SOMATOSENSORY INTERACTION

INVESTIGATING MECHANORECEPTION, THERMOCEPTION, AND PROPRIOCEPTION FOR ON-BODY HAPTIC FEEDBACK

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ABSTRACT

Haptics are an important factor to make virtual worlds and remote interpersonal interaction tangible. While current technological advances, such as Virtual Reality (VR), are reaching the mass market, they are primarily visual while available haptic devices are mostly limited to vibrotactile stimuli, such as smartphone notifications or embedded in game controllers. However, haptic feedback consists of more components that make an experience physically perceivable and lifelike. In addition to the vibrotactile stimulation of fine mechanoreception, these also incorporate stronger forces addressing pressure-based mechanoreception, temperature perceived by thermoception, and body position and movement perceived by proprioception, which are all parts of the somatosensory system. Consequently, to get closer to a full haptic experience, haptics need to be considered in the broader context of the complete somatosensory system.

In this thesis, novel haptic concepts will be introduced and implemented in prototypical systems to investigate them in a series of user studies, leading to a better understanding of somatosensory interaction. In this context, this dissertation provides six major contributions: (1) The first contribution presents a systematic investigation of fine and subtle mechanoreception involving vibrotactile stimuli on the hand for guidance and target acquisition. (2) The second contribution investigates more intense and pressure-based mechanoreception that employs pneumatically actuated air cushions to create immediate pressure sensations. (3) The third contribution on mechanoreception combines the findings of the previous two contributions and explores moving touches and stroke stimuli on the body, as well as their roughness perception in VR. (4) The fourth contribution addresses thermoception where the effects of cold and warm temperatures on the body are investigated within a VR environment. (5) The fifth contribution focuses on proprioception and kinesthesia and examines concepts for kinesthetic actuations that can evoke flexion and extension of body joints. (6) In a further contribution, a novel rapid prototyping platform is presented that considers the specific requirements for haptic actuations of the somatosensory system.

ZUSAMMENFASSUNG

Haptik ist ein wichtiger Bestandteil, um virtuelle Welten und zwischenmenschliche Interaktion auf Distanz greifbar zu machen. Während aktuelle technologische Fortschritte wie Virtual Reality (VR) den Massenmarkt erreichen, sind sie in erster Linie visuell und verfügbare haptische Geräte meist auf vibrotaktile Stimuli beschränkt, z.B. durch Smartphone-Benachrichtigungen oder eingebettet in Game-Controller. Haptik besteht jedoch aus wesentlich mehr Aspekten, die ein Erlebnis erst physisch wahrnehmbar und lebensecht machen. Zusätzlich zur vibrotaktilen Stimulation der Feinmechanorezeption beinhaltet dies auch stärkere Kräfte, die die druckbasierte Mechanorezeption ansprechen, die Temperaturempfindung durch Thermorezeption und die Erfassung der Körperposition und -bewegung durch Propriozeption, welche alle zum somatosensorischen System gehören. Um daher einer umfassenden haptischen Erfahrung näher zu kommen, muss Haptik im breiteren Kontext des gesamten somatosensorischen Systems betrachtet werden.

In dieser Arbeit werden dazu neuartige haptische Konzepte vorgestellt und in Prototypen implementiert, um sie in systematischen Nutzerstudien für ein besseres Verständnis der somatosensorischen Interaktion zu untersuchen. In diesem Kontext leistet diese Dissertation sechs wesentliche Beiträge: (1) Der erste Beitrag stellt eine systematische Untersuchung der Feinmechanorezeption mit vibratotaktilen Reizen an der Hand für Guidance vor. (2) Der zweite Beitrag adressiert druckbasierte Mechanorezeption, bei der pneumatisch betätigte Luftkissen eingesetzt werden. (3) Der dritte Beitrag zur Mechanorezeption kombiniert die Erkenntnisse der beiden vorherigen Kapitel und untersucht Streichelreize am Körper sowie deren Wahrnehmung in Bezug auf ihre Rauheit. (4) Der vierte Beitrag behandelt die Thermozeption, indem Einflüsse von kalten und warmen Reizen in VR untersucht werden. (5) Der fünfte Beitrag widmet sich der Propriozeption und untersucht Konzepte für kinästhetische Aktuierungen, die eine Beugung und Streckung von Körperteilen auslösen. (6) In einem weiteren Beitrag wird zudem eine Rapid-Prototyping-Plattform eingeführt, welche die spezifischen Anforderungen haptischer Aktuierung für die somatosensorische Interaktion berücksichtigt.

ACKNOWLEDGMENTS

If the technology you do isn't fun for you,
you may wish to seek other employment.
Without the fun, none of us would go on.

— I. Sutherland, 1996 [Sut96]

Besides technology, which has to be fun, something is only as good as the people who have accompanied you throughout such a long time. And I am grateful to have the best friends and colleagues who made it all so much enjoyable for me.

First of all, I would like to thank my doctoral supervisor, mentor, and supporter Prof. Max Mühlhäuser, who has encouraged and challenged me through all the ups and downs over the years. I could always rely on his great talent to engage with even the most insane ideas and, even in the most difficult situations, he always had my back. My humble thanks for everything! Further, I am very grateful for Prof. El Saddik who acted as my second reviewer and contributed so much inspiring work in the field of haptics. Also, many thanks to the other members of the committee, Prof. Hollick, Prof. Mezini, and Prof. Kuijper.

That being said, I would like to thank all the phenomenal people of TK and TEAMDARMSTADT, namely my long-time fellow Flo, Andrii, Martin, Domi, Jan, Karo, Hesham, Julius, Thomas, Markus, Mo, Niloo, Max-Elke, and Budget-Elke. Of course, this also includes the many wonderful students I had the pleasure to meet over the years. Particularly, thanks to Daniel, Julian, Mohit, Jan, Tamara, Simone, Marco, Megan, Felix H., Flo, and Omar. Further, thanks to all participants who volunteered to take part in the many studies that were conducted during the years.

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CONTENTS

Part I

INTRODUCTION AND BACKGROUND

1 INTRODUCTION AND MOTIVATION

We live in a time of rapid changes where we all experience an accelerating digitalization, not only shaping our everyday lives, but also becoming more accessible to all age groups, backgrounds, and levels of expertise. From microcomputers carried in our pockets like smartphones, over digitized government processes, all the way to location-independent businesses thanks to remote attendance. Taking a particular look at the last two years, the COVID-19 pandemic certainly boosted this development, and while many innovations were previously only of interest to technology enthusiasts, now even "our" non-tech-savvy parents, the artisan around the corner, or the neighbor's school children are becoming steadily more experienced with modern technology. Probably everyone had at least some opportunity or even obligation to meet online, e.g., through videoconferencing or basic online chats. But even beyond that, new interactive technologies continue to gain popularity, such as Augmented- and Virtual Reality (AR/VR), that are not limited to a "flat" representation of a video and try to immerse people in virtual worlds.

Whether for pure entertainment, vivid simulations, 3D-based meeting environments, or engaging in safe online learning spaces, AR/VR can be used in the living room at home, in professional training centers, or spontaneously with a mobile device in order to facilitate digitization of the surroundings or to dive into virtual worlds. Often, this success is attributed to modern AR/VR devices, such as the HTC Vive or the Microsoft Hololens, that made such a commercial breakthrough for AR/VR possible. However, these advancements are still mostly of visual nature and providing haptic stimuli to convey physical and tangible properties in a lifelike way for these virtual environments remain less accessible and available.

1.1 TOWARDS THE ULTIMATE DISPLAY

But what does *haptic* mean? The term *haptics*[1] hereby was first introduced by the German physiologist Max Dessoir in 1892 [Des92], to be used as an umbrella term for research on touch, similarly as optics stands for visual and acoustics for auditory research. Thus, it stands for how humans perceive the world by touch and "refers to the science of manual sensing and manipulation of surrounding objects and environments through the sense of touch" (El Saddik, 2007, [El 07], p. 10).

Also, haptics for Virtual Reality (VR) is not a recent idea and goes back much further, even present in pop culture for decades. For example, in 1982's sci-fi spectacle *Tron*[2], in which an entire conscious society exists in a virtual world, in 1992's science-fiction horror *Lawnmower Man*[3], in which a man develops supernatural abilities as a result of psychoactive substances taken while being in VR, or in 1994's *Aerosmith* music video to their song *Amazing*[4], in which the protagonist falls in love within a lifelike virtual experience. Dating back even further, in 1962, Morton Heilig presented the first VR device that could depict simple 3D visualizations, the so-called Sensorama [Hei62] that was also one of the first devices able to provide basic haptic stimuli to appeal to multiple senses, such as vibrations, odors, and wind [Hei62].

Though, why are pure visuals often not enough for an immersive experience, and haptic stimuli important? To answer these questions, we can take a look at the year 1965 to an early vision of Ivan Sutherland, a pioneer of Human-Computer Interaction (HCI) and VR. Here, Sutherland presented the idea of modern pervasive computer systems that would fully involve users and can present them with a lifelike *Virtuality*: he called it the ULTIMATE DISPLAY [Sut65]. This display, however, is not only a technical device to depict virtual contents visually, it has to be also seen as a completely immersive environment that renders visual, auditive, and haptic features as realistic and convincing as possible. Sutherland described it as follows:

1 Original German quote: "Ich erlaube mir, hierfür das Wort *Haptik* in Vorschlag zu bringen, das im Anschluss an Optik und Akustik gebildet [..] ist." (Max Dessoir, 1892, p. 242, [Des92]). Freely translated: "I would like to allow myself to suggest the word *haptic* that is formed in accordance with optics and acoustics."

2 `https://www.imdb.com/title/tt0084827/` (accessed March 01, 2022)

3 `https://www.imdb.com/title/tt0104692/` (accessed March 01, 2022)

4 `https://www.youtube.com/watch?v=zSmOvYzSeaQ` (accessed March 01, 2022)

> *"The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in.* [..] *such a display could literally be the Wonderland into which Alice walked."*
>
> Ivan Sutherland, 1965 [Sut65]

Yet, to achieve this vision of a persuasive virtual experience, it is necessary to find possibilities that can replicate his conception of the *existence of matter* [Sut65]. Visuals, therefore, are undoubtedly important and research has shown that *seeing* is one of the most dominant human senses. But, while it can even contribute to haptic expectations before and upon contact [YT15; Sun+16; EB02; LK04], there is still a lack of the actual tactile sensation of how something or even someone feels that cannot be conveyed just by visuals [Rob06]. For example, in 1986, another HCI pioneer, William Buxton, described it so dramatically that if a future civilization were to find the remnants of human developments, it would probably describe us as beings in which "the dominating characteristic would be the prevalence of our visual system" (Buxton [Bux86], p. 1) based on the strong focus on visual output of computer systems. Of course, much has happened in the field of haptics since the 1980s, and Buxton's example was meant to emphasize the importance of sophisticated input methods, but it already gave a notion of how much the interaction was and still is centered around visuals.

But what did happen in the past years and how close did we come towards the *ultimate display*? In a 2019 article, the AR/VR enthusiast Bob Stone stated that "we are decades away from achieving a wearable-free realistic multisensory interactive environment of the sort depicted on Star Trek" (Bob Stone, 2019 [Sto19]). This statement is indeed provoking as there are undoubted many great contributions in the field of haptics from the last years as highlighted in the related work sections of this thesis document, and also the very big tech companies working intensively on novel haptic devices for their VR experiences, such as the Metaverse[5]. However, the statement is also fairly accurate, as experiences like the Star Trek Holodeck[6], which is more or less an exact implementation of the *ultimate display*, continues to be science-fiction, not the current state-of-the-art.

5 https://tech.fb.com/inside-reality-labs-meet-the-team-thats-bringing-touch-to-the-digital-world/ (accessed March 01, 2022)
6 https://en.wikipedia.org/wiki/Holodeck (accessed March 01, 2022)

1.2 SOMATOSENSORY INTERACTION

This thesis systematically addresses on-body haptic feedback with regards to the different modalities of haptic perception, namely FINE MECHANORECEPTION, MECHANORECEPTION, THERMOCEPTION, PROPRIOCEPTION, and KINESTHESIA. Therefore, possibilities of providing haptic stimuli, interaction concepts, and new haptic techniques were systematically investigated in order to come closer to Sutherland's vision [Sut65] and to add to the body of haptic research. Therefore, it is also important to understand that haptics are not just the sensation of touch and neither is touch just another single sense. Rather, touch and haptics have to be seen as the composition of individual sensory input and perceptions that detect physical contact, temperature, deformation, pressure, pain, stroking, and other tactile stimuli. Additionally, in combination with the awareness of body position and movement, all these individual sensations are part of the so-called SOMATOSENSORY SYSTEM [Dou97; DBD20] (see also Section 2.2).

In this context, this thesis contributes a holistic view of haptic feedback and touch for FINE MECHANORECEPTION, MECHANORECEPTION, THERMOCEPTION, PROPRIOCEPTION, and KINESTHESIA, leading to a SOMATOSENSORY INTERACTION:

> **Definition: Somatosensory Interaction**
>
> Somatosensory Interaction encompasses the interaction with the haptic perception of subtle and pressure-based tactile touch, temperature, movement, and body position, sensed through MECHANORECEPTION, THERMOCEPTION, and PROPRIOCEPTION.

1.3 RESEARCH CHALLENGES

In order to address SOMATOSENSORY INTERACTION and to get closer to the vision of an *ultimate display*, the following challenges arise:

RECREATION OF HAPTIC STIMULI Before a haptic stimulus and the effects on the respective perception can be investigated, appropriate stimuli have to be generated technically and logically. In this process, it is particularly essential that such stimuli are not just a simple artificial imitation, but are designed to be as realistic and accurate as possible. For example, a subtle touch must not be too forceful, while a pressure-based touch cannot be too soft. A thermal stimulus of 40 °C may not suddenly become a temperature of 50 °C. And an actively caused movement of body parts cannot suddenly be pointed in the opposite direction. In other words, for each modality, it is vital to replicate precisely those factors that will ensure a true and fitting sensation.

SUITABLE INTERACTION CONCEPTS Each modality is part of the overall haptic perception, however, each comes with its advantages and disadvantages that apply to different interaction concepts. One challenge addressed by this work is to discover appropriate interaction concepts that convey (digital) information in a meaningful way based on the addressed perception. For example, the benefits of vibrotactile feedback for navigation purposes or notifications have been demonstrated in the past. However, for a realistic pressure sensation, vibrotactile stimuli are less suitable. Temperature changes, in contrast, should be centered on interaction concepts, where a very fast and spatially precise response is not essential, since the perception of temperature is rather slow and harder to pinpoint.

INDIVIDUAL CHALLENGES FOR EACH MODALITY In addition to the interaction concepts, each modality also carries unique challenges that pertain only to their specific perceptions. These challenges have to be addressed individually for each modality and arise primarily from the physiological and psychological characteristics as well as from the technical properties. In this thesis, the chapters address further challenges that go beyond the mere replication of a haptic stimulus. For example, the thesis investigated the relationship between thermal and visual stimuli, or how vibrotactile guidance can be transferred to remote assistance tasks. Moreover, each chapter explored novel methods for haptic interaction and how the perception of haptic stimuli can be adjusted to circumvent technical limitations.

1.4 CONTRIBUTIONS

This thesis contributes with concepts and systematic investigations on haptics related to the somatosensory system from an HCI perspective. After a detailed overview of the physiological mechanisms of somatosensory perception, the individual parts address the specific aspects of (1) Fine Mechanoreception, Pressure-based Mechanoreception, and the combination of both for a stroking sensation, (2) Thermoception, and (3) Proprioception and Kinesthesia (see Table 1.1). For each of them, the respective chapters introduce interaction concepts, prototypical implementations, and the results of user studies. In an additional chapter, this work also contributes (4) a rapid prototyping platform for creating haptic actuation devices, called ActuBoard. In detail, the contributions are as follows:

1. The first contribution focuses on the Mechanoreception in three parts. First, Fine Mechanoreception in the form of vibrotactile stimuli is examined. The interaction concepts presented in this chapter focus on the ability to perceive subtle vibrations on the hand for guidance. Using a prototypical glove with vibration actuators, called TactileGlove, different guidance cues and metaphors have been investigated for target acquisition and remote assistance tasks.

   The following sub-chapter contributes by examining Pressure-based Mechanoreception. The interaction concepts presented there introduce novel ways to achieve a more intense contact of externally applied forces through a pneumatic actuation on the body. Based on these concepts, a prototypical system was designed, called PneumoVolley, in order to investigate the potential of pressure-based feedback on the head for creating a more enjoyable and realistic experience in VR.

   The last sub-chapter in the area of Mechanoreception addresses a combination of subtle and pressure-based actuations. In this context, concepts are introduced to render moving touches or strokes on the body authentically. In particular, this chapter focuses on the perception of roughness and how well users perceive such haptic stimuli in a VR environment when displayed visualizations do not necessarily match the haptic expectations.

2. The second part contributes novel concepts and investigations on Thermoception. Thereby, interaction concepts to achieve an effective thermal stimulation on the body are introduced, referred to as Therminator. Using liquids with different temperatures in a closed cycle allows for providing a thermal actuation. Similar to the previous chapter, a particular focus of this contribution was the adjustment of the Thermoception by presenting different visualizations in a VR environment that did not necessarily match the thermal stimuli.

3. The third part contributes with methods of kinesthetic actuation for an immersive stimulation of Proprioception and Kinesthesia. Therefore, two concepts are introduced, referred to as PneumAct, which can contract or extend body parts at their joints through two types of pneumatic actuators based on the concepts and findings of the Pressure-based Mechanoreception chapter.

4. While the aforementioned contributions focus on the interaction with parts of the somatosensory system, another contribution of this thesis is a rapid prototyping platform for the development of haptic devices, called ActuBoard. The platform is based on the requirements of the different prototypes created in the context of this thesis and on devices from related work providing haptic feedback in HCI. It allows experienced and non-tech-savvy users to quickly design prototypes and operate actuators for haptic feedback on both, the hardware and software side. Further, it was published as an open-source to support the community.

Summarizing, this thesis investigates the effects of haptic actuation addressing the somatosensory system and their perception during different scenarios. Based on the findings, the proposed interaction concepts and techniques introduce novel methods to create haptic actuation to provide realistic illusions of physical contact. In addition, a prototyping platform based on the work of this thesis was designed and developed for controlling the required hardware actuators of haptic devices. Table 1.1 gives an additional overview of all chapters and contributions.

	Chapter 4 Fine and Subtle Mechanoreception	Chapter 5 Pressure-based Mechanoreception	Chapter 6 Combined Mechanoreception	Chapter 7 Thermoception	Chapter 8 Proprioception and Kinesthesia
Modality					
Fine and Subtle Mechanoreception	✓		✓		
Pressure-based Mechanoreception		✓	✓		✓
Thermoception				✓	
Proprioception and Kinesthesia					✓
Sub-Modalities	Vibration	Pressure	Vibration, Pressure	Warm, Cold	Dynamic Forces, Static Forces
Body Parts					
Head		✓			
Arms			✓	✓	✓
Hands	✓				
Abdomen				✓	
Upper Body		✓		✓	
Haptic Technologies	Vibrotactile Actuators	Pneumatic Actuators	Pneumatic and Vibrotactile Actuators	Liquid-based Actuators	Pneumatic Actuators and Muscles
Test Environment					
Virtual Reality		✓	✓	✓	✓
Augmented Reality	✓				
Analogue World	✓				✓
Publications	[Gün+18b] [Gün+18a]	[Gün+20b] [Gün+19]	[Gün+22]	[Gün+20a]	[Gün+19]

Table 1.1: Overview of the chapters that are investigating different aspects of the somatosensory system and introducing different sets of haptic concepts and technologies (excluding ActuBoard).

1.5 PUBLICATIONS

The aforementioned contributions of this thesis have been peer-reviewed and published at internationally renowned conferences. Therefore, some contents of this thesis might contain verbatim parts of the respective publications which are outlined at the beginning of each related chapter. As an overview, the chapters are based on the following seven publications:

Chapter 4 - Mechanoreception I is based on the publications

> Sebastian Günther, Florian Müller, Markus Funk, Jan Kirchner, Niloofar Dezfuli, and Max Mühlhäuser. "TactileGlove: Assistive Spatial Guidance in 3D Space through Vibrotactile Navigation." In: *Proceedings of the 11th PErvasive Technologies Related to Assistive Environments Conference*. New York, NY, USA: ACM, June 2018, pp. 273–280. ISBN: 9781450363907. DOI:

10.1145/3197768.3197785
Sebastian Günther, Sven Kratz, Daniel Avrahami, and Max Mühlhäuser. "Exploring Audio, Visual, and Tactile Cues for Synchronous Remote Assistance." In: *Proceedings of the 11th PErvasive Technologies Related to Assistive Environments Conference*. New York, NY, USA: ACM, June 2018, pp. 339–344. ISBN: 9781450363907. DOI: 10.1145/3197768.3201568

Chapter 5 - Mechanoreception II is based on the publications

Sebastian Günther, Dominik Schön, Florian Müller, Max Mühlhäuser, and Martin Schmitz. "PneumoVolley: Pressure-based Haptic Feedback on the Head through Pneumatic Actuation." In: *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (*CHI EA '20*). New York, NY, USA: ACM, Apr. 2020, pp. 1–10. ISBN: 9781450368193. DOI: 10.1145/3334480.3382916
Sebastian Günther, Mohit Makhija, Florian Müller, Dominik Schön, Max Mühlhäuser, and Markus Funk. "PneumAct: Pneumatic Kinesthetic Actuation of Body Joints in Virtual Reality Environments." In: *Proceedings of the 2019 on Designing Interactive Systems Conference*. New York, NY, USA: ACM, June 2019, pp. 227–240. ISBN: 9781450358507. DOI: 10.1145/3322276.3322302

Chapter 6 - Mechanoreception III is based on the publication

Sebastian Günther, Julian Rasch, Dominik Schön, Florian Müller, Martin Schmitz, Jan Riemann, Andrii Matviienko, and Max Mühlhäuser. "Smooth as Steel Wool: Effects of Visual Stimuli on the Haptic Perception of Roughness in Virtual Reality." In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (*CHI '22*). New York, NY, USA: ACM, Apr. 2022. ISBN: 978-1-4503-9157-3/22/04. DOI: 10.1145/3491102.3517454

Chapter 7 - Thermoception is based on the publication

Sebastian Günther, Florian Müller, Dominik Schön, Omar Elmoghazy, Max Mühlhäuser, and Martin Schmitz. "Therminator: Understanding the Interdependency of Visual and On-Body Thermal Feedback in Virtual Reality." In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (*CHI '20*). New York, NY, USA: ACM, Apr. 2020, pp. 1–14. ISBN: 9781450367080. DOI: 10.1145/3313831.3376195

Chapter 8 - Proprioception and Kinesthesia is based on the publication

Sebastian Günther, Mohit Makhija, Florian Müller, Dominik Schön, Max Mühlhäuser, and Markus Funk. "PneumAct: Pneumatic Kinesthetic Actuation of Body Joints in Virtual Reality Environments." In: *Proceedings of the 2019 on Designing Interactive Systems Conference*. New York, NY, USA: ACM, June 2019, pp. 227–240. ISBN: 9781450358507. DOI: 10.1145/3322276.3322302

Chapter 9 - ActuBoard is based on the publication

Sebastian Günther, Florian Müller, Felix Hübner, Max Mühlhäuser, and Andrii Matviienko. “ActuBoard: An Open Rapid Prototyping Platform to integrate Hardware Actuators in Remote Applications.” In: *Companion Proceedings of the 13th ACM SIGCHI Symposium on Engineering Interactive Computing Systems*. EICS ’21 Companion. New York, NY, USA: Association for Computing Machinery, 2021. DOI: 10.1145/3459926.3464757

In total, I have contributed to more than 35 publications[7] as first- and co-author. A complete overview can be found in the List of Publications at the end of this thesis document.

1.6 RESEARCH METHODOLOGY

In the course of this thesis, a total of eight user studies were conducted, investigating the concepts introduced with regard to different factors, such as the efficiency of users in performing a task, the immersion or presence in VR, or the dependencies of different stimuli. All experimental and study designs and their analyses followed accepted standards in HCI [LFH17]. During the studies, substantial amounts of quantitative data and qualitative feedback were collected and analyzed accordingly. Therefore, common analyses and statistical methods in Human-Computer Interaction (HCI) were used [RK16; LFH17]. In addition, qualitative feedback from users was gathered in the form of interviews and questionnaires in order to better interpret and understand the outcomes of the statistical analyses [CS08][8].

In the next subsections, an overview of the study designs, data analysis procedures, and reporting methods that were used is given. In addition, the respective methodology sections of each user study include more specific and in-depth explanations of the applied methods.

7 As of March 15, 2022.
8 For the interested reader, the following literature on common research methods in HCI is suggested by the author of this thesis: [LFH17; RK16; CS08; Elk+21]

1.6.1 *Study Design*

In HCI different study designs are possible, depending on the field of application. In this work, mainly CONTROLLED EXPERIMENTS were performed. These experiments are conducted in a carefully designed and controlled environment in which external factors that could influence the experiments are kept to a strict minimum. Therefore, one or more independent variable (IV) are clearly defined prior to the experiment, and care is taken that only one parameter is influenced at a time for each factor and variable.

The number of combinations of all factors from each IV then results in the study conditions. However, since order- or carry-over effects quickly occur when conditions are ordered identically for each participant, the order must be balanced to avoid, for example, influences on the results by just having participants that are getting better over time. In studies with few conditions, a BALANCED-LATIN SQUARE design is recommended [Wil49; Bra58], in which each condition is followed exactly n times by another condition. In addition, each position in the experimental order is taken exactly n times for each condition.

For the dependent variable (DV), the studies have relied on various performance metrics, such as the Task Completion Time (TCT) or the deviation distance to a target, and user assessments through established questionnaires, such as the *NASA Task Load Index* (*NASA TLX*) [HS88; Har06] or *Witmer-Singer presence questionnaire* [WS98]. An overview of those types of measurement is given in the following:

PERFORMANCE MEASUREMENTS If applicable, the performance of participants or a system was measured directly. For example, this was the Task Completion Time (TCT) a participant needed, the number of errors that participants did, the angle between body parts after an actuation, or the temperature of a system.

QUESTIONNAIRES AND LIKERT SCALES In some cases, the performance of participants or a system could not be measured directly through, for example, external tracking. Therefore, quantitative data and feedback had to be collected through questionnaires containing various scales and ratings that assessed different metrics, such as subjective enjoyment, realism, or perceived temperature. Typically, such scales have 5 or 7 ordinal, but not necessarily continuous, options that range, for example, from statements like *enjoyed the experience very much* to *did not enjoy the experience at all*. A special case of such scales are Likert scales[9] where the values are based on the agreement with a given statement, such as *strongly agree* to *strongly disagree* [Lik32; JM71; WUN12]. All questionnaires and scales that were used in the user studies of this work followed common guidelines in HCI or are based on established questionnaires, such as the Witmer-Singer presence questionnaire [WS98].

NASA TLX A special questionnaire to investigate the perceived mental load of participants is the so-called *NASA Task Load Index* (NASA TLX) [HS88; Har06]. Therefore, from six different factors that assess the mental, physical, and temporal demand, as well as the performance, effort, and frustration, an overall score is calculated. In this thesis, the RAW NASA TLX is used that does not include the pairwise comparisons of the aforementioned factors [Har06].

QUALITATIVE FEEDBACK AND OBSERVATIONS In addition to the analyses of quantitative data, the user studies also included qualitative feedback coming directly from participants in form of semi-structured interviews, free-text questionnaires, and spoken and written feedback [CS08]. Also, the experimenters of the studies carefully observed the participants during their performance and interaction with the proposed concepts and system [CS08].

Furthermore, all participants were informed about the study procedures, possible associated risks (e.g., allergies to materials or motion sickness in the VR environments), collected and stored data, and the respective data privacy and policies beforehand. For each study, the participation was completely voluntary and could be interrupted or stopped at any time without giving reasons. Therefore, participants were asked to sign a consent form before a study started. Besides the usual hygienic measures for every user study, such as cleaning materials and tidy experimental setups, extended hygienic measures in alignment with the TU Darmstadt and governmental health regulations were performed during one study that was conducted during the COVID-19 pandemic (user study of Chapter 6 SMOOTH AS STEELWOOL; see Section 6.5.3.1 for more details).

9 named after Rensis Likert [Lik32]

1.6.2 *Analyses*

NON-PARAMETRIC ANALYSIS For one-factorial designs (with non-continuous data, e.g., as often the case in the post-questionnaires), Friedman's tests were performed as it is the de-facto standard in HCI for the non-parametrical analysis [WK16]. If significant effects were found, error-corrected Wilcoxon Rank-Sum tests were used for pairwise posthoc comparisons, which are non-parametric equivalent to t-tests [WK16].

For questionnaires and study designs with more than one IV, the non-parametric Aligned Rank Transform (ART) procedure [Wob+11] was used to align the data by using the *ARTool*[10]. The ARTool offers the possibility to use the ART procedure with traditional repeated measures models (*aov*) or to fit mixed-effects models (LME) using *lmer*. In this work, mixed-effects models were preferred as suggested by the ARTool authors' examples. To assess the significance of the fitted model, ARTool uses the Kenward-Roger method to approximate the degrees of freedom. This is because the degrees of freedom of an LME model cannot be derived directly from the parameters of the model [Luk17], as would be the case for a comparable repeated measures (aov) model. For the posthoc tests, error-corrected t-tests were used or the alternative newer ART-C procedure as proposed by Elkin et al. in 2021 [Elk+21] (i.e., in the analysis of Chapter 6).

PARAMETRIC ANALYSIS For continuous data, such as performance measures, parametric analyses were used that "tests the equality of the means of a continuous outcome/dependent variable" ([RK16], p. 112). First, standardized assumption tests were performed [RK16], such as Shapiro-Wilk's test for normality and Mauchly's test to check for violations of the sphericity assumption. If normality was not given, the data were analyzed with non-parametric methods. If the sphericity was violated, the degrees of freedom were corrected using the Greenhouse-Geisser method. Second, if all assumptions were met, repeated measures analysis of variance (RM ANOVA) were performed to reveal significant effects [LFH17; RK16] and pairwise t-tests were used for

10 https://cran.r-project.org/web/packages/ARTool/readme/README.html (accessed March 01, 2022)

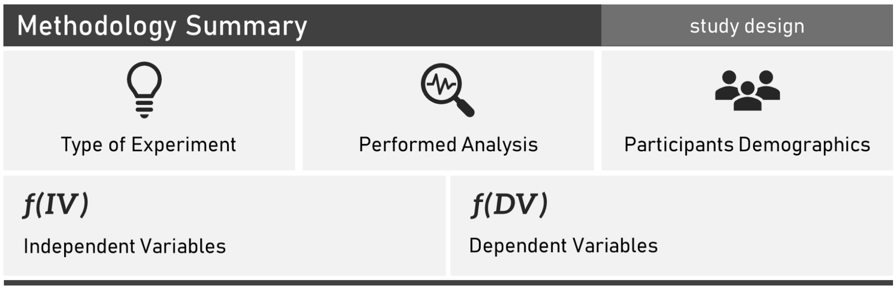

Figure 1.1: Uncolored summary example for user studies that will be shown at the beginning of each methodology section. The *lightbulb* icon indicates the type of experiment, the *magnifying glass* indicates the performed analyses, the *user* icon gives an overview of the participants' demographics, $f(IV)$ shows the independent variable (IV), and $f(DV)$ shows the measured dependent variable (DV).

posthoc comparisons [RK16]. Finally, the results of the posthoc analyses were corrected using approved error correction methods, such as Bonferroni or Tukey [WK16; RK16].

