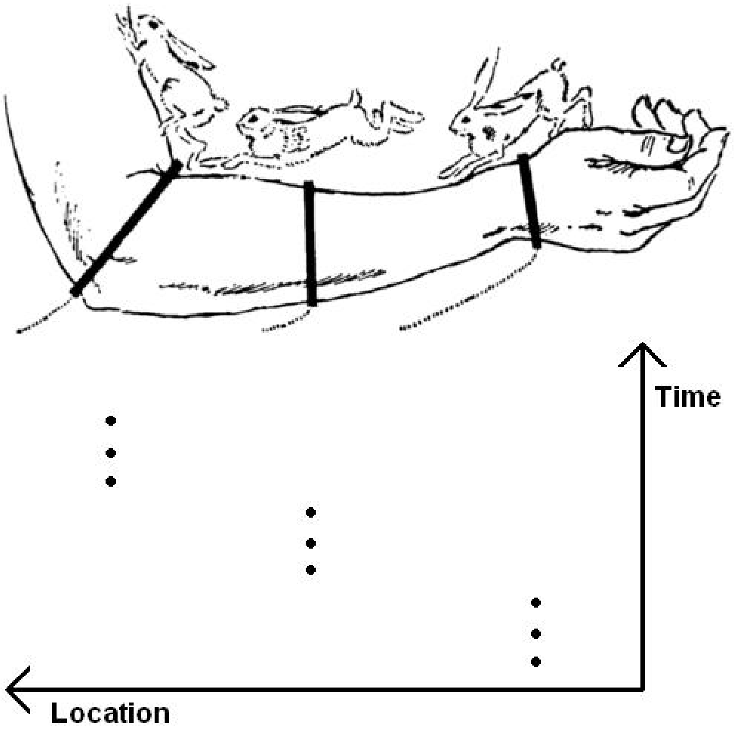

Figure 2.6: The cutaneous rabbit: several discrete taps are perceived as movement. (taken from Geldard [1975])

Chapter 3

Related work

Tactile feedback is a mostly underused but promising modality

Traditionally, technology mostly relies on visual and acoustic feedback to present information to users. Haptic interface research is less advanced than the visual or auditive one. But as the skin offers a wide stimulation area with its size of up to 2 m^2, tactile feedback has become a promising modality through which information can be presented. Nowadays, an increasing number of research projects is initiated exploring the haptic domain.

In this chapter, we will provide an overview of research projects addressing the field of tactile feedback. The chapter is divided into two main sections. In the first section, we will point out the variety of application domains into that tactile feedback has found its way to. These range from short warning signals to complex directional information for navigating. The second section deals with design guidelines that help making tactile feedback more effective. We will introduce the basic psychophysical limitations as well as the consequences these limitations have on more complex design guidelines.

3.1 Application Domains for Tactile Feedback

Application domains

As mentioned before, we first intend to present some projects that introduced haptic feedback into different application domains and show how helpful these systems can be. Most of them are wearable systems, where tactile displays are integrated into the clothing. Tactile displays are devices that stimulate the skin to generate haptic feedback.

3.1.1 Sensory Substitution for Visually Impaired People

Interaction of blind people with computers

For blind people touch is the most important channel, besides hearing, to gain information about their surroundings or to understand the content of digital sources. Nowadays most blind people take advantage of Braille displays and screen readers combined with synthetic speech when using their computer. By that they can read only textual content. Devices like the PHANTOM system, produced by SensAble Technologies[1] , and Immersion's[2] FEELit Mouse make it possible for blind people to feel texture and structure of objects in special computer programs. Sjostrom [2001] made some tests with these two devices to find out how blind people locate, understand, and physically interact with objects. With the help of his results, he proposed guidelines for the design of haptic computer interfaces that should improve the access to graphics.

Some decades before, Geldard [1956] used a totally different approach to translate written text to tactile cues. He used five actuators located at the chest to communicate letters and numbers to the user. As there are more than five different letters and numbers, they had to be encoded by intensity and duration of vibration. Figure 3.1 gives an overview of the coding scheme.

Improving the mobility of blind people

A system that had nothing to do with desktop computing is the wearable system developed by Cardin et al. [2007]. It aims at improving the mobility of visually impaired people by making them aware of obstacles in their surroundings. The system consists of four sonar sensors, a microcontroller, and eight vibrators, which are attached to a jacket.

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

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

The sonar is used to detect obstacles in the environment. Direction and distance of obstacles are signaled by vibration delivered to the body. The setup and the calculation principle of vibrotactile feedback is shown in figure 3.2.

Another system that helps visually impaired people to orientate themselves in their environment is the one described by Ross and Blasch [2000]. It is a shoulder-tapping system that uses a three by three array of small contact speakers attached to the person's back. Sequences of three taps were either moving straight up, from lower left to upper right, or from lower right to upper left, indicating to move forward, turn right, or turn left respectively.

3.1.2 Warning Signals and Directional Information for Navigation

Reduce drivers' workload

People without major handicaps also need navigational support in certain situations. van Erp and van Veen [2001] use a tactile navigation display for supplying drivers with

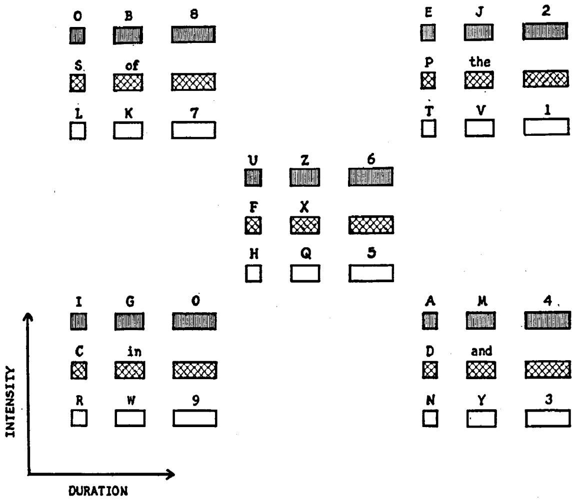

Figure 3.1: Coding of the vibration language: Each group of nine symbols belongs to one vibration motor, which varies in intensity (three steps) and duration (three steps). (Taken from Geldard [1956])

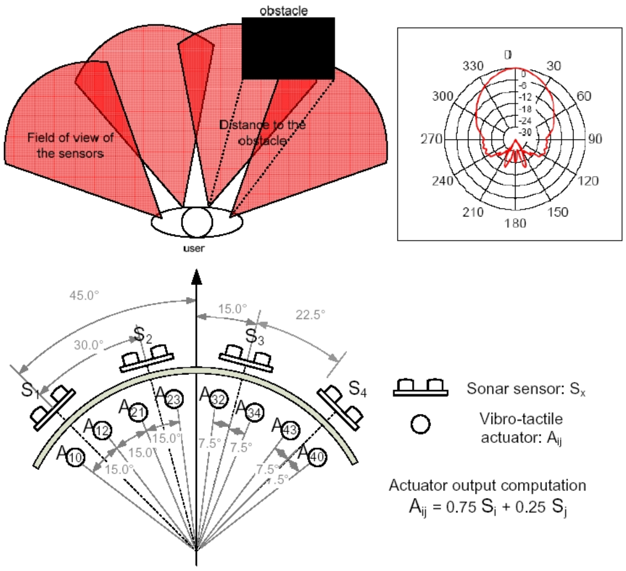

Figure 3.2: Wearable system for mobility improvement: Sensing map and feedback computation. (taken from Cardin et al. [2007])

information. Using a communication channel different from audio reduces the drivers' workload. The vibration motors they used for their system were mounted in the seat in two straight lines so that they have contact to the driver's thighs. Simple tactile patterns conveyed different messages. For example direction was encoded by activating four tactors under the left thigh for turning left and four tactors under the thigh for turning right. Another system using spatial vibrotactile cues to direct visual attention while driving is presented by Ho et al. [2005].

The vibrators were mounted in the seat (four for each thigh, in a straight line from rear to front) with a center-to-center distance of 4 cm).

Support awarenees for pilots

A similar system was developed by van Veen and van Erp [2001] to support spatial awareness during flights. Tactile actuators are inserted into a vest to present directional information to the pilot. The authors also found out that the perception of vibrotactile stimulation on the torso is not substantially impaired during high G-load conditions.

Optimizing tactual vests

A different wearable display integrated into a vest was designed by Gemperle et al. [2001]. They invested two years in optimizing the design of a tactile vest. They emphasize that their system is light-weight, silent, flexible, physically discrete, and has a low power consumption. Further projects dealing with spatial awareness during flights are presented in Cardin et al. [2006] and Rupert et al. [1994] who have probably done pioneering work in this special application domain.

Belt-type tactile displays

Most wearable systems mentioned before convey warning signals and directional information to the torso and therefore mainly use vests. But there are also belt-type solutions conveying information to the waist for navigation (see Tsukada and Yasumura [2004]) or to the head to avoid unseen objects (see Cassinelli et al. [2006]).

3.1.3 Music

Tactile feedback as aesthetic artifacts in music

Vibrotactile feedback has also been used to couple haptics technology with music. Gunther et al. [2002] use vibrotactile stimuli as aesthetic artifacts that accompany musical performances. The tactile stimuli during the music performance caused strong reactions of several participants, who claimed that "...it actually felt as if tactile stimulations were making them move".

Use tactile cues to indicate timing of dance motions

Nakamura et al. [2005] put their focus on dancing. They developed multimodal dance training system that enables beginners to learn basics of dance steps easily. For this, they use vibrotactile cues delivered at the wrists to indicate the timing of dance motions.

3.1.4 Mobile Devices

Augmentation of touchscreen keyboards

One of the most common uses of vibrotactile displays is for mobile devices. Hoggan et al. [2008] augmented touchscreen keyboards with tactile feedback in order to improve finger-based text entry.

They used the vibration motor of the mobile device to communicate simple tactile messages that represent different keyboard events that occur during the use of a touchscreen keyboard. Results show that the additional tactile feedback results in fewer errors and greater speeds of text entry compared to those without feedback. The authors also used special vibration motors mounted onto the device to provide localized feedback, where only a motor vibrates and not the whole device. This improved the performance even further.

The ComTouch device, developed by Chang et al. [2002], is a vibration display for personal communication by touch. The device is a handheld sleeve that fits onto the back of a mobile phone and augments remote voice communication with touch, by converting hand pressure into vibrational intensity between users in real-time. User studies showed that participants used the device in combination with encoding systems similar to that of Morse code to emphasize certain aspects of a conversation or to regulate turn-taking.

3.1.5 Virtual Reality

Vibrotactile feedback can also be used to increase user experience in virtual reality.

Collision feedback in virtual reality

Schätzle et al. [2006] investigated the main factors influencing the design of a vibrotactile feedback device for the human arm operating in virtual reality. Their system gives collision feedback by delivering vibrations to the arm. Their results showed that cylindrical vibration motors provide better feedback than pancake-like motors, as the vibration frequency of these motors is closer to 250 Hz, where the perception of vibration is best for the skin. They also found out that using six motors along the arm's perimeter is a good compromise between correct responses and the tactile resolution.

Haptic feedback for assembly tasks in virtual reality

Adams et al. [2001] explored how great the benefits of tactile feedback for training a real assembly task in virtual reality are. Participants had to construct a LEGO^{TM}biplane model and trained on a virtual building block simulation with or without haptic feedback. Analysis of completion times for the real task revealed that subjects trained with force feedback performed significantly better than those who received no force feedback training.

3.1.6 Medicine

Simulation of surgical operations and clinical evaluations

An interesting application area for tactile feedback is medicine. Today, haptic feedback is used for simulation of surgical operations. Some scenarios of providing feedback for minimally invasive surgery are described by Chen and Marcus [1998] and Eltaib and Hewit [2003]. They highlight the importance of tactile feedback to indicate important properties such as tissue compliance, viscosity, and surface texture. These properties can give information about the health of the respective tissue.

Riener et al. [2002] presented an orthopedic training simulator with haptic feedback. This training simulator supports a multi-modal environment for the training of clinical evaluation of the knee joint. The combination of haptic, visual, and auditory feedback gives the user the illusion of touching and moving the shank of a real patient. Force feedback simulates the behavior of real joints, e.g., immobility of the joint or the antagonizing muscles. In addition, sound samples are played, e.g., screaming, moaning, and the sound of joints. A graphic display visualizes internal anatomic components by showing computed tomographies or magnetic resonance tomographies.

3.1.7 Motion Training

Tactile feedback for motion training

Although touch is increasingly addressed in human-computer interaction, only few systems exists that use tactile feedback for motion training or skill learning. Morris et al. [2007] have developed one of these. Their system uses haptic feedback to teach an abstract motor skill that requires recalling a sequence of forces. They conducted a user study where participants had to train a sequence of one-dimensional forces with haptic, visual, or visiohaptic feedback, and later recall the sequence in a short test. Morris and his colleagues showed that the accuracy of force recall is significantly more precise following visiohaptic training than following visual or haptic training alone. Regarding each feedback channel alone, haptic feedback is inferior to visual feedback.

In section 3.1.3 we presented the multimodal dance training system developed by Nakamura et al. [2005]. The system helps dancing beginners to dance in right step.

3.2 Perception of Haptic Feedback

How does the somatosensory sense works and what are its limits?

In the past years, a lot of systems that use tactile feedback have been developed. In order to design effective patterns, the developer needs to know how the somatosensory sense works and what its limits are. Some research projects deal with this topic, e.g., Loomis [1981], Chan et al. [2005], Tan et al. [2000], and Eimer et al. [2005].

Loomis [1981] gives an overview of factors limiting tactile pattern perception. Some of these limiting factors are spatial resolution, temporal resolution, central processing rates, and focus of attention. For instance, he talks about different types of phantom sensations and cutaneous masking, explains how to evoke them and points out their influence on tactile feedback design.

Influence of workload on tactile perception

Chan et al. [2005] designed a set of short vibrotactile messages, also called *haptic icons* or *tactons*, and conducted tests to find out how good people can identify these tactons in the presence of varying degrees of workload. They found out that the time required to detect a change in haptic icons approximately doubles when subjects are visually and auditory distracted, and that stimuli designed to be subtle were affected more than those designed to be intrusive.

A psychophysical study was conducted with an open response paradigm by Tan et al. [2000] to test how saltatory signals are perceived by human observers without training. Horizontal, vertical and diagonal saltatory lines were delivered to the back by a 3-by-3 tactor array. The results showed unique and consistent interpretations of the saltatory signals.

Impact of cutaneous saltation

Several tests conducted by Eimer et al. [2005] point out the impact of cutaneous saltation. Three taps were presented successively to three possible forearm locations. The effect was so strong that when the last three taps were delivered to another arm next to the first one, location judgments on the first arm were shifted toward the tap subsequently delivered to the other arm. The experimental setup is visualized in figure 3.3.

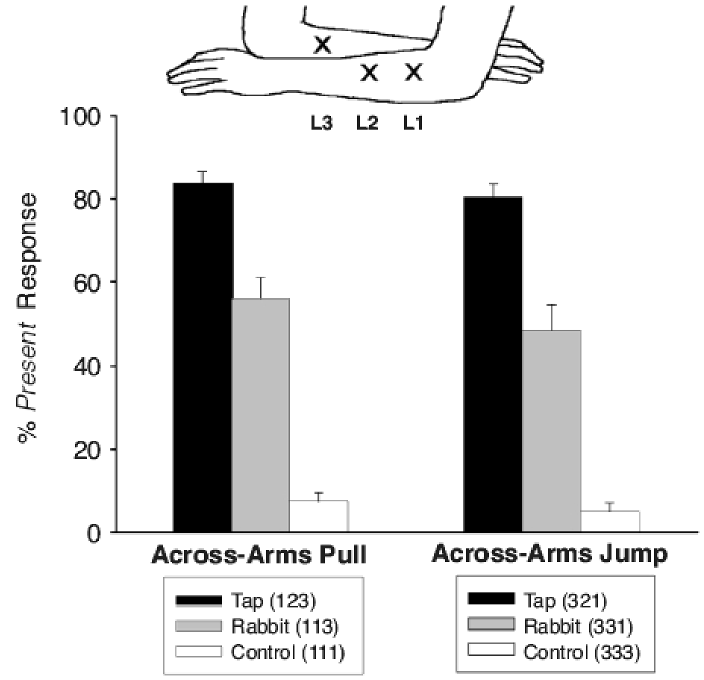

Figure 3.3: Cutaneous saltation across arms: the percentage of present responses indicates how often taps are perceived at location L2. A sequence of three taps (T1, T2, T3) was presented successively to three possible forearm locations (L1, L2, L3). For example for rabbit trials under across-arms pull condition, taps were triggered to locations L1, L1, and L3. (taken from Eimer et al. [2005])

3.3 Design Guidelines for Tactile Feedback

Design guidelines based on physical constraints

Based on the facts we know about cutaneous perception, a few scientists try to work out guidelines that address the design of tactile feedback. Two of them are Hale and Stanney [2004], who focussed on psychophysical constraints and derived some basic tactile interaction guidelines from it. One rule for instance says that inter-burst interval must be at least 5.5 ms long to ensure that receptors perceive individual cutaneous signals. Another rule points out that the force exerted by actuators must be greater than 0.06 to 0.2 Newtons per cm^2 to successfully activate human pressure sensors.