ERROR CORRECTION METHODS For both, non-parametric and parametric tests, the posthoc tests have been error corrected accordingly. Therefore, either Bonferroni or Tukey corrections were performed as suggested in literature [WK16; RK16].

QUALITATIVE ANALYSIS In order to understand and interpret the quantitative findings better, qualitative feedback should be gathered, for example in form of semi-structured interviews, as well as by written and verbal feedback from participants during the experiments. In this thesis, this feedback was then transcribed, structured, and analyzed by following open coding in order to find common features [CS08].

1.6.3 *Reporting*

Each respective methodology section in this work that covers a user study contains detailed information on the study design, performed analyses, and the reporting of the results. Hereby, the reports also contain additional information, such as significance values, medians, means, standard deviations, standard errors, confidence intervals, and other accepted metrics depending on the performed statistical analyses. For a better overview, all methodology sections also begin with a summary figure highlighting the type of experiment, the performed analyses, a short demographics of the participants, as well as the independent variable (IV) and dependent variable (DV). An example of this methodology summary is depicted in Figure 1.1.

1.7 THESIS STRUCTURE

This thesis document is structured as follows:

CHAPTER 1 motivates the importance of haptic feedback and somatosensory interaction. Further, it gives an overview of the topics within the scope of this thesis.

CHAPTER 2 discusses the background of the somatosensory system and its psychological and physiological properties. Further, it provides background to the different classifications of touch, material characteristics, and immersion and presence.

CHAPTER 4 highlights and discusses the importance of more FINE MECHANORECEPTION through expressive vibrotactile stimuli. Thereby, two user studies investigated how vibrotactile feedback on the hand can support target acquisition and remote assistance tasks.

CHAPTER 5 presents concepts for PRESSURE-BASED MECHANORECEPTION and how it can be implemented using a pneumatic actuation. In a user study, the effects of such pressure-based feedback on the head were investigated.

CHAPTER 6 combines both, the FINE MECHANORECEPTION and PRESSURE-BASED MECHANORECEPTION, for investigating stroke movements with regards to different roughness of materials and their interdependencies with visualizations.

CHAPTER 7 highlights and discusses the importance of THERMOCEPTION. Therefore, a prototypical system using liquids as a medium is introduced and the effects of temperature in VR were investigated in an in-depth user study.

CHAPTER 8 contributes on to PROPRIOCEPTION and KINESTHESIA by providing kinesthetic feedback around body joints. Through two user studies, the required forces for different actuation patterns and the effects of kinesthetic actuation in VR are investigated.

CHAPTER 9 presents the design of an open-source rapid prototyping platform for actuators that was created due to the demanding prototypes presented in the previous chapters, called ActuBoard.

CHAPTER 10 summarizes the previous chapters of this thesis and highlights potential directions for future research. Further, it provides examples of how the different aspects of this work can be integrated into specific use-cases.

The Chapters 1 and 2 are found in Part i: Introduction and Background. The Chapters 4, 5, and 6 are found in Part ii: Mechanoreception. Chapter 7 is found in Part iii: Thermoception. Chapter 8 is found in Part iv: Proprioception. Chapter 9 is found in Part v: Prototyping. Concluding, Chapter 10 is found in the last Part: Outlook and Conclusion.

1.7.1 *Chapter Overviews*

As an overview of the contents of the Chapters 4-9, each one introduces with an overview figure that highlights the respective somatosensory parts investigated in the chapter, the related publication(s) published by the author of this thesis, a thumbnail, and keywords on the discussed topic of the chapter. In addition, the color scheme of each chapter is related to the specific part of the somatosensory system. An uncolored example is depicted in Figure 1.2.

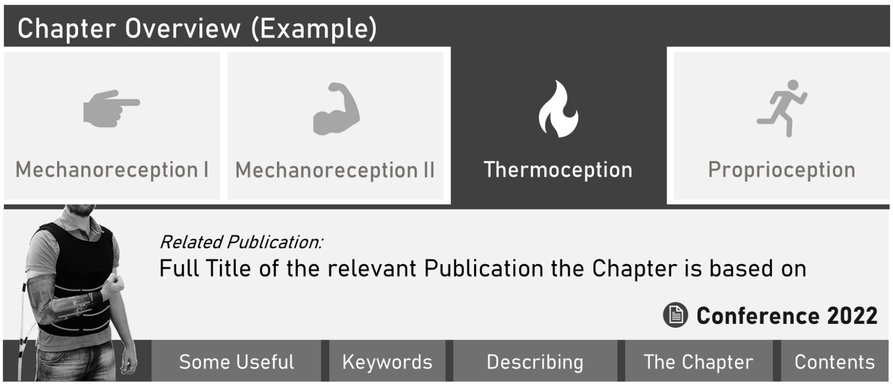

Figure 1.2: Uncolored example of the overview figure for each chapter.

2 BACKGROUND: THE SOMATOSENSORY SYSTEM, TOUCH, IMMERSION, AND PRESENCE

This chapter covers the different concepts and classifications of touch, backgrounds of the somatosensory system, and the different properties of materials and surfaces. Moreover, it provides background information on the concepts of immersion and presence, which are both essential for the assessment of VR applications.

2.1 CLASSIFICATIONS OF TOUCH

Before giving an overview of the somatosensory system and material properties, the term *touch* itself has to be defined[1]. In particular, touch can be categorized according to two main classifications: (1) ACTIVE and PASSIVE, and (2) DISCRIMINATIVE and AFFECTIVE.

ACTIVE AND PASSIVE TOUCH The first classification distinguishes how touch is perceived from the perspective of who was the initiator of the touch. In case of ACTIVE touch, a person *actively touches something* and is the initiator of the action [Cha94; Gib62]. This also means that a person typically touched something with their own hands.

In case of PASSIVE touch, a person is *passively being touched* by someone or something else [Cha94; Gib62]. Hereby, a different person or some object caused the contact by external forces. This particularly includes being touched on other body parts apart from the own hands, such as happening during a caress or strokes on the arm.

DISCRIMINATIVE AND AFFECTIVE TOUCH The second classification distinguishes how touch can DISCRIMINATE physical (object) prop-

1 Contribution Statement: This section is based on the following publication which was done under my lead: [Gün+22]

erties and how touch AFFECTS emotional responses of the subject. This means that DISCRIMINATIVE touch is emerging around how physical contact is perceived physiologically in order "to detect, discriminate, and identify external stimuli to ultimately make rapid decisions to guide subsequent behavior" (McGlone et al., 2014, [MWO14], p. 1). Thereby, body parts consisting of the so-called *glabrous skin*, such as the hands and fingertips, have better discriminative traits than other body parts which consist of *hairy skin* due to the distribution of responsible mechanoreceptors within the skin [MWO14; MR10] (a more detailed explanation can be found in the MECHANORECEPTION Section 2.2.1).

AFFECTIVE touch, in contrast, focuses on what touch elicits emotionally, conveying "anger, fear, disgust, love, gratitude, and sympathy" (Hertenstein et al., 2006, [Her+06], p. 1). Further, AFFECTIVE touch typically results in emotional immersion that causes individuals to feel more involved in certain situations [EA16; Hui17].

This background also resulted in the situation that typically most DISCRIMINATIVE touch research in HCI focuses on discriminative aspects for ACTIVE touch since the hand has better discriminative traits than other body parts (cf. Section 2.2.1). On the other side, research that investigated AFFECTIVE touch mostly focused on PASSIVE touch aspects that typically involve emotional feelings. That being said, both aforementioned combinations are not mutually exclusive and it is therefore also important to understand how PASSIVE touch is DISCRIMINATIVELY perceived to initiate certain affective responses. Therefore, this work contributes to this by investigating how different haptic stimuli are discriminated during passive touch in form of stroke movements on the arm (see Chapter 6).

2.2 THE SOMATOSENSORY SYSTEM

The SOMATOSENSORY SYSTEM is responsible for the perception of touch, temperature, pain, and body position and movement through a large network of cutaneous, tactile, and proprioceptive receptors as part of the nervous system [Dou97; DBD20]. Therefore, the whole somatosensory system embodies what people typically understand as the sense of touch. Taking a look at the everyday understanding of the human senses, people often consider sensory perception as the perception of the classic five senses: hearing, smelling, tasting, seeing, and touching. Although these five senses have been already characterized since ancient times by Aristotle (ElSaddik et al. [El +11], p. 15; [Gre07]), they are not sufficient to describe the entire sensory perception of humans. This becomes especially evident when it comes to the sense of touch. While touch was classically defined as a completely distinct sense, we nowadays know that touch is composed of a multitude of different senses that perceive different material characteristics, such as roughness, hardness, temperature, or friction [ONY13; ONH16; Hol+93] (see also Section 2.3).

This means touch persists in different sub-modalities. Probably most prominently, the perception of touch consists of the MECHANORECEPTION, which recognizes texture on the skin, as well as light and subtle touch through FINE MECHANORECEPTION and more intense contact like skin deformation through PRESSURE-BASED MECHANORECEPTION. Further, the somatosensory system comprises the THERMOCEPTION, which is responsible for the perception of temperature, as well as the NOCICEPTION, which recognizes pain.

Definition: Somatosensory

"Derived from the Greek word for 'body,' somatosensory input refers to sensory signals from all tissues of the body including skin, viscera, muscles, and joints. Somatic usually refers to input from body tissue other than viscera."

Gebhart and Schmidt [GS13]

An additional perception, the so-called PROPRIOCEPTION, is the perception of one's own position in space, as well as of the limbs in relation to another and their movement changes. In many cases, this is equated with the sense of balance (*equilibrioception*), which also does not occur in the classical model, but is another separate sense of balance and orientation. While the vestibular system is responsible for the sense of balance, the other senses, namely FINE MECHANORECEPTION, PRESSURE-BASED MECHANORECEPTION, THERMOCEPTION, PROPRIOCEPTION, and NOCICEPTION are part of the somatosensory system [Kaa12; Dou97; DBD20].

The somatosensory system is therefore usually responsible for all that we understand by touch or haptics in HCI. As part of the sensory nervous system, it is therefore responsible for the perception of subtle vibrations, pressure, temperature, pain, and body position and movement [Dou97]. Thereby, the latter comprises receptors and afferents[2] found within muscles and body joints (*proprioceptive receptors*) [Tay09; PG12], while the other are comprised by receptors within the skin (*cutaneous receptors*) [MR10; Joh01]. Mc Glone and Reilly, hereby, described the skin as "a highly complex organ, innervated by a wide array of specialized sensory neurons sensitive to heat, cold, pressure, irritation, itch and pain" (McGlone and Reilly, 2010, [MR10], p. 149).

In the following, the four parts of the somatosensory system, Mechanoreception, Thermoception, Proprioception, and Nociception, are explained in more detail and how they apply to haptic feedback in HCI and in this work[3].

2.2.1 *Mechanoreception*

The Mechanoreception is responsible for detecting light touch, flutter, and vibration through Fine Mechanoreception, and pressure, deformation, and stretching on the skin through Pressure-based Mechanoreception [Kaa12; Car19]. Yet, each type of sensation is perceived through four different cutaneous receptors found in the different skin layers (see Figure 2.1), also known as the *four-channel model* of Mechanoreception [Bol+88; BGV94]: (1) Merkel Cells, (2) Ruffini Endings, (3) Meissner Corpuscles, and (4) Pacinian Corpuscles [Kaa12; Bol+88; BGV94]. Those receptors are further classified into two types with regards to how they respond to skin contact. Merkel Cells (or Disks) and Ruffini Endings are slowly adapting (SA) receptors that "fire during a constant mechanical stimulus" (McGlone and Reilly, 2010 [MR10], p. 149). Meissner and Pacinian Corpuscles, in contrast, are fast or rapid adapting (RA) receptors that "respond to the initial and final contact of a mechanical stimulus on the skin" (McGlone and Reilly, 2010, [MR10], p. 149).

2 Gebhart and Schmidt defined afferents as "sensory neurons (axons or nerve fibers) in the peripheral nervous system that transduce information about mechanical, thermal, and chemical states of the body and transmit it to sites in the central nervous system." (Gebhart and Schmidt, 2013, [GS13], p. 3173-3174)

3 This work focuses on the somatosensory system from an HCI perspective. For a more detailed explanation of the neurological and physiological processes of the somatosensory system, which would go beyond the scope of this work, the author of this work recommends the following literature: [Kaa12; Dou97; DBD20; MR10; Bol+88; Dar84; PG12]

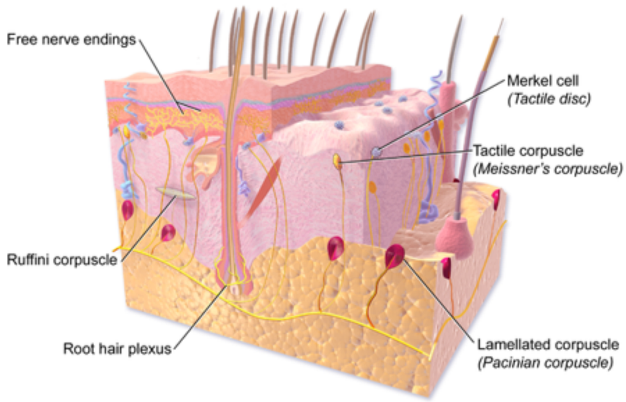

Figure 2.1: The four tactile receptors of MECHANORECEPTION as they are located within the different skin layers.
Image taken from the medical gallery of Blausen Medical 2014 [Bla14], licensed under CC BY 3.0, https://creativecommons.org/licenses/by/3.0/.

HAIRY AND GLABROUS SKIN: While those receptors are found all over the skin, they appear in different quantities and densities depending on the two skin types: (1) GLABROUS, and (2) HAIRY SKIN [Car19; Bol+88]. GLABROUS SKIN is found on parts of the body, such as the palm, fingers, lips, or bottom of the foot, and are mostly not covered by any hair [McG+12]. Thereby, traits of DISCRIMINATIVE touch are mainly attributed to the GLABROUS SKIN [McG+12]. HAIRY SKIN [HWG85], in contrast, is found on all other body parts, such as the arms, upper body, or legs, and typically respond better to “slow and light” strokes [Pac+17] with weaker DISCRIMINATIVE traits [Ola+10; Ack+14][4].

In the following, the four mechanoreceptors in the skin are described in more detail with regard to their characteristics and responsibilities:

SA1: MERKEL CELLS Merkel cells were first discovered and described by Friedrich Merkel in 1875 [Mer75] and are located in the “basal layer of the epidermis” (Carlson, 2019, [Car19], p. 70). Those slowly adapting afferents of type I are attributed to the sensation of high-resolution light touch of the skin, such as the detection of light pressure and edges [Mar+09; Car19; Kaa12]. A high density of Merkel cells are found in the glabrous skin of the hands and are,

4 Contribution Statement: This paragraph was based on the following publication done under my lead: [Gün+22]

therefore, able to detect even very fine edges and shapes [Joh01; Kaa12], for example for reading braille [JL81].

SA2: RUFFINI ENDINGS Ruffini endings are named after their discoverer Angelo Ruffini who first described them in 1894 [DBD20]. They are located deeper in the skin in the outer dermis [Car19]. Similar to the Merkel cells, Ruffini endings are slowly adapting afferents but of type II [Car19; Dar84]. Their main attributions are the detection of skin stretch and joint movement [Joh01; Car19; Kaa12] but are also able to detect pressure, however, less pronounced than SA1 receptors [Joh01]. Therefore, they are essential for the perception of deformation of the skin through horizontal stretching [Joh01].

RA1: MEISSNER CORPUSCLES Meissner corpuscles are named after Georg Meissner who discovered them in 1855 [DBD20] and are also known as *tactile corpuscles*. They are found in large quantity and density in body parts with glabrous skin (papillary layer of the dermis [DBD20]), such as the hands and fingertips [JYV00; Dar84; Car19], but are almost non-existent in hairy skin and are replaced by hair follicle receptors [DBD20; Dar84]. Similar to Merkel Disks, Meissner corpuscles detect touch but as a sense of flutter created by rapid movements on the skin [MR10; Joh01] and can detect low frequency vibration through changes of their intensity [Joh01]. Therefore, they are the most responsible receptor to detect sudden forces [Joh01; MHJ96], as well as for objects hold in the hand [MHJ96].

RA2: PACINIAN CORPUSCLES Pacinian Corpuscles (sometimes Vater-Pacinian Corpuscles) are the fourth class of mechanoreceptors and named after Abraham Vater, who first recognized them in 1741, and Filippo Pacini who described them in more detail in 1835 [DBD20; Dar84]. These rapid adapting afferents of type II are up to 1.5 mm in length and are found in deeper skin tissues [Dar84; BBH94]. Again, these types of skin receptors are mostly found in glabrous skin but were also identified close to blood vessels and muscles [BGV94; BBH94]. They are able to detect deep pressure and vibrations [Car19] resulting from fast accelerations over short distances (10 nm) with a very high responsiveness [Joh01]. This makes them the essential receptors for applications that involve vibrotactile sensations and texture-discrimination tasks on the hand.

In summary, Mechanoreception is the essential part of the perception to detect touch in the form of vibration, skin stretch, deformation, and pressure. Different cutaneous receptors are responsible for the individual submodalities and, thus, generate separate signals for the more gentle, subtle stimuli, such as vibrations, within the Fine Mechanoreception, while more intense pressure-based stimuli, such as skin deformation or stretching, are addressed by the Pressure-based Mechanoreception. Consequently, it is not sufficient for haptic systems, to offer only vibrotactile stimuli in an attempt to cover the entire Mechanoreception.

In this work, Part ii addresses the perception of different stimuli linked to Mechanoreception in three chapters. Chapter 4 examines Fine Mechanoreception using vibrotactile stimuli, Chapter 5 examines Pressure-based Mechanoreception for more intensive pressure-based feedback, and Chapter 6 examines the combination of both types for moving stroke stimuli.

2.2.2 *Thermoception*

The Thermoception is responsible for the perception of temperature changes on the skin through warm and cold receptors in the skin and around other organs [DJ77; Kaa12]. The perception of temperature is, therefore, the combination of sensing coldness and warmth separately as both types of afferents react only to certain temperature ranges [DJ77]. Thereby, the sensation of coldness is always perceived as more intense [SC98] and the overall perception of temperature always depends on the body part [GOH16] that lessens for older individuals [SC98]. Yet, very high temperatures above 45 °C [HWG52] or very low temperatures below 15 °C [HD99] result in pain and are detected by specialized nociceptors (see also Section 2.2.4).

Another special characteristic of the perception of temperature is how it is perceived over time. While faster changes in temperature of a few degrees Celsius are easily detected by humans, slow changes over several minutes are often not recognized [DJ77]. Moreover, due to the effect of a *spatial summation*, the localization of thermal stimuli is hard to detect, even two different areas on the skin are actuated independently [DJ77].

All those factors have to be considered when investigating the Thermoception in HCI [JH08]. Researchers and developers have to consider, how fast the actuation should happen and to what extent. Therefore, it is also essential to keep the spatial summation in mind, which may lead to unexpected side effects, as the spatial discrimination of thermal stimuli is low. In this work, thermal feedback will be investigated in Chapter 7, exploring how Thermoception is affected by visual stimuli and how to convey different temperatures through a liquid-based actuation.

2.2.3 *Proprioception and Kinesthesia*

Proprioception is the sense of the body position and movement. Taylor describes the Proprioception thereby as sensation "to judge limb movements and positions, force, heaviness, stiffness, and viscosity" (Taylor, 2009, [Tay09]). Thereby, two types of receptors, the so-called Golgi tendon organs, and muscle spindles, are responsible for this specific perception and are located under the skin, in the joints, and muscles [TA18; Dou97; Tay09]. Both are responsible for detecting movement changes and the position of body parts in relation to each other. The Golgi tendon organs, as the name suggests, are found in the tendons and detect muscle tension and contraction [Dou97; DBD20]. The muscle spindles, in contrast, detect the length of a muscle in relation to its stretching [DBD20].

While some literature distinguish Proprioception as "joint position sense and awareness of joints at rest" (Danzl and Wiegand, 2017, [DW17], p. 144) and Kinesthesia as "the awareness of movement" (Danzl and Wiegand, 2017, [DW17], p. 144), others use the terms Proprioception and Kinesthesia synonymously [Tay09; FFK08; PG12]. In HCI, for example, the terms are often not differentiated and when talking about one of them, the research is mostly concerned with either the kinesthetic actuation of body parts affecting the Proprioception or the perception of the own body (e.g., [FFK08]). In this work, Chapter 8 focuses on a kinesthetic actuation which is essential for altering the PROPRIOCEPTION as body parts and joints are actively moved to different positions and orientations.

2.2.4 *NOCICEPTION*

The NOCICEPTION has a special role within the somatosensory system as it is concerned with the perception of pain [Sne18; DBD20; Kaa12]. Hereby, it is a natural and complex alarm system that alerts potential threats or even physical injuries to the brain [DBD20]. That being said, "pain from injury cannot occur without nociception" (Sneddon, 2018, [Sne18], p. 63) and is detected by several free nerve endings (*nociceptors*) in the skin [Sne18].

While there exists a large number of different nociceptors, the most important for this work are the two main cutaneous nociceptors that respond to high and low temperature, as well as to strong mechanical stimuli [DBD20]. This means, (cutaneous) nociceptors are "afferents that respond to innocuous cooling, multimodal afferents responsive to heat, pinch, and cooling" (Kaas, 2004, [Kaa12], p. 1065). Even though this work does not address NOCICEPTION individually, it is an important factor for all of the investigated stimuli since it is essential to know the physiological pain thresholds in order to keep the experiments safe and harmless for users.

For MECHANORECEPTION, for example, too much pressure can cause serious tissue injuries and might result in bruises. For THERMOCEPTION, while depending on the body parts [GOH16], temperatures that are lower than 15 °C-17 °C can cause undercooling [HD99], and temperatures higher than 45 °C-52 °C can cause pain through burns [CB94; HWG52]. For PROPRIOCEPTION, similar nociceptors as for MECHANORECEPTION are responsible to perceive pain, for example, due to overstretching of the joints or issues within the muscles.

2.3 CHARACTERISTICS OF MATERIALS FOR HAPTIC PERCEPTION

The previous section addressed the somatosensory system, which accounts for the haptic perception of humans. This section continues with the definitions of material properties that can be perceived by humans.

As objects, things, and our whole environment are composed of different materials, surfaces, textures, shapes, and other properties, we can infer their nature, function, and characteristics. While the visual perception centers around characteristics that are visible to the eye, such as visual shapes [LS96], colors [WG18], or glossiness [BP81], everything also has tangible and tactile properties, which are the basis for haptic perception. Therefore, Okamoto et al. [ONH16; ONY13] divided material properties into five perceptual dimensions as follows: (1) fine roughness, (2) coarse roughness, (3) softness and hardness, (4) warmness and coldness, and (5) friction. All of these contribute to a holistic sensation, and are perceived by the somatosensory system via Fine Mechanoreception, Pressure-based Mechanoreception, Thermoception, Proprioception, and Nociception (see Section 2.2). However, each aspect also needs to be investigated independently to identify its effect on perception.

FINE AND COARSE ROUGHNESS As the dimensions indicate, roughness can be sub-divided into a fine and coarse (or macro) roughness [ONH16; ONY13; HR00]. Thereby, coarse roughness is defined as "voluminous, uneven, lumpy, coarse, and relief" ([ONH16], p. 5) that is mediated "by spatial cues" ([HR00], p. 1). Fine roughness, in contrast, "is typically described as harsh or rough" ([ONH16], p. 5) that is "mediated by vibrational cues" ([HR00], p. 1). While this makes sense from a physiological or material science perspective, roughness is most often considered as a single characteristic (e.g., [Hol+93]) since humans tend to not differ between the perception of vibration (fine roughness) and more voluminous gradations (coarse roughness) [ONY13]. Okamoto et al. observed that this is mainly because describing roughness verbally can be hard as "adjectives indicating the opposite poles of macro and fine roughness are semantically similar" ([ONY13], p. 83), such as *flat*, *smooth*, or *even* [ONY13]. In contrast, such a deep distinction from a HCI or psychological perspective is usually not necessary, since the transition from a very fine roughness, which can be triggered by vibrations, to a coarse roughness can be considered continuous, even though it is processed by different mechanoreceptors. Yet, this does not mean that the perception of fine roughness can only be created by vibrotactile stimuli, or that the perception of coarse roughness can only be created by physical textures. For example, subtle stimulation can be achieved by "dragging" very fine textures, and many works, notably in HCI, use a vibrotactile or ultrasonic actuation in an attempt to recreate all sorts of different rough textures (e.g., [CUK14; CK17; WF95]). While this work distinguishes between Fine Mechanoreception (Chapter 4), which is addressed by vibrotactile actuation, and Pressure-based Mechanoreception (Chapter 5), which is triggered by more intense forces, Chapter 6 approaches roughness as a whole and how the perception of roughness is affected by different haptic and visual stimuli, also in comparison to a vibrotactile actuation.

SOFTNESS AND HARDNESS The softness and hardness describe the "ratio of relative reaction force to relative surface displacement" ([ONH16], p. 9). Thereby, softer objects are more likely to be deformable by pressure, while more hard or rigid objects stay stiff. The deformation is detectable by the cutaneous mechanoreceptors that recognize the amount of pressure and the object's elasticity [ONY13; ONH16]. While soft- and hardness of objects are not the focus of this thesis, it still has a crucial role when investigating Mechanoreception. In Chapter 5, pressure-based feedback is introduced that typically results in more intense contacts that are perceived as harder than other more subtle cues. In Chapter 6, physical objects with different roughness are in the focus, however, the selection of objects also took hardness into account to balance the palette of stimuli.

WARMNESS AND COLDNESS Every object or environment has a certain temperature. Depending on a person's own temperature, an object's temperature is either perceived as warm, if the object's temperature is higher, or as cold if it is lower [JH08; ONH16]. However, the perception of the temperature (cf. Thermoception, Section 2.2.2) is also affected by thermal conductivity and heat capacity of materials [JH08], as some might feel colder than others, even if they have the same temperature, such as metal compared to plastic or wood [HJ06; ONH16]. In this work, concepts for providing different temperatures to users and how the physical warm and cold stimuli affect the visual thermal appearance of different objects are investigated in Chapter 7.

FRICTION Friction is the force that resists a relative sliding or movement of surface on another [Bri21] and can be slippery or sticky [NOY14; ONY13]. Since it always involves movement, the perception of friction is often attributed to Proprioception, however, Mechanoreception is essential, too [MOY14; ONH16]. In this work, friction has a subordinate role but is taken into account in Chapter 6 where moving stroke stimuli with different roughness were examined and relevant related work found evidence that friction also affects the perception of roughness to some degree [Smi+02; ONH16].

2.4 IMMERSION AND PRESENCE

When investigating concepts and technologies for AR/VR, two terminologies need to be considered: (1) Immersion, and (2) Presence.

The terms are often mixed or perceived similarly in their meaning, however, have distinct characteristics that explain their connection. As one of the pioneers of modern VR research, Mel Slater defined IMMERSION as "what the technology delivers from an objective point of view" (Slater, 2003, [Sla03], p. 1). Therefore, the technical quality of a (VR) application to reproduce the sensory fidelity of respective real-world counterparts is the key to a high level of immersion. As such, immersion is something that can be "objectively assessed" [Sla03]. For example, for a high visual immersion, the field of view, display size, display resolution, realism of physical characteristics, or the frame rate are essential [BM07]. With regards to haptic feedback, the technical quality of interactive devices that replicate sensations, such as the spatial precision of touch or the thermal propagation of a (virtual) object.

Presence, on the other side, is "a human reaction to immersion" [Sla03]. Originally, the term was derived from *telepresence* and described "the sensation of being at the remote worksite rather than at the operator's control station" [WS98]. With regards to VR, it indicates "a user's subjective psychological response to a system" [BM07; Sla03]. As such, a high degree of immersion in an involving situation or environment can result in a high-level presence. For example, being in a VR environment that provides characteristics close to the ultimate display (Section 1.1) where a user gets a sense of *being there* in an alternative world, with only a minor mental influence of the real world, can be an indicator for a high presence.

Throughout this work, both terms are essential and covered in many ways. The presented prototypes have to provide an objectively high degree of immersion to result in experiences with a subjectively high level of presence. Therefore, this work investigated how able the technical approaches were to provide lifelike sensations, and how much they could involve users in the VR environments.

Part II

MECHANORECEPTION

3

INTRODUCTION TO MECHANORECEPTION

Mechanoreception is one of the typical senses when thinking of haptic feedback in HCI and is concerned with the detection of tactile touch on the skin. Due to the four different cutaneous receptors that are involved in the process of sensing mechanical stimuli (cf. Section 2.2.1), Mechanoreception is able to recognize far more than a simple contact with the skin. For this, the receptors can sense and differ between fine and subtle touches, such as vibrations, as well as stronger pressure-based impacts. Furthermore, the interplay of all mechanoreceptors makes it possible to perceive both, static touches at a certain point and moving touches and strokes, such as caress.

This part of this work investigates the following aspects of Mechanoreception in three chapters: (1) Fine Mechanoreception, (2) Pressure-based Mechanoreception, and (3) a combination of both for stroke stimuli. All of these chapters present substantial concepts on how Mechanoreception can be leveraged for haptic feedback in HCI, each with a specific focus. The concepts outlined there are implemented in the form of several prototypical systems and systematically evaluated in user studies to determine how they are perceived by individuals. Although each of the chapters focuses on a particular manifestation of Mechanoreception, the concepts are not exclusive and the meshing among the concepts is particularly evident in the latter chapter, where both, subtle and pressure-based touch, are addressed for moving touch stimuli and the influences of visuals.

Before discussing the individual concepts in each chapter, the following section presents an overview of related work that examined Mechanoreception for haptic feedback. More specific related work that addressed the submodalities of Mechanoreception are discussed within the respective chapters.

3.1 REQUIREMENTS

Haptic devices have different requirements depending on the intended application. As mentioned in the introduction of this chapter, the type of actuation already has a significant influence on the Mechanoreception. Physical touch can be subtle and fine, even like a tickling feeling, often caused by vibrotactile stimulation and is superficial on the skin. Other stimulations, in contrast, are more intense and caused by pressure-based stimuli. In this case, an external force is applied to the contact point and mostly provokes a deformation of the skin layers, sensed by the involved cutaneous receptors (cf. 2.2.1). Further, besides the intensity of a touch, the perception of different material properties is part of the Mechanoreception. Thereby, the surface texture of an object can be perceived which has different effects on the Mechanoreception depending on the material characteristics. In the following, a set of requirements is defined for HCI applications addressing the Mechanoreception, which are then used to classify the relevant related work.

REQM1. PROVIDE FINE OR PRESSURE-BASED INTENSITIES
: Depending on the use case, rather fine and subtle intensity of actuations can be appropriate, for example, to convey subtle notifications or cues, or more intense pressure-based actuations, for example for establishing direct contact with (virtual) surfaces. Therefore, there should be no too gentle actuations for more intense touches, and vice-versa.

REQM2. FOCUS ON ACTIVE OR PASSIVE TOUCH
: Because of the different distribution of cutaneous receptors, some applications are better suited for active touch, i.e. touching something, while other applications have to account for the specific characteristics of passive touch, i.e. being touched by something (cf. 2.1). Therefore, haptic applications should always consider which type of touch is reasonable for corresponding skin regions.

REQM3. SUPPORT DISCRIMINATIVE OR AFFECTIVE TOUCH
: Similar to the previous requirement, the different distributions of cutaneous receptors also influence the sensitivity to different touches (cf. 2.1). Discriminative traits are more pronounced in glabrous skin (e.g., the hands) and are more suited for sensory perception. Hairy skin, in contrast, is more suited for affective touch, i.e. the elicitation of emotions in response to touch. There-

fore, applications should always take into account which type of sensory perception is appropriate for specific skin regions.

REQM4. PROVIDE STATIC TOUCH OR MOVING STROKES
Touch can be applied locally to a specific spot or stimulate larger areas of the skin. However, depending on the context, moving touches are sometimes preferable, for example, to convey directional cues, or to represent caressing gestures. While static touches are easier to technically implement, moving touches tend to be more challenging. Therefore, applications should always find a tradeoff whether static touches are sufficient or the effort for stroke stimuli is reasonable.

REQM5. SUPPORT DIFFERENT BODY PARTS
The previous requirements are always dependent on the actuated body part and its associated skin type. Additionally to those physiological properties, it is also essential to actuate body parts that are appropriate for a given application. Therefore, the context and the physiological properties have to be considered in order to provide an actuation for particular body parts in a meaningful way.

REQM6. SUPPORT DIFFERENT ENVIRONMENTS
For every use case, the environment has to be considered as well. In many cases, a tactile actuation of the body without a special auxiliary modality is sufficient, such as for smartphone notifications or navigation applications. In other situations, however, haptic stimuli can support applications that would perform worse without haptics, such as AR/VR environments where haptic feedback helps for more immersion, presence, and realism. Therefore, care must be taken for which environment, real, augmented, or purely virtual, the haptic actuation is implemented.

REQM7. SUPPORT FOR DIFFERENT DEVICES
Similar to the previous requirement, the device for haptic stimuli has an important role as well. This can be stationary, for example, built into a car seat or game controller, or should be compact and wearable, for example, to provide haptic feedback for interactive VR applications. Therefore, depending on the application, it is necessary to consider in what type of device the haptic stimuli can be generated in a meaningful way.

3.2 RELATED WORK

A large part of the haptic research in HCI focuses on actuation related to Mechanoreception. Individual research will be presented in this section, categorized by (1) general Mechanoreception in HCI through vibrotactile and pressure-based actuations, (2) the rendering of haptic textures for active and passive touch, and (3) guidance.

3.2.0.1 *Mechanoreception in HCI*

In the field of haptics in HCI, research has proposed a large amount of related work that can actuate users for a broad spectrum of applications. In probably most cases, this research focuses on the *affective* responses that are a result of tactile actuations, while *discriminative* aspects are more often investigated for use in AR/VR environments.

In general, HCI has investigated various interaction concepts, methods, and techniques to provide haptics to the body, such as the squeezing, twisting, or skin deformation of body parts [KR15; GIB17; Sim+20; Sim+21; Mut+20; Yar+17], various pneumatic actuation for pressure-based feedback [Poh+17; He+15; Del+18; Kan+19], thermal cues [Liu+21; Gün+20a], mechano-tactile forces with the help of small motors [Cas+15; Pez+19; Nun+20], and even by utilizing tiny robots for attention guidance [KF19]. Recently, the Meta company provided insights into their plans for the next years regarding haptic feedback for the *Metaverse* (a highly immersive VR environment). One of their current research is focusing on a haptic glove that relies on pneumatic actuation and microfluids to create a realistic sense of touch[1]. Yet, while this prototype is supposed to be very powerful, the idea to provide tactile feedback in a glove is not new. For example, one of the first tactile gloves, the Teletact [Sto01], already used a pneumatic actuation and in 1997, Caldwell et al. [CTW97] presented an updated version of it that also provides thermal feedback.

In the following, fine- and vibrotactile-based, as well as pressure-based feedback is presented in more detail. Furthermore, Section 4.3 of the following chapter on Fine Mechanoreception will provide an addi-

1 https://tech.fb.com/inside-reality-labs-meet-the-team-thats-bringing-touch-to-the-digital-world/ (accessed March 01, 2022)

	ReqM1. Intensity	ReqM2. Active / Passive	ReqM3. Discriminative / Affective	ReqM4. Static / Stroke	ReqM5. Body Part	ReqM6. Environment	ReqM7. Device Type
Barghout et al. [Bar+09]	✓	passive	discriminative	strokes	arm	RW	vibrotactile sleeve
Bloomfield and Badler [BB03]	✓	passive	discriminative affective	static	Up. Body	VR	vibrotactile suit
Elsayed et al. [Els+20b]	✓	passive	discriminative	strokes	body		vibrotactile suit
Funk et al. [Fun+16]	patterns	passive	affective	static	hand	AR	vibrotactile glove
Hamam et al. [HEE13]	✓	passive	affective	strokes	arm	mobile	vibrotactile sleeve
Huisman et al. [Hui+13]	✓	passive	discriminative affective	static strokes	arm	RW	vibrotactile sleeve
Israr and Poupyrev [IP11]	✓	passive	discriminative	static strokes	back	RW	vibrotactile chair
Israr et al. [Isr+14]	✓	passive	discriminative affective	static strokes	back	RW mobile	vibrotactile vest
Konishi et al. [Kon+18b]	✓	passive	discriminative	static strokes	body	VR	vibrotactile suit
Lindeman et al. [Lin+06]	✓	passive	discriminative	static	Up. Body	VR	vibrotactile vest
Park et al. [PLN10]	patterns	passive	affective	static strokes	head	mobile	vibrotactile phone
Rahman and El Saddik [RE11]		passive	affective	strokes	arm	RWVR	vibrotactile scarf
Rahman et al. [Rah+11]	✓	passive	discriminative	static	Up. Body	RW	vibrotactile jacket
Tsetserukou et al. [Tse+10]	✓	passive	affective	static strokes	Up. Body	RWVR	vibrotactile misc.
Zhang et al. [Zha+19]	patterns	passive	affective	strokes	arm	RW	vibrotactile sleeve
Ch. 4: TactileGlove	✓	passive	discriminative	static strokes	hand	RWAR	vibrotactile glove

Table 3.1: Overview of a set of related work in the field of Fine Mechanoreception. Legend: ✓ fulfilled requirement, patterns, active / passive, discriminative / affective, static / strokes, mobile, vibrotactile.

tional overview of the more specific application area of guidance and navigation in HCI.

fine and vibrotactile actuation Yet, while the aforementioned approaches showed the feasibility of mostly mechanical or pressure-based actuations, most related work and typical state-of-the-art solutions primarily evolve around vibrotactile stimuli. These are in most cases easy to deploy and have small form factors to fit easily into wearable devices, such as [PLN10; Tse+10; Tse10; RE11; Zha+19]. While vibrotactile stimuli are suitable for actuating smaller areas of the body, they are also found to be in sleeves [Hui+13], or, for example as done by Bloomfield et al. [BB03], Konishi et al. [Kon+18b], or Lindemann et al. [Lin+06], even applied to the whole body through wearable suits that aimed to enhance the immersion or situational awareness. Due to the advent of modern VR systems, these concepts were also already considered by various commercial or crowdfunded devices, such as Tactsuit[2], KOR-FX[3], Hardlight VR suit[4], or the neosensory vest[5]. Similarly, they also exist devices using voice-coil motors that provide slightly more intense vibrotactile-like stimuli[6]. Rahman et al. [Rah+11] created a jacket with embedded vibrotactile actuators to increase awareness while driving. Further, besides wearable vests, Israr et al. [Isr+12; Isr+14], for example, embedded vibrotactile actuators into furniture to stimulate the user's back.

That being said, vibrotactile stimuli are cost-efficient and effective to convey a lightweight sensation of being touched, emotionally affecting the users [Zha+19; RE11; Cha+09], and even providing moving stroke sensations through phantom sensations [IP11; Bar+09; Els+20b; All70; RE11]. However, although vibrotactile actuations are most suitable for a lot of situations and have low technical constraints, they typically suffer from a limited realism when it comes to the point where a lifelike touch needs to be rendered, e.g., during VR experiences. Further, while research has shown that vibrations (and similar ultrasonic actuations) can recreate textures, even for creating different roughness [CUK14; CK17; WF95], such approaches are still limited in providing haptic stimuli with the same quality as pure physical textures [LTC21; Geh+19].

Further application areas for vibrotactile stimuli are for augmenting multimedia videos [HEE13] or for enhancing remote social communication [Cha+09]. Funk et al. [Fun+16] compared different cues, i.e., visual, audio, and tactile, for error feedback during assembly tasks, while Kosch et al. [Kos+16] investigated these concepts for workers with cognitive impairments. Also, vibrotactile actuation is commonly used for guidance and navigation purposes, which will be addressed in the following chapter in Section 4.3.

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2 https://www.bhaptics.com/tactsuit/ (accessed March 01, 2022)
3 http://korfx.com/products (accessed March 01, 2022)
4 https://www.kickstarter.com/projects/morgansinko/hardlight-vr-suit-dont-just-play-the-game-feel-it/description (accessed March 01, 2022)
5 https://neosensory.com/vest/ (accessed March 01, 2022)
6 https://www.skinetic.actronika.com/ (accessed March 01, 2022)

An overview of the aforementioned works with regards to Fine Mechanoreception is highlighted in Table 3.1.

PRESSURE-BASED ACTUATION AND FORCE-FEEDBACK Although vibrotactile feedback already provides well perceptible stimuli, they are usually only well suited for applications involving Fine Mechanoreception. For more intensive stimuli related to Pressure-based Mechanoreception, which for example should represent a stronger contact with the body, more powerful pressure-based approaches are necessary.

Already in 2005, Suzuki and Kobayashi [SK05] showed a system to provide force feedback based on pressurized air coming from a table. Thereby, users could perceive 2D projections on this surface also in a three-dimensional way. Likewise, Sodhi et al. [Sod+13] and Gupta et al. [Gup+13] created a subtle force-feedback through small air vortices for punctual stimuli, e.g., for Augmented Reality (AR) environments or notifications. Further, some research embedded similar approaches or fans in handheld devices in order to create a counterforce [SKI02; Heo+18]. Similarly, various research evolved around ultrasonic haptics which provides subtle pressure due to ultrasonic sound waves [Car+13; Wil+14; Mar+18]. However, while this can be counted as pressure-based force-feedback in mid-air, the resulting force is still rather low and would stimulate mostly the Fine Mechanoreception.

A large part of this type of research investigated how motor-driven or SMA based devices can pinch, squeeze, or deform the skin in different ways [KR15; GIB17; Sim+20; Sim+21; Mut+20; Yar+17], mostly for the use of notifications or affective touch. Further, other approaches using pneumatics that can inflate small air cushions were explored for pressure-based notifications, e.g., as done by [Poh+17; He+15]. Yet, while notifications are just one use-case, Delazio et al. [Del+18] designed a haptic jacket that used compressed air to inflate silicone cushions at the upper body. With this, they could provide a strong pressure-based actuation in order to increase immersion in VR environments. Based on a similar technique, the commercial haptx[7] glove creates tactile sensation through tiny actuators for the fingers. While not directly creating pressure-based feedback, Lopes et al. [Lop+18; LIB15] used EMS to provide force-feedback and impact forces in Mixed-Reality. In one work, the authors investigated how the muscles of the

7 https://haptx.com/ (accessed March 01, 2022)

	ReqM1. Intensity	ReqM2. Active / Passive	ReqM3. Discriminative / Affective	ReqM4. Static / Stroke	ReqM5. Body Part	ReqM6. Environment	ReqM7. Device Type
Carter et al. [Car+13]	✓	active	discriminative	static	hand	mobile RW	tabletop
Delazio et al. [Del+18]	✓	passive	discriminative affective	static strokes	Up. Body	VR	air/pneumatic jacket
Gupta et al. [Gup+13]	✓	passive	discriminative affective	static	body	RW	air/pneumatic air vortex
Gupta et al. [GIB17]	✓	passive	affective	strokes	wrist	RW	SMA wristband
Heo et al. [Heo+18]	✓	active passive	discriminative	static strokes	hand	VR	air/pneumatic controller
Kettner et al. [Ket+17]	✓	passive	affective	static	wrist	RW	air/pneumatic wristband
Kim and Follmer [KF19]	✓	passive	discriminative	static strokes	arm hand	RW	mechanical/robotic sm. robots
Knierim et al. [Kni+17]	✓	passive	discriminative affective	static	body	VR	drone drone
Knoop and Rossiter [KR15]	✓	passive	discriminative affective	strokes	wrist	RW	SMA wristband
Liu et al. [Liu+21]	✓	passive	discriminative affective	strokes	arm	VR AR	thermal air/pneumatic sleeve
Lopes et al. [Lop+18]	✓	passive	discriminative affective	static	arm	AR	EMS pads
Pohl et al. [Poh+17]	✓	passive	discriminative	static strokes	wrist	RW	air/pneumatic wristband
Simons et al. [Sim+20]	✓	passive	affective	strokes	arm	RW	SMA sleeve
Simons et al. [Sim+21]	✓	passive	discriminative	strokes	arm	RW	accessibility SMA sleeve
Sodhi et al. [Sod+13]	✓	passive	discriminative	static	hand body	RWAR	air/pneumatic air vortex
Suzuki et al. [SKI02]		passive	discriminative	static	hand	VR	air/pneumatic controller
Suzuki and Kobayashi [SK05]	✓	active	discriminative	static	hand	AR VR	air/pneumatic tabletop
Teng et al. [Ten+21]	✓	active	discriminative	static	finger	AR VR	air/pneumatic thimble
Ch. 5: PneumoVolley	✓	passive	discriminative	static strokes	head Up. Body	VR	air/pneumatic pneu. cushions

Table 3.2: Overview of a set of related work in the field of Pressure-based Mechanoreception. Legend: ✓ fulfilled requirement, active / passive, discriminative / affective, static / strokes, mobile, RW Real World, accessibility, air/pneumatic, Shape Memory Alloy (SMA), mechanical/robotic, drone, thermal, Electrical Muscle Stimulation (EMS).

users could be actively stimulated when touching a virtual object, thus, giving the impression of physical contact.

While those approaches mostly focused on direct on-body feedback through wearables, research also used drones to poke users externally [Kni+17], or used a large number of small robots that can convey notifications through pushing the user [KF19].

But also on a smaller scale, more a lightweight pressure-based actuation can be achieved, e.g., through (compressed) air in shape-changing tangibles [Yao+13], in wearable devices for notifications [Ket+17; Poh+17], or for haptic feedback on the fingertips [Ten+21]. Fuji et al. [FNK21], for example, embedded electrohydrodynamic pumps into small tangibles that can inflate polymer chambers with liquids to provide a perceivable raised surface. An overview of some of these works concerning the aforementioned requirements is highlighted in Table 3.2.

3.2.0.2 *Creating Tactile Textures*

Besides the aforementioned works which mainly focus on either *affective* touch or FINE MECHANORECEPTION and PRESSURE-BASED MECHANORECEPTION in general, there is also a large number of works that aim to recreate not only a binary tactile sensation but also to provide haptic textures. Thereby, as objects and surfaces consist of different material characteristics, such as roughness or hardness [ONY13; ONH16], it is essential to find ways to create the fine structures of these and how they are *discriminatively* perceived.

In the following, the related work is grouped into *active* and *passive* touch research. Further, in the last Chapter 6 of this part, a deeper background on visual and tactile influences on MECHANORECEPTION will be provided (see Section 6.3).

TEXTURES FOR ACTIVE TOUCH Most often, research focusing on *discriminative* traits are evolving around *active touch* (cf. 2.1). Thereby, research investigated methods to provide haptic textures with various approaches [Pac+17; WOX20; WYL21]. Thereby, some recreate textures on flat surfaces [Bau+10; Ten+21; Nit+19], while others used vibrotactile arrays directly located on the fingertip [WGS18; Pac+17]. Similarly, research also embedded sophisticated mechanisms into handheld (VR) controllers that can dynamically provide surfaces with different macro and micro-roughness for the hand or thumbs [Whi+18; Ben+16; Kim+09; Cho+18; LTC21]. Other research found methods to recreate roughness and friction of surfaces using a stylus by vibrotactile stimuli [CUK14; CK17] or by directly applying ultrasonic vibrations to surfaces [WF95].

In addition to these approaches, which are usually fixed to a handheld device or attached to a stationary surface, there are also more interactive approaches, such as drones designed to provide tactile stimulation [Hop+18; Kni+17], as well as robotic arms equipped with the capability to interact with different parts of the body [Ara+16; MS94]. An overview of the most important of these works with regard to the aforementioned requirements is highlighted in Table 3.3.

	ReqM1. Intensity	ReqM2. Active / Passive	ReqM3. Discriminative / Affective	ReqM4. Static / Stroke	ReqM5. Body Part	ReqM6. Environment	ReqM7. Device Type
Ackerley et al. [Ack+14]	✓	passive	discriminative affective	strokes	ARM HEAD +	RW	mechanical/robotic rotary motor
Araujo et al. [Ara+16]	✓	active	discriminative	static strokes	HAND	VR	mechanical/robotic robotic arm
Bau et al. [Bau+10]	✓	active	discriminative	static	FINGER	mobile	electric tabletop
Benko et al. [Ben+16]	✓	active	discriminative	static	FINGER	VR	mechanical/robotic controller
Boldu et al. [Bol+19b]		passive	discriminative affective	strokes	ARM	RW	mechanical/robotic mag. powder
Cha et al. [Cha+09]		passive	affective	static strokes	UP. BODY	RW	vibrotactile jacket
Culbertson et al. [CK17]	✓	active	discriminative	static strokes	HAND	RW	vibrotactile mechanical/robotic stylus
Essick et al. [Ess+10]	✓	passive	discriminative affective	strokes	ARM HEAD +	RW	mechanical/robotic rotary motor
Hoppe et al. [Hop+18]	✓	active passive	discriminative	static strokes	HAND	VR	drone drone
Kim et al. [Kim+09]	✓	active	discriminative	static	FINGER	RW	mechanical/robotic mouse
Knoop and Rossiter [KR15]	✓	passive	discriminative affective	strokes	WRIST	RW	SMA wristband
Lee et al. [LTC21]	✓	active	discriminative	static strokes	FINGER	VR	mechanical/robotic controller
Liu et al. [Liu+21]	✓	passive	discriminative affective	strokes	ARM	VR AR	thermal air/pneumatic sleeve
Muthukumarana et al. [Mut+20]	✓	passive	discriminative affective	strokes	ARM	VR	SMA sleeve
Rahman and El Saddik [RE11]		passive	affective	strokes	ARM	RWVR	vibrotactile scarf
Yoshimi Sato et al. [Yos+08]	patterns	passive	discriminative affective	strokes	ARM	mobile	mechanical/robotic vibrotactile glove
Whitmire et al. [Whi+18]		active	discriminative	static	FINGER	VR	mechanical/robotic controller
Zhang et al. [Zha+19]	patterns	passive	affective	strokes	ARM	RW	vibrotactile arm sleeve
Ch. 6: SMOOTH AS STEELWOOL	✓	passive	discriminative	strokes	ARM	VR	mechanical/robotic rail

Table 3.3: Overview of a set of related work in the field of MECHANORECEPTION with regards to active and passive touch. Legend: ✓ fulfilled requirement, patterns, active / passive, discriminative / affective, static / strokes, mobile, RW Real World, air/pneumatic, Shape Memory Alloy (SMA), mechanical/robotic, drone, vibrotactile, thermal, electric.

TEXTURES FOR PASSIVE TOUCH Similarly, related research also investigated methods to recreate textures for applications focusing on *passive touch* (cf. 2.1), i.e., being touched by something, typically on other body parts than the hands. For example, Sato et al. [Yos+08] used an array of small motors with attached fishing lines to simulate ants walking on the arm of the users. Similarly, some approaches used vibrotactile arrays to give the sensation of being touched (or even kissed) for affective touch communication over distance [Zha+19; RE11; Cha+09; Hui+13]. Other approaches by Boldu et al. [Bol+19b; Bol+19a] used an iron powder-infused gel applied to the small hairs on the arm that were then stimulated by a strong magnet hovering over the arm in order to trigger the Fine Mechanoreception. In more recent work, Muthukumarana et al. [Mut+20] were utilizing shape memory alloys (SMA) that change their form by using bimetals allowing for a sensation of being stroked in VR, similar to Knoop et al. [KR15] who used SMAs for a tickling sensation by pinching and stretching the skin. Using a combination of pneumatic and thermal actuation, Liu et al. [Liu+21] presented a system that could provide caress stimuli on the forearm for social touch. In other experiments, such as conducted by Essick et al. [Ess+10] and Ackerley et al. [Ack+14], moving stroke sensations were performed by a rotary tactile stimulator that had different probes attached for different textures touching the participants. However, while Essick et al. investigated the influence of materials with different roughness and hardness on the pleasantness [Ess+10], Ackerley et al. researched the effects of the stroke velocity on the pleasantness [Ack+14]. An overview of some of these works with regard to the aforementioned requirements is highlighted in Table 3.3.

4

MECHANORECEPTION I: FINE TACTILE PERCEPTION

Chapter Overview

Mechanoreception I	Mechanoreception II	Thermoception	Proprioception

Related Publications:

TactileGlove: Assistive Spatial Guidance in 3D Space through Vibrotactile Navigation
PETRA 2018

Exploring Visual, Audio, and Tactile Cues for Synchronous Remote Assistance
PETRA 2018

Hand | Guidance | Vibrotactile | Controlled Experiment | Blindfolded | AR

> *"In humans [..], the hand and its complex neural "backup" is the quintessential tactile organ."*
>
> Ian Darian-Smith, 1984 [Dar84]

Mechanoreception is one of the most involved senses in the somatosensory system [Kaa12]. As introduced in Section 2.2.1, a distinction is often made between Fine Mechanoreception and stronger Pressure-based Mechanoreception depending on the corresponding tactile afferents [Dou97; Joh01; MR10; Mar+09; Ola+10]. In this chapter, the focus lies on the first one of these: concepts for a haptic actuation of Fine Mechanoreception. In particular, this involves a specific emphasis on the hands, which have particularly distinctive tactile receptors due to their glabrous skin, and are mainly involved in processes for *active* touch (see Sections 2.1 and 2.2.1).

Artificially actuating Fine Mechanoreception is often caused by vibrations, which stimulate the skin receptors by high-frequency oscillations. Much research has already investigated how vibrotactile stimuli can be used to simulate (subtle and fine) touch and utilized vibration cues in various use cases. On one side, they can hint analog information, such as a simple contact or attention to a certain direction. On the other side, and probably most familiar from everyday life, vibrotactile stimuli can be used for notifications, for example when receiving a message on a smartphone. In contrast to the direct or analog information of "just" a contact, notifications and other vibration patterns have an iconic meaning that needs to be learned and interpreted by the user. In the case of a notification, this might be short or long vibrations that distinguish from whom a message was received. More complex vibration patterns retain additional informational quality and might be used for iconic navigation purposes. For example, commercial navigation applications, such as Google Maps, use Morse code-like vibrations for subtle directional instructions during pedestrian navigation[1], while research has investigated other navigational cues for guidance via vibrotactile feedback, such as vibrating belts [Heu+08; TY04], spatial guidance applied to the head [KR17; de +17] or foot [Sch+15], or target acquisition in 2D space [Leh+12; Oro+07]. However, these are mostly limited to full body guidance, indirect cues, or one- or two-dimensional spaces.

This chapter investigates how Fine Mechanoreception is perceived on the glabrous skin (see Section 2.2.1) of the hand in form of vibrotactile actuations. Moreover, the chapter explores how vibrotactile feedback can be leveraged to enable direct spatial guidance cues to the hand for precise target acquisition in the three-dimensional space. Therefore, different concepts, such as the guidance method and the number of vibrotactile actuators, were varied and implemented in a prototype referred to as TactileGlove throughout this work. Through a systematic user study, these concepts were then evaluated with 15 participants. An additional second exploratory user study was conducted that investigated the applicability of such vibrotactile stimuli provided directly to the hand in a telecooperative task which is typically based on merely visual and auditory cues.

1 https://maps.google.com (accessed March 01, 2022)

4.1 CONTRIBUTION STATEMENT AND RELATED PUBLICATIONS

This chapter is based on the following publications:

Sebastian Günther, Florian Müller, Markus Funk, Jan Kirchner, Niloofar Dezfuli, and Max Mühlhäuser. "TactileGlove: Assistive Spatial Guidance in 3D Space through Vibrotactile Navigation." In: *Proceedings of the 11th PErvasive Technologies Related to Assistive Environments Conference*. New York, NY, USA: ACM, June 2018, pp. 273–280. ISBN: 9781450363907. DOI: 10.1145/3197768.3197785

Sebastian Günther, Sven Kratz, Daniel Avrahami, and Max Mühlhäuser. "Exploring Audio, Visual, and Tactile Cues for Synchronous Remote Assistance." In: *Proceedings of the 11th PErvasive Technologies Related to Assistive Environments Conference*. New York, NY, USA: ACM, June 2018, pp. 339–344. ISBN: 9781450363907. DOI: 10.1145/3197768.3201568 consulted to and reviewed the design process, contributing his vast experience.

Contribution Statement: I led the idea creation, concept design, implementation, performed the data analysis, and writing process. The former student *Jan Kirchner* supported building the prototype and implemented the study application based on my requirements. *Florian Müller* consulted to and reviewed the design process, contributing his experience. *Markus Funk* supported with his experience on statistical analysis. *Niloofar Dezfuli* and *Max Mühlhäuser* supervised the writing process of the publication and provided their valuable feedback. The second publication (found in Section 4.9) was part of on a internship at FXPAL in Palo Alto, California, and was supervised by *Sven Kratz* and *Daniel Avrahami*, as well as *Max Mühlhäuser* who supervised the initial concepts and writing process with his experience.

❗ *Some contents of this chapter might contain verbatim parts of the aforementioned publications.*

4.2 CHAPTER STRUCTURE

The remainder of this chapter is structured as follows: After the introduction, an overview of guidance approaches using tactile stimuli is given (Section 4.3). Based on this, concepts for using tactile cues on the hand are introduced, followed by their implementation in a prototypical system, called TactileGlove (Sections 4.4 and 4.5). Sections 4.6 and 4.7 then present a controlled experiment and its results that investigated the acquisition of invisible targets by following direct vibrotactile cues on the hand, concluded by a structured discussion and guidelines for future applications (Section 4.8). The findings will then be further discussed with regards to their limitations and future work (Section 4.10). Further, a second exploratory user study was conducted to investigate the usage of vibrotactile cues in a remote collaboration scenario (Section 4.9. The chapter closes by a short concluding summary (Section 4.11).

4.3 GUIDANCE IN HCI

In addition to the related work on Mechanoreception (Section 3.2.0.1), a major application area focuses on guidance in HCI. Most often, this is achieved through on-body tactile cues since those are found to be highly effective and perceivable by humans, cost-efficient, and also proven to be useful for guiding persons with visual impairments (PVI). Research, therefore, investigated navigation capabilities in handheld devices and controllers [CLO20; Chu+21; Jan83], wrist-bands [Tsa+21; Pan+13; SOH18; Sal+18; Elv+19; Rai+17; Leh+12], shoes [Sch+15], or on helmets and Head-Mounted Display (HMD)s [VSB21; Ari+17; de +17]. Weber et al. [Web+11], for example, investigated high-resolution guidance through a vibrotactile wristband to follow a predefined trajectory. Their system used six vibration motors located around the wrist and the authors observed that such feedback had limitations during translation tasks compared to verbal communication, however, performed better during rotational tasks. Further, the authors found positive effects during situations when verbal guidance was limited. However, they mentioned that guidance could be further improved by encoding more information into the vibration patterns, such as the distance.

	ReqM1. Intensity	ReqM2. Active / Passive	ReqM3. Discriminative / Affective	ReqM4. Static / Stroke	ReqM5. Body Part	ReqM6. Environment	ReqM7. Device Type
Ariza N. et al. [Ari+17]	✓	passive	discriminative	static, strokes	HEAD	VR	vibrotactile HMD
Chang et al. [Cha+18]	✓	passive	discriminative	strokes	HEAD	VR	mechanical HMD
Chung et al. [Chu+21]	✓	active	discriminative	static	HAND	VR	vibrotactile controller
Heuten et al. [Heu+08]	✓	passive	discriminative	static, strokes	WAIST	RW	vibrotactile belt
Kaul and Rohs [KR17]	✓	passive	discriminative	static	HEAD	VR	vibrotactile cap
Lehtinen et al. [Leh+12]	✓	passive	discriminative	static, strokes	HAND	RW	vibrotactile glove
Paneels et al. [Pan+13]	✓	passive	discriminative	static, strokes	WRIST	RW	vibrotactile bracelet
Raitor et al. [Rai+17]	patterns	active, passive	discriminative	static	WRIST	RW	air/pneumatic wristband
Salzer et al. [SOR10]	✓	passive	discriminative	static	WAIST	RW	vibrotactile belt
Schirmer et al. [Sch+15]	patterns	passive	discriminative	static	FOOT	RW	vibrotactile shoe
Spelmezan et al. [SHB09]	patterns	passive	discriminative	static	UP. BODY	RW	vibrotactile
Tsai et al. [Tsa+21]	✓	passive	discriminative, affective	strokes	ARM	VR	mechanical wristband
Tsukada and Yasumura [TY04]	patterns	passive	discriminative	static	WAIST	RW	vibrotactile belt
Uchiyama et al. [UCP08]	patterns	passive	discriminative	static	HAND	RW	accessibility, vibrotactile glove
Weber et al. [Web+11]	✓	passive	discriminative	strokes	WRIST	RW	visual impairments, vibrotactile bracelet
Zelek [Zel05]	patterns	passive	affective	static, strokes	HAND	RW	visual impairments, vibrotactile glove
Ch. 4: TACTILEGLOVE	✓	passive	discriminative	static, strokes	HAND	RWAR	visual impairments, vibrotactile glove

Table 4.1: Overview of a set of related work in the field of MECHANORECEPTION with regards to guidance and navigation tasks. Legend: ✓ fulfilled requirement, patterns, active / passive, discriminative / affective, static / strokes, RW Real World, air/pneumatic, mechanical, accessibility, visual impairments, vibrotactile.