Brewster and Brown [2004] went one step further and presented ways to develop structured tactile messages, called tactons. These abstract messages can communicate information haptically and are described by several parameters, including frequency, amplitude and duration of a tactile impulse, but also rhythm and location of impulse sequences. Brown [2007] went more into detail. She worked out concrete guidelines for multidimensional tactons on a wide scale.

Tactile messages should be self-explaining

van Erp [2002] also set up a small set of guidelines for vibrotactile displays. One main rule is that messages conveyed by the tactile display should be self-explaining, so that the interpretation of received tactile stimuli is not an additional burden.

Rate of discrimination errors increases with more actuators and commonality

Geldard and Sherrick [1965] discovered important characteristics of cutaneous perception dealing with the discriminability of vibration patterns delivered across the body. They found out that the rate of discrimination errors increases with large numbers of actuators and with a high number of elements that patterns have in common. They also point out that there is no especially error-prone body location.

Gallace et al. [2005] were concerned with similar cognitive limitations. They found out that people are unable to reliably detect changes in similar patterns presented sequentially. In their tests they used a burst duration of 200 ms and an inter-burst interval of 800 ms. The used patterns consisted of one to three vibrotactile vibrotactile stimuli presented across the body surface.

Numerosity judgements

In Gallace et al. [2006b] they went deeper into this topic and did some further experiments. They tested patterns comprising up to seven actuators distributed across the body surface, which were vibrating simultaneously. After having perceived a pattern, participants had to tell how many actuators were vibrating. Results showed that the accuracy of a participant's numerosity judgments decreased linearly as the number of vibrating actuators increased. The authors also tested performance for different types of intervals that the patterns were separated by. These were either no interval, an 110 ms empty inter-stimulus interval, and a masked-interval block, consisting of a 50 ms empty interval, followed by a 10 ms vibrotactile mask (all tactors activated simultaneously), and then a second 50 ms empty interval. Change detection was almost errorless in the no-interval block, deteriorated in the empty-interval block, and was by far the worst in the masked-interval block. A sketch of the different intervals can be seen in figure 3.4.

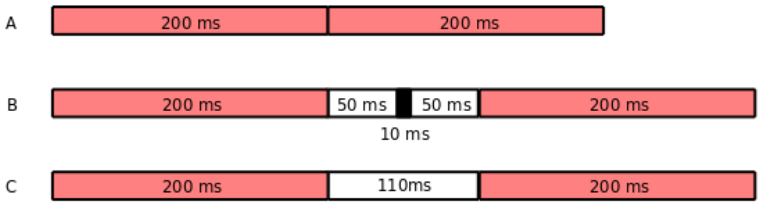

Figure 3.4: Different types of intervals used in Gallace's numerosity judgement test: the no-interval condition (A), masked-interval block (B), and empty inter-stimulus interval (C). The red bars represent the patterns and the black bar stands for the masking stimulus.

Subitising does not occur for tactile stimuli

In the same year Gallace et al. [2006a] also discovered that subitising, i.e., instantly recognizing the number of objects in a small group without counting, does not occur for tactile stimuli.

Influence of workload on location identification

Bhargava et al. [2005] explored the influence that cognitive load has on tactor location identification. Their user study took place in a NASA KC-135A reduced gravity aircraft during a parabola flight. Participants had to wear a vest with integrated tactors that transmitted the stimuli. Their task was to enter the perceived location of the activated tactor by pressing the corresponding key on a keypad under conditions of low and high cognitive load. The setup can be seen in figure 3.5. Thereby being strapped down was regarded as low cognitive load and the possibility to fly freely as high cognitive load. Results show that identification of

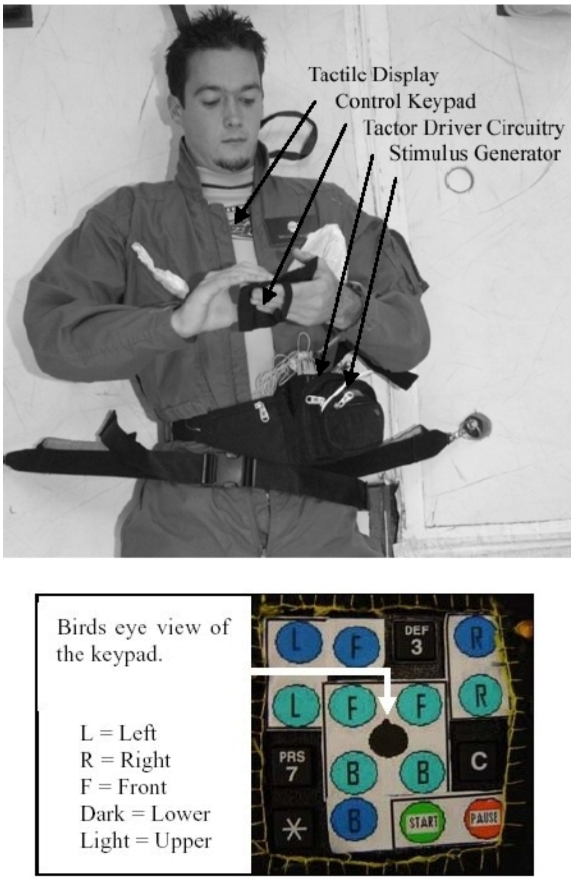

Figure 3.5: Experimental setup and keypad used in Bhargava's zero-G identification experiment. (taken from Bhargava et al. [2005] ©2005 IEEE)

tactor location is significantly less accurate under high cognitive load than under low cognitive load.

Higher localization accuracy near reference points

In Cholewiak et al. [2004], the authors also deal with vibrotactile localization. In contrast to Bhargava et al. [2005] they investigated the effect of place and space on localization performance. They found out that the identification of the body location being stimulated is more accurate if the stimuli are presented near some anatomical reference points, i.e., the wrist, elbow, shoulder, spine, and navel. In addition, results show that decreasing the separation among the tactors leads to average performance decrease in localization.

3.4 Summary

Tactile feedback is an emerging research field. In this chapter we introduced research projects in which systems were developed that use tactile stimulation for communication. Most of these are wearable feedback systems from various application domains. We mentioned some examples belonging to the following domains:

- sensory substitution for visually impaired people,
- warning signals and directional information for navigation,
- music,
- mobile devices,
- virtual reality,
- medicine, and
- motion training.

In some of these domains tactile feedback has been explored more extensively than in others. Especially in sports and motor skill teaching, tactile feedback is still underused. By choosing snowboarding as domain for this thesis we make a contribution to the field of sports and motion skill training.

Prior research mainly focussed on force feedback. In contrast to this we based our motion instructions on vibrotactile stimulations. In previous work, patterns of simple vibration signals, i.e., single vibrations at single body locations, were mainly used to design small sets of patterns. Building upon this work, we will design larger vibrotactile patterns and improve them throughout several design cycles with the goal to design a small pattern language to systematically trigger body movements.

Chapter 4

Designing the Tactile Feedback Patterns

The main goal of this work is to develop tactile feedback patterns for the snowboarding domain and test their suitability for application under real conditions. These patterns will later be an integral part of the Snowboard Assistant[1] project. The aim of this project is to develop a wearable system that detects wrong movements or bad postures of snowboarders by using different types of sensors, and gives realtime feedback to make users aware of their mistakes, so that movements and posture can be corrected.

Requirements for our tactile feedback patterns

The tactile feedback patterns we will develop should be intuitive at best, and if not, they should at least be easy to understand and learn. Therefore, we have to pay attention that the snowboarder perceives and interprets our feedback patterns correctly. It is very important that the tactile sensation does not feel uncomfortable or handicap users in their movements. We investigated whether tactile feedback while snowboarding is unobtrusive but still noticeable, so that it can effectively communicate the desired correction of body posture.

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[1] http://hci.rwth-aachen.de/snowboard

4.1 Hardware Setup

We chose electric vibration motors for delivering feedback

In order to deliver vibrations to the body, they need to be generated and transfered by actuators. There are several different types of vibration devices available, some of which are presented in Jones et al. [2004]. For our purpose, we chose eccentric rotation of electric motors as the underlying principle to create the vibrations.

Two types of vibration motors

There are two main types of vibration motors: cylindrical and pancake-like motors. As reported by Schätzle et al. [2006], cylindrical motors vibrate at a frequency closer to 250 Hz, which yields maximum stimulation of the skin's mechanoreceptors. Therefore, we decided to use cylindrical vibration motors as found in Nokia 3210 mobile phones to render vibrotactile feedback. They are small, light-weight, inexpensive, simple to control, and have a reasonable power consumption, which is a great benefit for battery-powered applications like ours.

Frequency linked to amplitude

Unfortunately, the physics of rotationally induced vibrations link frequency to amplitude, as they are both dependent on the same parameter, the angular velocity (which is in turn linked to the voltage level). Therefore, we cannot control the vibrations' frequency and strength independently.

For our setup, each motor was placed inside a thin plastic tube to avoid blocking of the rotating mass when attached to the body. All motors are connected to individual cables that supply them with about 4 V when vibration is needed. Figure 4.1 shows a bare Nokia 3210 vibration motor (very left) and the same motor encapsulated in a plastic shield with a cable and a 2.5 mm TS (tip/sleeve) connector attached (middle) for easy connection to our hardware.

Sensor/actuator boxes are our prototyping platform

The prototyping platform we were using in our user tests consists of up to three custom-build sensor/actuator (SensAct) boxes that were developed in the scope of a prior diploma thesis (see Schanowski [2008]). One of them, with three actuators connected, can be seen in figure 4.2.

ArduinoBT

The SensAct boxes are based on small and robust cases

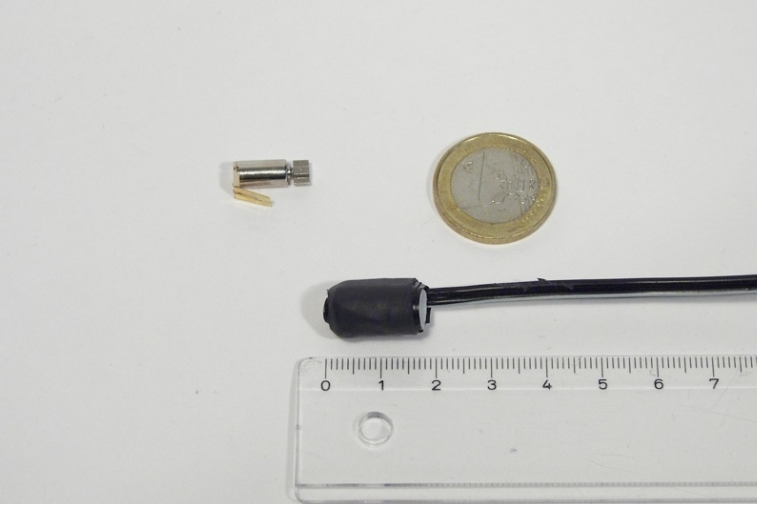

Figure 4.1: Actuators: The cylindrical vibration motors (original and encapsulated) we used in our user studies.

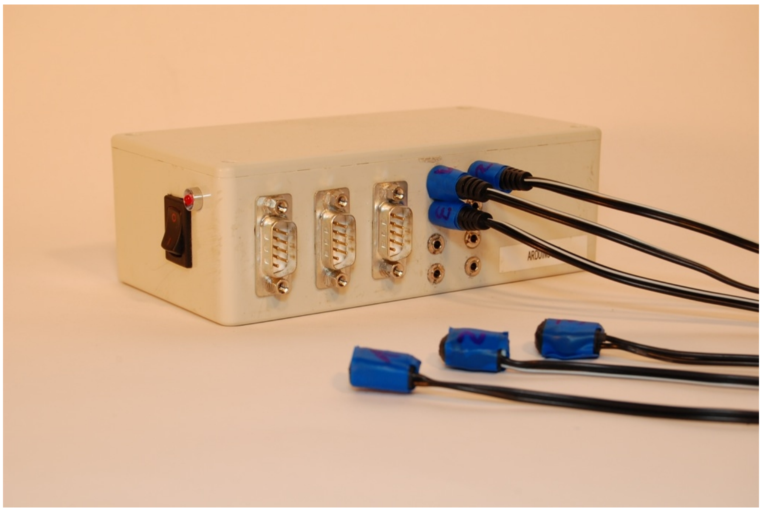

Figure 4.2: SensAct Box: The main part of the hardware platform we used for our user studies, showing the SensAct box and three actuators.

(15 cm x 8 cm x 5 cm) that offer space for controllers and power supply. Their main component is an ArduinoBT board, an open-source electronics prototyping platform based on flexible, easy-to-use hardware and software. The Arduino can be extended by add-on daughter-boards, so-called "shields". For our studies, we used custom-build motor shields that each can drive up to six vibration motors. That way, an Arduino board can control the vibrations by simply switching the power on and off. A more sophisticated means of control is the use of pulse-width modulation (PWM), which is in fact switching on and off the current in rapid succession, where the ratio of on- to off-times defines the effective voltage supplied to the motors. The latter can be used to control the strength of the vibrations, but as mentioned above, this also affects their frequency.

Communication via Bluetooth

Assembling and triggering of the vibration patterns is done by a host device, that is wirelessly connected to the SensAct boxes via the Bluetooth interface the ArduinoBT offers. The host uses the Bluetooth Serial Port Profile to transmit simple commands to control each motor directly. In order to allow changes on-the-fly and to prevent problems of synchronization, all timing is done by the host.

During the indoor tests, we used a MacBook Pro as the host device, running a self-written Cocoa program, to send the control messages that triggered the vibration patterns. For our final study at SnowWorld Landgraaf, a Nokia N70 mobile phone running a Python script replaced the MacBook Pro.

4.2 Thresholds of Vibration Perception

Determine minimal and maximal vibration thresholds

Before we designed any feedback pattern, we conducted some tests to determine minimal and maximal vibration perception thresholds for different body parts that came into consideration for later testing.

4.2.1 Users

Nine people participated in this user study. Six of them were female and three male. Their age ranged from 20 to 53 years, of which two were older than 50 years and the rest younger than 27. The fact that not all participants belonged to the target group "snowboarders", i.e., young and healthy people, could have affected the test results. However, the results for the two elder people did not differ significantly from the other results. In our following user studies, we kept in mind to test only people belonging to the main target group of the Snowboard Assistant project.

4.2.2 Setup and Task

Velcro straps used for attaching the actuators

To determine the thresholds of minimal-perceivable and maximal-bearable vibration, we tested the participants in a silent room where we would not be disturbed. We used Velcro straps for attaching the actuators to the body. The vibration motors were connected to the SensAct box.

We gave the test persons a short introduction of the hardware setup and their task. The participants were told to stand straight but relaxed. They wore headphones during the experiment to cancel the sound of the motors, so the vibration could solely be detected by the cutaneous sense and not by hearing.

ArduinoBT's internal PWM generator usd to regulate vibration

As stated in section 4.1, the Arduino uses pulse-width modulation (PWM) to control the desired voltages driving the vibration motors. The internal PWM generator allows values from 0 to 255, where rotation of the motors started at a value of about 3. The maximal PWM value of 255 corresponds to a voltage of approximately 4 V, at which the motors reach their peak vibration strength and frequency, averaging at about 180 Hz.

PWM values are the primary parameter for this user test

In our setup, the PWM value is our only means of control, as it is neither reasonable nor feasible to measure the actual vibration strength for every actuator in order to use it as feedback. However, the exact mapping of a PWM value to a vibration strength and frequency is not possible, because it differs for every motor. Furthermore, it is also affected by the orientation (e.g. attaching the actuator vertically or horizontally) and to some extent even the by movements the motors are subjected to. Therefore, it was most advisable to use the PWM values as our primary parameter for this user test.

Experimental methodology

We started the test by slowly increasing the vibration by specifying Arduino pulse-width modulation (PWM) values from 0 to 255. The stimuli we applied to the test persons had a duration of about two seconds. We started with a PWM value of 0 and then slowly increased the value to the point where the test subjects said that they felt the vibration. After a short break, the strength of vibration was increased up to the point where the test subjects stated that the vibration became unpleasant.

The procedure of the two main steps, i.e., determination of minimal and maximal threshold, was repeated for every body location to be tested. A sketch of all locations addressed in our first user study can be seen in figure 4.3. During the test, participants were allowed to make comments and ask questions.

4.2.3 Evaluation

Homogeneous results for the minimal thresholds

The user study showed homogeneous results for the minimal vibration thresholds of almost all body parts. The average minimal PWM values for almost all locations accumulate between 22 and 28. The only outlier were the feet, that were really sensitive with an average minimal value of 15.7. Because of this, we had to think of using a lower vibration frequency for giving tactile feedback to the feet.