Also, besides the aforementioned devices, a lot of research investigated gloves that are augmented with vibrotactile actuators that are supposed to improve pedestrian navigation and guidance. For example, Uchiyama et al. [UCP08] presented a glove for persons in a wheelchair in order to guide them through directional vibrotactile stimuli (though, not using phantom sensations) on a 3x3 vibration motor grid. Paneels et al. [Pan+13] used six actuators on the user's wrist and compared different vibration patterns for indoor navigation. Similarly, Zelek et al. [Zel05] designed a glove for active obstacle avoidance and notifications for PVIs. However, for full-body guidance, tactile belts have been established that vibrate in the horizontal direction of a point of interest or path [TY04; Heu+08; SOR10]. Similarly, but for a 3D space, Kaul et al. [KR16; KR17] encoded spatial information in form of vibrotactile patterns around the head to navigate users. Here, the authors compared their system with AR and audio guidance approaches, namely attention funnels [Bio+06]. Both, visual and vibrotactile, outperformed audio-based guidance with visual having the best ranking. In another work by Kerdegari et al. [KKP16], the authors compared haptic and audio cues for head-mounted augmentation in low visibility environments in a similar way to guide the attention of participants.

Although most of the presented work used vibrotactile cues, there also exist various approaches that use a more direct guidance through mechanical forces. For example, Chang et al. [Cha+18] used small motors mounted to the sides of an HMD to generate torque that resulted in a normal force steering the attention of the user in VR. In a different work, Raitor et al. [Rai+17] used air cushions in a wristband that could be pneumatically inflated for motion guidance, i.e., during medical interventions.

Further, guidance is not limited to navigation but is also interesting from a motion guidance perspective, where tactile instructions help to perform certain body movements [Elv+19; SHB09; Sch+12; Che+16]. Besides vibrotactile stimuli, Goto et al. [Got+18], for example, used a kinesthetic actuation of the hand for more direct motion guidance (cf. Chapter 8).

An overview of important guidance and navigation approaches with regards to Mechanoreception and the aforementioned requirements (Section 3.1) are highlighted in Table 4.1.

4.4 SPATIAL NAVIGATION CONCEPTS

Three-dimensional guidance of the hand allows for diverse approaches to how vibrotactile patterns can be efficiently used for spatial navigation. On the one hand, these are technical decisions, such as the resolution of the actuation or the positioning of actuators. On the other hand, mental models of users have to be taken into account to provide an accurate understanding of how such subtle vibrotactile patterns have to be interpreted. Based on the requirements of Fine Mechanoreception and related work on this topic (Section 3.2.0.1), as well as the previ-

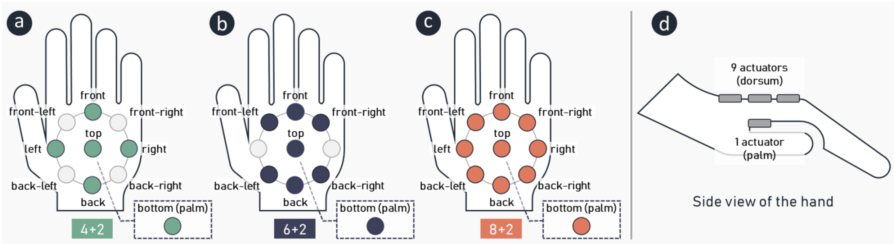


Figure 4.1: Concepts of different arrangements and number of vibration actuators with (a) 4+2, (b) 6+2, and (c) 8+2 actuators in a radial layout. The first number indicates the amount of active actuators on the outer ring, while the +2 represents the top (dorsum) and bottom (palm) actuators. Subfigure (d) show the arrangment from a side perspective.

ously introduced approaches for guidance, this section will introduce concepts for spatial navigation in a full 3D space through vibrotactile actuation on the hand.

4.4.1 *Actuator Placement and Arrangement*

Since the entire environment of a person should be covered to provide full guidance in a 3D space, two types of actuator arrangements are imaginable: (1) a matrix-like or (2) a spatial arrangement.

In a matrix-like arrangement, individual vibration motors can be actuated similarly to a pixel on a two-dimensional display. This makes it possible to reproduce patterns or even to create vibrotactile animations, depending on the resolution of the matrix, e.g., as proposed for guidance instructions for persons in wheelchairs [UCP08; Sch+15]. However, such a setup is typically more suitable for traditional GPS-based navigation systems relying on a horizontal plane for navigation or forces a user to learn different patterns that may not directly reflect the actual direction but have to be interpreted.

In order to provide tactile cues for the complete 3D space, it is necessary to convey all three axes in a meaningful and direct way, at best without the need to learn a multitude of varying patterns. For example by having a spatial arrangement of actuators to directly pin-point directions through directional cues. However, this also means that actuators need to be arranged carefully to be distinguishable by users. For 2D-based navigation, previous research has already shown that circular arrangements are preferable and able to convey such cues effectively [Heu+08; SOR10; TY04]. Similarly, this has to be also adapted for 3D-based navigation to include full spherical coverage of all possible directions. This was, for instance, proven to be effective for full-body guidance through a vibrotactile actuation on the head [KR17]. However, as the hand is independent of the viewing direction and provides much less potential actuation surface but with higher discriminative traits due to the glabrous skin (cf. Section 2.2.1), the quality of such cues might be also dependent on the vibrotactile resolution and further research is necessary.

Following the above insights, glove instrumentation was conceptualized to provide a circular layout on the back of the hand (*dorsum*) for providing directional cues on a horizontal plane as shown in Figures 4.1a-c. Yet, to extend it for all three dimensions, a single actuator in the center of this ring can be utilized to give navigational cues orthogonal to the back of the hand, while another actuator located at the palm does the same for the opposite direction as highlighted in Figure 4.1d.

4.4.2 *Push and Pull*

Besides the layout of actuators, directional cues need to be interpreted by users. Hereby, depending on an applied force on a person, a directional cue can be either a Push or Pull action. However, this typically requires an external force that would mechanically push or pull the person in a certain way. For wearable systems and devices, which should restrict the movement as little as possible, this is difficult to accomplish as large setups may be required.

As an alternative, directional cues can also be conveyed indirectly or iconic, for example through vibrotactile patterns. In such a case, the user has to interpret the cues individually and translate them into physical movements. However, this requires a longer learning phase in order to understand how such indirect feedback has to be interpreted and might change depending on the mental model of users. Therefore, to design an effective guidance system that uses a vibrotactile actuation, direct stimuli pointing in the physical direction seem more suitable. Yet, such

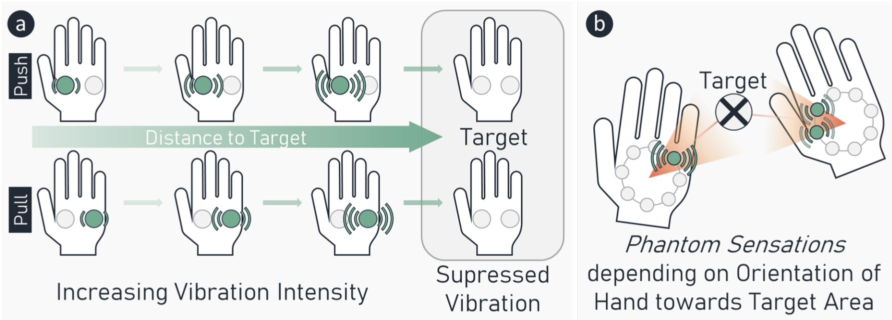


Figure 4.2: Two different actuation methods based on a (a) Push and Pull model. The closer the hand gets towards a target, the stronger the vibration intensity will be. Further, (b) phantom sensations allow for the illusion of a continuous vibration independent of the hand orientation.

direct directional cues can still be interpreted differently, for example as a Push or Pull analogy. In the context of this work, (1) Push and (2) Pull are defined and investigated as follows:

PUSH indicates a stimulus applied to the hand opposing the target, resulting in direction cues that are *furthest* from the actual target, perceived as pushing of the hand. As an example, consider a second person pushing the first person's hand in a certain direction to draw attention towards it.

PULL indicates a stimulus applied to the hand in the direction of the target, represented as directional cues that are *closest* towards the actual target, perceived as dragging or pulling of the hand. For example, one might imagine a person's hand is pulled by a dog on a leash in the direction the dog is walking.

Both approaches are encountered in everyday situations and do not seem to affect the learning curve for haptic guidance [SHB09]. However, while both mappings seem to perform similarly for vibrotactile patterns on the wrist in a 2D-space [Sal+18], it remains unclear to which degree both approaches are preferable for spatially guiding the hand in a three-dimensional manner.

4.4.3 *Continuous Vibrations through Phantom Sensations*

Phantom sensations are a known phenomenon that was already investigated decades ago [All70] and are sometimes also referred to as funneling illusion [Bar+09]. By carefully actuating two or more adjacent vibration motors, it is possible to create the illusion that - depending on the intensity of the actuators - a flowing, continuous movement among the actuators occurs. As a result, fewer actuators are required on a particular surface, and it is possible to create the illusion of intermediate values and finer gradations. Depending on the body part, the distances necessary for a successful phantom sensation are varying. If actuators are too far apart, no fluid or continuous motion can be conveyed. If actuators are too close to each other, they may overlap each other's sensation [Els+20b]. As the hand is surrounded by GLABROUS SKIN, it has a very high resolution of mechanoreceptors (cf. Section 2.2.1). Therefore, adjacent actuators shall be located in a rather small interval, so that their actuation of them is not interpreted as two independent points (two-point discrimination) [JV79; JV83]. In the context of the TactileGlove concepts, a phantom sensation allows for a more precise presentation of directional cues as the vibrotactile actuation can always continuously point straight towards a target independent of the hand orientation (Figure 4.2b). Further, with respect to the spherical arrangement of all actuators (Section 4.5.1), users can rotate the hand in all axes while the vibrotactile cues are updated correspondingly.

4.5 TACTILEGLOVE PROTOTYPE

For the investigation of the different metaphors and possible resolutions of vibrotactile guidance, a prototypical glove was designed implementing the aforementioned concepts: the TactileGlove. As a basis for this, a unisized glove with removed fingertips, as commonly used for cycling, was utilized. For the vibrotactile actuation, ten disc vibration motors with a diameter of 10 mm each were woven into the glove. Eight of them were arranged in a circular array equally distributed on the back of the hand (*dorsum*), one vibration motor was located in the center of this circular array, and another was attached to the lower side of the hand (*palm*). The prototypical glove is depicted in Figure 4.3.

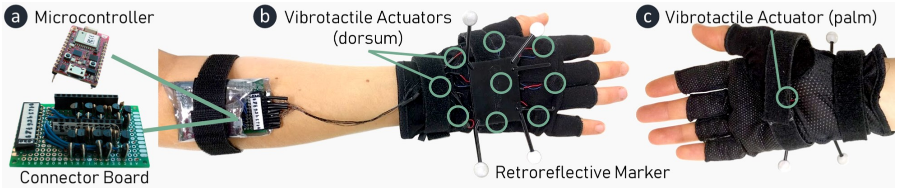


Figure 4.3: The TactileGlove prototype showing the (a) microcontroller and custom connector board. Further, the location of all vibrotactile actuators are shown from a (a) top-down and (b) palm-side perspective.

The ten vibration motors had a nominal voltage of 3.3 V and were regulated by Pulse-Width Modulation (PWM) using an Arduino compatible microcontroller [2] with Bluetooth LE support that received instructions via a separate workstation with an update rate of 60 Hz. In addition, safety diodes [3], transistors [4], and resistors [5] were soldered onto a connector board between the microcontroller and the actuators so no harmful reverse voltages would damage the board (see Figure 4.3c). For better portability, the small microcontroller was attached to a separate pocket on the forearm of the users, leaving the hand as mobile and unobstructed as possible.

An optical motion tracking system (Optitrack) was used to track the position and rotation of the hand, respectively the TactileGlove in the full 3D space. Therefore, a total of six high-speed infrared cameras were pointed toward the users' position and hand that were tracking an arrangement of four retro-reflective markers to be recognized as unique trackables (see Figure 4.3a). This tracking data was then processed by the separate workstation, which calculated the intensity of the actuation according to the absolute distance for a target point in the physical 3D space. This very precise tracking also made it possible to provide full spherical coverage for every possible direction, regardless of the orientation of the hand. This means that independently of how a user rotates the hand, the actuation is always directed at the current target.

2 RedBearLab Duo with Bluetooth Low Energy
3 Superfast Switching Silicon-Rectifier Diodes, FE1B, nominal current = 1 A, repetitive peak reverse voltage = 100 V
4 NPN Epitaxial Silicon Transistor, BC548BTA, collector-emitter voltage = 30 V, $h_{fe} = 200 - 450$
5 Carbon Film Resistors, CFR25JT-52-1K0, Tolerance: 5%, 0.25 W

4.5.1 *Direction and Distance Encoding*

For effective vibrotactile guidance, the vibrations have to be reasonably understood by users. In addition to the actuation metaphor (Push and Pull) and location of the actuators, the vibration pattern is also of importance. As demonstrated in related work (e.g., [LS10; Pan+13; Oro+07]), modulated vibrations are ideal candidates by increasing their FREQUENCY the closer the hand is to a target. Moreover, the direction to the target has to be encoded by vibration patterns as well. To this end, PHANTOM SENSATIONS provide the illusion of continuous actuation even between neighboring vibration motors and consequently require dynamic changes in INTENSITY (cf. Section 4.4.3). For TactileGlove, INTENSITY and FREQUENCY were implemented as follows:

THE INTENSITY of each actuator defines how strong a vibration occurs and is calculated by the angle towards the target. Therefore, a virtual cone with an opening angle of 60°, which was found to be effective during informal tests, is projected from the center of the hand towards the target. All actuators within the cone are included in the intensity calculation in order to achieve a continuous PHANTOM SENSATION (cf. Section 4.4.3). For each of these actuators, the cosine to the perpendicular of the cone is taken as a factor and multiplied by 255 (maximum for the PWM control and a voltage of 5 V). Hence, if there is a direct straight line to the target, the intensity results at full 5 V. On the contrary, the larger the angle to the perpendicular towards the target, the lower the factor down to a minimum of 0.5 (defined by the cosine of 60°). A factor of 0.5 thus equals a PWM value of 128 and 2.5 V, respectively, as voltages below would not operate the vibration motors. In addition, all actuators outside the virtual cone, i.e. an angle to the target greater than 60°, will result in an intensity of 0, as seen in equation 4.1.

$$Intensity = \begin{cases} 5\ V * \cos(\alpha), & \text{if } \alpha <= 60°, \\ 0, & \text{otherwise.} \end{cases} \mid \alpha = \text{angle to target} \tag{4.1}$$

THE FREQUENCY of each actuator defines how often it vibrates within a second. As shown in related work [LS10; Pan+13; Oro+07], changes in the frequency are an effective method to improve spatial awareness of users when a pulsating stimulation with increasing frequency towards the target is performed. In the context of TactileGlove, the frequency was defined as a rather slow 2 Hz for a distance of 1 m and was linearly getting faster the closer the hand gets to a target. The calculation is defined as in equation 4.2. In addition, a suppression of the vibration once the target is reached indicates a successful navigation [Oro+07]. Since the hand cannot be held perfectly steady over a longer period of time, the target is defined to be within a spherical area with an adjustable radius. During informal tests, a radius of 7.5 cm was found to be a reliable reference value.

$$Frequency = \begin{cases} \frac{1}{d \times 2Hz}, & \text{if } d > 7.5cm, \\ 0, & \text{otherwise.} \end{cases} \mid \text{d = distance in meter} \quad (4.2)$$

4.6 USER STUDY AND METHODOLOGY

Methodology Summary — within-subjects design

Controlled Experiment Lab Study Blindfolded Participants	parametric analysis 2-way RM ANOVA	15 participants 6 female, 13 male 20 – 33 years

f(IV)	*f(DV)*
Push/Pull Metaphor Number of Actuators	NASA Raw Task Load Index Target Selection Time Number of Errors

This section introduces the methodology of a controlled experiment assessing how effective users can interpret vibrotactile patterns on the hand for guidance. The aforementioned TactileGlove was thereby used to provide the different navigational cues in a 3D space. Even though the targets were invisible, to reduce effects and distractions from seeing the single actuators vibrating, all participants were blindfolded during the study. In particular, the user study investigated the following research questions for vibrotactile guidance in hand-reachable distances:

RQ1. How do Push and Push metaphors affect spatial guidance?

RQ2. How do different NUMBERS OF ACTUATORS affect spatial guidance?

4.6.1 *Design and Task*

The user study was performed as a within-subjects design. As IV, the GUIDANCE METHOD and NUMBER OF ACTUATORS were varied in a repeated-measures design. For the DV, the TARGET SELECTION TIME (TST) and NUMBER OF ERRORS (NOE) were tracked. Further, the NASA TLX [HS88; Har06] was used to measure the perceived workload. This resulted in $2 \times 3 = 6$ conditions. The first three conditions were either consistently PUSH or PULL, followed by the respective opposite for the latter three. Together with the NUMBER OF ACTUATORS, everything was counterbalanced using a Balanced Latin Square design. All IV and DV are explained in more detail in the following subsections.

4.6.1.1 *Independent Variables (IV)*

There were two IV: (1) NUMBER OF ACTUATORS and (2) GUIDANCE METHOD.

NUMBER OF ACTUATORS (3 FACTORS): The NUMBER OF ACTUATORS consisted of three levels which varied the active vibration motors (4+2, 6+2, and 8+2) as defined in Section 4.4.1. The actual arrangements of all three levels are depicted in Figure 4.1.

GUIDANCE METHOD (2 FACTORS): The GUIDANCE METHOD consisted of two levels, namely PUSH and PULL as defined in Section 4.4.2. For a better understanding, an example of how this two actuation methods are visualized in Figure 4.2a.

4.6.1.2 *Dependent Variables (DV)*

There were three different DV in order to assess the performance using TACTILEGLOVE: (1) TARGET SELECTION TIME (TST), (2) NUMBER OF ERRORS (NOE), and (3) NASA RAW TASK LOAD INDEX (RLTX).

TARGET SELECTION TIME (TST): The TST is defined as the time from starting a trial until a participant confirms a target by clicking the presenter. It was measured in milliseconds.

NUMBER OF ERRORS (NOE): The NoE is defined as the number of wrong confirmations of a target when clicking the presenter during a condition. Training targets are not counted which means that there can be a maximum of 27 errors per condition.

NASA RAW TASK LOAD INDEX (RLTX): The RLTX is a well-established measurement and questionnaire for perceived workload [HS88]. It contains individual questions regarding the mental, physical, and temporal demand, performance, effort, and frustration on 100-point scales with 5-point steps. The overall score is then calculated by the average of each subscale. A lower score is better and means a lower task load. While the original TLX also contains a pairwise comparison of each category, this study did not include it as commonly known as the RAW TLX [Har06]. For more information, see also Section 1.6.

4.6.1.3 *Task*

The task was to identify 5 training targets and 27 real targets during each condition. While the training targets were always identical and intended to familiarize the participants with the current condition, all real targets were evenly distributed in a $3 \times 3 \times 3$ invisible grid-like space in front of the participants (Figure 4.4b). Yet, the order in which the participants had to find the targets was randomized and unknown to them. To find a target, the participants had to follow the vibration patterns coming from the TACTILEGLOVE while being blindfolded. Every time the participants identified a target, indicated by a suppressed vibration, the participants had to confirm it by clicking a provided presenter. If they could not find the current target and wanted to give up a trial, the participants were asked to click the presenter in order to count the trial as an error. Combining all the 6 conditions with the 5 training targets and 27 real targets per condition, the participants had to identify a total of $6 \times (5 + 27) = 192$ targets.

4.6.1.4 *Participants*

In total, 15 participants participated in the study (6 female, 9 male) with an age range between 20 and 33 years (M=25.5, SD=3.8). All of them were right-handed with an average hand length of 18.4 cm and a hand diameter of 20.6 cm which was suitable for the glove design. Most of the participants had no prior experience with vibrotactile feedback (n=11, 73%), one worked with vibrotactile systems before, and three had some experience with haptic feedback in-game controllers. Besides snacks and drinks, no compensation was provided.

4.6.2 *Study Setup and Apparatus*

The apparatus in the form of TactileGlove was employed as outlined in Section 4.5. This included the layout of the vibration motors, their actuation, and the tracking of the hand using a high-precision motion-capturing system. In addition, a backless stool was fixed in the experiment room so that participants would sit in the same spot at all times. The experimenter remained in the back of the room to observe the participants and control the study using a desktop computer. Figure 4.4c shows a participant while performing a condition.

4.6.3 *Procedure*

BEFORE THE STUDY: The participants were first welcomed and introduced to the study. Thereby, they were briefed on the goals, the TactileGlove prototype, and the setup of the study. Once participants had no further questions, they were asked to fill out a demographic questionnaire and consent form.

In the next step, participants were asked to sit down on a fixed stool comfortably. Then, the experimenter assisted with putting on the glove and assured it was fitting tightly but did not restrict arm movements. While sitting on the chair, the experimenter also explained the rough scale of the potential target areas, however, without disclosing exact positions or distributions of any target. Therefore, participants were also asked to remain seated and did not need to reach behind them.

As soon as participants felt comfortable, the experimenter assisted with putting on the blindfold and handed a presenter to their left hand for confirming targets and to proceed to the next trial. However, before starting with the first condition, the participants

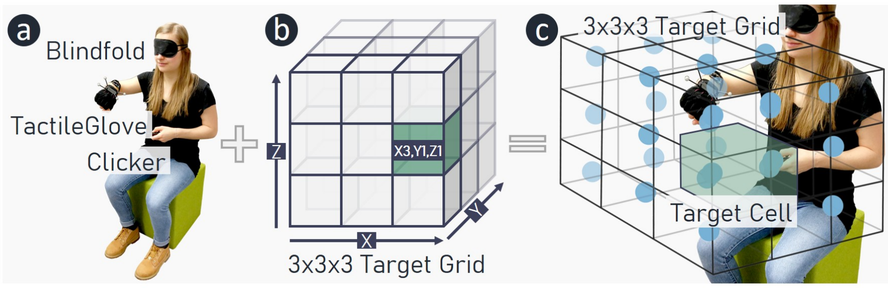


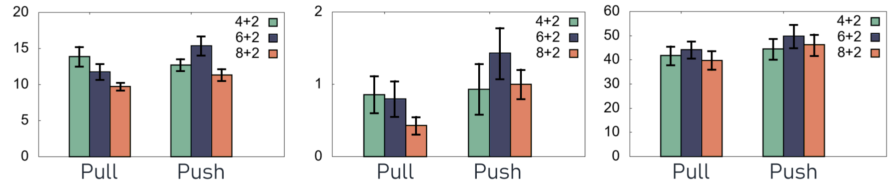
Figure 4.4: Setup of the study with (a) a participant wearing the TactileGlove, a blindfold, and a presenter. The 3x3x3 cube in (b) depicts how the target areas were defined, including an example area at the coordinate 3,1,1 highlighted in green. (c) shows the participant during a target acquisition task.

were introduced to the concepts of the Push and Pull methods and how the vibration patterns are to be interpreted with regard to FREQUENCY and INTENSITY by initiating example vibrations.

DURING THE STUDY: A condition always started by telling the participants the current vibration patterns (Push or Pull, and the number of actuators active). To get familiar with it, five identical training trials always preceded the first real target. However, the five training trials were not communicated to the participants and the 27 real trials started directly afterward in random order. When participants were confident to correctly identified a target or if they wanted to skip the current trial, they had to press the presenter, as described above.

After finishing all training and targeting trials of a condition, an audio notification informed the participants and they could put off the blindfold. Then, the experimenter provided a laptop to answer a questionnaire and NASA Raw NASA-TLX (RTLX). Before proceeding with the next condition, participants could take a break.

AFTER THE STUDY: Once the participants had finished all six conditions, they could take off the glove and blindfold. In a semi-structured interview and post-questionnaire, the participants were asked for overall feedback and rank each condition, as well as for additional qualitative feedback, ideas, and suggestions. Overall, the whole procedure took about 60 to 75 minutes per participant.



(a) Target Selection Time (in seconds)
(b) Number of Errors
(c) Raw TLX score

Figure 4.5: Results of the user study showing the means of the (a) Target Selection Time (TST), (b) Number of Errors (NoE), and (c) Raw TLX (RTLX) score grouped according to the NUMBER OF ACTUATORS and GUIDANCE METHOD. All error bars depict the standard error.

4.7 RESULTS

In this section, the results of the controlled experiment are reported by first describing the performed analysis, followed by the qualitative and quantitative feedback. The latter is further split into general feedback with regards to the interaction with TactileGlove and potential application scenarios.

4.7.1 *Analysis*

To analyze the data, the entire logs were pooled and analyzed using a 2-way repeated-measures ANOVA. If significant main effects were observed, Bonferroni-corrected paired-sampled t-tests were used for pairwise posthoc comparisons. Further, outliers in the data were removed by identifying data points with a deviation from the mean that is larger than three times the standard deviation[6].

4.7.1.1 *Target Selection Time (TST)*

The analysis revealed significant main effects of the NUMBER OF ACTUATORS on the TARGET SELECTION TIME (TST) (p =.02). Post-Hoc analysis further showed significant interaction effects between 4 and 8, as well as between 6 and 8 active actuators (both $p < .05$). There were no sig-

6 outlier if: $\{x \in \mathbb{R} \mid M - 3 \times SD < x < M + 3 \times SD\}$

nificant effects with regards to the GUIDANCE METHOD ($p > .05$) and no significant interaction effects were found ($F_{2,78} = 2.172$, $p > .05$).

Overall, during PULL conditions, participants performed faster than using PUSH ($M_{pull} = 11.84\ s$, $SD_{pull} = 4.63\ s$ and $M_{push} = 13.24\ s$, $SD_{push} = 4.55\ s$). Looking into more detail, participants performed best when having 8+2 NUMBER OF ACTUATORS, followed by 6+2 and 4+2 during the PULL conditions (Pull: $M_{8+2} = 9.72\ s$, $SD_{8+2} = 2.33\ s$, $M_{6+2} = 11.78\ s$, $SD_{6+2} = 4.26\ s$, and $M_{4+2} = 13.89\ s$, $SD_{4+2} = 5.77\ s$). Similarly, during PUSH conditions, 8+2 performed better than 4+2 and 6+2 (Push: $M_{8+2} = 11.33\ s$, $SD_{8+2} = 3.48\ s$, $M_{6+2} = 15.38\ s$, $SD_{6+2} = 5.5\ s$, and $M_{4+2} = 12.69\ s$, $SD_{4+2} = 3.4\ s$). All results are depicted in Figure 4.5a.

4.7.1.2 *Number of Errors (NoE)*

The analysis showed significant main effects of the GUIDANCE METHOD on the NUMBER OF ERRORS (NOE) (p =.048). No significant main effects were found for the NUMBER OF ACTUATORS ($p > .05$) nor interaction effects ($F_{2,82} = 1.193$, $p > .05$).

Overall, during PULL conditions, participants were able to identify more targets and did less errors than during PUSH conditions ($M_{pull} = .7$, $SD_{pull} = .89$ and $M_{push} = 1.33$, $SD_{push} = 1.92$). Within PULL conditions, participants made the least errors when having 8+2 NUMBER OF ACTUATORS, followed by 6+2 and 4+2 (Pull: $M_{8+2} = .43$, $SD_{8+2} = .51$, $M_{6+2} = .8$, $SD_{6+2} = 1.01$, and $M_{4+2} = .86$, $SD_{4+2} = 1.03$). In contrast, during PUSH conditions, 4+2 active actuators resulted in less errors than 8+2 and 6+2 (Push: $M_{8+2} = 1.0$, $SD_{8+2} = .85$, $M_{6+2} = 2.07$, $SD_{6+2} = 2.82$, and $M_{4+2} = .93$, $SD_{4+2} = 1.44$). All results are depicted in Figure 4.5b.

4.7.1.3 *NASA Raw Task-Load-Index (RTLX)*

The analysis could not reveal any significant main effects on the NASA RAW TASK-LOAD-INDEX (RTLX) ($p > .05$), as well as no interaction effects ($F_{2,84} = .108$, $p > .05$).

Both, for PUSH and PULL conditions, participants rated the RTLX on a similar level ($M_{pull} = 42.02$, $SD_{pull} = 16.34$ and $M_{push} = 46.9$, $SD_{push} = 17.81$). For PULL conditions, the lowest scores were given a NUMBER OF AC-

TUATORS of 8+2, followed by 4+2 and 6+2 (Pull: $M_{8+2} = 39.87$, $SD_{8+2} = 16.78$, $M_{6+2} = 44.27$, $SD_{6+2} = 14.55$, and $M_{4+2} = 41.93$, $SD_{4+2} = 16.34$). During PUSH conditions, 4+2 performed better than 8+2 and 6+2 (Push: $M_{8+2} = 46.25$, $SD_{8+2} = 18.06$, $M_{6+2} = 49.97$, $SD_{6+2} = 19.2$, and $M_{4+2} = 44.49$, $SD_{4+2} = 16.91$). All results are depicted in Figure 4.5c.

4.7.2 *Qualitative Feedback*

Participants were invited to give verbal feedback throughout the study, and written feedback during the post-questionnaire. In general, the spatial guidance with the TACTILEGLOVE was found to be a novel concept and was a new experience for the participants. The vibrotactile feedback was described as "*quite simple, can instantly be understood and used*" (P5), as well as "*an interesting experience to use the glove*" (P2). This was further supported by high success rates as "*it eventually brings you to the target and gives you a feeling of success*" (P4). The analysis showed that conditions with a PULL generally performed better than PUSH. However, some participants thought their performance was best using PUSH, yet, still felt more confident during PULL.

Some of the participants reported having issues distinguishing single actuators. In particular, the location of the top and back actuators was occasionally felt too close. This also was the case for the top and bottom actuators and P12 stated that "*the localization of the vibrators on the back of the hand are a bit difficult to differentiate from up and down*". Participants sometimes also reported that "*the lower vibration motor felt stronger*" (P12) or "*the impression on the backside of the hand was harder*" (P7). Those issues were mostly observed if participants had rather slim hands.

The TACTILEGLOVE as a wearable was found to be "*lightweight and fits the hand very well*" (P15), while one participant even described it to be "*cuddly*" (P10). However, the prototype used a unisized glove, and participants with smaller hands expressed that vibration motors should have been "*closer to skin*" (P1) and "*tighter*" (P13).

4.7.2.1 *Potential Use-Cases suggested by Participants*

In addition to the aforementioned feedback, participants provided ideas for potential future use-cases during semi-structured interviews after finishing all conditions. Hereby, the experimenters asked explicitly for real-world situations where the participants could imagine using such vibrotactile guidance.

Participants were highly motivated during these questions and thought of a large number of potential situations. Most often, chances for supporting persons with visual impairments were highlighted as "*hands are free for other work and things can be done blind(-folded)*" (P7). Thereby, the vibrotactile guidance can assist while trying to "*find objects without looking*" (P2), "*support for visual search*" (P10), and "*positioning an object precisely with vibration help*" (P7). As a more specific example, P3 described it as support for "*visually impaired persons* [..] *to find buttons like door-openers in public transport or at traffic lights*". Independent of the assistive aspects, P12 suggested using the TactileGlove to faster find "*groceries in a supermarket*".

Another suggestion was to use vibrotactile guidance on the hand for educational purposes, such as support for art classes where the hand could be guided to follow a path while painting. Similarly, P11 highlighted positive effects for learning handwriting in school and P7 suggested it for "*teaching driving*". However, this would require even more fine-grained actuations. Other potential use-cases encompassed situations where "*some kind of physical interaction is required*" (P1) during industrial tasks, or for "*medical tasks like surgeries*" (P13) and "*maintenance tasks* [..] *at a machine*" (P5). Nevertheless, for such an environment, participants explained the device has to be "*more robust to be used in industrial scenarios*" (P13).

Also, the usage of such a system for haptic feedback in AR/VR environments was mentioned (P6). This participant further elaborated that an increase in the number of actuators with a "*a finger-granularity* [..] *might be good to feel virtual objects and perceive them as tangible*" (P6). Considering AR situations, some participants (P6, P8, P15) named gaming purposes to benefit from haptic feedback, however, did not stat explicit examples.

4.8 DISCUSSION AND GUIDELINES

The analysis and feedback from the participants showed that fine-grained guidance in close range to them is achievable through vibrotactile actuation on the hand. However, the performance of the guidance is highly dependent on the NUMBER OF ACTUATORS as well as the GUIDANCE METHOD. In this section, three design guidelines are presented and discussed for future guidance applications.

4.8.1 *Prefer Pull over Push*

The results showed significantly better performances for following vibrotactile patterns during Pull conditions. Participants were able to identify and select targets on average about 20% faster while doing fewer errors or giving up. This was further supported by the qualitative feedback of participants who typically preferred a Pull guidance method as more natural and intuitive. Still, the effects on the task load (RTLX) were slightly lower for Push conditions and some participants subjectively thought they performed better during those conditions. However, no significant effects were confirmed during the analysis and further research is necessary with regard to the task load.

4.8.2 *Higher Actuators Resolutions are more effective*

Conditions using 8+2 actuators always resulted in a lower Target Selection Time (TST), Number of Errors (NoE), and task load (RTLX) when using Push, and were seconded by 6+2. While using phantom sensations, vibrotactile guidance was still working for a lower NUMBER OF ACTUATORS, however, more fine-grained actuations with less physical spacing between actuators helped to increase the overall performance. This is in alignment with statements of participants that described that fewer actuators are better distinguishable. However, requiring a high distinguishability was shown to be less important than a high precision of the guidance as the target acquisition time would have been longer. Also, further research is needed to identify when this effect is no longer given and a maximum resolution is reached. In any case, designers always have to consider a trade-off between wearability and effectiveness depending on the use case.

4.8.3 *Equal Distances between Actuators are important*

The results are indicating another interesting effect that was observable when comparing 8+2 and 4+2 active actuators with 6+2. In almost all cases the first two layouts were faster or more reliable ways to perform the targeting task, even in cases with 4+2 which has fewer motors. Yet, during 6+2 conditions, the outer ring of actuators had two disabled motors that were located on the left and right sides of the hand. This had the effect that the distance between two neighboring motors could be slightly varying compared to the two other layouts that were always having an equidistant spacing. However, this negative impact for 6+2 conditions could also come from missing cardinal directions as participants might map the vibration patterns like a compass on the hand, thus, anticipating stronger signals coming from the left or right side. Therefore, as a general guideline, there is a tendency to take care of both aspects and always provide actuators in cardinal directions of the hand, but also locate vibrotactile actuators with the same distance between each neighbor.

4.9 EXPLORATORY STUDY: VIBROTACTILE GUIDANCE FOR REMOTE ASSISTANCE

Methodology Summary — mixed-subjects design

Controlled Experiment Lab Study Two Participants as Team	parametric analysis 2-way RM ANOVA	8 participants 4 female, 4 male 20 – 50 years

f(IV)
Voice-Only, Audio, Visual, or Haptic Cues
Participants either Worker or Expert

f(DV)
NASA TLX Task Load Index
Task Completion Time
Ranking of Cues
Questionnaires:
Effectiveness, Distraction, Overall Ratings

A potential use case for vibrotactile guidance in a user's nearby surroundings can be found in the area of remote collaboration and assistance. There are often complex situations in which an inexperienced person needs the help of an experienced expert. Despite modern video conferencing solutions, they may be inadequate in certain situations, for example when objects are occluded by others or objects are out of

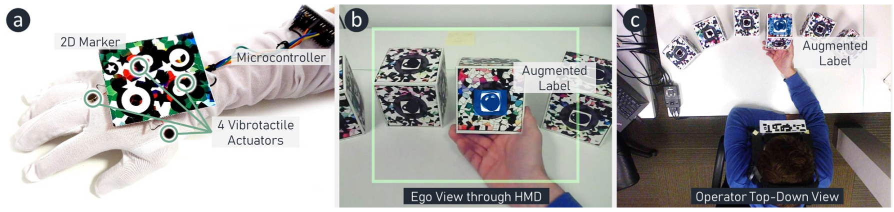


Figure 4.6: Views during the study showing (a) the vibrotactile glove, (b) view through the HMD with recognized object and additional AR label, and (c) top-down view of the same scene as seen by the operator.

the camera's field of view. In this section, an exploratory study investigates how vibrotactile guidance for the hand performs against auditory and visual feedback. Through an abstracted task that required active communication between two remote parties, participants were asked to use the different cues to form an effective team.

4.9.1 *Study Design*

The study used a between-subjects design with two participants either acting as REMOTE EXPERT or FIELDWORKER together. As IV, three different supporting cues were compared with verbal communication only as a baseline. The supporting cues were (1) verbal communication, (2) visual cues, (3) audio cues, and (4) tactile cues (as described in Section 4.9.2).

As for the DV, a questionnaire after each condition was used, asking for feedback on the provided cues. Further, the TCT was measured for each condition.

In a final post-questionnaire, the participants had to rank each condition with regards to their perceived EFFECTIVENESS and DISTRACTION, as well as an OVERALL RATING.

4.9.2 *Study Setup and Apparatus*

The setup was divided into two areas so that two different roles for each participant group could be performed separately: (1) the remote expert, and (2) the fieldworker space.

In the remote expert space, a common desktop computer was available to run the operator study application. This application offered both, a first-person view of the fieldworker and a top-down view of the field-worker's workspace. In either of these views, the expert could perform a simple click to set a tactile, auditory, or visual cue, depending on the condition, which was then passed to the fieldworker. Additionally, a headset was provided for the expert to communicate verbally. A printed codebook with the sorting sequences was also provided for the specific tasks.

On the fieldworker's side, a workspace was provided with six similar-looking boxes for performing the tasks. The boxes had different weights between 100 g and 1,100 g in 200 g steps, without the weight of the boxes being visually recognizable. Also, the fieldworker was equipped with a HMD[7] and headset. During conditions with tactile cues, the fieldworker also wore the TactileGlove provided in the room.

An additional top-mounted camera[8] was located in the fieldworker's room to track the position and orientation of the boxes, the HMD, and the hand. The camera image was broadcast to the remote expert, as was the first-person perspective of the fieldworker through the HMD.

4.9.2.1 *Audio Cues*

Audio cues were presented in form of stereo signals. Depending on the head orientation of the fieldworker, a subtle sound loop was hearable either on the left or right ear. The closer the fieldworker's view was towards the marked target, the louder the audio cue got. If the view was directly towards the target, both stereo channels were active and the sound loop changed the frequency.

7 META1 augmented reality glasses
8 Microsoft Kinect 1

Figure 4.7: Setup of the study showing (a) the fieldworker space with a top-mounted Kinect for tracking, (b) the fieldworker wearing the HMD, headset, and boxes of the task in front, and (c) the working space of the operator including the codebook for solving the task.

4.9.2.2 *Visual Cues*

Visual cues were presented in form of virtual labels augmented directly to the view of the fieldworker. Each label was translucent and was either a simple marker or could contain custom text. If the label was outside of the view, the respective side of the view was highlighted by a visual indicator.

4.9.2.3 *Tactile Cues*

Tactile cues were presented through vibrotactile patterns on the hand by the TactileGlove. As the task was based in a 2D space, only four vibration actuators were active, depicting the direction towards a selected target through phantom sensations. Similar to the aforementioned prototype, the frequency of the vibration increased the closer the hand gets towards a target. Only the suppression of the pattern was not included as the remote experts were asked to do it manually once the fieldworkers reached a target.

4.9.3 *Verbal Communication*

Verbal communication was available during all conditions to recreate a realistic environment. However, it was also the baseline condition where no additional cues were active. The communication was done as a bi-directional voice-to-voice interface, similar to traditional audio calls using a headset.

4.9.4 *Task and Procedure*

The task should represent an abstracted version of a typical scenario where two parties with different knowledge about a situation have to work together and actively communicate to solve the problem. For example, this could be a situation where a first-aider has to contact a doctor or paramedic to help during an emergency or a situation where a worker in the field has to fix a broken machine and has to contact an expert of the vendor. The task was created with this in mind and the procedure was as follows:

After welcoming the participants, introducing them to the study, and assigning them to one of the two roles, they had to solve the task as follows:

(1) A prepared order of the six boxes by the experimenter was presented to the fieldworker who had to communicate them to the remote expert.

(2) Based on this initial order, the remote expert then had to find the box pairs that have to be compared by their weight by the fieldworker.

(3) The fieldworker then compared the box pairs and had to communicate which box is lighter or heavier.

(4) Based on the comparison, the expert looked up the final order in the provided codebook, which had to be communicated a last time to the fieldworker.

(5) The fieldworker now had to put the boxes in the final order. Once both sides agreed to have solved the task, the experimenter stopped the trial.

The experimenter encouraged the participants to actively use the provided cues that were available in each condition. Further, they were asked to try out how they can achieve their ideas with it but were completely free in how they were using the cues.

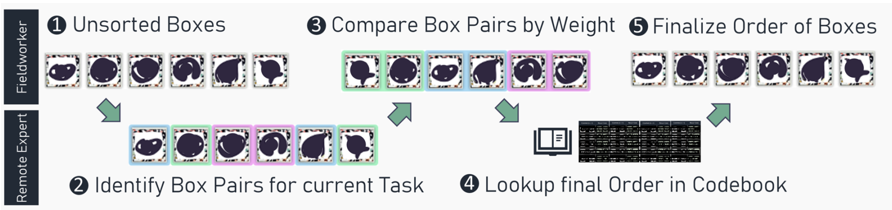


Figure 4.8: Sequence of the task solving process. (1) The fieldworker had to communicate the initial order of the boxes to the remote expert, (2) then the expert had to identify the boxes to compare, (3) the fieldworker had to compare them as told by the expert and communicate the weights back. (4) In a final step, the expert had to figure out the final order in the codebook (5) which had to be communicated one last time to the fieldworker who had to sort it accordingly.

After each condition, the participants were asked to fill out a questionnaire as described in Section 4.9.1. Once all conditions were completed, a final questionnaire had to be answered which should emphasize overall feedback on each cue.

4.9.5 *Observations and Discussion*

In this section, the results of the study are discussed. Due to the low number of participants and explorative nature of the study, no statistical analysis was performed and the focus was on the qualitative feedback given.

Overall, verbal communication was strongly used and participants were able to find a common ground quickly [FK89]. Besides that, participants ranked visual cues as most effective, followed by tactile and audio cues. With regards to the TCT, verbal communication and audio cues were fastest while visual and tactile cues remained on a similar slightly slower level (verbal: $M = 2:55\,min$, audio: $M = 2:29\,min$, visual: $M = 3:13\,min$, tactile: $M = 3:14 min$). Although, the times are not reliable given the low number of repetitions and the experimenters could observe that the times often varied considerably when participants tried out new cues first, the study could show useful insights into how participants relied upon and interacted with these cues as discussed in the following.

4.9.5.1 *Audio Cues*

AUDIO cues were mostly disliked as participants described them as distracting and not very effective. While one participant acknowledged that "*the sound was interesting and somewhat intuitive*" (W1), the general observation was that participants were insecure in identifying the correct box if there was another box too close by. Interestingly, W3 reported that audio cues "*helped to get to the right place more quickly than the verbal instructions*". However, W1 stated that they "*did like the audio signals* [..] *it may have overloaded the aural channel with the voice contact*". In contrast, one remote expert described AUDIO cues as effective as "*audio seemed to help the worker a little bit more*" (E4).

4.9.6 *Visual Cues*

VISUAL cues were reported to be the most effective from both parties as they were "*able to see the match without the urge to describe it*" (W3) and "*it took less time to describe which boxes to chose*" (E1).

However, the VISUAL cues could overlay the real world too much and, thus, reduce the ability to focus. W3, for example, suggested that "*a brief flash*" rather than a constant visualization could improve this modality. Also, technical limitations of the HMD did not work well for people with debility of sight, making it hard for them to see the contents.

4.9.7 *Tactile Cues*

TACTILE cues were a novelty for the participants and appreciated "*the concept in general* [..] *for guidance*" (W3). However, this also meant that participants reported needing "*more time to learn the patterns*" (W4). As a result, fieldworkers also often asked if the expert meant a certain box when hovering over it with their hand. Therefore, one expert found the accuracy too low and "*gave up sending tactile feedback* [..] *from the middle of this task*" (E1). However, W2 said the TACTILE stimuli were "*a helpful additional reminder*".

While this study investigated the applicability of TACTILE cues in a preliminary experiment, they remain an interesting support when objects are hardly visible or workers have to visually focus on something else. Further, the study showed that TACTILE cues, even when used in such a direct form, need additional training phases in order to better compete with the strong VISUAL cues and VERBAL communication that people are typically familiar with.

4.9.8 *Verbal Communication*

The VERBAL communication was often enough for this task and participants thought that it "*might be enough for most of the use cases*" (E1). While the task was kept simple and boxes to sort were hard to verbally describe at first, participants started to have a common ground very fast [KFS03].

Also, because the TACTILE and AUDIO cues were something new for them, participants used to describe what they can feel or hear. For example, "*I hear a sound on my left now*" (W4) or "*it is guiding me to this box, is this correct?*" (W2). While using VISUAL cues, this effect did not occur. However, when using VERBAL communication only, participants often just described what they see and used a lot more communication overhead as they more often acknowledged what they mean. Although, experts intervened if workers reached for the wrong box.

As such, future systems should always support VERBAL communication as a base channel as speech will remain a powerful tool. However, if situations are noisy, other cues, such as the VIBROTACTILE or VISUAL, should be used as additional support.

4.10 LIMITATIONS AND FUTURE WORK

With the TactileGlove prototype, vibrotactile guidance for the hand in a full 3D space could be shown feasible and effective. Still, there exist some limitations that should be addressed in future research. Further, additional studies can help to better understand how such a system performs in other situations.

4.10.1 *Guidance Improvements*

The concepts implemented in the TactileGlove prototype were reliably conveying spatial information to the participants. However, some of the patterns were not completely convincing or harder to distinguish. As such, the up and down actuators that were located in the palm and center of the backside of the hand were sometimes too similar to other actuators around. Therefore, a few participants during the first study could be observed to rotate their hand more often and rely on the outer ring of actuators, thus, ignoring the other two. This might be improved by re-locating the *up* and *down* actuators or giving them more unique characteristics. For example, they could in general have a stronger intensity to be perceived as more present and distinct. However, further research is necessary.

Additionally, the frequency of the vibrotactile patterns was intentionally lower when targets were further away from the hand, as suggested by related work. However, if the distance was too large, the frequency tended to be too low and less recognizable by participants. As a potential improvement, a minimum threshold of the frequency should be considered for larger distances.

4.10.2 *Accessibility Studies*

As stated in the motivation of this work, accessibility is a highly relevant topic and accessible guidance for persons with visual impairments, in particular, is more relevant than ever before due to fast-changing and distracting situations around them. The TactileGlove concepts can assist in situations, such as finding buttons in public transport, reaching objects in close but unknown range, or giving spatial cues during navigation, by conveying information in subtle and non-stigmatizing ways as the whole device could be worn as a regular glove.

Yet, while accessibility was in mind, the first user study was performed only with blindfolded participants and further studies are necessary to deepen the insights on how the vibrotactile patterns can be perceived by persons with visual impairments.

4.10.3 *Virtual Reality Capabilities*

The TactileGlove system was suitable for a blindfolded guidance task and in remote assistance scenarios. However, it is still unknown to what degree the glove can render haptic feedback in complex VR or AR environments. For example, related research already investigated how vibrotactile grids on the head or wrist can be leveraged in VR [KR17; Pez+19], as well as how vibrotactile actuation can support the perception of a virtual object or canvas [KG18; Els+20a]. Yet, the presented prototype in this chapter was found to also convey the presence of invisible objects as participants sometimes described that they could feel the target zone as a sphere during the blindfolded experiment.

4.10.4 *Tracking of Environment*

Currently, the presented approach used external tracking in form of expensive infrared motion tracking during the first study. While this approach provided a high accuracy with a very fast update rate, it is not suitable for real-world appliances as it always has to be installed in a fixed location with a cumbersome calibration process. During the remote assistance study, a more easy-to-deploy tracking was used, however, the Kinect tracking is generally less accurate.

As such, future devices could be improved with two visionary solutions. First, as already known from modern AR glasses, such as the Microsoft Hololens, constant tracking of the environment through a set of embedded cameras might allow for a high-resolution 3D map of the surroundings. However, in the current state, the tracking is still not accurate enough for high-fidelity recognition and localization of small spots, and the tracking needs to know what it "sees", e.g., through well-trained machine learning models. Second, the environment itself could provide information about how it "looks". For example, street lamps could gather context information about their surroundings, or buttons on street crossings could send their location to the user. A TactileGlove-like system then could identify its world position through the ubiquitous information coming from beacons in the environment, and also recognize which interaction methods or guidance possibilities are available for the user.

4.11 CONCLUSION

This chapter investigated vibrotactile stimuli for Fine Mechanoreception. Thereby, it was shown how vibrations on the skin surface were perceived by users and how this perception was affected by actuations with different parameters and intensities. After introducing interaction concepts for using vibrations for spatial guidance, a prototypical glove was designed that was capable of mapping directional instructions for all three dimensions. Through a systematic user study, it could be shown that a PULL metaphor, i.e. the actuation of vibrators closest to a target point, was the most intuitive to follow and easiest to interpret by the participants. Furthermore, a higher resolution of the actuation supported the effectiveness of conveying fine-grained directional instructions.

In a second exploratory user study, this chapter applied the vibrotactile guidance to a remote assistance task in which participant pairs had to effectively and efficiently solve an abstract task remotely. Therefore, the haptic cues were compared to visual and auditory cues. While it was found that haptic cues took longer to be interpreted, they were seen as a useful addition to support the dominant visual or auditory sensory system.

In summary, this chapter emphasizes the importance and ability of Fine Mechanoreception to detect subtle stimuli on the skin. In particular, the studies showed how such stimuli were even precisely detectable on the smaller surface of the hand. In the scope of somatosensory interaction, addressing Fine Mechanoreception is, therefore, an important factor to give explicit instructions to users to convey spatial information without overloading the haptic perception. However, while this type of feedback was ideal for these tactile instructions and participants even reported to *feel* the spherical target areas during the first study, more intense contacts, e.g., when touching or being touched by virtual objects, require stronger actuation, such as pressure-based feedback that will be addressed in the following chapter.

5

MECHANORECEPTION II: PRESSURE-BASED FEEDBACK

Chapter Overview

Mechanoreception I | **Mechanoreception II** | Thermoception | Proprioception

Related Publications:

PneumoVolley: Pressure-based Haptic Feedback on the Head through Pneumatic Actuation — **CHI EA 2020**

PneumAct: Pneumatic Kinesthetic Actuation of Body Joints in Virtual Reality Environments — **DIS 2019**

Body | Head | Force Feedback | Pneumatic Actuation | Controlled Experiment | VR

As previously mentioned, Mechanoreception is commonly subdivided into Fine Mechanoreception and Pressure-based Mechanoreception. After having investigated the first in the previous chapter, this chapter focuses on pressure-based stimuli. Albeit both types of Mechanoreception mostly interplay, pressure-based stimuli differ in that external forces with more intensity elicit stronger and deeper contact with the skin. These more forceful contacts further differ to the extent that a touch often produces a skin deformation at the pressure point, rather than mere superficial contact with the skin.

Therefore, such pressure-based stimuli are always essential when there is physical contact with a solid (virtual) surface or external force, for instance in the case of physical contact with other persons, contact with solid objects, and collisions with objects or surfaces. In the case of modern AR or VR applications, this type of haptic feedback is particularly valuable, since virtual overlays and obstacles are intangible and cannot be reached physically. Accordingly, novel approaches must be found to create the illusion of a tangible experience and contact with the environment, also in the form of a counterforce.

This chapter, therefore, investigates how pressure-based stimuli for touch, contact, and collisions on the body in form of *passive* touch can be haptically rendered. In the first step, requirements were derived based on related and existing work. Based on these requirements, a pneumatic-based approach was designed, using air cushions inflated by compressed air to provide a pressure-based actuation. In particular, through variable actuator sizes and placements on the body, this prototypical system allowed to perceive the virtual environment in a physical form. As a proof-of-concept, the novel interaction concepts for Pressure-based Mechanoreception were implemented in two VR applications. One of them, named PneumoVolley, was afterward systematically investigated in a user study focusing on realism and presence.

5.1 CONTRIBUTION STATEMENT AND RELATED PUBLICATIONS

This chapter is based on the following publications:

Sebastian Günther, Dominik Schön, Florian Müller, Max Mühlhäuser, and Martin Schmitz. "PneumoVolley: Pressure-based Haptic Feedback on the Head through Pneumatic Actuation." In: *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems (CHI EA '20)*. New York, NY, USA: ACM, Apr. 2020, pp. 1–10. ISBN: 9781450368193. DOI: 10.1145/3334480.3382916

Sebastian Günther, Mohit Makhija, Florian Müller, Dominik Schön, Max Mühlhäuser, and Markus Funk. "PneumAct: Pneumatic Kinesthetic Actuation of Body Joints in Virtual Reality Environments." In: *Proceedings of the 2019 on Designing Interactive Systems Conference*. New York, NY, USA: ACM, June 2019, pp. 227–240. ISBN: 9781450358507. DOI: 10.1145/3322276.3322302

Contribution Statement: I led the idea creation, concept design, implementation, performed the data analysis, and writing process. The former student *Mohit Makhija* supported building the initial pneumatic-based prototypes and with the conduction of the studies. The former student *Dominik Schön* supported the implementation of the second Virtual Reality application. *Florian Müller* and *Markus Funk* consulted to and reviewed the design process and shared their experiences for the statistical analysis of the data. For the second publication *Martin Schmitz* supported the writing process by sharing his experiences. *Max Mühlhäuser* supervised and supported the writing process of both publications and gave valuable feedback during the design process.

❗ *Some contents of this chapter might contain verbatim parts of the aforementioned publications.*

5.2 CHAPTER STRUCTURE

The remainder of this chapter is structured as follows: After this introduction, a set of requirements and concepts for a successful pressure-based actuation are presented (Section 5.3). Based on those, a prototypical proof-of-concept was implemented using pneumatically-driven actuators together with a proof-of-concept application (Section 5.4). Then, the concepts were deepened to pressure-based feedback on the head as this part of the body requires even a more careful actuation, and evaluated in a controlled experiment (Section 5.5). Section 5.6 presents the results which are then discussed in Section 5.7. The chapter closes by discussion current limitations (Section 5.8) and a short concluding summary (Section 5.9).

5.3 PRESSURE-BASED FEEDBACK

Pressure-based stimuli allow a wide range of applications. This being that, the requirements always depend on the application, the environment, and also on the actuated body parts. For example, smaller body parts should have appropriate small actuators. Larger body parts, however, can accommodate larger actuators, or similarly small actuators but with a higher resolution. In the following, requirements and concepts for pressure-based actuation are defined, in addition to the general requirements for MECHANORECEPTION as presented in Section 3.1.

REQP1. PROVIDE FITTING ACTUATOR DIMENSIONS

The size of the actuators takes a decisive factor in the design in order to provide a fitting experience. Therefore, the size of the actuated body part in correspondence to the contact has to be taken into account, and actuators should not exceed the available space nor be too small for larger areas of the body.

REQP2. PROVIDE APPROPRIATE RESOLUTION OF ACTUATION
Typically, the higher the resolution, the more precisely body parts can be actuated depending on the given space. Though, a higher resolution also yields in potential higher energy consumption and requires more complex control mechanisms. To mitigate this demand, phantom sensations as known from vibrotactile feedback can be also applied to a pressure-based actuation (cf. [All70; PC18] and also see Section 4.4.3). Thereby, two or more actuators can be interpolated to provide the illusion of a larger actuation while reducing the overall resolution.

REQP3. PROVIDE VARYING APPLIED PRESSURE
The pressure should be adjustable to provide enough stimulation to the body but without harming the user. Therefore, careful thresholds need to be identified beforehand to reproduce a life-like sensation of forces that do not apply too much pressure. For example, research has shown that 300+ kPa are usually harmless when applied to most body parts that consist of a large buffer of adipose tissue or musculature between the skin and skeleton (e.g., [Del+18; Gün+19]). However, other body parts, such as the head, do not have such a large layer of fat which results in a lot more direct pressure force on the skull. Further, as the head also hosts the brain, no damage should occur to the brain cells which are easily harmed even by forces of softer head balls during football matches [Dur18; Has+13].

REQP4. PROVIDE VARYING ACTUATION PATTERNS
Actuation patterns allow perceiving haptic feedback in different ways. The most basic ones are direct patterns that would be perceived as force feedback directly on the body, appropriate for simulating the sensation of contact with surfaces, external forces, or binary on/off states. That being said, more complex patterns that vary in speed, acceleration, or actuated regions can be also used for indirectly conveying information, such as direction cues or notifications. The large range of possible patterns includes pulsating stimuli, i.e., inflating and deflating of actuators in a wave-form sequence, and rotating stimuli, i.e., a circling actua-

tion around the head. Even combinations of different patterns are conceivable.

Following these requirements and concepts, providing pressure-based stimulation has to be considered carefully to generate an appropriate sensation. As highlighted in the related work section of this part (Section 3.2.0.1), most research used vibrotactile stimuli, however, this was shown to be ineffective for a realistic and immersive stimulation for Pressure-based Mechanoreception. Therefore, in this chapter, a different approach using a pneumatic actuation (similar to [Del+18]) will be presented. Using textile actuator cushions that can be inflated through compressed air, a proof-of-concept system was designed and concepts for a pressure-based actuation on the head were evaluated.

5.4 PROOF-OF-CONCEPT: A PNEUMATIC PRESSURE-BASED ACTUATION

A haptic system that provides pressure-based stimuli needs more force than traditional vibrotactile systems. While some use external devices (cf. Section 3.2.0.1), in the thesis a different approach using compressed air within a closed system that can inflate air cushions was designed following the aforementioned requirements. Therefore, a system was created that used an air compressor[1] that can power the system for intense stimulation. However, as such high pressure is more than needed to operate such a system, a physical pressure regulator was used to limit the amount of pressure to 250 kPa (2.5 bar).

Actuators were designed as rectangular air cushions made of a synthetic flexible fabric that could not stretch. Each of the cushions was stitched together with standard sewing thread and had a custom 3D-printed port for receiving the pressurized air. While, for example, Delazo et al. [Del+18] used vacuum pumps to release air from the actuators, the presented design in this thesis did not need additional electronic components since the actuator cushions would rapidly inflate through the high pressure but automatically release air once the inflation stopped. Through informal pre-test, it was observed that this approach was ideal to reduce the overall complexity as the cushions released the air fast enough to remove any pressure, but would remain strong and stiff while the air supply is still given.

1 Dürr Technik TA-200K, up to 1200 kPa (12 bar) coming from a 25 liter aggregate

For connecting actuators to the air compressor, PVC tubes with a diameter of 4 mm were used which allowed for enough airflow. For each actuator, a separate solenoid valve was used to release and stop the airflow[2]. The solenoid valves were then connected to a metal distributor which was behind a separate solenoid valve acting as the main inlet, and connected directly to the air compressor. As the pressure-based actuation had to be as instant as possible, the selected solenoid valves only took 30 ms on average to open or close.

Communication with a remote workstation to control the solenoid valves was realized by using the ActuBoard platform as introduced in Chapter 9. All solenoid valves were directly connected to the ActuBoard which provided a C# serial interface that was implemented to react to different events within a Unity application. Therefore, custom trigger elements were linked to a respective valve and initiated pressure-based feedback once the trigger was activated. An actuator in its inflated and deflated state is shown in Figure 5.2 b.

5.4.1 *Safety Measures*

The system operated at a reduced maximum pressure of 250 kPa (2.5 bar) which is strong enough for the actuation but too weak to provide any harm. Further, the pressure could immediately be released through the air cushions once one of the safety mechanisms was triggered. Therefore, there were software-based switches, as well as emergency hardware switches to turn off the power. As the solenoid valves were normally-closed, they blocked any incoming air pressure after the power supply was turned off.

5.4.2 *Example Application for On-Body Pressure-based Feedback*

As a proof-of-concept application, a snowball fight was implemented in VR[3]. Hereby, the player had to use the VR controllers to grab snowballs from the ground and throw them at an enchanted snowman. On the other side, the snowman did the same and threw snowballs back at the

2 U.S. Solid G12V DC solenoid valve, 12 V, 7 bar, normally closed

3 This application was also the foundation of one of the Thermoception examples as described in Section 7.9.3 of Chapter 7.