Strong variance for thresholds of maximal-bearable vibration

In contrast to that, results revealed a strong variance for thresholds where the vibration started to become unpleasant. The standard deviation was always greater than 76, which is rather large, given the range from 0 to 255. As a consequence of this huge variance, we arrived at the conclusion that the vibration strength has to be adjusted to the user for final application. Moreover, some participants

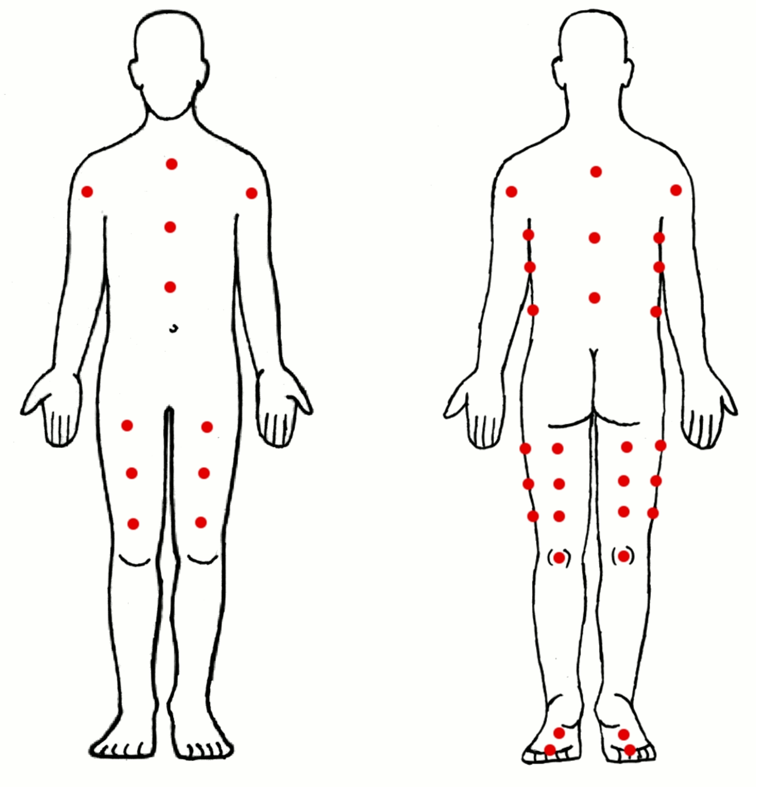

Figure 4.3: Different body locations we tested in our first user study.

stated that vibrations at the hollows of the knees felt extremely ticklish and unpleasant. Therefore, we excluded the hollows of the knees from our further pattern design process.

Feet and calves not suitable for tactile feedback while snowboarding

While snowboarding, both feet are enclosed by tight boots. These might apply so much pressure on the skin that the vibration of the actuators might not always be perceived. In addition, the feet are fixed to the snowboard so that the vibrations caused by bumps in the slope might overlap the vibration of the actuators. Because of these two reasons we decided not to use the feet and calves for tactile feedback.

Velcro straps loosened during test

During the user tests some problems arose. Often the Velcro straps opened and changed position as a consequence of breathing, contracting muscles, or just moving. To avoid this, the fastening mechanism had to be changed before we could start further user studies.

We thought of using conductive thread, sewed onto tight clothes, in combination with a mechanism like snap fasteners to reversibly fix the actuators. The conductive thread could be connected to the snap fastener on one side and on the other to a big socket that could be used to control all motors.

LilyPad Vibe Board not suitable

This inspired us to test the LilyPad Arduinos[2] , developed by Leah Buechley. Unfortunately the vibration strength of the vibration motor "LilyPad Vibe Board" was not strong enough for our purposes.

So in the end we decided to use tight clothes with sewed-on laps to which the actuators can be attached. This setup allowed to easily remove the actuators and wash the clothes.

4.3 Finding Appropriate Patterns

On our way to develop suitable feedback patterns we reviewed a lot of literature. Chapter 3 mentions several guidelines for their design. The most important points are described in the following paragraphs.

We modified four different attributes to encode information

As mentioned in Brewster and Brown [2004], Brown [2007], and van Erp [2002], information can be encoded using frequency, amplitude, waveform, IBI, BD, location, and relative order. Due to reasons described in chapter 2.4.2 we only varied the latter four attributes to design discriminable and effective feedback patterns.

Spatial location

Brown [2007] states that spatial location is one of the factors that can be discriminated most reliably. Because of this, it might be advantageous to deliver feedback at the appropriate location on the body to indicate a direction or to mark the body part that needs to be adjusted. For instance, an

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[2] http://www.cs.colorado.edu/~buechley/projects/e-textile_kit/e-textile_kit2.html

impulse delivered to the right thigh can signal to "move the right leg" or "turn right". Ross and Blasch [2000], van Erp and van Veen [2001], and Gemperle et al. [2001] also followed this approach. For instance Ross and Blasch [2000] used three speakers, two located at the back shoulders and one in between, to communicate directional information. A double-tap of the center actuator once every two seconds indicated the person should move straight forward. If the user has to turn by more than 7.5 degrees to the right or left, the left or right tapper respectively would tap in addition to the center tapper. If the angle the user has to turn exceeds 15 degrees, only the left or right speaker respectively would tap in response.

Inter-burst interval and burst duration

According to Tan et al. [2000] the length of inter-burst intervals can vary from about 20 to 300 ms. Geldard [1985] states that an optimum is reached at around 100 ms. Both also indicate that the length of burst durations (BDs) of the impulses can vary even more. In their experiments they used short BDs between 2 and 26 ms. Other researchers, like Jones et al. [2007] used much longer BDs of 500 ms.

Number of vibration impulses

Another important design factor for tactile feedback patterns is the number of impulses to be sent to each tactor. We oriented ourselves on Tan et al. [2000] and Geldard and Sherrick [1972] and limited the number of impulses per tactor to three.

Number of tactors per pattern

The number of tactors per pattern should also be taken into consideration. Gallace et al. [2005] point out the linear relationship between the number of tactors activated and the mean reaction time and mean error rate respectively. For this reason, we designed patterns that activated at most six different actuators. Most of our patterns included only three or less motors.

Minimal distance

We also needed to take care of the minimal distances between actuators. If this distance is too short, the location of taps becomes hard to distinguish and the effect of cutaneous saltation might degrade. The minimal distances between actuators is determined by two-point threshold. A too long distance has also negative effects. The human body cannot find a connection between loci that are too far apart, and the cutaneous saltation might not become evident either (see Gallace et al. [2005]). The vibration motors used to communicate our tactile feedback patterns were mounted to the experimental clothes with a center-to-center distance of 6 cm at the thighs, 4.5 cm at the lateral torso, and more than 10 cm at the belly, the breast, and the back.

Avoid ambiguity and established consistency

All in all, we tried to avoid ambiguity and establish consistency among all patterns. This makes it easier for users to distinguish patterns and map them to body posture corrections.

Frequency and intensity of vibration could not be controlled individually with our hardware. In addition, only three levels of frequency and intensity can be identified absolutely by the tactile sense (see Brown [2007]). Because of these two reasons, we did not use frequency and intensity to distinguish tactile feedback patterns.

4.3.1 Snowboard Domain

Tactile patterns are tailored to snowboard domain

As we mentioned before, the tactile feedback patterns we wanted to design should be tailored to the snowboarding domain, considering the guidelines presented in the section before. This means, that the patterns should induce movements adjusting the user's body posture.

Common beginner mistakes of snowboarders

In his preceding work, Guggenmos [2007] conducted interviews with snowboard instructors and classified four common beginner mistakes:

Wrong Weight Distribution: One fundamental mistake beginners make is not shifting their weight to the front foot (the nose of the snowboard) during a turn, which makes it easier to turn the snowboard. Keeping the weight on the front foot accelerates the board for a short time. As this is an unusual position towards the fall line (greatest incline), most people shift their weight to their back foot, thus loosing control.

Straight Knees: The basic position for snowboarding is to slightly bend your major joints (“basic stance”). By that you can easily compensate small bumps. Beginners tend to keep their legs straight. This posture hinders them in compensating bumps.

Wrong Upper Body Postures: In the ”basic stance” the center of gravity should be above the snowboard in order to maintain balance. But beginners often bend their upper body forward to look at their feet. This wrong body posture shifts the center of gravity away from the board so that the snowboarder becomes unbalanced and might fall. One further problem of looking down at the feet is that people are not aware of the surrounding situation. Instead, they should better look towards the driving direction in order to prevent accidents.

Upper Body Counter Rotation: Another common mistake is counter rotation, where the upper body remains twisted against the lower body during the ride. This posture makes it difficult to introduce turns.

The mistakes described above reveal several body movements that correct the wrong body postures while snowboarding. They can be grouped pairwise into five categories:

Correctional movements can be grouped pairwise into five categories

C1: Stretch the legs (SL) vs. flex the legs (FL),

C2: Shift weight from the right to the left foot (WL) vs. shift the weight from the left to the right foot (WR),

C3: Lean upper body to the left (LL) vs. lean upper body to the right (LR),

C4: Rotate upper body to the left (RL) vs. rotate upper body to the right (RR),

C5: Lean upper body forward (LF) vs. lean backward or straighten up (LB).

Our goal is to find patterns that best represent these movements. The detailed description of the initial tactile feedback patterns is presented in chapter 5.

4.4 A Notation for Tactile Patterns

Notation for further description of feedback patterns

Before we present our initial tactile feedback patterns, we define some notations that ease their description.

As an impulse is the smallest unit to deliver information, we will use impulses as basic building blocks to compose patterns that represent motion instructions. The different ways to combine these impulses to patterns and the notation for this are described in the following paragraphs.

Pulsing of motor x for three times is expressed by P_x^3. This is a basic pattern consisting of one element. This single element can then be used to build more complex patterns.

Another single-element pattern is the directional pattern, also called "rabbit" (R). The "rabbit" pattern R consecutively pulses three motors located in line to render directional information on the skin.

To describe the composition of more complex patterns, we need some operators. In this work we will use the symbol $\rightarrow$ to denote consecutively triggered patterns and the symbol + to denote simultaneously triggered patterns. The pattern R can be written as R = $P_1^3 \rightarrow P_2^3 \rightarrow P_3^3$ for example.

By using $\rightarrow$ and + we can create compound patterns (CP), which display single-element patterns in succession, and simultaneous patterns (SP), which activate multiple actuators across the body at the same time.

As an abbreviation, we will denote upward direction on the body with RU (for "Rabbit Upward"), downward direction with RD (for "Rabbit Downward"), and rotation with RR (for "Rabbit Rotation"), with RR possibly using more than three motors.

We used a standard burst duration (BD) of 100 ms and an inter-burst interval (IBI) of 50 ms for P^3_x, which is considered optimal for pattern R to elicit sensory saltation. Later in this work, some durations are changed. This is described in more detail in the respective chapter.

Standard inter-burst interval and burst duration used in tests

What is still missing are abbreviations to name the locations where tactile cues are delivered on the body. Figure 4.4 illustrates the placement of actuators on the body as investigated in this work and the assigned abbreviation. With help of the introduced notation, we can describe patterns and the location where these patterns are rendered on the body.

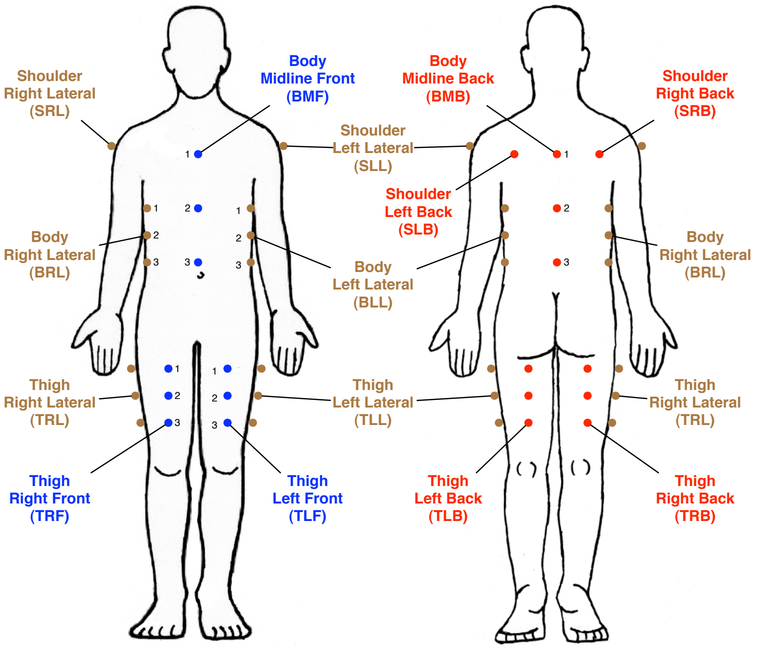

Figure 4.4: The location of vibration motors on the user's body and their labeling.

Before agreeing on specific tactile feedback patterns, we tested our first ideas in a preliminary user study. Participants were instructed to say what movement or corrections in body posture they associate with the patterns.

Chapter 5

Natural Interpretation of Tactile Feedback Patterns

We did not take the elaborate approach

At this point, we could have explored the influence of factors like number of simultaneous vibrations or direction of vibration sequences by testing innumerably feedback pattern at different body locations. As some of these patterns are not reasonable and due to time constraints, we did not take this elaborate approach. Instead, we limited the number of tactile motion instructions to 26. The tactile feedback patterns we designed are described in the following section.

5.1 Initial Feedback Patterns

Considering the important design factors we took from the literature review in chapter 4.3, we had a brainstorming session where we discussed how to design adequate tactile feedback patterns and with what body movements they could be associated.

As can seen from the pattern grouping in the following paragraphs, we had some expectations about what patterns may come into consideration to represent certain body movements from categories C1 to C5. Despite these expectations, we based our decisions on the results of the user study. We were open-minded about whether an expected, or a totally unexpected pattern fits best to a certain category.

We designed 26 feedback patterns

We first designed a small set of 26 tactile motion instructions. We did not design more patterns because of the time limitations mentioned before. A higher number of feedback patterns would have lead to user studies with either more test subjects for between-groups tests or more time needed to test all patterns on each user for within-group tests.

5.1.1 C1: Stretching and Bending Legs

Stretching and bending legs communicated by rabbit patterns on front & back of thighs

We thought that stretching and bending legs could best be communicated by giving tactile feedback to the thighs. As we were not sure whether the front or back of the upper legs is the best location and whether we should use an upward or downward sequence of vibrations, we tested all combinations. This means that we had one pattern where two rabbit patterns are simultaneously running up the front legs, one where they are running down the front legs, and two in the same manner on the backside of legs (see figure 5.1). These patterns are:

Patterns 1–4

PATTERNS 1–4:

Pattern 1: front, up: RU(TRF) + RU(TLF)

Pattern 2: front, down: RD(TRF) + RD(TLF)

Pattern 3: back, up: RU(TRB) + RU(TLB)

Pattern 4: back, down: RD(TRB) + RD(TLB)

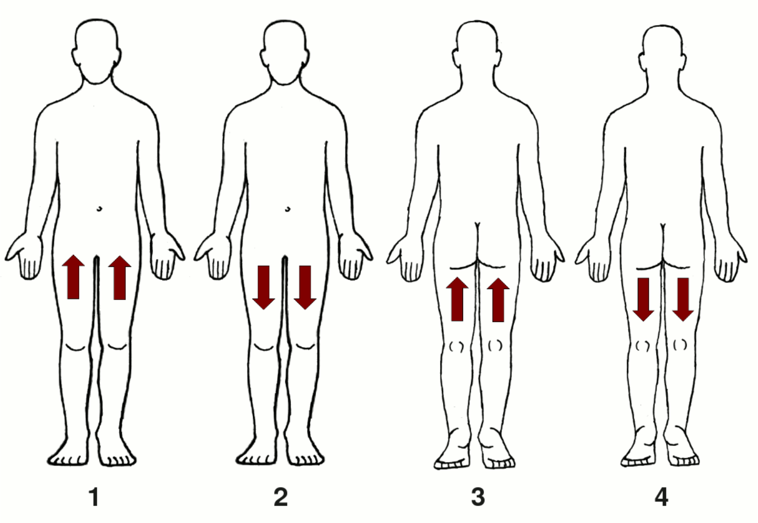

Figure 5.1: Patterns 1–4 belonging to category C1: Stretching and flexing legs is expressed by upward and downward rabbit patterns at the front or back of thighs.

In addition we designed two further patterns that included all motors of the legs (see figure 5.2). These are:

Patterns 5 and 6

PATTERNS 5 AND 6:

Pattern 5: all motors up:

> RU(TRF) + RU(TLF) + RU(TRB) + RU(TLB) +
> RU(TRL) + RU(TLL)

Pattern 6: all motors down:

> RD(TRF) + RD(TLF) + RD(TRB) + RD(TLB) +
> RD(TRL) + RD(TLL)

We used the standard BD and IBI for all feedback patterns. Exceptions to this are explicitly mentioned. The notation used here is explained in chapter 4.4 and figure 4.4.

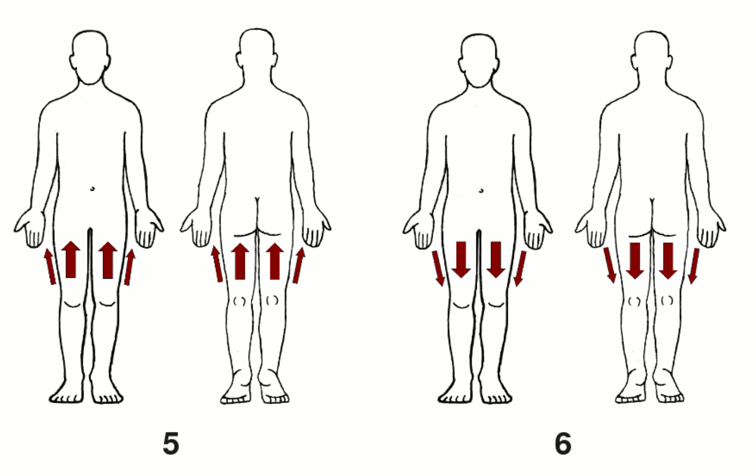

Figure 5.2: Patterns 5 and 6 belonging to category C1: Stretching and flexing legs is expressed by upward and downward rabbit patterns using all motors of the thighs.

5.1.2 C2: Shifting Weight

Patterns 7–10

PATTERNS 7–10:

Pattern 7: to the left, simultaneously:

RU(TRL) + RD(TLL)

Pattern 8: to the right, simultaneously:

RU(TLL) + RD(TRL)

Pattern 9: to the left, successively:

RU(TRL) → RD(TLL)

Pattern 10: to the right, right successively:

RU(TLL) → RD(TRL)

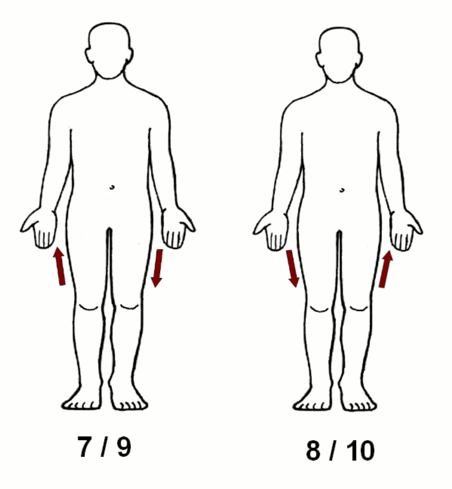

Figure 5.3: Patterns 7–10 belonging to category C2: Patterns 7 and 8 are simultaneous patterns (SP) consisting of two rabbit patterns (R) triggered simultaneously at the lateral thighs. Patterns 9 and 10 are compound patterns (CP) that trigger the same rabbit patterns (R) in succession.

When shifting your weight to one side, you take away weight from one leg and put it onto the other. We decided to take the thighs also as location for tactile feedback that should incite the user to shift weight. We created two different types of patterns. Patterns of the first type are simultaneous patterns (SP) consisting of two rabbit patterns (R) triggered simultaneously at the lateral thighs. Patterns of the second type are compound patterns (CP) that trigger the same rabbit patterns (R) in succession. Figure 5.3 shows a sketch of these tactile feedback patterns, which are:

Shifting weight is communicated by rabbit patterns on the lateral thighs

5.1.3 C3: Leaning the Upper Body to the Side

As patterns of category C3 should trigger sideward movements of the upper body, we thought that both sides of the torso are the best location to communicate these movements. For this category we also designed two different types of patterns, single-element patterns of type P and rabbit patterns R (see figure 5.4 for visualization). The four different patterns are:

Leaning the upper body to the side communicated by lateral rabbit pattern or shoulder tapping

Patterns 11–14

PATTERNS 11–14:

Pattern 11: 3 impulses at right shoulder: $P^3(SRL)$

Pattern 12: 3 impulses at left shoulder: $P^3(SLL)$

Pattern 13: rabbit on right side: RU(BRL)

Pattern 14: rabbit on left side: RU(BLL)

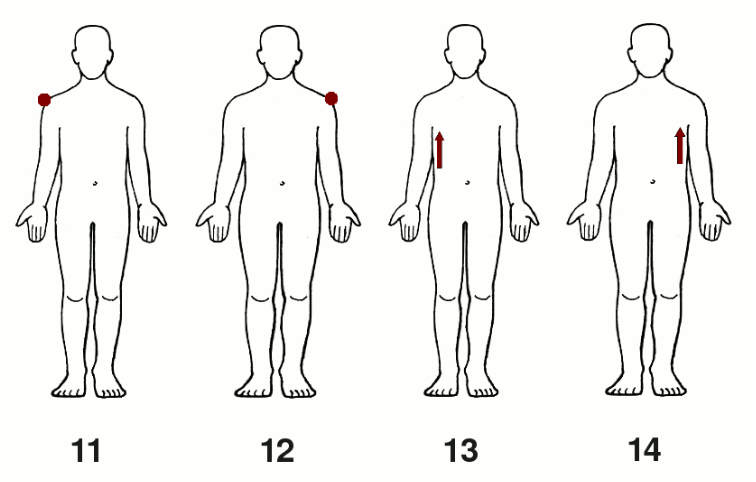

Figure 5.4: Patterns 11–14 belonging to category C3: Leaning the upper body to the sides is triggered either by single-element patterns of type P located at the shoulders and rabbit patterns R located at lateral torso.

5.1.4 C4: Rotating the Upper Body

Circular vibration sequences indicate to turn the upper body

We designed three different types of patterns from which we thought that they would best confer the rotational movement of the upper body.

For patterns of the first type four motors located around the waistline were used. The actuators vibrated three times each, one after the other, until the first actuator is reached again. The burst duration (BD) for this type was 100 ms and the inter-burst interval (IBI) 50 ms. The two patterns belonging to this group are the following:

PATTERNS 15 AND 16:

Patterns 15 and 16

Pattern 15: 1 rotation to left with 1 motor:

$$P_2^3(BMF) \rightarrow P_1^3(BLL) \rightarrow P_2^3(BMB) \rightarrow \\ P_1^3(BRL) \rightarrow P_2^3(BMF)$$

Pattern 16: 1 rotation to right with 1 motor:

$$P_2^3(BMF) \rightarrow P_1^3(BRL) \rightarrow P_2^3(BMB) \rightarrow \\ P_1^3(BLL) \rightarrow P_2^3(BMF)$$

Patterns of the second type were equal to the ones of the first except the vibration running twice around the waistline. In order to keep the patterns short, we reduced the BD to 30 ms and the IBI to 50 ms.

PATTERNS 17 AND 18:

Patterns 17 and 18

Pattern 17: 2 rotations to left, shorter period:

$$P_2^3(BMF) \rightarrow P_1^3(BLL) \rightarrow P_2^3(BMB) \rightarrow \\ P_1^3(BRL) \rightarrow P_2^3(BMF) \rightarrow P_1^3(BLL) \rightarrow \\ P_2^3(BMB) \rightarrow P_1^3(BRL) \rightarrow P_2^3(BMF)$$

Pattern 18: 2 rotations to right, shorter period:

$$P_2^3(BMF) \rightarrow P_1^3(BRL) \rightarrow P_2^3(BMB) \rightarrow \\ P_1^3(BLL) \rightarrow P_2^3(BMF) \rightarrow P_1^3(BRL) \rightarrow \\ P_2^3(BMB) \rightarrow P_1^3(BLL) \rightarrow P_2^3(BMF)$$

The last type differed from the first one by the numbers of motors used. Time intervals and number of rotations stayed the same. This time all twelve actuators of the upper body were used. The three motors that were located above each other were always vibrating three times simultaneously. The three vibrations were running around the waist one time. The three sequences of vibrations should feel like a ”vibration bar” running around the waistline one time. These tactile feedback patterns are described in detail here:

Patterns 19 and 20

PATTERNS 19 AND 20:

Pattern 19: 1 rotation to left with all motors:

$$P^3(BMF) \rightarrow P^3(BLL) \rightarrow P^3(BMB) \rightarrow$$
$$P^3(BRL) \rightarrow P^3(BMF)$$

Pattern 20: 1 rotation to right with all motors:

$$P^3(BMF) \rightarrow P^3(BRL) \rightarrow P^3(BMB) \rightarrow$$
$$P^3(BLL) \rightarrow P^3(BMF)$$

Figure 5.5 graphically illustrates the three different types of rotational feedback patterns.

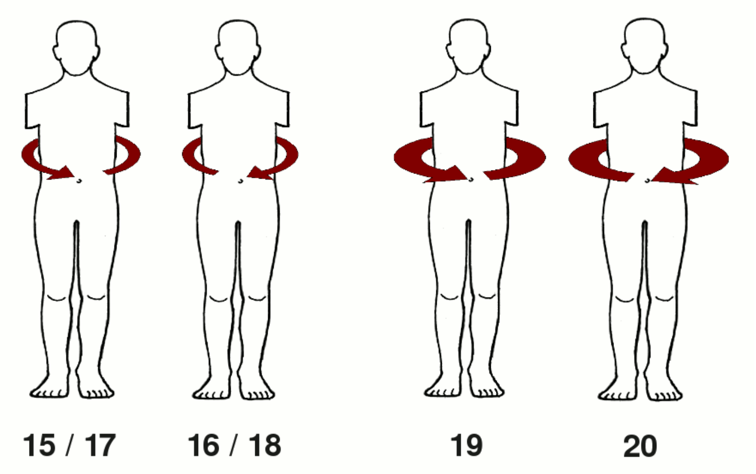

Figure 5.5: Patterns 15–20 belonging to category C4 (rotation of upper body): Patterns 15 and 16 comprise one rotation with standard BD and IBI, patterns 17 and 18 comprise two rotations with BD = 30 ms and IBI = 50 ms, and patterns 19 and 20 comprise one rotation of three simultaneous vibrations with standard BD and IBI.

5.1.5 C5: Leaning Forward and Backward

We thought that leaning forward and backward could best be communicated by also giving tactile feedback to the upper body. We designed three different types of patterns, the first one including single-element patterns of type P and the second one comprising rabbit patterns R. A sketch of the first two types can be seen in figure 5.6.

Rabbit and punctual patterns on the back and chest indicate to lean forward and backward

PATTERNS 21–14:

Pattern 21: 3 impulses at back: $P_1^3(BMB)$

Pattern 22: 3 impulses at chest: $P_1^3(BMF)$

Pattern 23: rabbit pattern at back: RU(BMB)

Pattern 24: rabbit pattern at back chest: RU(BMF)

Patterns 21–14

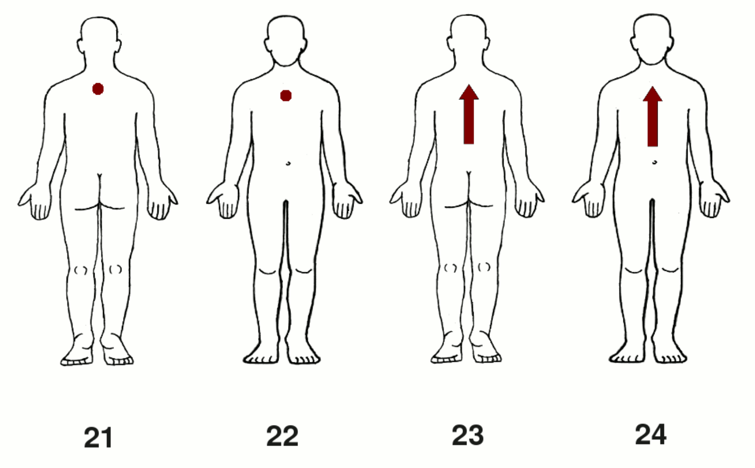

Figure 5.6: Patterns 21–24 belonging to category C5: Leaning forward is expressed either by single-element patterns of type P located at the chest and breast and upward rabbit patterns R located at the front and back of the torso.

The last group comprises two compound patterns (CP) consisting of rabbit patterns in upward or downward direction on all four sides of the upper body (see figure 5.7 for illustration).

Patterns 25 and 26

PATTERNS 25 AND 26:

Pattern 25: all sides, up:

RU(BRL) + RU(BLL) + RU(BMB)+ RU(BMF)

Pattern 26: all sides, down:

RD(BRL) + RD(BLL) + RD(BMF)+ RD(BMB)

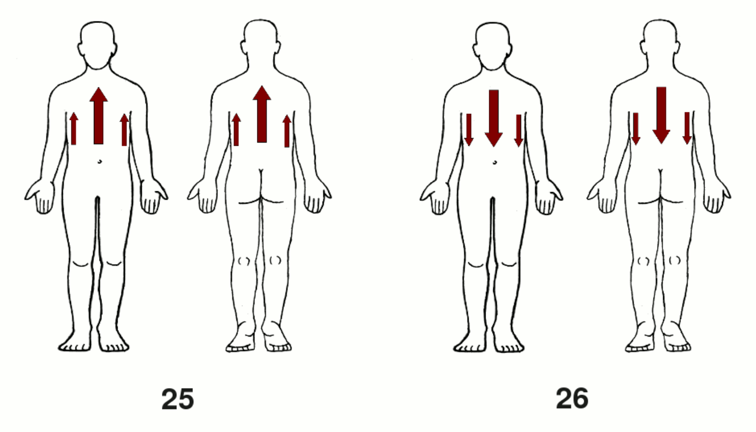

Figure 5.7: Patterns 25 and 26 belonging to category C5: Leaning forward and backward is triggered by upward and downward rabbit patterns using all motors of the upper body.

We would like to emphasize that although we had some expectations about the classification of patterns, we tried to stay unbiased and based our later choice of patterns on the outcome of the following user study.

User study to explore the natural interpretation of our patterns

After designing the first set of tactile motion instructions, we conducted an exploratory study in our Media Space Lab to identify how users without prior experience with tactile feedback perceive and interpret our patterns.

Open-response paradigm used in tests

For collecting data about the natural interpretation of our tactile feedback patterns we used an open response paradigm. This means that participants could freely assign any meaning to the tactile output they perceived. Our aim was to find out if patterns exist that can be inherently associated with a specific movement. We did this by investigating which patterns spontaneously induce the desired posture correction most often. Regarding future tests, we also wanted to reduce the original number of designed feedback patterns to one pattern per desired body posture correction.

5.2 Users

20 people participated in our user study. All of them belonged to the target group "snowboarders". They were young healthy people, twelve male and eight female participants aged 22–28 years. 19 of the users were students from the RWTH and one was a translator. Three participants stated that they have experience in snowboarding, without further specifying their skills. Except one person, all test subjects stated to regularly do sports. None of the participants had previous experience with tactile feedback.

5.3 Setup and Task

User study conducted under lab conditions

The test was conducted in a lab environment. Tactile feedback patterns were delivered to the participants. Their task was to say what they had perceived and with what body posture correction they would react to it, if at all.

Participants wore headphones during the experiment to cancel vibration from the motors. The vibration should solely be detected by the somatosory sense and not by hearing as under realistic condition on a slope there also exist distracting noises.

In addition, test subjects had to wear cycling tights and a shirt that were both prepared with flaps that helped fixing the motors to the clothes. (see figure 5.8)

Figure 5.8: The clothes used during the study, motors were inserted inside the small pouches.

Hardware limitations

Because of hardware limitations, we had to test patterns addressing the upper body and the legs separately. The order of tested body parts was fully counterbalanced.

Between-subject design

As testing all patterns with each participant was too time consuming we decided to use a between-subject design and to distribute the patterns across both groups. To each test group ten participants were assigned.

The first test group received the patterns 1, 2, 9, 10, 11, 12, 17, 18, 21, and 23. The participants of the second test group received patterns 3, 4, 7, 8, 13, 14, 15, 16, 22, and 24. Patterns 5, 6, 19, 20, 25, and 26 were tested by both test groups.

We tried to balance position effects by randomly triggering patterns of each test group in different orders.

The test persons were given a short introduction about the hardware setup and their task. They were told that they would perceive tactile feedback at different body locations and that the delivered cues were intended for posture correction. Information about the application domain, i.e., snowboarding, was not given, as this would bias the participants and by that distort the results.

Patterns triggered with maximal intensity

Patterns were triggered with maximal intensity. We had chosen to use full strength, because the threshold test described in 4.2 shows a wide range for the strongest, but still tolerable, vibration. This means the vibration strength could be reduced if the participant asked for it. We learned that participants considered full strength vibration as still being tolerable. As people were sometimes too surprised, they could ask for a repetition of the patterns.

The test subject were encouraged to react freely to the impulses and perform any movement that they link with the according pattern. They were also explicitly encouraged to think aloud.

Users had to describe the sensation and how they would react

People were asked at what places motors vibrated and whether several motors vibrated. If participants stated that there was more than one motor vibrating, we wanted to know whether these motors vibrated successively or synchronously and in what direction, e.g., up, down, left, or right. After this, we asked the participants with what posture correction they would react to the given pattern. We told them that they do not have to specify a correction if they could not anticipate one to the stimulus and that they are also allowed to tell us more than one possible reactions.

All sessions were recorded on video tape for evaluation. We told the participants that the collected data is treated confidentially. Subjects had to fill out a personal data form. After the test we resolved all the participants' questions.

5.4 Evaluation

No pattern was truly intuitive

The user study revealed that none of the tactual feedback patterns was truly intuitive. Some patterns showed a greater accordance across all subjects than others. Other feedback patterns were completely confusing as participants did not know how to react to the pattern.

Motors on the back were hardly perceived

One major problem arose during the test. Some motors, namely the three motors on the back, were hardly recognized by the test subjects. A reason for that might have been the fact that the clothes, especially the shirt, did not tightly fit the body at those locations.

Participants were more sensitive to their sides

One phenomenon that became apparent was that people were more sensitive on the sides than on their back or front. This was affirmed by the interpretations of patterns 5, 6, 19, 20, 25, and 26 that used all motors. The vibration on the sides seemed to overlay the ones of the front or back, so that the subjects stated that they had perceived only the motors on the sides. In addition, in some cases the motors on the sides, especially the ones directly under the armpits, felt rather ticklish.

Participants preferred rabbit patterns

Another point that emerged from later interviews was that participants generally preferred cues with directional information (R) over simple localized impulses (P_x^3). People argued that the directional patterns were easier to link to specific body motions, as the first vibration designates the body part that requires the correction and the direction indicates what to do with this body part.