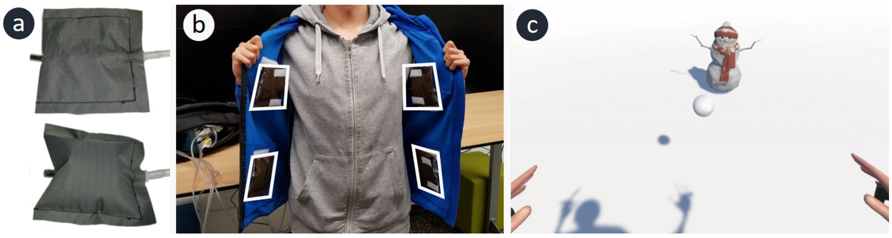


Figure 5.1: Proof-of-concept implementation of pressure-based actuators in form of air cushions in a (a) inflated and (b) deflated state. Four of them were (c) embedded in a jacket to provide feedback on the chest during a (d) example VR snowfight game.

player. The idea thereby was to explore how convenient it would be to include pressure-based actuators in that VR application. As a result, if the player would not dodge the snowballs and was hit on the body, respective actuators would rapidly inflate in the same spot to give the impression that the player had been hit and felt an impact force.

Therefore, four air cushions were designed as described earlier with a size of 7.5×7.5 cm and a strong but flexible synthetic fabric (see Figure 5.1a). Then, they were sewn into the inside pockets of a jacket to act as pressure actuators and connected to a control unit. The actuators inside the jacket are depicted in Figure 5.1b, the example VR game in Figure 5.1c.

During informal experiments with this prototypical implementation, it was found to increase the enjoyment of the testers. They described the impact sensation as realistic and were not afraid of the actuation. Further, it was observed that all testers did not perceive the unusual pressure-based actuation as uncomfortable or dangerous. However, while the presented proof-of-concept application was not formally evaluated, the observations were in alignment with the findings of Delazio et al. [Del+18]. Yet, the authors and this proof-of-concept were only focusing on the actuation of the upper body while other body parts were not considered. Therefore, the presented concepts in this thesis were applied to the head which has specific additional requirements due to the different physiology, and were then evaluated in a follow-up study, as presented in the next section.

Methodology Summary — within-subjects design

Controlled Experiment Lab Study	non-parametric analysis Wilcoxon Rank-Sum Tests	9 participants 4 female, 5 male 21 – 62 years

f(*IV*)	*f*(*DV*)
Type of Actuation: Pneumatic Actuation No-Haptics Baseline	Subset of Witmer-Singer Questionnaire: Involvement Real-World Consistency Level of Natural Interaction Responsiveness of Environment

5.5 PRESSURE-BASED FEEDBACK ON THE HEAD: A USER STUDY

To further investigate the potential of pressure-based stimuli through pneumatic actuation, a systematic evaluation was performed. Related work and the presented proof-of-concept could already show how such actuation can leverage the user experience for on-body feedback, such as the torso or limbs [Del+18]. Yet, providing force feedback to the head is still explored less. Also, contrary to most other parts of the body, adipose tissue plays only a subordinate role in the mostly bony and muscle-free structure of the cranium. Further, the head may react differently to pressure-based feedback as it is found to be very sensitive to an excess amount of external forces, typically described as scalp tenderness [DD87].

As also discussed in MECHANORECEPTION introduction (Chapter 3), some existing work used vibrotactile arrays (e.g., [VSB21; KR17; Ari+17; de +17]) that particularly focused on directional or guidance aspects. Others investigated torque forces of the head and pushed towards the face through mechanical and pneumatic approaches (e.g., [Kon+18a; Cha+18]). However, research has shown that vibrotactile actuators have limitations to fully convey a realistic experience of force in VR [KR17] and pressure-based stimuli on the upper head remained underexplored.

5.5.1 *Pneumatic Actuation of the Head in Virtual Reality*

As a first step towards force feedback on the head and to investigate the feasibility of the presented concepts and system of this chapter, a second VR application, called PNEUMOVOLLEY, was designed together

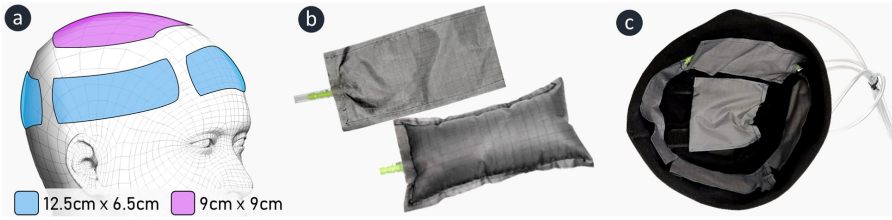


Figure 5.2: (a) The location of the air cushions conceptualized around a model of the head. There were four actuators around the longitudinal cross-section of the head (blue), and one actuator at the top center (pink). (b) shows two actuators in an uninflated and inflated state, while (c) shows how the final prototype for the evaluation was designed, including all five air cushions within a fabric cap.

with a prototype in form of a pneumatic actuated cap. As the primary goal was to investigate how such a pressure-based actuation performs on the head, the original prototype as introduced in Section 5.4 was adjusted for the respective individual requirements.

After initial and informal tests, the actuators in form of five air cushions were designed to fit in a fabric cap to provide full coverage of the upper parts of the head. Four of the actuator cushions had a dimension of $12.5 \times 6.5cm$ which was found to be effective in the pre-tests. The actuator cushions were then placed on the longitudinal cross-section of the head in a ring layout. On the top center of the head, another actuator cushion was located. This cushion had a square dimension of $9 \times 9cm$ to better fit this location, as elongated actuators would have provided an uneven actuation space. For easy replacement and to better adapt to different head sizes, all of the cushions were attached to the inside of the cap using *hook-and-loop* fasteners. Further, the inflation duration for contact was set to 150 ms and directly released afterward.

5.5.1.1 *PneumoVolley VR Game*

The game designed for the evaluation, which will be referred to as PNEUMOVOLLEY in this work, was based on the idea of the open-source game *Blobby Volley*[4], a Volleyball-like classic 2D-game. The twist here is that instead of playing the game with hands, the ball has to be brought to the other side with the head. The rules of the game specify that only the player who has the serve can score points. To earn those points, the ball must be brought over the net with a maximum of three consecutive

4 https://github.com/danielknobe/blobbyvolley2 (accessed March 01, 2022)

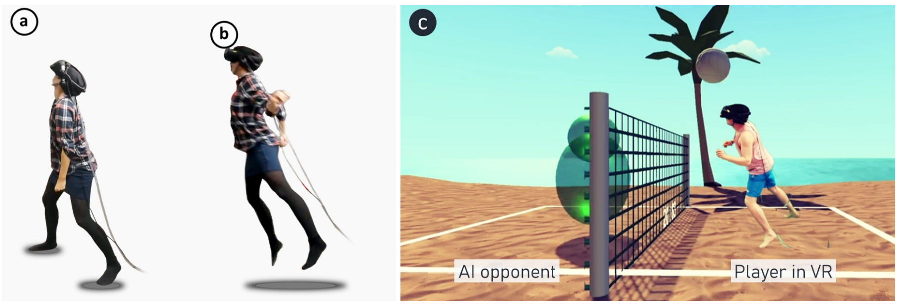


Figure 5.3: A participant (a) preparing to get a ball, and (b) reaching the ball with the head. (c) A participant within the VR environment playing against the Artificial Intelligence (AI) opponent.

headers and land on the opponent's court. If, on the other hand, the ball lands on the own side's court or if more than three headers were executed, the right to serve - and thus the chance to score points - passes to the opponent. The first player to score 15 points wins.

As the original game is only playable from a 2D side perspective, the game had to be rethought for a full 3D experience in VR and the use with a HMD. Therefore, no code or assets of the original game were re-used and PneumoVolley was created from scratch. That being said, the visuals were similar to the original, however, completely remodeled in 3D, and the game mechanics were implemented with the Unity engine and SteamVR framework. Further, the playable area and game court were made to be dynamically adjusting to the boundaries of the VR tracking space plus an additional safety buffer of 1.5 m to physical walls and obstacles to avoid collisions. For the user study, the available area for the player had a resulting size of $3 \times 2m$. In a similar fashion to the original, the playable area had no *out* and the boundaries were 3 m high invisible walls that would bounce back the ball.

To trigger the force impact of the ball once it hit the head, an invisible sphere first was modeled around the virtual center position of the HMD, to represent a participant's head. On this sphere, five *hot zones* were defined in an identical layout to the physical cap. Attached physics colliders then reacted to contacts with the virtual ball and initiated the inflation of the underlying air cushion, as well as played back the ball physically accurate. As for the inflation of the air cushions, pre-tests showed that a duration of $150ms$ provided an intense but harmless impact force to the head.

SINGLEPLAYER AI AND MULTIPLAYER MODE The PNEUMOVOLLEY game could be played as multiplayer or singleplayer. In multiplayer, two players were able to compete against each other using either their own VR tracking spaces or with a traditional keyboard. However, as there was only one haptic prototype designed, a maximum of one player could benefit from the additional pneumatic PRESSURE-BASED feedback. Further, as this would influence the study or would require additional setup, an additional singleplayer mode was implemented where the player had to compete against an AI opponent.

The AI opponent was based on Unity's *ML Agents* [Jul+18] using a *Proximal Policy Optimization* reinforcement learning algorithm. As such, the AI opponent was trained using thirty simultaneous instances with a total of fifty million steps for the user study. For learning the movements, the learning agent was able to move the AI opponent on two axes by forward, backward, left, and right commands, as well as a command to trigger jumps. As the AI opponent had to learn the rules of the game, it was rewarded for each ball that was played over the net and received a penalty if the ball landed on the own court. If the latter was the case, the ball was returned to the AI opponent in a random direction to simulate potential balls that come from the opponent or that bounce from the court limits.

5.5.2 *Study Design*

The user study evaluating the aforementioned concepts for an actuation on the head investigated the following research questions:

RQ1. How does pressure-based feedback affect the realism in VR?

RQ2. How does pressure-based feedback affect the involvement in VR?

RQ3. How does pressure-based feedback increases the enjoyment while being in VR?

Therefore, the study used a within-subjects design and participants played in singleplayer mode against the AI opponent (see Section 5.5.1.1). Therefore, the experiment focused on one IV with PRESSURE-BASED feedback and a NO-HAPTICS baseline as the two levels. To avoid bias, half of the participants started with the PRESSURE-BASED condition, while the other began with the NO-HAPTICS baseline.

As for the DV and to assess the enjoyment, realism, and presence of the PRESSURE-BASED feedback compared to the NO-HAPTICS baseline, the participants had to answer questions based on the Witmer-Singer (WS) presence questionnaire [WS98] after each condition. Hereby, the following items were included (all used 7-Points scales):

- Q1. How involved were you in the Virtual Environment experience? (WS item 23)
- Q2. How much did your experiences in the Virtual Environment seem consistent with real-world experiences? (WS item 12)
- Q3. How natural did your interactions with the environment seem? (WS item 3)
- Q4. How responsive was the environment to actions you initiated or performed? (WS item 2)

Additionally, the overall enjoyment and realism of the PRESSURE-BASED condition were assessed in a post-questionnaire (both 7-Points scales), as well as through additional qualitative feedback.

5.5.3 *Task*

The participants were invited to play a VR variation of the original *BlobbyVolley*[5] game. The rules are derived from the traditional Volleyball game, however, the ball has to be brought over the net with the head. Therefore, participants had to compete against the AI opponent in the complete 3D space. The first player who achieved 15 points won the match. However, participants could play as much as they wanted until proceeding to the next condition. A detailed implementation of the game and its rules are found in Section 5.5.4.

5 https://github.com/danielknobe/blobbyvolley2 (accessed March 01, 2022)

5.5.4 *Apparatus and Study Setup*

The apparatus and the setup of this study were identical with the aforementioned system described in the Section 5.5.1.

5.5.5 *Procedure*

The procedure was as follows:

BEFORE THE STUDY: Participants were welcomed and the experimenter explained the goal of the study. Then, they were introduced to the system and the game, including a brief explanation of the rules. Once participants had no further questions, they were asked to sign a consent form and the experimenter assisted with putting on the HMD and actuation cap.

DURING THE STUDY: Participants either started playing the NO-HAPTICS baseline or PRESSURE-BASED feedback condition first. They had to play against the AI opponent until one of the parties reached a score of 15 as a minimum. However, they could restart the match as often as they wanted and play again. Once they finished a condition, they were asked to fill out the questionnaire and could continue with the respective other condition.

AFTER THE STUDY: After playing the game with both types of feedback, participants were assisted to put off the prototype and HMD. Then, they were asked to fill out a demographics questionnaire and invited to provide additional feedback in a post-questionnaire. During the whole procedure, participants were free to provide verbal feedback noted by the experimenter. Further, they were allowed to take a break or stop the study at any time.

5.5.6 *Participants*

In the study, 9 individuals between 21 and 62 years participated (M=35.7, SD=13.6, 4 female, 5 male). None of them described themselves as a proficient user, yet, one participant reported using VR reg-

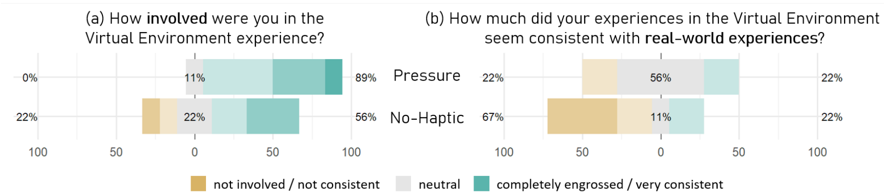


Figure 5.4: Plots of the responses with regards to the (a) involvement and (b) real-world consistency.

ularly. Four participants had some experiences with VR, and four had never used VR before. Besides snacks and drinks, no compensation was provided.

5.6 RESULTS

In this section, the results of the described user study are reported.

5.6.1 *Analysis*

A non-parametric analysis of the questionnaires' responses was performed using Wilcoxon rank-sum tests for pairwise comparisons (only two levels for the IV). For further insights, the median, interquartile range (IQR), and a plot for each item is given.

5.6.1.1 *How involved were you in the Virtual Environment experience?*

The analysis revealed significant higher scores for the PRESSURE-BASED feedback compared to the NO-HAPTICS baseline with regards to the involvement of the VR experience ($\tilde{x}_{no} = 5$, $IQR_{no} = 2$, $\tilde{x}_{pb} = 5$, $IQR_{pb} = 1$, $W = 0.00$, $p < .05$[6]). Figure 5.4a shows the distribution of the participants' responses.

6 3 pairs of values were tied

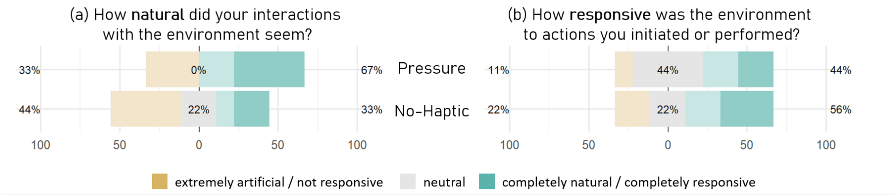


Figure 5.5: Plots of the responses with regards to the (a) natural interaction and (b) responsiveness.

5.6.1.2 *How much did your experiences in the Virtual Environment seem consistent with real-world experiences?*

The results showed higher overall score for the PRESSURE-BASED feedback compared to the NO-HAPTICS baseline. However, the analysis could not reveal any significant differences ($\tilde{x}_{no} = 3$, $IQR_{no} = 2$, $\tilde{x}_{pb} = 4$, $IQR_{pb} = 0$, $W = 2.50$, $p > .05$[7]). Figure 5.4b shows the distribution of the participants' responses.

5.6.1.3 *How natural did your interactions with the environment seem?*

The PRESSURE-BASED feedback received a higher median rating as the NO-HAPTICS baseline with regards to how natural the interaction was perceived. However, the analysis could not reveal any significant differences ($\tilde{x}_{no} = 4$, $IQR_{no} = 2$, $\tilde{x}_{pb} = 5$, $IQR_{pb} = 3$, $W = 1.50$, $p > .05$[8]). Figure 5.5a shows the distribution of the participants' responses.

5.6.1.4 *How responsive was the environment to actions you initiated or performed?*

The PRESSURE-BASED feedback and the NO-HAPTICS baseline showed comparable high scores for the responsiveness to the initiated actions. However, the analysis could not reveal any significant differences ($\tilde{x}_{no} = 5$, $IQR_{no} = 2$, $\tilde{x}_{pb} = 4$, $IQR_{pb} = 1$, $W = 15.50$, $p > .05$[9]). Figure 5.5b shows the distribution of the participants' responses.

7 2 pairs of values were tied
8 4 pairs of values were tied
9 2 pairs of values were tied

5.6.1.5 *Post-Questionnaire: Overall rating of the realism and enjoyment of the pressure-based feedback*

In the post-questionnaire, the participants were asked to rate the overall realism and enjoyment of the PRESSURE-BASED feedback while interacting with the system. The responses were overall on a high level, indicating a well-perceived amount of realism ($\tilde{x} = 5$, $IQR = 2$). Moreover, the overall enjoyment was rated even higher and participants appraised the novel feedback ($\tilde{x} = 6$, $IQR = 1$).

5.6.2 *Qualitative Feedback*

In addition to the quantitative results of the questionnaires, the participants were asked to give subjective feedback verbally during the study, as well as in written form within the post-questionnaire. Further supporting the aforementioned results, participants described the PRESSURE-BASED feedback on the head as "*fun VR experience*" (P3, P7) with a positive attitude towards "*implementation of the haptic feedback*" (P5). Thereby, they were surprised how "*air cushions give very localized feedback where it hit the head*" (P2) or where the participants even hit the ball (P2).

In that regard, also the comfort was described as positive and one participant stated that "*the cap was comfortable*" (P9) which they did not expect before (P9). None of the participants reported the impact forces of the pneumatic actuation as too heavy, in fact, contrary to the initial assumption, some participants expressed that the feedback "*could have been stronger*" (P1, P4, P9).

The game experience and implemented scenario was reported to be "*fun*" (P5) with "*nice visuals*" (P6). Participants liked the "*competitive gameplay*" (P4) and the "*nostalgic experience*" (P4) when remembering the inspiration of the game. However, the AI opponent seemed to "*immature*" (P6) and in some cases "*unfair*" (P5) which a ball behavior that "*sometimes feels unrealistic*" (P2). Further, as the playable area had to be limited due to the boundaries of the physical space, some participants found the field as "*too small*" (P3, P6).

5.7 DISCUSSION

To recapitulate, this chapter presented concepts for pressure-based haptic feedback to stimulate Pressure-based Mechanoreception. Based on pneumatic actuated air cushions, a system was implemented that can provide forces onto a user's body. Further, through an investigation of those concepts applied to the head, the findings could show a high level of realistic impact forces which will be discussed in-depth in this section.

5.7.1 *Pressured-based Actuation increases Involvement*

The involvement was consistently rated higher for pressure-based feedback compared to the no-haptics baseline. This was further underlined by the high rating of enjoyment and the qualitative feedback of the participants. As such, VR experiences can benefit from the additional feedback to be one step closer to the idea of an ultimate display [Sut65] which would render a virtual world more persuasive. Still, it remains unclear to which degree pressure-based feedback can be utilized for different scenarios and how it compares with vibrotactile feedback.

5.7.2 *Pressure-based Actuation increases Realism*

The results of the study could show a higher degree of realism when perceiving pressure-based feedback compared to the no-haptics baseline. Participants rated the experience as more natural and consistent with their real-world experiences. Although, a completely realistic experience compared to real-world experiences still seems not reached as participants had divided opinions. While appraising the benefits compared to the no-haptics baseline, some participants reported that the feedback felt too unresponsive or sometimes not strong enough to represent a realistic collision with a volleyball.

5.7.3 *Pressure-based Actuation could be stronger than experienced*

While initially assumed that less pressure is more reasonable and to be particularly cautious to avoid any pain or irritations, participants felt that the level of applied pressure could be more intense. However, this would require more stiff air cushions which conform less to the shape of the body while producing an even more rapid contact pressure. In addition, the air cushions currently remain in direct contact with the body even in the uninflated state, however, a small offset or space between the actuator and the body might make it possible to perceive inflation more intensively by making the contact feel more like a light slap.

5.8 LIMITATIONS AND FUTURE WORK

This chapter comes with some limitations that are addressable for future iterations.

5.8.1 *Additional User Studies*

The user study investigated the haptic feedback on the head. The focus was on immersion and realism of the pressure-based actuation and was able to deliver promising results respectively. For additional findings, the study should be extended and conducted with a larger group of participants. Further, other experimental setups are recommended, such as use-cases in the area of notifications or guidance, as well as a comparison to a state-of-the-art vibrotactile actuation. While related work [Del+18] could highlight how a pressure-based actuation is perceived on the body, more research is necessary to identify the limits of such an actuation, for example how accurately the actuator placement has to be and how the visual perception during VR situations can affect the perception of the actuation.

5.8.2 *Number of Actuators and Patterns*

Even though the concepts are suitable for even a large number of actuators, the user study only investigated a layout with five actuators located in a cap. Future investigations could increase the number of actuators and also explore how combining different regions of the body could be affected by pressure-based actuation.

Also, the investigated actuation was mainly a very direct contact once the virtual ball collided with the head. However, as described in the concept and system sections 5.4, other types of actuation are possible, such as varying timings and intensities, as well as complex actuation patterns which have to be interpreted by the participants.

5.8.3 *Wearability*

The wearability of the presented approach using a pneumatic actuation is still limited. While the PneumoVolley game of the user study required a lot of movements and space for the participants, none reported feeling restricted in their movement. However, it could be observed that the tubes going to the participants sometimes entangled an arm, but were quickly untangled again. As a future improvement, the system could increase mobility by using small gas-filled cartridges to supply the actuators. However, this would require a regular refill of the cartridges. Alternatively, a mechanical solution that pumps compressed air from one closed chamber to an actuator cushion might require no external air supply at all, although require more space and electrical power to drive the pumping process.

5.9 CONCLUSION

In this chapter, the aspect of a pressure-based actuation was examined for the Pressure-based Mechanoreception. Based on related work, requirements and concepts were identified, which were essential for a pressure-based actuation. In this context, the emphasis was on the characteristics that actuators should provide to adapt to the physiology of the human body, the human perception, and how stronger forces can stimulate the mechanoreceptors. Therefore, a system based on compressed air was designed, capable of inflating custom air cushions. Thereby, these air cushions enable localized pressure-based actuation that can reproduce physical contact, impact forces, and collisions within virtual worlds.

As a proof-of-concept, two VR applications were prototyped as demonstrators. While the first application applied a pressure-based actuation to the upper body, the second application was designed for direct actuation of the head. Furthermore, a user study was conducted to investigate the effects of pressure-based actuations in terms of involvement, realism, and enjoyment for the second application. The results confirmed that the concepts developed in this chapter increased the realism within the VR environment and led to better involvement and enjoyment for the participants.

In the larger picture of Mechanoreception, this chapter demonstrated that a pressure-based actuation is a useful addition to present a life-like illusion of real collisions with virtual objects and environments. However, since the Mechanoreception is a complex construct, which is stimulated by the four cutaneous receptors in very different ways, further investigations are necessary. While this and the previous chapter investigated static and position-fixed stimuli, the subsequent chapter examines the influence of moving stimuli, such as strokes and caress. Further, it integrates the findings from both, Fine Mechanoreception and Pressure-based Mechanoreception.

6

COMBINING FINE AND PRESSURE-BASED MECHANORECEPTION: HAPTIC STROKE STIMULI

Chapter Overview

Mechanoreception I | **Mechanoreception II** | Thermoception | Proprioception

Related Publications:
Smooth as Steel Wool: Effects of Visual Stimuli on the Haptic Perception of Roughness in Virtual Reality
CHI 2022

Body | Arm | Caress Feedback | Haptic Illusion | Controlled Experiment | VR

The previous two chapters investigated the individual aspects of Fine Mechanoreception and Pressure-based Mechanoreception. In this chapter, both aspects are investigated together for moving stroke stimuli. Further, while both previous chapters focused on interpreting vibrotactile cues and pressure-based feedback for AR/VR, this chapter is focusing on how to recreate special object properties, in particular their roughness, and how the haptic perception is affected by visuals in VR and vice-versa.

Although great progress has been made to provide a large variety of physical textures for haptic feedback in VR, most approaches are usually limited to a specific scenario, as the physical devices are limited number by the number of actual textures they can provide. Therefore, while there is a need for haptic stimuli of an almost indefinite amount of visualizations, only a subset can be recreated one-to-one due to the limited physical space of actuators. Therefore, it is essential to understand how visuals affect the haptic perception and how textures are perceived in general, to find an ideal trade-off between the requirement of a large number of physical textures and a sub-set that is still sufficient to convey a realistic illusion.

That being said, a first understanding of human perception is essential. For example, previous work highlighted that one of the most dominant senses is the visual that also contributes to tactile expectations before and during contact [YT15; Sun+16; EB02; LK04]. This means for example that if someone sees something rough, they expect to also feel something rough. But how does this differ when the visual expectation and haptic stimuli are not matching and to which degree are these visual expectations affecting haptic perception until users still would perceive a matching sensation?

This chapter, therefore, investigates how users *discriminatively* perceive haptic stimuli together with visualizations during *passive touch* on the example of texture roughness by assessing their perceived haptic and visual roughness, matching, degree of realism, and pleasantness. For this, in a first online questionnaire, the roughness expectations of 50 items were explored to identify a list of objects categorized into five levels of roughness ranging from *very smooth* to *very rough*. Then, through a second controlled experiment, the haptic perception of five physical textures with different levels of roughness combined with the perception of ten visualizations was conducted with the help of a designed prototype that facilitates haptic stroke stimuli along the arm and a VR environment for showing the different visualizations. Further baselines for comparison were the visualizations' real-world materials, silicone cushions, state-of-the-art vibrotactile feedback, and a no-haptic baseline.

In summary, this chapter contributes (1) the investigation of the visual roughness expectation of 50 items, (2) a systematic evaluation of the interdependency between haptic stroke stimuli and visualizations in VR with regards to perceived roughness, matching, realism, and pleasantness, and (3) a comparison of the haptic strokes with vibrotactile phantom sensations, the visualizations' real-world materials, and a no-haptics baseline.

6.1 CONTRIBUTION STATEMENT AND RELATED PUBLICATION

This chapter is based on the following publication:

Sebastian Günther, Julian Rasch, Dominik Schön, Florian Müller, Martin Schmitz, Jan Riemann, Andrii Matviienko, and Max Mühlhäuser. "Smooth as Steel Wool: Effects of Visual Stimuli on the Haptic Perception of Roughness in Virtual Reality." In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (*CHI '22*). New York, NY, USA: ACM, Apr. 2022. ISBN: 978-1-4503-9157-3/22/04. DOI: 10.1145/3491102.3517454

Contribution Statement: I led the idea creation, conceptual design, implementation, methodology of the both user studies, performed the data analysis, and writing process. The former student *Julian Rasch* supported building the prototype, and assisted the conduction of the second study. *Dominik Schön* supported the implementation of the VR application. *Florian Müller*, *Martin Schmitz* and *Andrii Matviienko* consulted to and reviewed the design process. *Florian Müller* gave valuable input for the statistical analysis of the data. *Jan Riemann* helped with his experience to solve technical challenges that occurred while building the initial prototype. *Max Mühlhäuser* and *Andrii Matviienko* supervised the project and writing process.

❗ *Some contents of this chapter might contain verbatim parts of the aforementioned publication.*

6.2 CHAPTER STRUCTURE

After this introduction, this chapter is structured as follows: First, a background on visual and tactile effects on haptic perception is given in Section 6.3. Afterwards, this chapter presents a pre-study that investigated the roughness expectations of 50 different items by a group of 40 participants (Section 6.4). The findings of this pre-study were then used for a follow-up user study that investigated the interdependencies of haptic stimuli with different roughness and visualizations in VR. Section 6.5, therefore, describes the methodology of the user study, including details on the prototypical system implementing the underlying concepts. The results are then presented in Section 6.6, followed by in-depth discussions of the findings in Section 6.7. The chapter closes then by a discussion of the limitations (Section 6.8) and a concluding summary (Section 6.9).

6.3 BACKGROUND: HAPTIC AND VISUAL STIMULI ON PERCEPTION

Before considering the actual haptic perception, it is important to recognize how the visual expectation of things influences the haptic perception even before contact [Sun+16; YT15] which also means that the texture perception is commonly multisensory [LK04]. For example, Yanagisawa and Takatsuji [YT15] observed significant differences in the haptic perception depending on the visual material shown before. Still, Lederman and Abbott [LA81] found that, while vision seemed not the most dominant factor, the visual and haptic perception is able to independently classify the grit of a physical texture in almost identical quality. In their follow-up experiments, Lederman et al. [LTJ86] further highlighted that the "multidimensionality of texture perception" (Lederman et al., 1986, [LTJ86], p. 1) is important and that the visual and haptic perception influence each other based on attention. However, Guest and Spence [GS03] found that the roughness perception is not improved by a combination of visual and haptic perception if users perceived roughness individually. Bergman Tiest and Kappers [BK07] extended those investigations for a set of flat textures.

Although these experiments provided careful insights, their focus was on *active touch*, where participants had to discriminate the roughness of surfaces by directly touching them. Moreover, mostly the visual and haptic stimuli were typically of similar materials and further explorations are necessary to identify to which degree haptic perception is modified, if a physical texture is completely unrelated to the visual appearance of an object, e.g., as it might happen when having limited haptic feedback for VR.

On the side of texture perception and visual interplay during *passive touch*, Botvinick and Cohen introduced the Rubber Hand Illusion (RHI). Thereby, people perceive a "rubber hand as belonging to themselves" (Botvinick and Cohen, 1998, [BC98], p. 756). For example, Schütz-

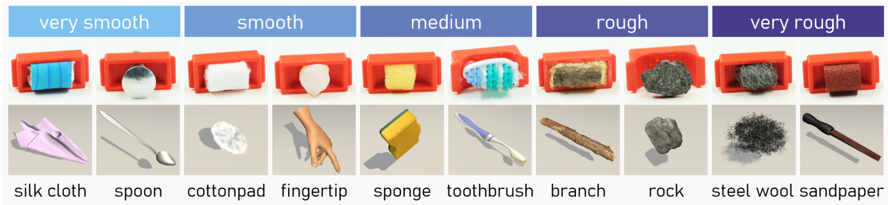


Figure 6.1: The ten VISUALIZATIONS of the study (bottom) and their physical real-world counterparts (top), categorized into five increasing levels of roughness: *silk*, *spoon*, *cotton*, *finger*, *sponge*, *toothbrush*, *branch*, *rock*, *steel wool*, and *sandpaper*.