5.4.1 Choice of Patterns

As mentioned at the beginning of this chapter, we had to agree on one tactile feedback pattern per requested body posture correction and reject all others. Due to the fact that we had to split the participants and the composed patterns into two groups, drawing strong conclusions was not always possible.

We did not base our decision solely on numbers. The results for the single patterns did not show big differences, only trends. One reason for this was the open response paradigm. Answers to a particular pattern often considerably varied across participants or could not be related to any particular motion. Because of this, it was not easy for us to remain unbiased when interpreting some of our participants' reactions and responses.

Choice of patterns not solely based on numbers

We paid attention to the consistency of the pattern language. In addition, we avoided to keep feedback patterns that were very confusing, i.e., with which participants did not associate any correction in body posture. One last factor we considered were the subjective statements of the users made during the debriefing.

Tactile Feedback Patterns Including all Actuators of a Body Part

The first decision we made was to exclude all simultaneous patterns that activate all motors at the thighs and upper body at the same time. These are patterns 5, 6, 19, 20, 22, and 23. They confused many test subjects and were usually described as strong and unpleasant. In relation to the other patterns this means that a higher percentage of people stated that they had no idea how to react when they received the test signal. Evaluation of the video tapes confirmed this impression.

We excluded all simultaneous patterns activating all motors

As it can be seen in table 5.1, the rate of the participants' confusion when receiving the simultaneous feedback patterns lies within 25 % and 40 % (average 32,5 %). In comparison to this, the rates of confusion of all other patterns lie within 0 % and 30 % (average 19,53 %). This is much less, so we did not chose to keep the six patterns mentioned before for further experiments.

Cutaneous Saltation Versus one Single Actuator

The second main decision we made was to choose which

General choice in favor of rabbit patterns

Induced pattern		**No body posture correction associated**
Pattern 5	(rabbit, all motors)	30 %
Pattern 6	(rabbit, all motors)	40 %
Pattern 19	(1x rotation)	40 %
Pattern 20	(1x rotation)	25 %
Pattern 25	(rabbit, all motors)	35 %
Pattern 26	(rabbit, all motors)	25 %
Pattern 4	(rabbit)	0 %
Pattern 22	(single)	30 %

Table 5.1: Rate of confusion when receiving tactile feedback patterns of category C3 compared to the remaining patterns (best and worst).

patterns could best communicate to lean the upper body to the front, back, left, and right. Table 5.2 shows that the overall results for rabbit patterns are more convincing than those for patterns with only one vibrating actuator. Solely for the body posture correction "leaning forward" a pattern with only one actuator achieved most hits.

Impulses delivered either to the right or the left shoulder ($P^3(SLL)$ and $P^3(SRL)$) were usually interpreted as instructions to "move" the corresponding arm rather than to lean sidewards or to turn the upper body to the left or to the right.

As we wanted to create a pattern language in which the patterns are consistent, we decided to take rabbit patterns for the categories C3 (leaning to the sides) and C5 (leaning forward and backward). The rate of confusion did not have any crucial effect on our decision. Equally often, participants could not map patterns of both types R and P^3 to a posture correction.

Two ways to assign patterns to different posture corrections

The next step was to assign the rabbit patterns to different body posture corrections. In general, two different ways to react to the test stimuli emerged. About 50 % of the participants preferred to move away from impulses delivered at the upper body, while the others tended to move towards the stimulation. We had to decide whether to use a push or

Induced pattern		Associated body posture correction					
		No idea	Lean forward	Lean backward	Lean left	Lean right	Other reaction
Pattern 11	(rabbit)	30 %	0 %	0 %	20 %	10 %	40 %
Pattern 12	(rabbit)	20 %	0 %	0 %	0 %	10 %	70 %
Pattern 21	(rabbit)	10 %	30 %	30 %	0 %	0 %	30 %
Pattern 23	(rabbit)	30 %	0 %	30 %	0 %	0 %	40 %
Pattern 13	(single)	10 %	0 %	0 %	20 %	20 %	50 %
Pattern 14	(single)	10 %	0 %	0 %	30 %	10 %	50 %
Pattern 22	(single)	30 %	20 %	40 %	0 %	0 %	10 %
Pattern 24	(single)	30 %	10 %	40 %	0 %	0 %	20 %

Table 5.2: Rates of different body posture corrections that participants linked to the received tactile feedback patterns that come into consideration for leaning the upper body.

pull metaphor to assign tactile instructions to body movements.

Push and pull metaphor

To illustrate the difference between these two approaches, assume that one was instructed to lean his body to the left. The pull technique will trigger an impulse on the left side of his body to indicate the direction of movement. The push technique, on the other hand, will trigger an impulse on the right side of his body to evoke the sensation of being "pushed" to the left. Choosing one of these metaphors seems to be a matter of preference.

The mere numerical results gave us no answer to this question. For the body posture correction "leaning forward" the push metaphor seemed to be best. For "leaning left" it was the pull metaphor, and for "leaning back" no tendency could be seen. We included the video evaluation into the decision process, but the recording also showed no hint.

Push metaphor used to assign patterns

In the end we decided to use the push metaphor for our pattern language. We were interested in finding out in the course of the following user studies whether these patterns could be learned by participants who intuitively preferred the pull metaphor.

The following tactile feedback patterns were assigned to the body posture corrections of categories C3 and C5:

Patterns LL, LR, LF, and LB

PATTERNS LL, LR, LF, AND LB:

Lean left: (Pattern 13) LL = RU(BRL)

Lean right: (Pattern 14) LR = RU(BLL)

Lean forward: (Pattern 23) LF = RU(BMB)

Lean back: (Pattern 24) LB = RU(BMF)

Shifting Weight

For future tests, we also had to select a tactile feedback pattern that could be best associated with the body posture corrections ”shifting the weight to the left” and ”shifting the weight to the left”.

Shifting weight represented by successive rabbit patterns

As you can see in table 5.3, the only pattern that was associated with shifting the weight to the right was pattern 10 (successive vibrations from right to left). In addition pattern 9 (successive vibrations from left to right) was associated most often with shifting the weight to the left. Pattern 9 and 10 are also opposite patterns like shifting weight to the left and right are also contrary movements. This makes it easy to learn the patterns.

In contrast to that, simultaneous patterns 7 and 8 (simultaneous vibrations from one side to other) were processed more slowly and demanded more attention from participants to identify directional information.

As a consequence, we decided to take these two patterns for shifting. In detail, pattern 9 was assigned to shifting the weight to the left, and patter 10 to shifting the weight to the right.

Induced pattern		**Associated body posture correction**			
		No idea	Shift weight left	Shift weight right	Other reaction
Pattern 7	(simultaneous)	20 %	30 %	0 %	50 %
Pattern 8	(simultaneous)	10 %	30 %	0 %	60 %
Pattern 9	(successively)	20 %	40 %	0 %	40 %
Pattern 10	(successively)	10 %	0 %	30 %	60 %

Table 5.3: Rates of different body posture corrections that participants linked to the received tactile feedback patterns that come into consideration for shifting weight.

The set of tactile motion instructions for C2 comprises:

PATTERNS WL AND WR:

Shift weight left: (Pattern 9)

WL = RU(TRL) → RD(TLL)

Shift weight right: (Pattern 10)

WR = RU(TLL) → RD(TRL)

Patterns WL and WR

Rotational Tactile Feedback Patterns

Rotation is represented by vibrations running twice around the waist

The two patterns 17 and 18 (two short rotations of vibration) achieved highest results for rotating the upper body to the left and right (see table 5.4). With 60 % these two patterns achieved the greatest consensus among all participants. In addition, most people stated that two faster turns were easier to understand than one slow turn. With 10 % the rate of confusion was very low for patterns 17 and 18. In contrast to that, with 20 % and 40 % patterns 15 and 16 were rather confusing. In this case it was easy for us to decide which pattern to keep, namely pattern 17 for turning the upper body to the left and pattern 18 for turning the upper body to the right:

Patterns RL and RR

PATTERNS RL AND RR:

Rotate left: (Pattern 17)

RL = $P_2^3(BMF) \rightarrow P_1^3(BLL) \rightarrow P_2^3(BMB) \rightarrow P_1^3(BRL) \rightarrow P_2^3(BMF) \rightarrow P_1^3(BLL) \rightarrow P_2^3(BMB) \rightarrow P_1^3(BRL) \rightarrow P_2^3(BMF)$

Rotate right: (Pattern 18)

RR = $P_2^3(BMF) \rightarrow P_1^3(BRL) \rightarrow P_2^3(BMB) \rightarrow P_1^3(BLL) \rightarrow P_2^3(BMF) \rightarrow P_1^3(BRL) \rightarrow P_2^3(BMB) \rightarrow P_1^3(BLL) \rightarrow P_2^3(BMF)$

Induced pattern		**Associated body posture correction**		
		No idea	Turn upper body left	Turn upper body right
Pattern 15	(1 rotation)	20 %	50 %	0 %
Pattern 16	(1 rotation)	40 %	0 %	30 %
Pattern 17	(2 rotations)	10 %	60 %	0 %
Pattern 18	(2 rotations)	10 %	0 %	60 %

Table 5.4: Rates of different body posture corrections that participants linked to the received tactile feedback patterns that come into consideration for rotating the upper body.

Stretching and Flexing the Legs

Patterns to communicate stretching and flexing of the legs

At last, we had to determine two patterns for stretching and flexing the legs. Pattern 1 (upward rabbit at front of thighs) could best be associated to the body posture correction ”stretch legs”, and pattern 4 (downward rabbit at back of thighs) to ”flex legs” (see table 5.5). In addition pattern 4 is some kind of counterpart to pattern 1, as flexing legs is the opposite of stretching them. This will facilitate learning the pattern language in the next user tests. We preferred pattern 1 for stretching legs and pattern 4 for bending them:

PATTERNS SL AND FL:

Stretch legs: (Pattern 1) SL = RU(TRF) + RU(TLF)

Flex legs: (Pattern 4) FL = RD(TRB) + RD(TLB)

Patterns SL and FL

Induced pattern		**Associated body posture correction**			
		No idea	Stretch legs	Flex legs	Other reaction
Pattern 1	(front, upward)	11 %	22 %	11 %	56 %
Pattern 2	(front, downward)	10 %	20 %	40 %	30 %
Pattern 3	(back, upward)	40 %	0 %	20 %	40 %
Pattern 4	(back, downward)	0 %	10 %	60 %	30 %
Pattern 8	(sides, simultaneously)	10 %	10 %	10 %	70 %

Table 5.5: Rates of different body posture corrections that participants linked to the received tactile feedback patterns that come into consideration for bending and stretching legs.

5.4.2 Further Conclusions

Proposal for two new shifting patterns

During debriefing, participants proposed two new patterns for category C2, i.e., shifting weight. They suggested to skip the second part of the compound patterns 9 and 10, i.e., the vibration should only run up on the outer side of the leg that you should move away from. The resulting patterns for category C2 look like this:

PATTERNS WL2 AND WR2:

Shift weight left (2nd): rabbit right: WL2 = RU(TRL)

Shift weight right (2nd): rabbit left: WR2 = RU(TLL)

Patterns WL2 and WR2

The main argument for the proposal was that the participants often felt incited to perform “contradicting” movements. When they perceived patterns 9 or 10 people first

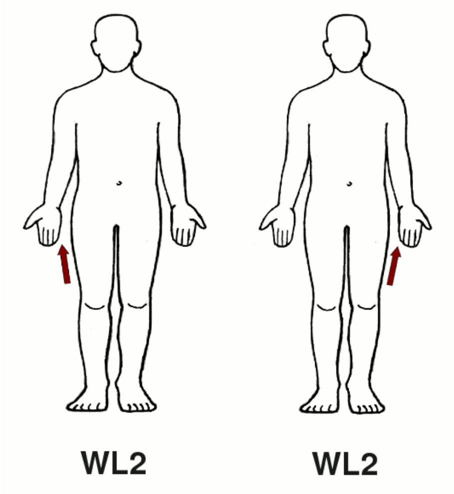

Figure 5.9: Two alternative patterns for shifting weight to the left (WL2) and to the right (WR2): Each pattern consists of an upward rabbit pattern at the lateral thigh from that the user has to move away.

shifted their weight away from the leg where the first rabbit pattern was triggered, e.g., the right leg. However, when the stimulation ceased at the first thigh and started at the other thigh (in this case the left one), participants shift their weight back to the other leg.

With the new patterns this could probably be avoided. In order to affirm this idea, we consulted the video tapes, which seemed to support the assumption. Therefore we included the patterns WL2 and WR2 in our next study described in the following chapter 6.

Chapter 6

Learnability of Patterns and Influence of Cognitive Load

In the last user study we collected data about the natural interpretation of our tactile feedback patterns. Results show that some patterns are more suitable to communicate body posture corrections than others. We reduced the number of patterns to one for each movement. These patterns had to undergo another test, where we wanted to find out how easy to learn these patterns are. This crucial characteristic is one main requirement for telling the user to perform the right movements in the final application.

In addition to the original patterns we also included the patterns for shifting weight, proposed in the last user study (see chapter 5.4.2). We thought that the newly proposed patterns might be easier to learn than patterns 9 and 10. Furthermore, the number of actuators could be reduced, resulting in less hardware the users have to wear.

Investigate the learnability of patterns and the influence of cognitive load

We conducted another user study under lab conditions to find out whether the tactile feedback patterns are easy to learn and which of the weight shifting patterns is best for later application under realistic conditions. In order to find an answer to these two questions we investigated whether the patterns induced the desired posture correction under cognitive load after a short training phase.

6.1 Users

17 people participated in this user study. All of them belonged to the target group "snowboarders". They were young healthy people, 13 male and four female. Their age ranged from 19 to 30 years. 15 of the users were students from RWTH Aachen University and two were pupils of a vocational school. Seven of the subjects had already participated in the initial study and had previously experienced tactile feedback. Three participants stated that they do snowboarding, without further specifying their skills. Except four people, all test subjects stated to do different kinds of sport during their free time.

6.2 Setup and Task

Tests conducted under lab conditions

The test took place in the Media Space Lab of our chair on two consecutive days. The aim of this experiment was to determine how well people can learn and remember the designed set of tactile motion instructions over a period of two consecutive days.

The participants had to wear earphones and listen to music in order to to cancel vibration from the motors. The vibration should solely be detected by the somatosory sense and not by hearing, as at later application on a real slope there might also exist distracting noises.

In addition, test subjects had to wear the cycling tights and the shirt we already used in the second user study. Again, because of hardware limitations, we tested the upper body and the legs separately.

Between-subject design

We set up two groups with ten participants each. By splitting them up, we wanted to see which patterns could communicate the posture corrections "shift weight left" and "shift weight right" most effectively. Therefore the first test group received the old consecutive patterns for weight shifting, WL (right leg → left leg) and WR (left leg → right leg). In the second test group these were replaced by the two newly proposed rabbit patterns WL2 (right leg) and WR2 (left leg). In addition, both test groups tested the six patterns for the upper body and the ones for flexing and stretching legs.

We tried to balance position effects by randomly triggering patterns of each test group in different orders., i.e., we varied the order of upper body and legs, but also the order of single patterns during each session.

Patterns were triggered with full strength

The participants were given a short introduction of the hardware setup and their task. We delivered the feedback patterns for the test persons with full-strength vibration. Again, full strength was chosen for the same reason as in the study before. The vibration strength could be reduced, if the participant asked for it. Practice showed us that full-strength vibration was neither painful nor uncomfortable for any test person.

Test took place on two consecutive days

As mentioned before, the test took place on two consecutive days. On the first day, the experiment consisted of a training phase followed by a test phase. In the training phase, participant familiarized themselves with the patterns by pressing dedicated buttons on a graphical user interface (GUI) (see figure 6.1). The participants were allowed

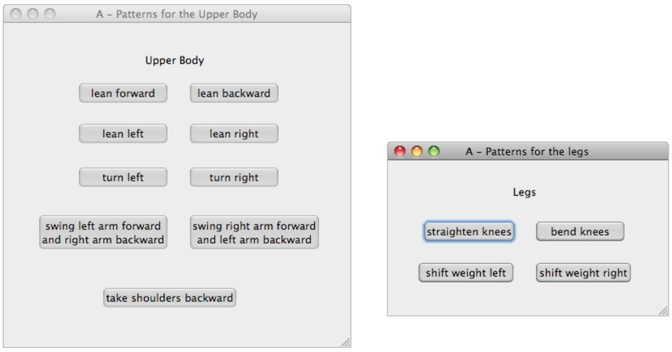

Figure 6.1: Graphical user interface used by the test subjects during the training phase of the third user study.

to test the patterns as long as they liked until they were sure that they would remember all pattens.

Relaxed condition

After the training phase, we tested whether the subjects could remember the patterns under relaxed conditions. Participants had to stand upright. Whenever they perceived a tactile feedback pattern, our participants had to say out aloud the body posture correction assigned to it. We did not correct participants in case they made mistakes. The patterns were randomized and delivered with a delay of 10 to 15 seconds. We repeated this procedure two times for each pattern. On each run we changed the order of triggered feedback patterns.

Cognitive load condition

A second test phase followed the first one. This time we asked the participants to snowboard on the Wii Fit[1] (see figure 6.2) as a cognitive demanding task. This task is similar to snowboarding under real-world conditions on a slope. Riders cannot solely concentrate on recognizing patterns delivered across the body but also have to concentrate on keeping their balance and pay attention to obstacles.