Bosbach et al. [STW09] applied this concept to research how soft cotton and a rough sponge affect the roughness perception and observed that non-matching stimuli were not able to alter the roughness perception. However, they could also identify that stroking the rubber hand with a smooth fabric resulted in a lower rating of its smoothness compared to the same physical sensation applied to their real hand. In a different experiment, Ward et al. [WMJ15] could confirm that a mismatch of expected hardness has a negative impact on the body ownership illusion, e.g., when seeing a hard pencil but feeling a soft brush, while the roughness had less effect on the persuasion of the RHI. Other related work investigated emotional responses resulting from different visual appearances and haptic strokes from other persons where they identified that a stranger's touch was more unpleasant [Ipa+21; IHI19].

In summary, the aforementioned work highlighted to which extent visuals might affect the haptic perception. However, further research is necessary to identify how the aspect of roughness is affecting human perception, in particular for *discriminative passive touch* in VR scenarios.

6.4 PRE-STUDY: VISUALIZATIONS OF DIFFERENT ROUGHNESS EXPECTATIONS

Typically, people have different conceptions and mental models of how various objects are perceived (cf. [STW09]). Therefore, in order to provide different visualizations for the main study, a broad variety of possible visualizations that propagate different roughness had to be identified. In this pre-study, an online questionnaire was conducted to obtain a diverse variation of VISUALIZATIONS with different expectations of roughness based on the mental models of participants. As

Methodology Summary		within-subjects design
Online Questionnaire	Custom Clustering Exclusion of items with high uncertainty	40 participants 20 female, 20 male 23– 57 years
f(IV) 50 different Items (potential visualizations)	*f(DV)* Expected Roughness Rating	

a hypothesis, items with a low deviation of the ratings were thought to share a similar conception of the roughness among all participants, and therefore, should also propagate similar characteristics. Overall, 50 initial items that span a scale from smooth-to-rough were carefully selected for this pre-study by a group of five HCI experts during a brainstorming session.

6.4.1 *Procedure*

During the online questionnaire, the participants were asked to rate the subjective roughness of the 50 items in a randomized order on 5-Point scales ranging from 1 (*very smooth*) to 5 (*very rough*). None of the items included any visual representation to have the participants focus on their specific mental models of the items' expected roughness. On average, it took 15 minutes per participant to answer the questionnaire. No compensation was provided.

6.4.2 *Participants*

In total, 40 participants, acquired through the institute's network, online discussion groups, and among contacts, answered the questionnaire (20 female, 20 male). The participants were aged between 23 and 57 years ($M = 30.9, SD = 6.2$).

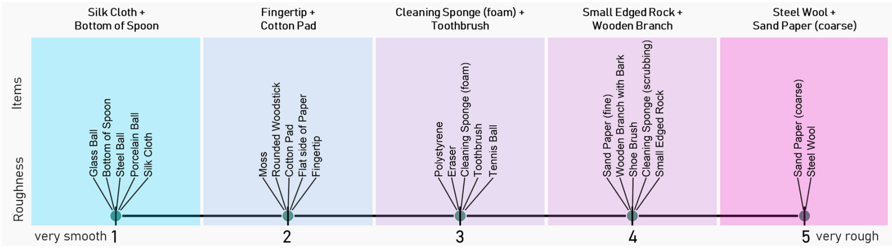


Figure 6.2: Results of the pre-study showing the five best rated items per roughness category and the selected items that were used in the follow up user study.

6.4.3 *Results of Pre-Study*

In a first step, all responses were aggregated and the 50 items were sorted by their median ratings. Afterward, items that showed a high uncertainty in terms of a high deviation ($IQR > 1$) were excluded. From the remaining list of items, two VISUALIZATIONS for each of the five levels of roughness were selected with respect to their suitability for VR. As additional criteria, the final items should have high versatility, meaning their appearance should highly vary. For example, both, the silk cloth and bottom of spoon, were ranked as *very smooth* ($\tilde{x} = 1$) but are seen differently regarding their hardness. An overview of five items per roughness category[1] that had the most promising features after the pre-study is listed in Figure 6.2.

In total, 10 VISUALIZATIONS were identified and grouped into five ascending levels of expected visual roughness: (1) *very smooth* (Silk Cloth, Bottom of Spoon), (2) *smooth* (Cotton Pad, Fingertip), (3) *medium* (Foam side of Cleaning Sponge, Toothbrush), (4) *rough* (Small Edged Rock, Wooden Branch with Bark), and (5) *very rough* (Steel Wool, coarse Sand Paper).

6.5 USER STUDY AND METHODOLOGY

In order to investigate the influence and interdependencies of HAPTIC STIMULI and VISUALIZATIONS on the perception of roughness, the following research questions were investigated through a controlled experiment:

1 only two items were suitable for the *very rough* category

Methodology Summary — within-subjects design

Controlled Experiment Lab Study	non-parametric analysis Aligned Rank Transform (ART-C) Cumulative Link Mixed Models Friedman & Wilcoxon Rank-Sum	31 participants 17 female, 14 male 18 – 50 years

f(IV)

Visualizations:
10 Items + No Visualization Baseline
Haptic Stimuli:
5 Levels of Roughness + No Haptics Baseline, Vibrotactile Baseline, Real Material, Silicone

f(DV)

Custom Questionnaires:
Haptic Roughness
Visual Roughness
Matching of Haptic Stimuli and Visualizations
Consistency with Real-World

RQ1. How do different physical textures of HAPTIC STIMULI affect the roughness perception?

RQ2. How do different VISUALIZATIONS affect the perception of physical textures?

RQ3. How do different physical textures with varying roughness compare to the VISUALIZATIONS' real-world materials?

RQ4. How do users perceive haptic strokes compared to vibrotactile phantom sensations?

RQ5. How do the perception of roughness and the matching of stimuli affect the pleasantness?

6.5.1 *Study Design*

The experiment was using a within-subjects design with HAPTIC STIMULUS and VISUALIZATION as the IV. In total, 11 levels of the VISUALIZATION in VR and 9 levels of the HAPTIC STIMULUS were varied during the experiment, resulting in $11 \times 9 = 99$ conditions. Both IV are described in detail in the following.

6.5.1.1 *VISUALIZATION (10+1 levels)*

There were 10+1 VISUALIZATIONS based on the results of the pre-study (Section 6.4). Hence, the following VISUALIZATIONS with different levels of expected roughness were defined (two for each level of roughness): (1a) *silk*, (1b) *spoon*, (2a) *finger*, (2b) *cotton*, (3a) *sponge*, (3b) *toothbrush*, (4a) *branch*, (4b) *rock*, (5a) *steel wool*, and (5b) *sandpaper*. In addition, a neutral *no-visuals* baseline was defined. All VISUALIZATIONS as they appeared in VR are depicted in Figure 6.1.

6.5.1.2 *HAPTIC STIMULUS (5+4 levels)*

The HAPTIC STIMULI were based on five textures with different roughness and four additional baseline comparisons. For an even gradation of roughness, the five textures were based on four types of abrasive sandpaper and one strip of high-gloss polyethylene, similarly to related work (e.g., [Hel82; HR00; BK07], more information in the Apparatus section 6.5.2). As baselines, the untextured *Silicone Cushion*, the VISUALIZATIONS' *real-world* materials, and state-of-the-art *vibrotactile* phantom sensations were used, together with a *no-haptics* baseline.

To summarize, the haptic levels were: (1) *very smooth* (polyethylene), (2) *smooth* (sandpaper 1000), (3) *medium* (sandpaper 400), (4) *rough* (sandpaper 120), (5) *very rough* (sandpaper 80), (6) *silicone*, (7) *vibrotactile* phantom sensation, (8) *real* baseline, and (9) *no-haptics* baseline. Figure 6.3 depicts the HAPTIC STIMULI and the *real-world* counterparts for each VISUALIZATION, which are shown in Figure 6.1.

6.5.1.3 *Dependent Variables*

For the dependent variable (DV), the participants were asked to rate the following five aspects through questionnaires: (Q1) *perceived haptic roughness*, (Q2) *perceived visual roughness*, (Q3) *matching* of HAPTIC STIMULI and VISUALIZATIONS, (Q4) *real-world expectation and realism* (based on the Witmer-Singer Presence Questionnaire [WS98]), and (Q5) *pleasantness* of each actuation. All these items were assessed using on a 5-Point scale [JM71; WUN12] through the following questions:

Q1. How would you rate the roughness of the HAPTIC STIMULUS? (*very smooth* to *very rough*)

Q2. How would you rate the roughness of the VISUALIZATION? (*very smooth* to *very rough*)

Q3. The HAPTIC STIMULUS and VISUALIZATION matched. (*did not match* to *did match completely*)

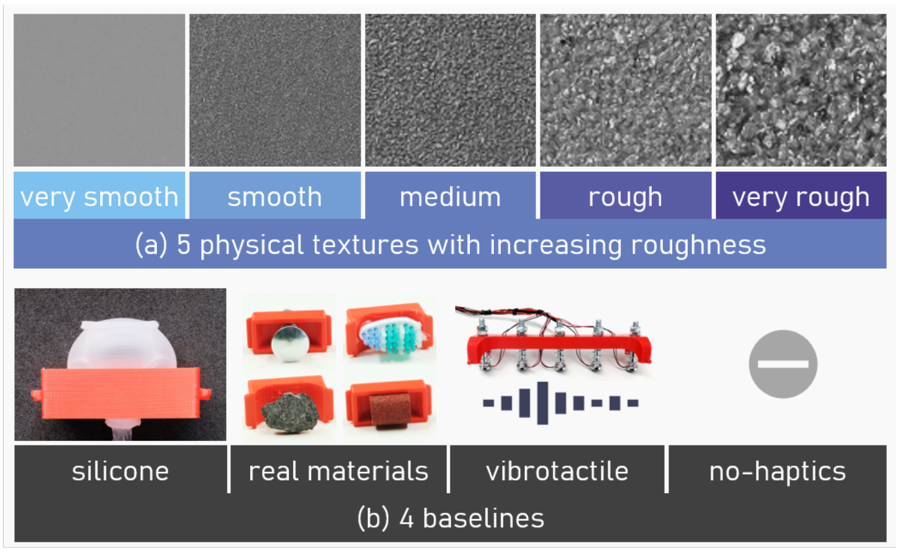


Figure 6.3: The Haptic Stimuli showing (a) the five physical textures with increasing roughness (desaturated macro shots for a better contrast and comparison), and (b) the four haptic baselines that are the untextured silicone cushion, the Visualizations' real-world counterparts, the *Vibration Mount* for vibrotactile phantom sensations, and the no-haptics baseline.

Q4. How much did your experiences in the virtual environment seem consistent with your real-world experiences?[2] (*not consistent* to *very consistent*)

Q5. The actuation felt pleasant. (*not pleasant* to *very pleasant*)

6.5.2 *Apparatus and Study Setup*

For the study, a prototypical device was designed to create a moving haptic stimulus with the different levels of roughness on the arm, including a *Vibration Mount* for the vibrotactile baseline. A wearable *Guiding Rail* for the arm that could accommodate various *Actuator Sledge*s was designed. The *Actuator Sledge*s were designed to embed small objects, such as the real-world counterparts, or inflatable *Silicone Cushions*[3] (Figure 6.4.1, 6.4.2, and 6.4.3).

2 based on Q12 of [WS98]
3 The silicone cushions were made of the 2-component silicone EcoFlex 00-30 by Smooth-on Inc.

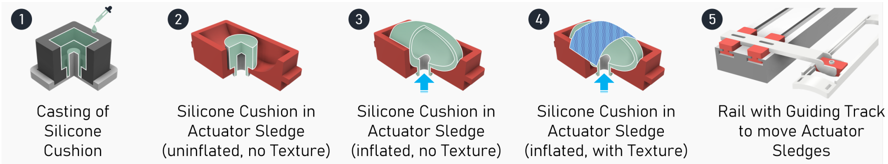


Figure 6.4: The actuator design from the fabrication process to the final actuator showing (1) the casting of the *Silicone Cushion*, (2) the uninflated and (3) inflated *Silicone Cushion* without texture and (4) with a texture. Also shown is (5) the motion rail for the actuator sledges.

To move an *Actuator Sledge* along the *Guiding Rail*, a timing belt driven by a stepper motor[4] on a stationary aluminum rail (Figure 6.4.5) was used and controlled with a connected ESP-32 microcontroller. While the prototype was able to provide different velocities and driving patterns (e.g., a fast acceleration at the beginning, linear movements, or sinus-wave-like movements), the velocity was set to a linear value of 10 cm s^{-1} during the user study, which was shown to have a higher pleasantness rating than others [TAS14; Ack+14]. A flexible cantilever translated the motion to the *Actuator Sledge* that was placed in the *Guiding Rail*. This had the advantage that to compensate for slight movements of the users and to better fit the uneven surfaces of their arms. Additionally, a 3D-printed armrest as a support to keep the arm in place comfortably was provided. To further increase an even actuation, it was also assured that the profile of the *Guiding Rail* adapted to the individual shapes of arms. Therefore, the arms of 8 individuals[5] were measured. Then, the following convex and concave profiles for the *Guiding Rail* could be derived to counter various arm shapes: (1) 0 mm linear, (2) +1.5 mm convex, (3) -1.5 mm concave, and (4) -3 mm concave curved.

6.5.2.1 *Design of Actuators*

The *Silicone Cushion* was designed to provide an even contact surface to the skin for all materials. Therefore, the *Actuator Sledge*s using a *Silicone Cushion* could provide a flexible actuation through textures with different levels of roughness. The inflation of a *Silicone Cushion* could be performed at any point (Figure 6.4.4), however, for the study,

4 NEMA-17 stepper motor
5 We measured 8 diverse individuals: 3 female, 5 male, between 26 and 61 years (M=33.5, SD=10.7), between 168 cm and 192 cm tall (M=178, SD=8.2), and between 50 kg and 116 kg weight (M=76.4, SD=18.0)

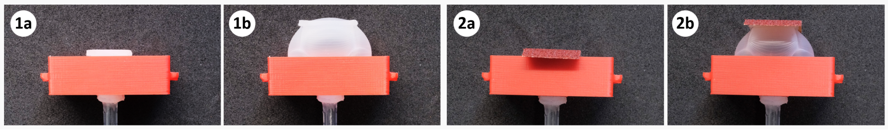


Figure 6.5: The actuators in (1a) an uninflated and (1b) inflated state without texture, and (2a) an uninflated and (2b) inflated actuator with a physical texture.

the actuators were always inflated to provide an even actuation. The inflation of the *Silicone Cushion* was controlled through an array of two diaphragm pumps and solenoid valves that were directly connected to an ActuBoard (cf. Chapter 9, Figure 6.5.1 and Figure 6.5.2).

For the textures that could provide different levels of roughness, several approaches were considered. For example, textures could have been 3D printed [TZG18; DZK19], however, the fabrication process is fragile, and using different grits of abrasive sandpaper also guaranteed a normalized scale based on international standards while still being versatile and flexible [Hel82; HR00; BK07]. Another approach by casting textures with different roughness directly into the *Silicone Cushion* was explored. However, this only resulted in very subtle perceivable differences that could not provide the required roughness. Research also proposed vibrotactile [CUK14; CK17] or ultrasonic patterns [WF95] to create surface roughness as well. However, those methods require sophisticated setups that would still be limited by *replicating* the physical roughness [WF95]. Still, vibrotactile feedback remains a common approach to providing a haptic sensation and vibrotactile phantom sensations were added as baseline (see Section 6.5.2.3).

As a result, abrasive sandpapers with grits of 80, 120, 400, and 1000[6] were found to be the most reliable for the study. In addition, the specific grits were also selected carefully to not cause pain by involuntarily trapping hairs. For the *very smooth* texture, however, sandpaper was not suitable and a high-gloss strip of polyethylene was used. In the last fabrication step, the flexible strips of sandpaper and polyethylene were glued to the center of a *Silicone Cushion*, while having the *Silicone Cushion* without any texture as an additional baseline (*silicone*).

6 according to the Coated Abrasive Manufacturers Institute (CAMI) notation; the smaller the value, the rougher the texture; non-linear

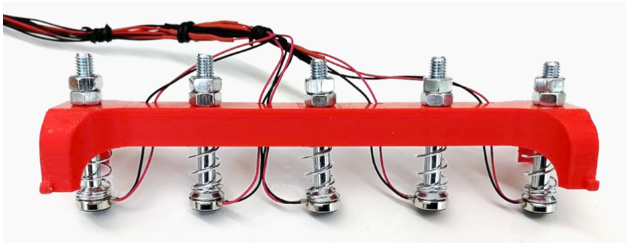


Figure 6.6: The design of the *Vibration Mount* that could be inserted into the *Guiding Rail* in a plug-and-play approach. It consisted of five vibration motors that were controlled by the application.

6.5.2.2 *Real-World Materials Baseline*

The *real* materials and counterparts fitted the VISUALIZATIONS' 3D-models. However, this means that they could not be used with a *Silicone Cushion* due to their rigidity or sizes. Therefore, to maintain an even contact and flexibility, most were glued together with a flexible sponge into an actuator sledge. For the *very smooth* and *vibrotactile*, however, a spring-loaded design was used that limited the maximal extension to avoid too much pressure on the skin but still enough flexibility for different arm shapes. Also, for the *smooth*, a comparable actuation could not be guaranteed nor to be performed synchronously when using a real finger (e.g., from the experimenter). Therefore, a silicone finger was cast by using a plaster negative of a real finger and then treated with magnesia chalk commonly used in sports to reduce friction. All real-world counterparts are shown in Figure 6.1.

6.5.2.3 *Vibrotactile Baseline*

Another baseline was a state-of-the-art vibrotactile actuation using phantom sensations [All70; PC18; Bar+09], similarly as it was done for the TACTILEGLOVE prototype (see Section 4.4.3). Hereby, the vibrotactile motors create the illusion of a continuous motion by changing the intensity of adjacent vibration motors instead of having a physical movement on the arm [All70; Bar+09].

Therefore, a *Vibration Mount* (Figure 6.6) as plug-and-play attachment for the *Guiding Rail* was designed and was the basis for five vibration motors[7]. Each of them was placed equidistant with a spacing of

7 Vibrating Mini Motor Discs, PWM, 2 V - 5 V

31.5 mm [Els+20b] for a total actuation range of 129 mm, likewise to the length of the physical stroke actuation, to keep up the phantom sensation [Els+20b; TMG13; Ack+14]. Similar to the real-world baseline, a spring-loaded approach was used for the motors to keep an even contact between the vibration and skin. For limiting the maximum pressure applied, each spring-loaded screw was countered with a nut for every participant.

The illusion of a continuous motion through vibrotactile signals was maintained by modulating the intensity in a similar way as done by related work (e.g., [IP11; Isr+12; IA18]). For this, the actuation was always beginning at one side depending on the direction with the respective outermost motor and was then modulated in a wave-like pattern to the other side where the leading motor was set to full intensity in the direction of the movement and followed by a trail of lesser intense vibration signals. Thereby, it was essential to keep the timing and velocity of the phantom sensation in alignment with the physical strokes at 10 cm s^{-1}. The controlling of the vibration was again handled with ActuBoard (see Chapter 9).

6.5.2.4 *Virtual Reality Environment and Visualizations*

A virtual room using the Unity Engine[8] was designed for the experiment's VR environment. The appearance was based on the real-world experimentation room including an identical setup consisting of a wooden table with the same height and measurements.

For almost all ten Visualizations besides the cotton pad, steel wool, sandpaper, and *no-visuals* baseline, realistic 3D models from different professional online archives[9] were utilized. The others were designed by a professional digital media artist. All Visualizations are shown in Figure 6.1.

8 https://unity.com/ (accessed March 01, 2022)
9 CGTrader.com (cgtrader Royalty Free License): Silk Cloth; Turbosquid.com (TurboSquid 3D Model License): Spoon, Toothbrush, Small Edged Rock; Sketchfab.com (CC BY 4.0): Cleaning Sponge, Wooden Branch; Makehumancommunity.org (CC0 1.0): Fingertip

6.5.2.5 *Calibration for Synchronicity of Visualization and Haptic Stimulus*

Different measures were taken to increase the synchronicity between the haptic strokes and the VR experience. First, an HP Reverb G2 HMD with inside-out tracking[10] was used. However, this can reduce the reliability of the tracking if not enough visible features are available for the tracking cameras, so the experimentation room was additionally augmented with visual markers of different shapes, colors, and sizes until no offsets or shifts from the tracking were recognizable.

Second, the spatial consistency between the real and virtual worlds was ensured by inspecting and re-calibrating the scene before starting the study for new participants. To do so, the virtual and real table edges, as well as the surface of the table, were manually aligned with help of the VR controllers until the layout of the virtual scene was identical to the physical boundaries, position, and rotation.

Also, it was essential that participants could self-identify with their virtual avatar as shown by related work [YS10; Sla08; HIK08; IKH06]. Therefore, the 3D avatar was a realistic human model[11] that could be modified in size, texture, and color for each participant [IKH06; TH05]. Thereby, the model of the avatar also used an *inverse kinematic* script for the upper body and right arm [Par+18] to make the behavior more lifelike. However, before starting the experiment, participants always were asked to familiarize themselves with the VR environment and their avatar which was then followed by potential re-calibrations. Further, when the left forearm was actuated and the spatial synchronicity between the virtual and real arm was assured, as previous work highlighted its importance for a high sense of embodiment [IKH06; STW09; Ack+14]. An additional armrest on the table was used to restrict arm movements, which was also modeled for the VR environment.

Third and most importantly, the actuation had to be time-synchronous [Ack+14] where the physical actuation range was identical to the movement in the virtual scene [PSS12]. Therefore, in the first step, the distance between the wrist and the *Guiding Rail* was measured and was then defined as the starting point for the VISUALIZATIONS. In a second step, the physical actuation range of the *Guiding Rail* (129 mm) was mapped to the virtual scene together with

10 https://circuitstream.com/blog/hp-reverb-g2/ (accessed March 01, 2022)
11 http://www.makehumancommunity.org/ (accessed March 01, 2022)

Figure 6.7: A participant during the experiment showing (1) the real-world setup and apparatus, (2) a simulated mixed reality view indicating a blend between real and virtual worlds, and (3) the virtual scene in VR.

the synchronous velocity of 10 cm s^{-1} for the physical and virtual movements.

In Figure 6.7, a participant in the (1) real-world setup as observed from the outside, (2) a mixed-reality view of how the participant would perceive the setup, and (3) the study scene as it appeared in VR are shown.

6.5.3 *Procedure*

BEFORE THE STUDY: The participants were welcomed and introduced to the study. They were also informed of the data logging and asked to sign a consent form once they agreed. Further, the experimenter asked for potential allergies to certain materials to be sure no negative reactions would occur.

Then, the participants were asked to uncover their left forearm and the experimenter checked the arm shape for a fitting *Guiding Rail*. After assisting in putting on a fitting *Guiding Rail*, it was ensured that the actuation was comfortable and safe by manually moving the *Actuator Sledge* along the arm and making sure the contact was even, and applied an appropriate amount of pressure with a contact surface of around 1-2 cm^2. In a similar step, the *Vibration Mount* was calibrated to the arms of the participants with the spring-loaded screws. During the whole calibration process, participants were asked to look away so they were unable to see the actuators in advance. That being said, they were also not informed verbally of how the textures and actuators look like and no information on any of the baselines was given.

Once ready, participants had to put on the HMD, rest the left arm on the armrest, and get familiar with their virtual avatar until it felt natural and they could identify with the avatar. (cf. [Sla08]).

DURING THE STUDY: For each condition, participants saw a VISUALIZATION in VR while feeling one of the physical HAPTIC STIMULI on the arm. Every combination of a HAPTIC STIMULUS and VISUALIZATION was presented at least by two back-and-forth movements to give the participants enough time to feel the texture. If a participant desired to repeat the actuation of a condition, it was repeated. Afterward, participants were asked to answer the questionnaire that could be answered with the VR controller. Additional verbal feedback was written down by the experimenter at any time. Once ready, the experiment continued with the next condition.

AFTER THE STUDY: After finishing the 99 conditions, the experimenter helped to take off the HMD and *Guiding Rail*. Then, participants were asked to fill out the final questionnaire, including the overall experience, enjoyment, and realism of the feedback, as well as a demographics survey. While optional, participants were invited to discuss the experiment for supplementary qualitative feedback. Throughout the whole experiment, participants could pause or stop at any time without giving reasons. On average, the procedure took 90 minutes for each participant.

6.5.3.1 *Hygienic Measures*

As this study was conducted during the COVID-19 pandemic, extended hygienic measures were applied. All of them were approved prior to the experiment by the university's health department and in line with the governmental measures at that time. Further, all participants and experimenters had to sanitize their hands before the study and wear medical masks throughout. All materials, textures, the HMD, and contact surfaces were sanitized before and after each participant. The study room was regularly ventilated and an additional ventilation break of at least 30 minutes between two participants was applied. All experimenters were fully vaccinated and tested regularly with *SARS-CoV-2 antigen rapid tests*.

6.5.4 *Participants*

31 participants (17 female, 14 male) between 18 and 50 years (M=28.7, SD=5.4) were recruited. 9 of them had no VR experience, 16 used it a few times before. 4 other participants stated to be regular and 2 to be proficient VR users. 4 participants needed the 0 mm, 14 the -1.5 mm, and 13 the -3 mm *Guiding Rail*. Besides snacks and drinks, no compensation was provided.

6.6 RESULTS

In the following, the results of the study are presented. After introducing the performed data analysis, the quantitative results are described, followed by qualitative feedback from the participants.

6.6.1 *Analysis*

For analyzing the data, different methods were performed as described in the following. More detailed background information on the used methods can also be found in Section 1.6.

(1) Aligned Rank Transform (ART): For the responses of the questionnaires (Q1-Q5), a non-parametric analysis using the ART procedure [Wob+11; Elk+21] using mixed-effects models was performed, together with the ART-C procedure as proposed by Elkin et al. [Elk+21].

(2) Cumulative Link Mixed Models (CLMM): To identify influences of the *perceived haptic roughness* (Q1) and *perceived visual roughness* (Q2) on the *matching* of HAPTIC STIMULI and VISUALIZATIONS (Q3), as well as the influences of the *perceived haptic roughness* (Q1) and *matching* (Q3) on the *pleasantness* (Q5), a *cumulative link mixed model* (CLMM) was fitted using the Laplace approximation. The results report the $pseudo{-}R^2$ of the ANOVA.

(3) Friedman's test and Wilcoxon Rank-Sum tests: For analyzing the post-questionnaires assessing the overall enjoyment and realism, as well as for a comparison of the *matching ratings* (Q3) with the *expected*

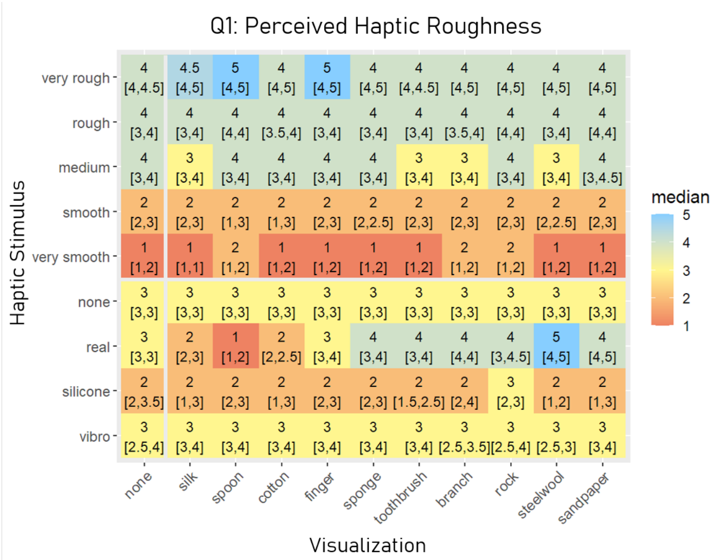


Figure 6.8: Heatmap representation of the results on the perceived haptic roughness. Each cell contains the median rating and the 1st and 3rd quartile in brackets. The horizontal line separates the five physical textures (top) from the four baselines (bottom).

matching, Friedman's test with Bonferroni-corrected Wilcoxon rank-sum tests for posthoc comparisons were performed.

6.6.2 *Perceived Haptic Roughness (Q1)*

The analysis revealed significant main effects of the HAPTIC STIMULUS on the *perceived haptic roughness* ($F_{8,2941} = 361.68$, $p < .001$). Post-hoc tests confirmed significant effects for almost all HAPTIC STIMULI contrasts (*silicone-no-haptics* and *medium-rough* $p <.01$, other $p <.001$, except *vibro-tactile-real* and *silicone-smooth* $p >.05$). Although participants showed a good ability to distinguish between different roughness, the data revealed that levels with a higher roughness a similar perceived roughness (*medium*, *rough*, and *very rough* with $\tilde{x} = 4$).

Significant effects of the VISUALIZATION on the *perceived haptic roughness* were found ($F_{10,2941} = 6.71$, $p < .001$). However, post-hoc tests only confirmed significant effects for some contrasts with higher anticipated mismatch regarding this questionnaire item, such as *no-visuals-finger*, *cotton-finger*, *spoon-finger*, *toothbrush-rock*, and *toothbrush-sandpaper* (all $p <.05$), as well as *no-visuals-rock*, *no-*

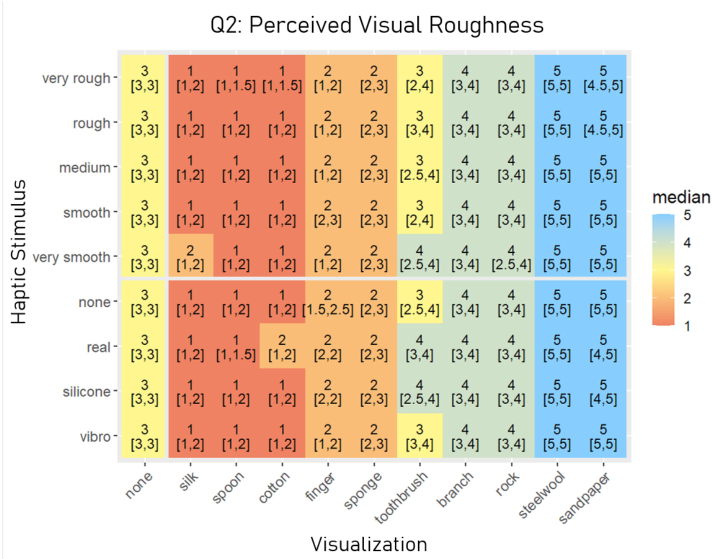


Figure 6.9: Heatmap representation of the results on the perceived visual roughness. Each cell contains the median rating and the 1st and 3rd quartile in brackets. The horizontal line separates the five physical textures (top) from the four baselines (bottom).

visuals-sandpaper, *silk-rock*, *silk-sandpaper*, *spoon-rock*, *spoon-sandpaper*, *cotton-rock*, and *cotton-sandpaper* (all p <.001).