In the second phase participants did not have to wear earphones but listen to the game's sound from the speakers. We made this decision because it is easier for unexperienced users to play the snowboarding game with sound than without it. In addition, in reality one also does not wear headphones while snowboarding to stay aware of sound stemming from the surrounding environment.

The second test phase further included several practice sessions on the Wii balance board to allow participants to become acquainted with controlling the avatar on the screen.

Playing Wii Fit

The remaining procedures equaled the one from the "relaxed" test phase. Whenever participants perceived a tactile feedback pattern, they had to say out aloud the body posture correction assigned to it. They were not corrected in case that they made mistakes. Patterns were randomized and delivered with a delay of 10 to 15 seconds. Participants had to replay the game until all pattern were tested twice. At the end of the first day, we told the participants which

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[1] http://www.nintendo.com/wiifit/launch/

Figure 6.2: Experimental setup: While playing a snowboarding game on the Wii Fit console the test person had to recognize the perceived feedback patterns (belonging to categories C1 and C2).

patterns they had confounded during the experiment.

No training before retention test

No training session was included before the retention test on the second day. We directly conducted the tests under relaxed conditions and under cognitive load in the same procedure as on the day before.

After completing the test, participants had to fill out a personal data form. At this point we also answered all further questions that test subjects had about the project.

6.3 Evaluation

No major difficulty in learning and identifying patterns

The user study concerning the learnability of our tactile feedback patterns revealed that participants had no major difficulty in learning and identifying motion instructions based on the push metaphor. In the following sections we will discuss the results in detail.

6.3.1 Learnability of Tactile Feedback Patterns

High identification rates for both days under both conditions

The user study revealed that the tested tactile feedback patterns were relatively easy to learn. Except for the four patterns "turn upper body left/right", "stretch legs" and "flex legs", all other patterns achieved identification rates above 90 % on both days (training as well as retention) and under both conditions (relaxed and cognitive load). The results of the tests under relaxed conditions are listed in table 6.1, and under cognitive load (with Wii Fit) in table 6.2.

Feedback Patterns	**Identification Rate**	
	Day 1	Retention
Lean forward	100.0 %	97.1 %
Lean backward	100.0 %	100.0 %
Lean left	100.0 %	100.0 %
Lean right	97.1 %	100.0 %
Turn left	91.2 %	94.1 %
Turn right	93.9 %	94.1 %
Stretch legs	94.1 %	88.2 %
Flex legs	94.1 %	91.2 %
Shift weight left (original)	100.0 %	93.8 %
Shift weight right (originial)	100.0 %	100.0 %
Shift weight left (newly proposed)	100.0 %	100.0 %
Shift weight right (newly proposed)	100.0 %	100.0 %

Table 6.1: Results of the experiment under relaxed condition: Identification rates of correct associated body posture corrections.

Cognitive load did not degrade recognition accuracy

Furthermore, cognitive load did not considerably degrade the recognition accuracy of the designed patterns. Except

Feedback Patterns	**Identification Rate**	
	Day 1	Retention
Lean forward	100.0 %	100.0 %
Lean backward	94.1 %	100.0 %
Lean left	100.0 %	100.0 %
Lean right	94.1 %	94.1 %
Turn left	80.0 %	82.9 %
Turn right	91.4 %	85.7 %
Stretch legs	94.1 %	94.1 %
Flex Legs	91.2 %	88.2 %
Shift weight left (original)	100.0 %	100.0 %
Shift weight right (original)	100.0 %	94.1 %
Shift weight left (newly proposed)	100.0 %	100.0 %
Shift weight right (newly proposed)	100.0 %	100.0 %

Table 6.2: Results of the experiment under cognitive load condition: Identification rates of correct associated body posture corrections.

for instructions that signaled rotation, the percentages of correct identification are similar under relaxed and cognitive load conditions. This trend is visualized in figure 6.3.

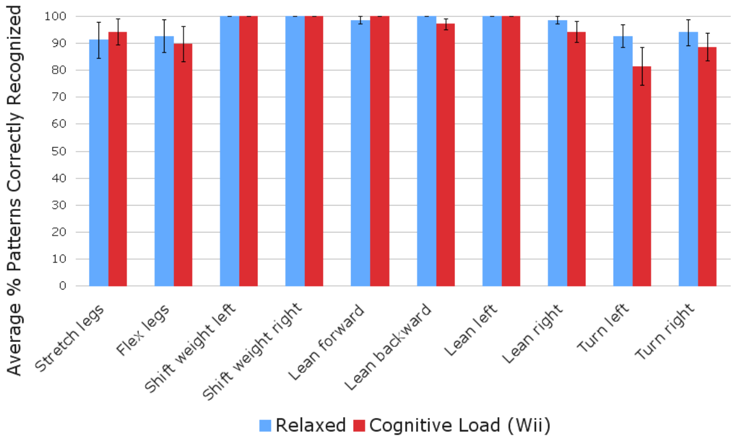


Figure 6.3: Percentage of correctly recognized patterns before and while playing Wii snowboard, averaged over both days (with standard error).

Results of the retention test similar to those of day 1

The results of the retention test were not considerably worse than the ones of the first day. The average value for the identification rates of day one without cognitive load was 97.5 % and 96.5 % for the retention test. For the test under cognitive load the average identification rates are 95.4 % for day 1 and 94.9 % for the retention test on the second day. Figure 6.4 shows a comparison of the average identification rates under both conditions across both days (first day = practice, second day = retention).

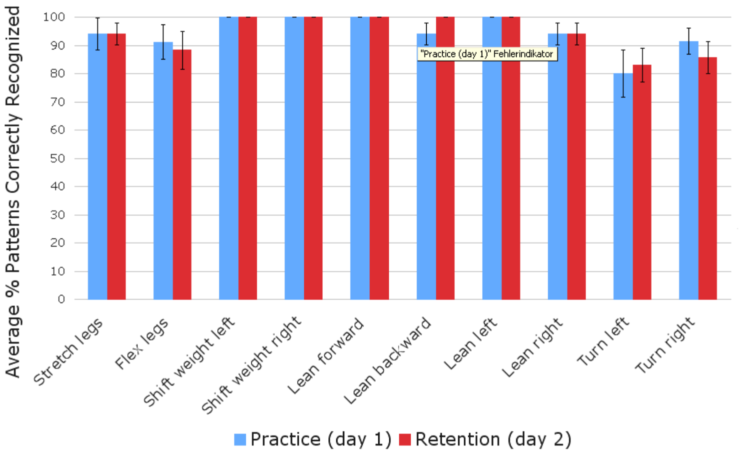


Figure 6.4: Percentage of correctly recognized patterns while playing Wii Snowboard on day 1 and on day 2 (with standard error).

Confoundation of rotational patterns

Two of the patterns not so easy to learn were "turn upper body left" and "turn upper body right". Participants stated that they had two major problems. Firstly, they could not identify the direction of the vibrations around the torso correctly. This made it difficult for them to distinguish between the two rotational patterns. From the test protocols we could see that most mistakes were caused by confounding patterns "turn upper body left" and "turn upper body right".

Secondly, they did not perceive the circular alignment of vibrating motors. The wandering vibration did not cause a saltation effect, as people felt no connection between the individual vibration loci. Because of the missing connection, participants felt only an arbitrary sequence of vibrations that again made it difficult to distinguish the rotational patterns. Distinguishing them from the rest was no problem, as an arbitrary sequence of vibrations felt different enough from the linear vibrational arrays that the other patterns consisted of. In addition, the other patterns were addressing different body locations.

Confoundation of stretching and flexing legs

The other tactile feedback patterns obviously worse than the majority were "stretch legs" and "flex legs". Again most mistakes were made by confusing the two patterns.

In what processing stage does confoundation occur?

The problem of mixing up the two patterns could occur at two different stages in the perception process. They are either perceived as equal or the brain confounds the two patterns due to other reasons (e.g., cognitive overload) although they are perceived as different.

To explore at which of these two stages the mistakes are made in the case without cognitive load, we went one step back and looked at the results of the user study described in chapter 5 that explored the natural interpretation of our patterns. We were interested in how often users had correctly perceived patterns that consisted of vibrations running up and down the front and back of the test person's legs. We also went into more detail and determined the rates for correct perception of the location and the direction of each of these patterns. The numbers are listed in table 6.3.

Feedback Patterns	**Rates of correct Perception**		
	Location & direction	Location	Direction
Front, upwards	100.0 %	100.0 %	100.0 %
Back, upwards	80.0 %	90.0 %	80.0 %
Front, downwards	100.0 %	100.0 %	100.0 %
Back, downwards	80.0 %	100.0 %	80.0 %
Average	90.0 %	97.5 %	90.0 %

Table 6.3: Perception of vibration on the legs under relaxed condition.

In order to find out at which stage the mistakes are made under cognitive load, we conducted another user study. Similar to the approach in the tests investigating the intuitiveness, participants received tactile feedback pattern 1 (front thigh, up), pattern 2 (front thigh, down), pattern 3 (back thigh, up), and pattern 4 (back thigh, down) described in chapter 5.1. After the perception the test subjects had to specify at which places the motors vibrated, whether several motors vibrated successively, and the direction of the pattern (up or down). The rest of the experimental setup was equal to the learnability user study before. The rates of correct perception of the patterns, and their location and direction, can be seen in table 6.3.

Feedback patterns mainly distinguished by location

During the learnability user study most participant stated that they distinguish the feedback patterns mainly by the location of the vibrations. They told us that they had problems to identify the direction of the vibration sequence. These statements are supported by the rates of correct perception shown in table 6.3 and table 6.4. The values for location were very high with 97.5 % and 95.5 %. In comparison to that, the values for direction were slightly lower with 90.0 % and 95.5 %.

Too much commonality leads to confoundation of rotational patterns

The theory that patterns are mainly distinguished by location would explain the confounding of rotational patterns RL and RR. These two patterns share the same starting point, namely $P_1^3(BMF)$, and include the same overall actuators, thus hardly bearing any difference.

Patterns FL and SL are perceived correctly but later mixed-up

The results in table 6.3 and table 6.4 also allow us to draw conclusions why participants confounded the patterns "stretch legs" and "flex legs". The results indicate that the location of stimuli is correctly perceived. This suggests that the patterns FL and SL are perceived as being different but are confounded during processing mechanisms in the brain.

Also, the fact that participants were standing upright may have further influenced our results. This might be one reason why RU, delivered either to the back or the front of thighs, was rather inexpressive and showed no clear trends to incite the users to stretch the legs. Further research will be needed to explore the possible effects of tactile feedback across the body while being in different body postures than standing upright.

Feedback Patterns	Rates of correct Perception		
	Whole pattern	Location	Direction
Front, upwards	88.0 %	94.0 %	94.0 %
Back, upwards	81.0 %	94.0 %	88.0 %
Front, downwards	94.0 %	94.0 %	100.0 %
Back, downwards	100.0 %	100.0 %	100.0 %
Average	90.8 %	95.5 %	95.5 %

Table 6.4: Perception of vibration on the legs under cognitive load (Wii Fit).

In addition, results showed that stimuli are localized equally accurate at the front and back side of the thighs. The identification rates for upward and downward direction of rabbit patterns were significantly lower.

Participants can discriminate patterns under cognitive load

Altogether, our results show that participants were able to reliably discriminate six patterns delivered to the upper body and four patterns delivered to the thighs during cognitively demanding tasks in the lab.

6.3.2 Choice of Shifting Patterns

Chose pattern WL2 and WR2 for shifting weight

In the course of this learnability user study we also had to decide which tactile feedback pattern would be best to make a person shift his weight to a certain side. We tested two different types of patterns. For the first type the vibration was consecutively running up the side of one leg and down on the side of the other leg. For the second type the running down was skipped. The patterns WL and WR showed identification rates above 94 % under both conditions (relaxed and cognitive load). As the identification rates for WL2 and WR2 were perfect (all 100 %), we decided in favor of these patterns. Another advantage of this choice is that less actuators are required to render feedback, which makes the system more lightweight.

6.3.3 Further Conclusions

New pattern for leaning forward

Due to the body anatomy and the fact that we did not attach actuators directly to the skin, the spine and sterna turned out to be less suited for delivering directional cues. Several participants pointed out that they always noticed vibration at the upper back and the belly but seldom at the lower back and the chest. Therefore we changed the pattern LF (upward rabbit at the back) and used the simultaneous pattern LF2 in our final user study. Pattern LF2 consists of two elementary pattern of type P_x^3 that are simultaneously vibrating at the shoulder blades:

Pattern LF2

PATTERN LF2:

Lean forward (2nd): 3 impulses at the back:

LF2 = $P^3(SLB) + P^3(SLB)$

New rotational Patterns

We further modified instructions for rotation to avoid that users confound patterns RL and RR by changing the starting point. The new pattern RL2, telling the user to turn left, starts and ends at the right side of the body. RR2, telling the user to turn right, starts and ends at the left side of the body. An illustration of these three new patterns can be seen in figure 6.5

Pattern RL2

PATTERN RL2:

Rotate left (2nd): 2 counterclockwise rotations starting at right side:

RL2 = $P_1^3(BRL) \rightarrow P_2^3(BMF) \rightarrow P_1^3(BLL) \rightarrow P_2^3(BMB) \rightarrow P_1^3(BRL) \rightarrow P_2^3(BMF) \rightarrow P_1^3(BLL) \rightarrow P_2^3(BMB) \rightarrow P_1^3(BRL)$

Pattern RR2:

Rotate right (2nd): 2 clockwise rotations starting at left side:

RR2 = $P_1^3(BLL) \rightarrow P_2^3(BMF) \rightarrow P_1^3(BRL) \rightarrow P_2^3(BMB) \rightarrow P_1^3(BLL) \rightarrow P_2^3(BMF) \rightarrow P_1^3(BRL) \rightarrow P_2^3(BMB) \rightarrow P_1^3(BLL)$

Pattern RR2

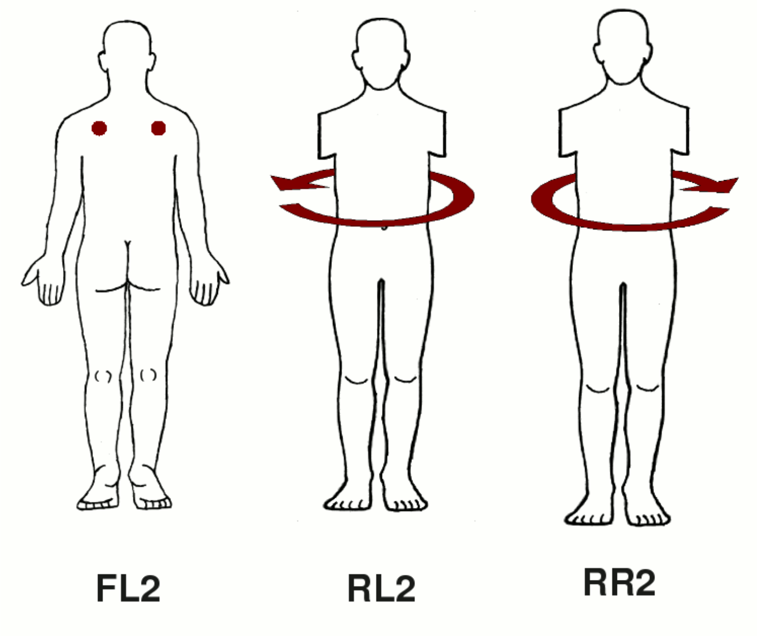


Figure 6.5: Three modified patterns for leaning forward (LF2), rotating left (RL2), and rotating right (RR2).

Chapter 7

Testing Patterns Under Realistic Conditions

Snowboarding is cognitively and physically demanding

Snowboarding is both cognitively and physically demanding. First of all, snowboarders have to pay attention to the environment to find an appropriate way on the slope without endangering themselves or others. The harsh environment and the exhausting physical stress during the ride often lead to cold limbs, pain, and muscular strains. These factors will probably influence the perception of tactile feedback patterns.

Test patterns under realistic conditions

All user studies conducted so far took place in lab environments like the Media Computing Lab at our chair. These environments do not support realistic conditions for snowboarding tests. Because of that, we conducted our final user study on a 520 m long slope at the indoor winter sports resort "SnowWorld" in Landgraaf.

Compare tactile and audio channel

Beside the effects of extreme physical activities, we also wanted to compare the identification rates of tactile feedback patterns with the rates of corresponding audio counterparts in order to find out how well they perform in comparison. Audio instructions are a common method for teaching motion skills and feel natural because of their daily use. Despite the promising results obtained in the second experiment, we expected that the recognition rate of tactile patterns would degrade considerably compared to the lab study on the Wii balance board.

As described in section 6.3.3 we noticed that the vibration delivered vertically along the spine and sterna were hardly perceivable. Therefore, we used the modified simultaneous pattern LF2 for our final user study. To investigate whether the discrimination of rotational patterns RL and RR delivered around the torso could be improved, we used the modified instructions RL2 and RR2.

We renamed patterns

In contrast to the lab study, where instructions were named as illustrated in the movement categories C1 to C4, we used a different verbal description for instructions delivered during the ride. Following Wulf [2007], we rephrased the audio instructions such that they guide the rider's attention to the movement effect. Wulf calls this "external focus". Snowboard trainers proposed expressions that they commonly use during snowboard lessons. The following list shows the new description of instructions delivered to a rider whose left foot points towards the riding direction:

- "Fries" (SL)
- "Burger" (BL)
- "Pressure towards the nose" (WL, LL)
- "Pressure towards the tail" (WR, LR)
- "Hello mountain" (RR)
- "Hello valley" (RL)

7.1 Users

Participants were recruited by email with the help of our university's sports center. Ten snowboarders, between the age of 23 and 28 years, took part in this experiment. Six of them were male and four female. All of the users were students from the RWTH. Everyone stated to practice snowboarding but at different levels of proficiency. In the questionnaire that was handed out after the test, participants could choose from five different levels: beginner, advanced beginner, advanced, proficient, and expert. Two participants rated their skills as advanced beginners (level 2), six as advanced (level 3), and two as proficient (level 4). Participants practiced snowboarding between one and three weeks per year during their holiday. One participant had previous experience with tactile feedback, as he took part in one of our previous user studies.

7.2 Setup and Task

The participants had to wear the cycling tights and the shirt we already used in our last user studies. Similar to the previous studies, we tested upper and lower body separately.

A second Nokia N70 mobile phone was used to record the answers given by the test person. Vibration motors were connected to the SensAct boxes, which were then put into a backpack the test person had to carry (see figure 7.1).

Figure 7.1: SensAct boxes in a backpack during our user studies in SnowWorld Landgraaf

Within-subject design

As mentioned before, we wanted to compare tactile with audio feedback. Therefore we chose a within-subjects design with two conditions for our final user study: tactile motion instructions and audio instructions played back over earplugs.

In order to collect enough data on the short slope, participants descended the slope four times for each condition. Two descents addressed the instruction set for the upper body. Two other descends tested the instruction set for the lower body. The order of conditions as well as the order of instruction sets were fully counterbalanced. In addition, the order in that instructions were triggered during each descent was randomized for every participant. A random delay of 5 to 10 seconds was chosen between consecutive instructions.

We gave the test persons a short introduction about the hardware setup and their task. Feedback patterns were triggered with full-strength vibration, for the same reason as in the learnability user study, described in chapter 6. The vibration strength could be reduced, if the participant asked for it, but practice showed us that vibration intensity could have been even stronger.

Participants were first familiarized with tactile instructions before descending the slope. Patterns were triggered by the instructor and repeated on request. After the training phase, we tested whether the subjects could remember the patterns. While descending the slope, participants had to say out aloud the instructions they were perceiving. For audio and tactile conditions, we used one Nokia N70 mobile phone to record the vocal responses using a microphone that was attached to the collar of the jacket. The first cellphone triggered tactile and audio feedback patterns and logged these triggered patterns for data analysis. The second phone recorded the answers given by the participant.

Use audio recordings for evaluation

The audio recordings were later used for evaluation. By comparing the audio recordings and the log files we could see whether the answers given by a test person were correct. After the test, people had to fill out a personal data form and provide information about how they assessed tactile and audio feedback delivered during the ride (see questionnaire in Appendix A).

7.3 Evaluation

In our final user study, audio instructions achieved higher identification rates than tactile feedback patterns. In the following paragraphs we will discuss the results in detail.

Near-perfect identification rates for audio instructions

As you can see in table 7.1, the identification accuracy for audio condition was near perfect. All instructions achieved values of over 96 %. The only outlier was "rotate right" with 92.6 %.

Feedback Patterns	**Identification Rate**	
	Tactile	Audio
Lean forward	100 %	100 %
Lean backward	82.1 %	100.0 %
Lean left	90.0 %	100.0 %
Lean right	92.6 %	96.2 %
Turn left	81.8 %	100.0 %
Turn right	71.4 %	92.6 %
Stretch legs	87.8 %	97.2 %
Flex legs	83.3 %	100.0 %
Shift weight to the left	95.0 %	100.0 %
Shift weight to the right	86.5 %	96.9 %

Table 7.1: Learnability of feedback patterns (audio and tactile) under real snowboarding conditions: Identification rates of correctly associated body posture adjustments.

High rates also for tactile feedback

Regarding the tactile condition, results revealed that the designed set of tactual feedback patterns can still be discriminated with high accuracy under real-world conditions. All recognition rates are clearly above chance level, which is 16.6 % for upper body patterns, and 25.0 % for lower body patterns. Applying a paired t-test on the measured identification rates revealed that there is no significant difference between male and female snowboarders and between the individual skill levels.

The modified tactile instruction LF2 representing "lean forward" achieved remarkable results. It was correctly recognized by all participants.

In contrast to LF2, LB ("lean backward") was not perceived in about 18 % of trials. Especially women had difficulties in perceiving this pattern, because the upper motors were situated above the cleavage, thus having no tight contact to the skin.

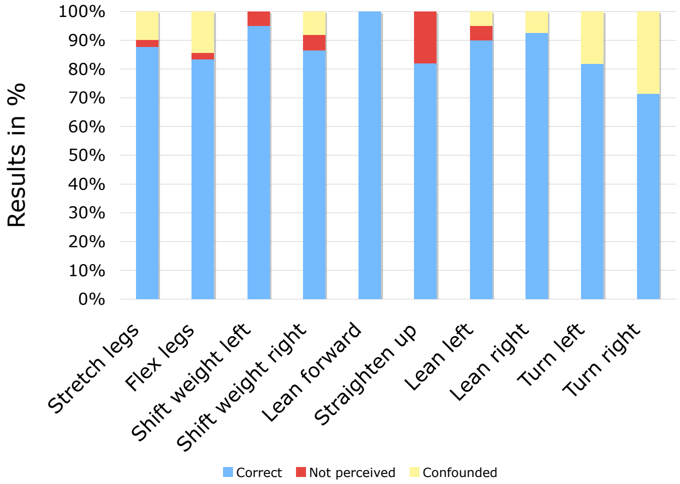


Figure 7.2: Percentage of patterns recognized while snowboarding.

Participants confounded contrary patterns

On closer examination of the causes of mistakes, it shows that participants missed only few cues delivered on the slope. Figure 7.2 reveals that participants generally tended to confound instructions with their counterparts.

Tactile pattern are discriminated by location

Similar to the results obtained in the user study that addressed the learnability of patterns under lab conditions, most participant stated during debriefing that they distinguished the feedback patterns mainly by the location of the vibrations. They told us that they had no problems to identify the location where feedback was delivered to the body, but had difficulties to determine the direction of the vibration sequence. To solve this problem, several participants suggested to increase the intensity level of the vibration because tactile feedback was rather weak, thus demanding more attention to identify direction. Another suggestion was to use more extensive stimulations across the whole body. For example, instead of punctual vibration, bands of vibration, i.e., several simultaneously vibrating motors arranged in a row or a big circle, could be used to design tactile feedback patterns.

Likert Ratings for audio instructions not relevantly better than for tactile patterns

As mentioned before, participants had to evaluate aspects like comfort, intuition, and incitement. Figure 7.3 shows the Likert scale ratings for the two conditions. In general, audio instructions achieved slightly better ratings. But a t-test showed that the differences—except the one for the difficulty of mapping patterns to posture corrections—are not statisticly significant. This indicates that tactile feedback did well in comparison to audio feedback.

Another conclusion that can be drawn from the Likert scale is that tactile feedback felt more subtle and less distracting. Some participants stated it was difficult to understand the audio instructions because of the interfering external noise. As tactile feedback uses touch and not sound as communication channel, external noise does not interfere with the recognition of tactile feedback patterns.

Push metaphor patterns also learnable by people preferring pull metaphor

We wanted to find out, whether our tactile feedback patterns could be learned by participants who intuitively preferred the pull metaphor. In fact, three participants stated that they actually preferred the pull metaphor. Like the rest of the participants, these three people achieved good results. Therefore this last study reveals that tactile motion instructions based on the push metaphor can be learned by people preferring the other metaphor.

Majority preferred audio

A direct comparison between the audio and tactile channel revealed a slight preference for audio instructions. Six participants voted for audio and four for tactile feedback. 75 % of the test persons preferring the tactile channel were female. In addition, snowboarders with little riding experience rather voted in favor of tactile patterns than snowboarders with more experience.

The better rating for audio feedback probably relates to the users' statement that the audio channel was easier to interpret. The mapping of audio instructions to movements

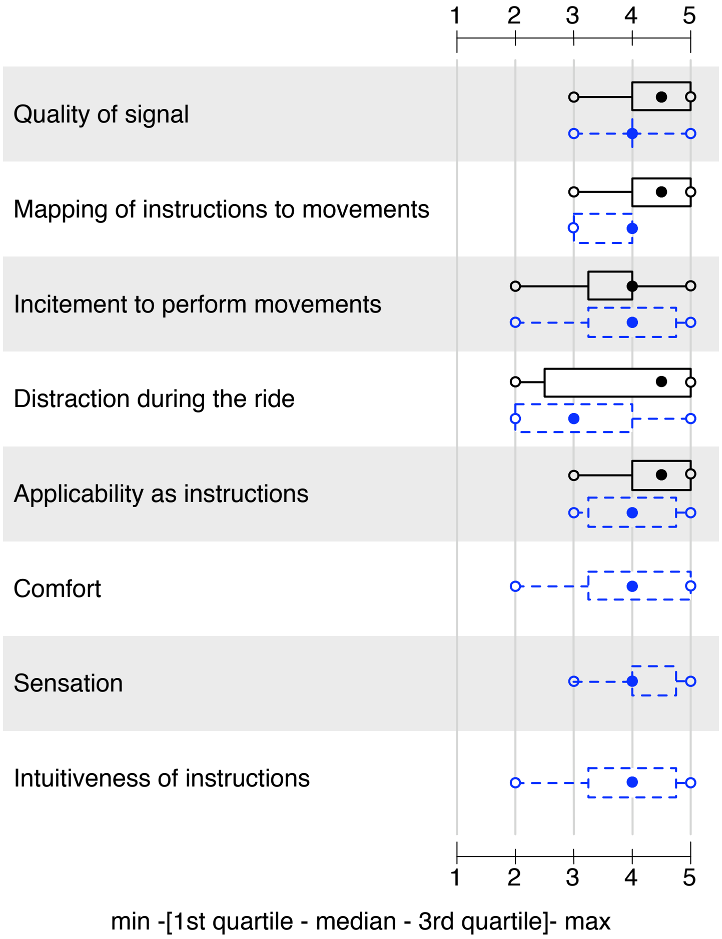


Figure 7.3: Results of post-test questionnaire for audio instructions (continuous line) and for tactile instructions (dashed line).

was less difficult, as they simply had to repeat the perceived audio message when giving answers during the ride. Tactile feedback patterns first need to be translated into words representing the patterns' meaning. As mentioned before, the rating for the difficulty of mapping patterns to posture corrections is the only one where audio feedback achieved significantly better results.

But participants also stated that they tended to perform the required action instead of answering verbally when perceiving tactile patterns. Tactile feedback might have the advantage that the user can directly react to it by performing movements. No translation of audio messages to movements is necessary.

Furthermore, participants received only brief training before descending the slope. More familiarization with the tactile feedback patterns could have increased the preference of the tactile channel.

All in all, results of our final user study under realistic conditions strongly suggest that tactile instructions can potentially be used to replace or to augment audio instructions during physical activities.

Chapter 8

Summary and Future Work

Tactile feedback is a mostly underused but promising alternative to the audio feedback channel. This thesis makes a contribution to tactile feedback research, as we designed tactile feedback patterns that indicate how to adjust body posture. Our goal is to link tactile feedback to sensor data in order to give realtime feedback while snowboarding.

In this last chapter we will summarize the results of our work and identify open challenges that should be solved in the near future.

8.1 Summary and Contributions

Background

At first, we introduced the somatosensory system and explained how this system is structured. We gave an overview of the different types of mechanoreceptors and explained the way they sense coutaneous stimulation.

Related work

Afterwards, we presented previous research work exploring the domains of tactile feedback, wearable computing, and design guidelines that were derived from different characteristics and limitations of the cutaneous sense.

Preliminary work

In chapter 4 the hardware setup is described. It also covers our preliminary tests, where we determined limits of vibration perception. We arrived at the conclusion to trigger tactile feedback patterns with maximal intensity and to reduce vibration strength, if participants asked for it.

First set of feedback patterns

We designed a first set of 26 tactile feedback patterns as candidates for communicating the following snowboard-related motion instructions:

Category C1: Stretch the legs (SL) vs. flex the legs (FL)

Category C2: Shift weight from the right to the left foot (WL) vs. shift the weight from the left to the right foot (WR)

Category C3: Lean upper body to the left (LL) vs. lean upper body to the right (LR)

Category C4: Rotate upper body to the left (RL) vs. rotate upper body to the right (RR)

Category C5: Lean upper body forward (LF) vs. lean backward or straighten up (LB)

Design guidelines applied to our pattern

Thereby, we followed several design guidelines. We use spacial location, inter-burst interval, burst duration, and relative order to encode information. As spatial location can be discriminated most reliably, we deliver feedback to the body part that needs to be adjusted, in this case the torso, the lateral shoulders, and the thighs. The direction of rabbit patterns indicates the direction in which the body part that has to be adjusted should be moved. We have defined the standard burst duration to be 100 ms and the standard inter-burst interval to be 50 ms, as these are optimal values to elicit the cutaneous saltation effect. Details are described in chapter 4.3.

From the first set of 26 tactile feedback patterns we picked ten that were best representing the motion instructions belonging to categories C1–C5. When choosing the patterns, we tried to avoid ambiguity and to establish consistency among all patterns. As some participants proposed modifications of patterns for shifting weight, we additionally designed the two alternative patterns WL2 and WR2.

Pattern improvement throughout several design cycles

Finally, we refined our tactile feedback patterns throughout several DIA cycles. We conducted a user study to investigate the learnability of our patterns and the influence of cognitive load on the identification performance. Results showed that our patterns are easy to learn, as they achieved identification rates above 90 % on both days (training as well as retention) and under both tested conditions (relaxed and cognitive load). Cognitive load did not considerably degrade the recognition accuracy of the designed patterns. The study proves that tactile feedback patterns are capable of triggering specific body posture corrections under cognitive and physical demanding conditions.

During the test, participants often confounded pattern RL (turn upper body left) with RR (turn upper body right) and pattern SL(stretch legs) with FL (flex legs). They explained that they distinguished the tactile feedback patterns mainly by the location of the vibrations and experienced problems with identifying the direction of vibration sequences. As a result, we designed the new patterns RL2 and RR2 for communicating rotation the upper body.

Test under realistic conditions

In our final user study that took place under realistic conditions on a slope at SnowWorld Landgraaf, we compared the identification rates of tactile feedback patterns with the rates of corresponding audio counterparts. We wanted to find out how well the tactile feedback patterns perform in comparison to audio instructions, which are a common method in teaching motion skills and feel natural because of their daily use.

Even under real-world conditions, tactual feedback patterns were discriminated with high accuracy. Nevertheless, audio instructions achieved higher identification rates, as participants tended to confound tactile instructions with their counterpart.

Ratings for audio not significantly better

Evaluation of the questionnaires revealed that audio instructions achieved slightly better ratings. Test subjects pointed out that the audio instructions were easier to map to body movements. Except for these interpretation problems, a t-test showed that the differences in ratings are not statisticly significant, thus indicating that tactile feedback performed quite well in comparison to audio feedback.

Participants preferred audio

Being asked which communication channel they favored, 60 % of the participants preferred audio feedback. But they also mentioned that they felt more incited to correct their body posture when receiving tactile feedback. So full-body tactile feedback has the potential to be an alternative or augmentation for audio instructions during physical activities.

Push metaphor patterns also learnable by people preferring pull metaphor

In the course of this thesis, we decided to use a "push" metaphor for designing our tactile feedback patterns. We were interested in finding out whether these patterns could be learned by users who intuitively preferred the pull metaphor. Therefore the positive results of the last study reveal that tactile motion instructions based on the push metaphor can be learned by people preferring the other metaphor.

8.2 Future Work

Link tactile feedback to sensor data

During our tests, participants criticized that tactile feedback patterns were given independently from the actual context. For the near future it is planned to couple tactile feedback with sensor data, so that people perceive the tactile feedback patterns in the right context.

Improve the perception of vibrating tactors

A big problem that arose in our user studies was that participants had problems in perceiving some of the vibrating actuators located at the torso. This was due to the shirt not tightly fitting the body. Especially the motors on the back (BMB) were problematic, as the spine lies within a shallow dent such that the actuators were not in close contact with the skin. Similar problems arose with the tactors placed on the chest. Female test subjects hardly felt the vibration, because the motors were situated above the cleavage. For future work, new ways of transferring vibration to the torso should be developed in order to improve the perception of vibrating tactors and thus the identification of tactile feedback patterns, e.g., straightening up.

Make the system more comfortable

Further hardware changes can make the system more comfortable. Reducing the wiring and decreasing the size of the

SensAct box are desirable refinements, resulting in an ease of donning and doffing and in less weight to carry.

Make SensAct box control more actuators

Perhaps individual parts of the platform have to be reconsidered and could be improved by using new lightweight technology. That way, the SensAct box could be modified to control more actuators so that only one SensAct box is needed for future test of our patterns.

Improve tactile feedback patterns

Despite the positive results, this project is far from being complete. Our tactile feedback patterns can still be improved. Further user studies should be conducted to reduce the possibility of confounding patterns and to ease their mapping to desired posture corrections.

Another promising approach is the design of basic patterns for tactile feedback. For example, single impulses could be considered as a basic element. These elements would then be tested systematically in large-scale studies to validate their effect on body posture. Later, larger patterns could be composed of these basic elements in a modular way. Unfortunately, we did not have enough time to further look at this approach.

Other application domains

In our work, we concentrated on snowboarding as the application domain. It would be reasonable and helpful for later research projects to test these patterns for other domains. In this context, new patterns could be designed that represent movements not covered by this thesis.

Methodical recommendations

For the user study in which we investigated how users naturally perceive and interpret our tactile feedback patterns, we used an open response paradigm. As participants could freely assign any meaning to the vibrations they perceived, answers often considerably varied across all subjects or could not be related to any particular motion. Moreover, it was not easy for us to remain unbiased when interpreting some of our participants' reactions and responses. Repeating the experiment with a forced-choice paradigm might help to resolve some of this ambiguity. Also, the fact that participants were standing upright may have further influenced our results. An actuator pulsing three times at the chest while leaning forward might be interpreted differently when standing upright. Further research will be needed to explore the possible effects of tactile feedback while being in different body postures.

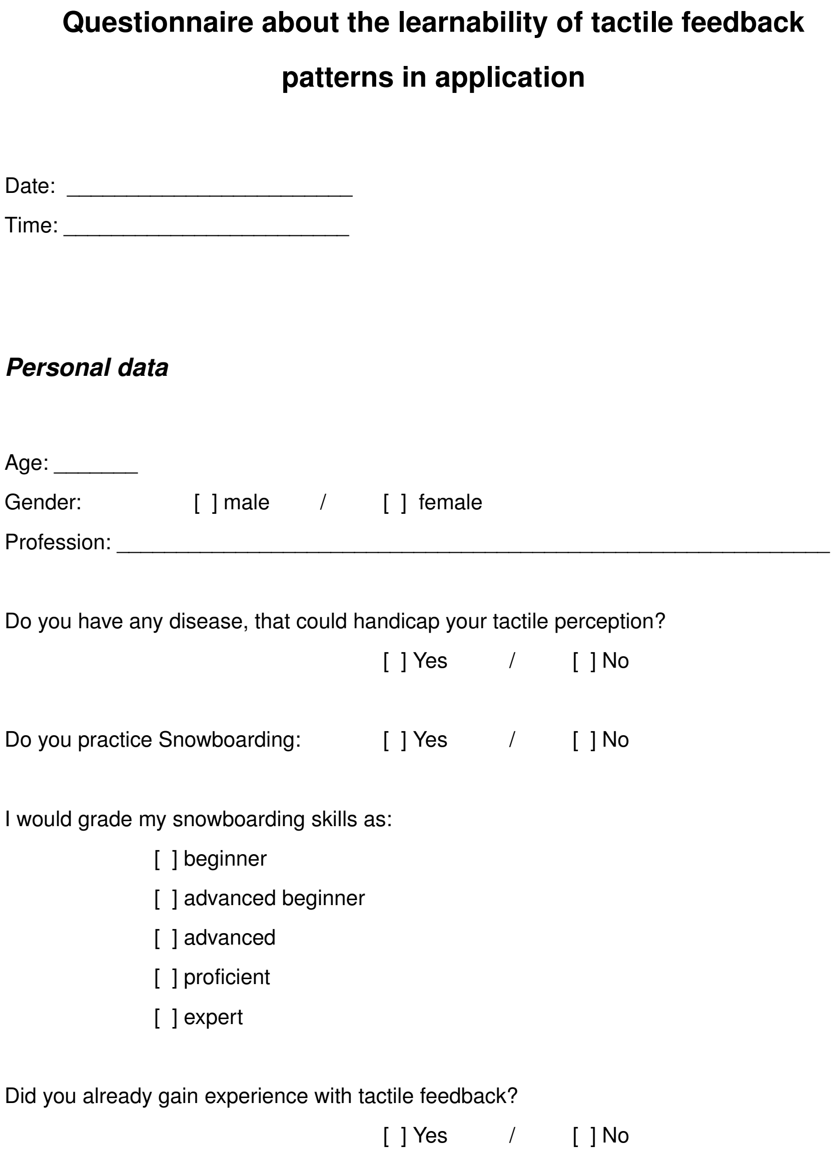
Test pull metaphor

As mentioned before, we decided to use a “push” metaphor for designing our tactile feedback patterns. Results of our last user study revealed that tactile motion instructions based on the push metaphor can be learned by people preferring the other metaphor. We assume that this constellation could be reversed. This means that testing pull metaphor patterns could probably yield similar results, also for participants that prefer the push metaphor. This would prove that tactile motion instructions can be based both on the push and the pull metaphor.

All in all, we proposed an interesting application of tactile feedback. In combination with the proposed refinements and enhancements, this might provide an opportunity to ease the learning of snowboard skills, to increase the usability of automatic training devices, and to create an expressive universal pattern language. We are curious about the future progress in the field of tactile feedback and looking forward to the first proper implementation of the Snowboard Assistant project.

Appendix A

Questionnaire for the User Study at SnowWorld Landgraaf



Questionnaire about the learnability of tactile feedback patterns in application

Date: ________________________
Time: ________________________

Personal data

Age: _______
Gender: [ ] male / [ ] female
Profession: ____

Do you have any disease, that could handicap your tactile perception?
[ ] Yes / [ ] No

Do you practice Snowboarding: [ ] Yes / [ ] No

I would grade my snowboarding skills as:
- [ ] beginner
- [ ] advanced beginner
- [ ] advanced
- [ ] proficient
- [ ] expert

Did you already gain experience with tactile feedback?
[ ] Yes / [ ] No

Figure A.1: Questionnaire for the final user study at SnowWorld Langraaf - page 1

Audio feedback

1.) I could understand the audio feedback during the ride (quality of audio):

[ ] Very Good
[ ] Good
[ ] Barely Acceptable
[ ] Poor
[ ] Very Poor

2.) I could map audio instructions to body movements:

[ ] Always
[ ] Very Often
[ ] Sometimes
[ ] Rarely
[ ] Never

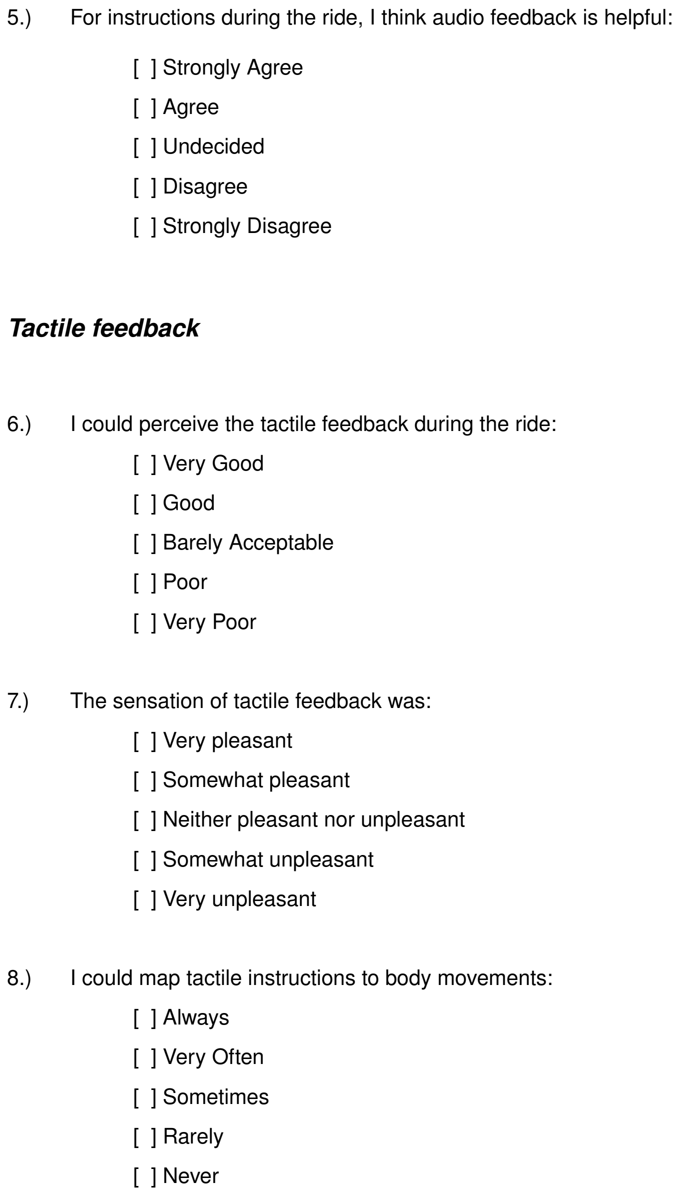
3.) Having perceived audio feedback, I felt incited to perform the movement:

[ ] Strongly Agree
[ ] Agree
[ ] Undecided
[ ] Disagree
[ ] Strongly Disagree

4.) Audio feedback distracts from focusing on riding:

[ ] Strongly Agree
[ ] Agree
[ ] Undecided
[ ] Disagree
[ ] Strongly Disagree

Figure A.2: Questionnaire for the final user study at SnowWorld Langraaf - page 2



5.) For instructions during the ride, I think audio feedback is helpful:

[ ] Strongly Agree
[ ] Agree
[ ] Undecided
[ ] Disagree
[ ] Strongly Disagree

Tactile feedback

6.) I could perceive the tactile feedback during the ride:

[ ] Very Good
[ ] Good
[ ] Barely Acceptable
[ ] Poor
[ ] Very Poor

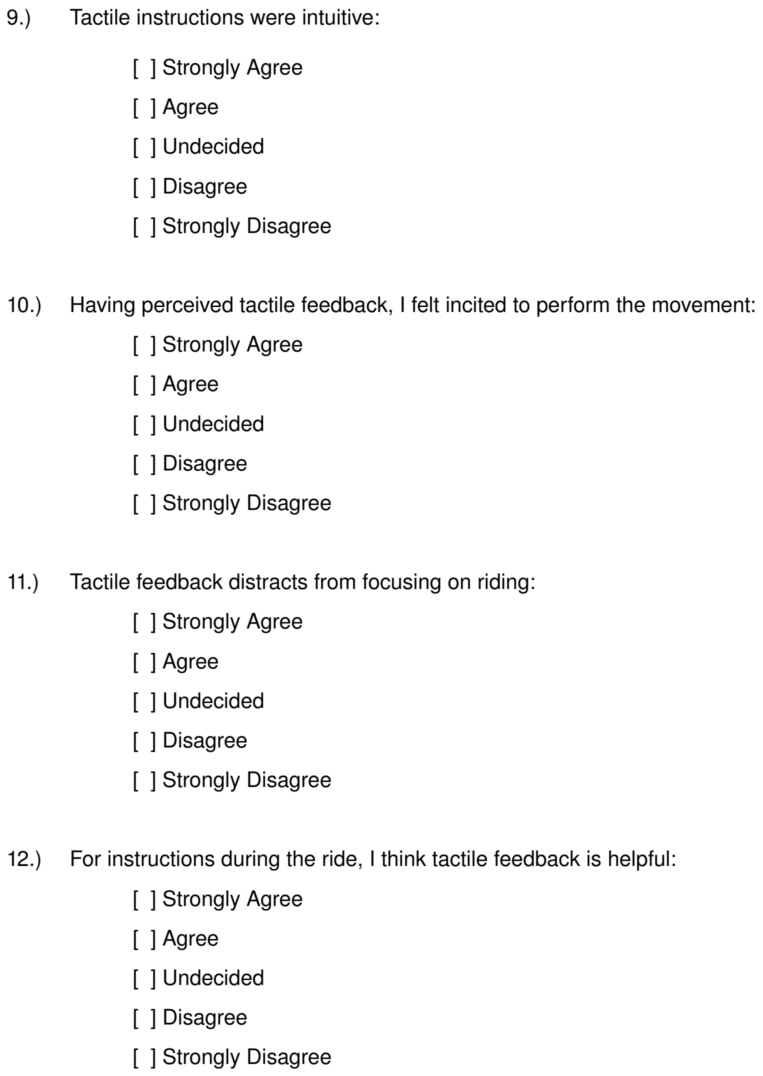
7.) The sensation of tactile feedback was:

[ ] Very pleasant
[ ] Somewhat pleasant
[ ] Neither pleasant nor unpleasant
[ ] Somewhat unpleasant
[ ] Very unpleasant

8.) I could map tactile instructions to body movements:

[ ] Always
[ ] Very Often
[ ] Sometimes
[ ] Rarely
[ ] Never

Figure A.3: Questionnaire for the final user study at SnowWorld Langraaf - page 3



9.) Tactile instructions were intuitive:

[ ] Strongly Agree
[ ] Agree
[ ] Undecided
[ ] Disagree
[ ] Strongly Disagree

10.) Having perceived tactile feedback, I felt incited to perform the movement:

[ ] Strongly Agree
[ ] Agree
[ ] Undecided
[ ] Disagree
[ ] Strongly Disagree

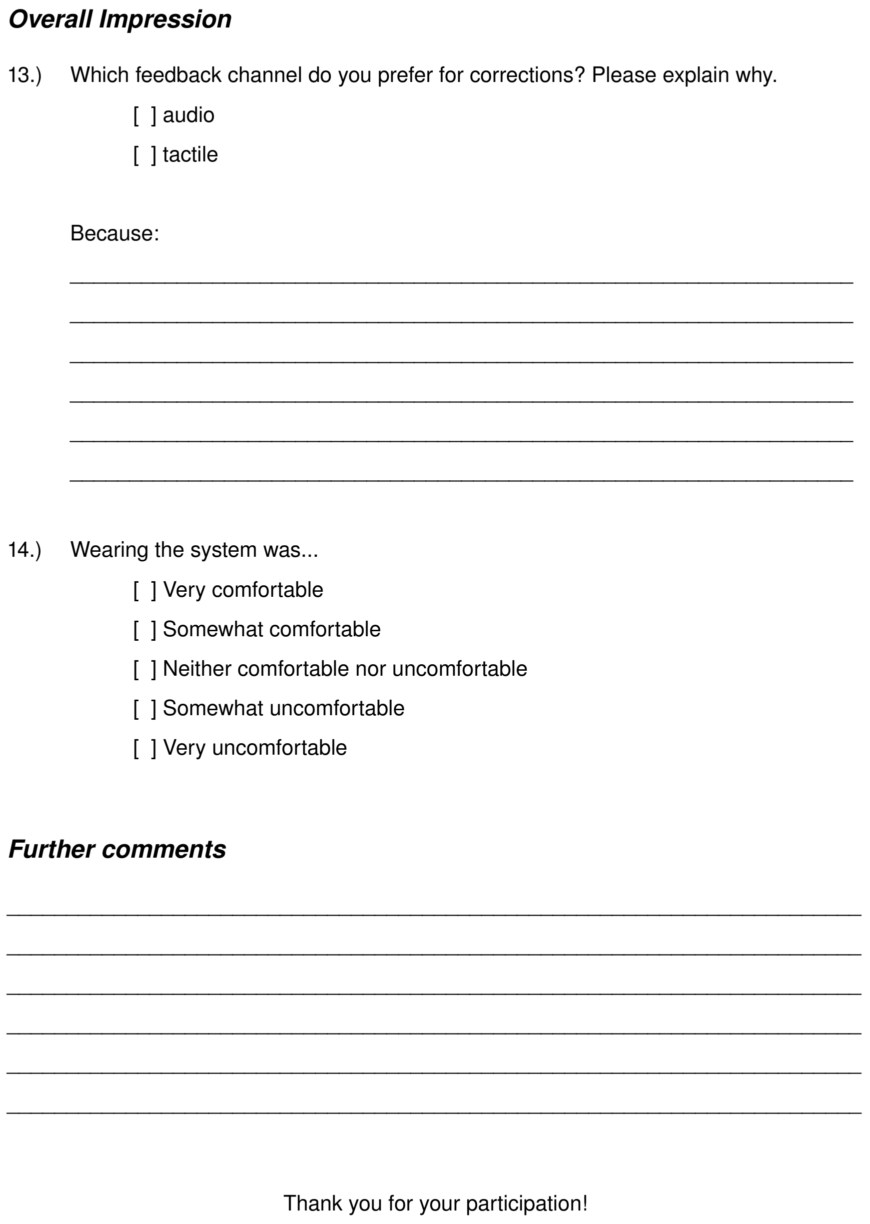
11.) Tactile feedback distracts from focusing on riding:

[ ] Strongly Agree
[ ] Agree
[ ] Undecided
[ ] Disagree
[ ] Strongly Disagree

12.) For instructions during the ride, I think tactile feedback is helpful:

[ ] Strongly Agree
[ ] Agree
[ ] Undecided
[ ] Disagree
[ ] Strongly Disagree

Figure A.4: Questionnaire for the final user study at SnowWorld Langraaf - page 4



Overall Impression

13.) Which feedback channel do you prefer for corrections? Please explain why.

[ ] audio
[ ] tactile

Because:

____

____

____

____

____

____

14.) Wearing the system was...

[ ] Very comfortable
[ ] Somewhat comfortable
[ ] Neither comfortable nor uncomfortable
[ ] Somewhat uncomfortable
[ ] Very uncomfortable

Further comments

____

____

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____

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____

Thank you for your participation!

Figure A.5: Questionnaire for the final user study at SnowWorld Langraaf - page 5

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Index

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