The analysis also found significant interaction effects between Haptic Stimuli and Visualizations ($F_{80,2941} = 5.46$, $p < 0.001$). The ratings of the *haptic roughness* are depicted in Figure 6.8.

6.6.3 *Perceived Visual Roughness (Q2)*

The analysis unveiled that the Visualizations had a significant effect on the *perceived visual roughness* ($F_{10,2941} = 733.32$, $p < .001$). Post-hoc tests confirmed significant effects for almost all Visualizations except five (*no-visuals-sponge* and *toothbrush-rock* p <.05, others p <.001, except *silk-spoon*, *silk-cotton*, *spoon-cotton*, *branch-rock*, and *steel wool-sandpaper* with p >.05). Comparing the medians of each Visualization, almost identical ratings of the perceived roughness and the expected roughness compared to the pre-study were observed. However, a shift by one point was found for the *cotton* towards *very smooth* ($\tilde{x} = 2$ towards $\tilde{x} = 1$) and *sponge* towards *smooth* ($\tilde{x} = 3$ towards $\tilde{x} = 2$). The *no-visuals* baseline was largely rated as neither *smooth* nor *rough* ($\tilde{x} = 3$).

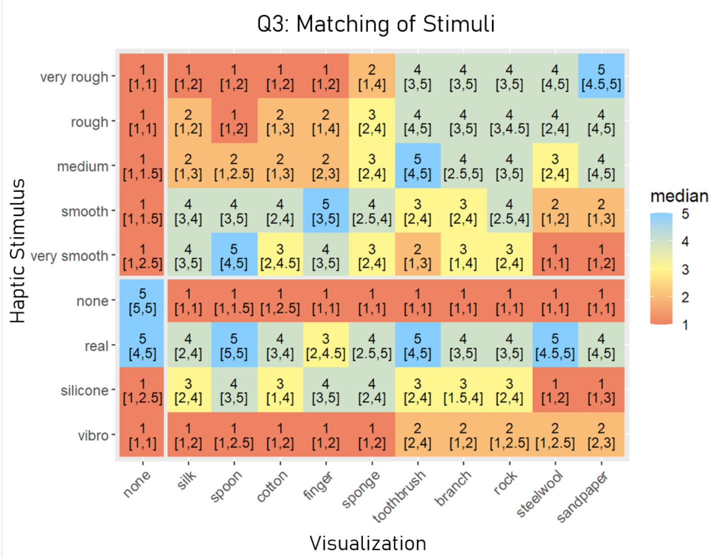


Figure 6.10: Heatmap representation of the results on the matching of each combination of a Haptic Stimulus and a Visualization. Each cell contains the median rating and the 1st and 3rd quartile in brackets. The horizontal line separates the five physical textures (top) from the four baselines (bottom).

The analysis did not reveal any significant effects for the Haptic Stimulus ($F_{8,2941} = 0.93$, $p > .05$) nor any interaction effects ($F_{80,2941} = 0.46$, $p >$ .05). The ratings of the *visual roughness* are depicted in Figure 6.9.

6.6.3.1 *Confirming suitability of selected Visualizations*

The ratings of the *perceived visual roughness* could show that the selected Visualizations were equally distributed and in alignment with the roughness ratings of the same items in the pre-study (as also visible by comparing each column of Figure 6.8b). Although there was a slightly lower perceived visual roughness for the *cotton* and *sponge*, the results still confirmed that the selection of the ten Visualizations covered all five defined levels of roughness, indicating a largely persistent expectation on the roughness.

6.6.4 *Matching of Haptic and Visual Stimuli (Q3)*

The analysis found a significant main effect of the Haptic Stimulus on the *matching of both stimuli* ($F_{8,2941} = 148.58$, $p < 0.001$). Post-hoc tests confirmed significant effects for all HAPTIC STIMULI involving the *real* material (p <.001), between *very rough* and *no-haptics*, *vibrotactile*, *smooth* and *real* (all p <.01), as well as between *no-haptics* and *silicone*, *very smooth*, *smooth*, *medium* and *rough* (all p <.001). Significant effects were also found for all *vibrotactile* contrasts except *no-haptics* (p >.05, all others p <.001).

The analysis further revealed significant effects for the VISUALIZATION ($F_{10,2941} = 26.91$, $p < 0.001$) and post-hoc tests revealed significant effects for all *no-visuals* contrasts (all p <.001), except for the *finger* (p >.05).

Moreover, significant interaction effects were identified ($F_{80,2941} = 19.44$, $p < 0.001$). The ratings of the *matching* are depicted in Figure 6.10.

6.6.4.1 *Influence of Haptic and Visual Roughness on Matching*

A *cumulative link mixed model* (CLMM) was fitted to predict the *matching* (Q3) with the roughness of HAPTIC STIMULI (Q1) and VISUALIZATIONS (Q2). The model included the participant as random effect ($N = 31, SD = 0.55$). The measures of goodness-of-fit were calculated as $pseudo{-}R^2_{McFadden} = 0.209$ and $pseudo{-}R^2_{Nagelkerke} = 0.499$. An analysis of variance based on mixed ordinal logistic regression indicated no statistically significant effect of Q1 on Q3 ($\chi^2(4, N = 31) = 0.00$, $p > .05$) or of Q2 on Q3 ($\chi^2(4, N = 31) = 0.00$, $p > .05$). However, there was a statistically significant interaction of $Q1 \times Q2$ ($\chi^2(16, N = 31) = 1834$, $p < .001$).

6.6.4.2 *Comparison to Expected Matching*

In order to examine if the matching ratings from the participants in the study are in alignment with the initial expectations of how stimuli should match, all VISUALIZATION-HAPTIC STIMULUS pairs[12] that had a maximum median deviation of ± 1 regarding their visual and haptic roughness were grouped and it was hypothesized that those would be *expected matching*. In contrast, pairs with a median deviation $> \pm 1$ were marked as *expected non-matching*. All baselines were categorized in

12 including only the five level of roughness; the baselines were treated as individual groups

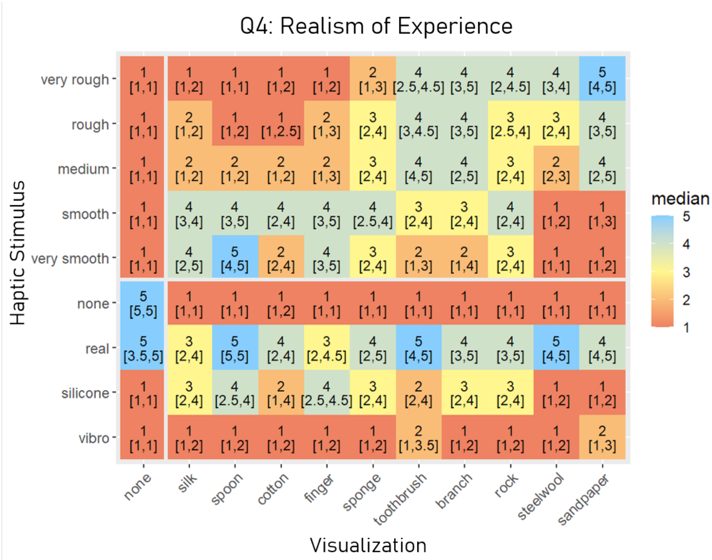


Figure 6.11: Heatmap representation of the results on the realism rating of each combination of a HAPTIC STIMULUS and a VISUALIZATION. Each cell contains the median rating and the 1st and 3rd quartile in brackets. The horizontal line separates the five physical textures (top) from the four baselines (bottom).

individual groups (as introduced in 6.5.1.2). Friedman's test indicated significant effects ($\chi^2(5) = 125$, $p < .001$) and Bonferroni-corrected Wilcoxon rank-sum post-hoc tests revealed significant effects between pairs with an *expected matching* and *expected non-matching* confirming the original hypothesis ($p <.001$, $\tilde{x}_{matching} = 4$, $\tilde{x}_{non-matching} = 2$). The analysis further found significant effects for all other groups except for *vibrotactile*-*expected non-matching*, *vibrotactile*-*no-haptics* and *expected matching*-*real* (all three $p >.05$, all others $p <.05$; $\tilde{x}_{none} = 1$, $\tilde{x}_{real} = 4$, $\tilde{x}_{silicone} = 3$, $\tilde{x}_{vibro} = 1$).

6.6.5 *Real-World Consistency (Realism, Q4)*

The analysis showed significant main effects for the HAPTIC STIMULUS ($F_{8,2941} = 149.85$, $p < .001$). Post-hoc tests showed significant differences for all contrasts involving the *real* material (all $p <.001$) and for the *no-haptics* contrasts ($p <.001$), except for *vibrotactile* ($p >.05$, all other contrasts including *vibrotactile* $p <.001$). Significant effects were also found for *smooth*-*very rough* ($p <.001$), *smooth*-*silicone* ($p <.01$) and *smooth*-*medium* ($p <.05$).

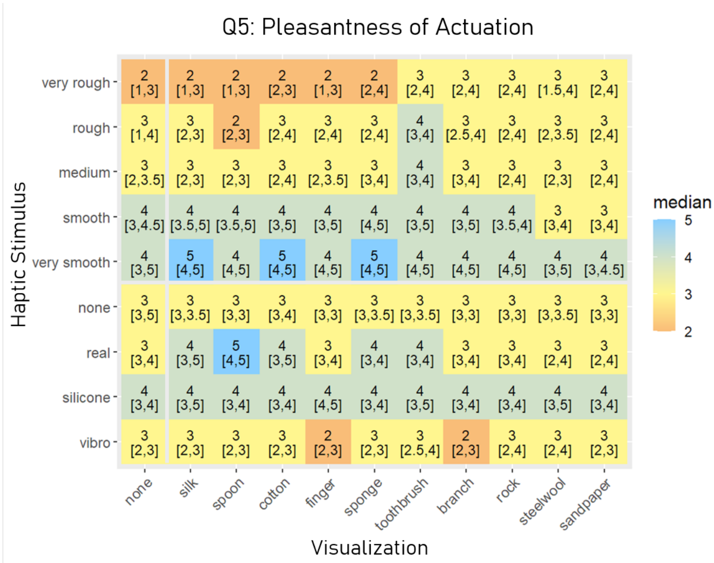


Figure 6.12: Heatmap representation of the results on the pleasantness. Each cell contains the median rating and the 1st and 3rd quartile in brackets. The horizontal line separates the five physical textures (top) from the four baselines (bottom).

The anylsis also showed significant main effects for the VISUALIZATION ($F_{10,2941} = 26.36$, $p < .001$). Post-hoc tests revealed significant differences for all contrasts involving the *no-visuals* baseline (all p <.001) except for *cotton* (p >.05). However, there were significant effects between the *cotton* and *spoon*, *sponge*, *toothbrush*, *branch*, *rock*, *sandpaper* and *finger* (all p <.001)Other significant effects were found for *spoon-silk*, *spoon-steel wool* (both p <.05), *spoon-toothbrush* (p <.01), and between *silk* and *toothbrush*, *branch*, *rock* and *sandpaper* (all p <.001), as well as for *finger-toothbrush*, *toothbrush-sponge*, *toothbrush-steel wool*, *steel wool-branch*, *steel wool-sandpaper* and *finger-vibrotactile* (last p <.01, rest p <.001).

Again, the analysis showed significant interaction effects between HAPTIC STIMULI and VISUALIZATIONS ($F_{80,2941} = 18.75$, $p < .001$). The ratings of the *matching* are depicted in Figure 6.11.

6.6.6 *Pleasantness (Q5)*

The analysis revealed significant effects for the HAPTIC STIMULUS on the pleasantness rating ($F_{8,2941} = 117.2$, $p < .001$. Post-hoc tests revealed that almost every contrast had significant differences, most with

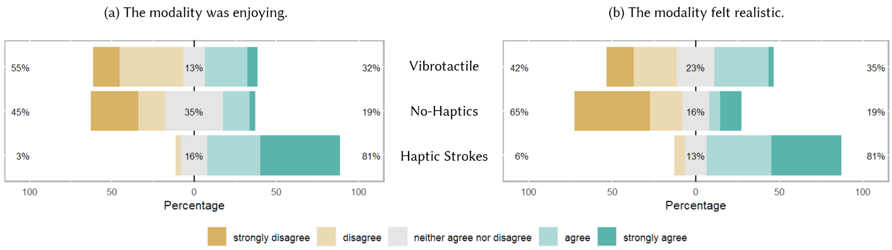


Figure 6.13: Likert responses of the post-questionnaire asking for (a) the enjoyment, and (b) the realism comparing vibrotactile, no-haptic, and haptic stroke feedback.

p <.001, except for *vibrotactile-rough*, *vibrotactile-very rough*, *silicone-real*, *silicone-smooth*, *no-haptics-medium*, and *medium-rough* (all p >.05).

Significant effects for VISUALIZATION ($F_{10,2941} = 2.85, p < .01$) were observed, too. However, post-hoc tests only revealed significant differences between *toothbrush* and *no-visuals* and *sandpaper* (both p <.01), as well as *spoon*, *finger* and *steel wool* (all p <.05). Additionally, significant interaction effects were identified ($F_{80,2941} = 2.22, p < .001$). The ratings of the *pleasantness* are depicted in Figure 6.12.

6.6.6.1 *Influence of Haptic Roughness and Matching on Pleasantness*

After reviewing the data, it was expected that the pleasantness would be also dependent on the *matching* rating with the ratings of the *haptic roughness perception*. Therefore, a *cumulative link mixed model* (CLMM) was fitted to predict the *pleasantness* (Q5) with the *haptic roughness* (Q1) and *matching* (Q3) ratings. The model included the participant as random effect ($N = 31, SD = 0.86$). The measures of goodness-of-fit were calculated as $pseudo{-}R^2_{McFadden} = 0.202$ and $pseudo{-}R^2_{Nagelkerke} = 0.472$. An analysis of variance based on mixed ordinal logistic regression indicated no statistically significant effect of Q1 on Q5 ($\chi^2(4, N = 31) = 0.00, p > .05$) or of Q3 on Q5 ($\chi^2(4, N = 31) = 0.00, p > .05$). However, there was a statistically significant interaction of $Q1 \times Q3$ ($\chi^2(16, N = 31) = 31.98, p < .05$).

6.6.7 *Post-Questionnaire: Overall Enjoyment and Realism*

Participants were asked to rate the *haptic strokes*, *vibrotactile* feedback, and *no-haptic* feedback in the post-questionnaire with regards to the overall *enjoyment*. Here, participants rated *haptic strokes* as best ($\tilde{x} = 4$), followed by *no-haptic* ($\tilde{x} = 3$), and *vibrotactile* ($\tilde{x} = 2$, Figure 6.13a). Friedman's test showed significant results ($\chi^2(2) = 24.3$, $p < .001$) and Bonferroni-corrected Wilcoxon rank-sum post-hoc tests revealed significant effects for *haptic stroke-no-haptic* and *haptic stroke-vibrotactile* (both $p <.001$). No significant effects were found for *no-haptic-vibrotactile* ($p >.05$). In general, the majority of the participants responded to enjoy the whole experiment (12 strongly agreed, 14 agreed, 3 neither agreed nor disagreed, and 2 disagreed, $\tilde{x} = 4$).

As for the overall *realism* between the three modalities, *haptic strokes* were ranked first ($\tilde{x} = 4$), followed by *vibrotactile* ($\tilde{x} = 3$), and *no-haptic* feedback ($\tilde{x} = 2$, Figure 6.13b). Friedman's test found significant results ($\chi^2(2) = 21.4$, $p < .001$. Bonferroni-corrected Wilcoxon rank-sum post-hoc tests revealed significant effects for *haptic stroke-no-haptic* and *haptic stroke-vibrotactile* (both $p <.001$). No significant effects were found for *no-haptic-vibrotactile* ($p >.05$).

The majority of the participants responded to be able to identify haptic textures reliably (6 strongly agreed, 13 agreed, 10 neither agreed nor disagreed, and 2 disagreed, $\tilde{x} = 4$) and they largely agreed that the experiment was pleasant (12 strongly agreed, 13 agreed, 3 neither agreed nor disagreed, and 3 disagreed, $\tilde{x} = 4$).

6.6.8 *Subjective Feedback*

The experiment was generally well-received, in particular, if "the haptic fitted to the visualization" (P29, P20). P21 explained to have "*wow* moments when it already closely matched the object". This was also confirmed by several participants describing the haptic stroke sensation as "realistic" (P15, P21, P23, P24, P27, P29), "very convincing" (P31), and even "increases the immersion when the haptic feedback matches the scene" (P2). Participants thereby enjoyed "when the object feels as expected and seemed real" (P10) and "the haptic stroke matched the visual object" (P19). Interestingly, P29 quoted that "the haptic also influenced my expectations towards the object" and "concluded additional information (wet sponge, cold hands)". In contrast, non-matching stimuli were often reported as unpleasant or even "weird" (P16). P26, for example, described it felt "less realistic [..] and also felt much more uncomfortable" when "very rough haptic stroke feedback was felt for very smooth looking objects". In alignment with the analysis, rougher textures were also typically considered more unpleasant (P25, P27) but had more positive feedback if the roughness was matching (P9, P17, P25).

For P14 it was "super exciting to see how the visual appearance changed in imagination when the haptic feedback was unexpected". For P8 it was "an interesting challenge to try to identify what is touching you" and P10 said that "you could forget for a moment that you are in VR due to the well-depicted objects".

Although the study focused on the roughness of haptic stimuli and visualizations, some participants also reported insights on other characteristics, such as the temperature. For example, P5, P6, P7, and P15 highlighted that some materials, such as the *spoon*, felt more cooler, and P11 stated that a matching temperature "fits to the expectation".

Most of the negative comments were related to the *vibrotactile* feedback as "it was just not a nice feeling" (P9) and "felt unrealistic" (P19) or "unnatural" (P20). In terms of roughness, there was a tendency of describing it as rough or scratchy rather than smooth (P17, P22, P27). However, participants did describe the vibration as quite appropriate for the toothbrush, if it had been electric (P7, P9, P11, P13, P20, P21), or a smartphone notification (P2), and P21 perceived it as "small electric impulses when you are in love" (P21).

If there was no Haptic Stimulus, participants were often unsure how to respond at the beginning. For example, P10 stated that "nothing touched me, but I don't know" and P21 asked if it was "Fake?" and said to "have the impression that I feel something, although there was nothing there". However, in some cases, even the *no-haptics* stimulus was somewhat convincing. For example, P20 told to feel "nothing, but it was still kind of a match because it seemed so light."

6.7 DISCUSSION

This section discusses the results of this Chapter. Most interestingly, the data showed that two levels of roughness, a *smooth* and *very rough* texture, could be conveying enough to keep a matching and realistic experience. Thereby, also the expectation of a visualization's roughness can still adapt to the haptic stimulus. Further, it was also observed that the pleasantness is depending not only on the roughness of a physical haptic stimulus alone but also on the matching with a visualization. These and the other findings are discussed in the following.

6.7.1 *Two distinct Textures can be sufficient for a Matching and Realistic Experience*

The analysis revealed that it is possible to convey a matching and realistic experience for all of the ten visualizations by providing just a *smooth* and *very rough* texture of physical roughness. Although participants were able to discriminate the textures of the HAPTIC STIMULI accurately, the expectation of a VISUALIZATION's roughness was strong enough to blur the boundaries of the haptic perception. Also, without having a direct comparison between two physical gradations, participants had stronger issues pinpointing a texture to a certain level of roughness.

For all VISUALIZATIONS, the experiment showed that the high matching of realism with only two physical textures was also comparable to the perception of the real-world counterparts. This means the results indicated that participants distinguish HAPTIC STIMULI only binary to whether something is either smooth or rough and then adjusted their expectations respectively. Hereby, the two *rough* and *very rough* textures were consistently rated similarly in their perception, likewise to smoother textures. However, differences between a *smooth* and *very smooth* roughness were more common to recognize. For example, while being exposed to the *very smooth* texture when seeing the *spoon* visualization with an initial *very smooth* visual expectation, the sensation was mostly described to be a *smooth* texture. This might support the initial idea of the binary selection process.

As a consequence of future haptic systems, immersive experiences could be already created with a lower amount of physical textures which would reduce the complexity of the underlying architecture. In particular, such haptic devices would allow a more compact design by providing only two textures of different roughness, namely a rough and smooth one. This would also yield additional space for wearable devices that can be used to recreate other material characteristics, such as temperature or hardness.

6.7.2 *The Expectation of a Visualization's Roughness adapts to the Haptic Stimulus*

Adding to the aforementioned finding, some Visualizations (*sponge*, *toothbrush*, *branch*, and *rock*) were rated as equally matching across several haptic levels of roughness. In particular, these four Visualizations were classified and anticipated correctly. However, once the Haptic Stimulus was applied to the arm, the expected visual roughness also changed towards the Haptic Stimulus, even though the Visualization was the same as before.

This resulted in situations, where some participants described that a rock could be both, *smooth* or *rough*, although the visualization of the *rock* was intended to be edgy and sharp. Asking participants why they thought the *rock* was rather smooth now, they argued that it might also have been a rounded pebble that would also match their experience. This effect was also observed for the *branch* where participants indicated that both, rough and smoother stimuli, were matching since the bark of the *branch* might not only be rather scratchy but also more flattened and, thus, smooth. In addition, both examples were objects that also occur in a wide range of variations naturally which means they are already well known in different forms, shapes, and characteristics, such as the dryness or age of the piece of wood. As result, although the mental models and roughness expectations were similar purely based on the visual appearance (cf. results of the pre-study and Section 6.6.3), more atypical smooth stones or branches can also fit the expectation as realistically as long as they would also occur in the wild.

Looking at other Visualizations, such as the *steel wool* or *spoon*, it could be observed that they had less variability in their perceived and expected roughness. For example, the *steel wool* was commonly rated as very rough and scratchy, and no participant could imagine that it might also feel smooth when they were asked for it (after their initial response). The bottom of the *spoon*, on the other hand, only matched with smoother Haptic Stimuli, since the typical expectation would correspond to just such a smooth surface. For example, a very rough *spoon* is typically uncommon as it might injure the oral cavity. An old and rusty *spoon* might be more matching to rough textures but would then also result in different expectations.

Overall, the results indicated that the Haptic Stimulus is able to override the roughness expectation without negatively affecting the matching or realism depending on the shown object. For future devices, this means that objects of the same type but with different visual appearances might be having an identical Haptic Stimulus and would still match the users' expectations.

6.7.3 *Pleasantness depends on Roughness and Matching*

Stimuli with a *smooth* texture were typically perceived as more pleasant than stimuli that were more *rough*, as also shown by existing research [Ess+10]. However, the findings could also show that the matching of Haptic Stimuli and Visualizations influenced the pleasantness. In particular, a high matching rating was observed to have positive effects even for *rough* textures, for example as seen for the *toothbrush*. Contrary, a low matching of stimuli let participants perceive the same *rough* Haptic Stimulus as significantly more unpleasant. For example, a *very rough* texture was largely described as less pleasant for *very smooth* or *smooth* Visualizations than for the expected *rough* or *very rough* Visualizations. Likewise, a vibrotactile sensation that was mostly reported as a non-matching also resulted in lower pleasantness ratings.

Future applications, therefore, could have a direct influence on the perceived pleasantness by altering matching and non-matching Haptic Stimuli and Visualizations. Also, while *very rough* texture was covering a broader spectrum than a *rough* texture, the *rough* should be preferred due to its higher pleasantness rating.

6.7.4 *Prefer Physical Textures over Vibrotactile over no Haptics*

HAPTIC STIMULI based on the sandpaper and the real-world baseline materials showed the highest enjoyment and realism ratings. The *vibrotactile* baseline, however, was rated as a less matching and realistic experience which was also supported by some participants who indicated a strong uncertainty of how to perceive the vibrotactile actuation. While they could recognize a continuous movement, the participants rarely said it was matching to the shown VISUALIZATION. However, even though this indicates that a more physical and mechanical stroke highly improves the experience, the benefits of vibrotactile feedback will remain until true haptic actuation is more technically achievable. This was further underlined by the observation that vibrotactile feedback was still more favorable than the *no-haptics* baseline, as also indicated by results from related work (e.g., [Geh+19]).

However, for the *no-haptics* baseline, it was also interesting that during early trials, participants were often uncertain if there was really a non-existent HAPTIC STIMULUS. For future applications, this could probably also indicate that a physical actuation may not be mandatory in every situation, as long as the visuals are dominant enough.

6.8 LIMITATIONS AND FUTURE WORK

In the previous section, the main findings were discussed. However, the experiments also had some limitations which will be discussed together with potential future work in the following.

6.8.1 *Selected Set of Visualizations and Textures*

During the intensive brainstorming sessions and the pre-study, the HAPTIC STIMULI and VISUALIZATIONS were identified. All of them are of course just a subset of a potentially infinite amount. Yet, while selecting the VISUALIZATIONS, it was also assured that they cover a broad spectrum of objects with different roughness that is known from everyday life, so participants are familiar with them, even though some of them are typically not something that people would perceive on the arm, such as the spoon or sandpaper file.

In future studies, experiments should try to use other objects to elaborate on how the findings apply to different items. Also, the combination of different stimuli at the same time is interesting as it might affect the perception differently or more intensely.

6.8.2 *Other Object Characteristics*

Along with the aforementioned limitation, the experiments in this chapter focused on the perceived roughness, and potential confounding influences were kept minimal, such as other object properties like temperature or friction. For example, with regards to hardness, all Visualizations were selected to consist of one material that is typically more hard or rigid, and one that is rather soft. With regards to stickiness and friction, all items were similar. However, the stickiness of the silicone finger had to be reduced by applying magnesia chalk. The temperature for all objects was at room level with comparable thermal conductivity. However, the spoon, which was made of metal, was mostly perceived as colder. As consequence, future research should investigate the other properties as well to add to the full picture of haptic perception. As a step towards it, this thesis also includes an investigation of temperature as shown in Chapter 7.

In addition to the perception of object properties, the investigation of how the haptic perception is affected by visuals is important. In the past, similar experiments in HCI investigated the influence of visuals on temperature (e.g., [FSH10; BNL20] and the experiments of Chapter 7). However again, more research is necessary for the remaining characteristics, namely the hardness, stickiness, or even combinations of them. For example, as the spatial resolution on the arm is rather low compared to other body parts [TMG13; McG+12], future studies remain relevant to identify how spatially accurate a haptic actuation within VR has to be to still convey a realistic illusion.

6.8.3 *Affective Responses to Combined Stimuli*

The main objectives of the experiments presented in this chapter were DISCRIMINATIVE aspects during PASSIVE TOUCH. Therefore, almost every VISUALIZATION was a static object that was moved along the arm. Yet, while those objects also create AFFECTIVE responses, typical HCI research on AFFECTIVE aspects are focusing on interpersonal interactions [EA16; Hui17]. Therefore, a *fingertip* was included as one of the VISUALIZATIONS. However, the haptic *fingertip* was made of silicone and not a real finger as it would have been impossible to guarantee a consistent actuation between all participants. As a consequence, the matching and realism ratings were identified as rather low for the fake finger.

6.8.4 *Applicability for Active Touch*

Again, the focus of the experiment was on DISCRIMINATIVE aspects during PASSIVE TOUCH. Yet, the underlying concepts could also be applied to ACTIVE TOUCH. However, both are typically involving the two different skin types, *hairy* and *glabrous* skin, that have individual discriminative traits. This also means that the parameters for ACTIVE TOUCH probably have to be adjusted to fit the better ability to detect subtle differences, e.g., by having even more fine-grained gradations of textures. Therefore, further investigations are necessary to evaluate how the results of this contribution are transferable to ACTIVE TOUCH.

6.8.5 *Pleasantness over Time*

High pleasantness is essential for the acceptability of any novel application. The findings of this experiment showed that pleasantness was highly dependent on the matching and roughness of the HAPTIC STIMULI. However, skin fatigue or irritations in response to an experiment duration of about 90 minutes per participant could have negatively affected the pleasantness ratings. The randomized order of the conditions is typically an effective countermeasure to avoid such effects over the whole experiment and participants also did not actively report this. However, lower pleasantness ratings over the duration of the experiment might have occurred sub-consciously as a prolonged exposure to haptic stimuli could cause greater fatigue or even an unwanted sensory over-stimulation.

That being said, after checking the median ratings of pleasantness over time including all participants, a small trend of fewer than 0.5 points was observed. At the same time, the median ratings of haptic roughness over time increased slightly. Both can be an indicator of actual skin fatigue, however, could be still just a coincidence due to the randomization. As such, further research is necessary to investigate the effects on skin fatigue and how this type of actuation affects pleasantness with regard to the density and intensity of physical stroke stimuli.

6.8.6 *Technical Limitations*

The haptic strokes were provided through a prototypical system. However, since uniform actuations were in the focus, the prototype was not in a wearable state that would be necessary for real-world VR applications.

Also, the sandpaper textures were glued onto the *Silicone Cushion*s which was ideal for the study. However, this might be too fragile for future systems where textures with different roughness could be embedded directly into the actuators. For example, it was initially planned to cast smooth and rough textures on a macro-level directly in a *Silicone Cushion*'s surface, similar to Yao et al. [Yao+13]. Unfortunately, this approach was ineffective as textures could not provide a rough enough sensation. Also, when trying to mix fine grains of sand directly into the silicone, actuators were not durable enough since the silicone tended to tear.

6.9 CONCLUSION

This chapter investigated how users perceived Haptic Stimuli with different roughness, in particular when interacting with Visualizations in VR through a controlled experiment with 31 participants. Taking a closer look at the vision of a future versatile and lightweight multimodal device for somatosensory interaction, the results on Fine Mechanoreception and Pressure-based Mechanoreception from this chapter are particularly encouraging. By conducting the presented user studies, it was possible to show how to provide a strong sensation of stroking with different levels of roughness. Further, the findings revealed that for different VISUALIZATIONS, just two real surfaces were required, one smooth and one rough, in order to provide a matching and realistic experience. In addition, the results also highlighted that the pleasantness is strongly affected by the haptic roughness and the degree to which they match the expected roughness. Consequently, under the further assumption that this sensation can be congruently supported by visual stimuli, future systems implementing a stroking modality can benefit from the results with comparatively low effort for the devices. This, in turn, increases the potential for the feasibility of a multi-modal somatosensory device in the close future.

Part III

THERMOCEPTION

7

THERMOCEPTION: ON-BODY THERMAL FEEDBACK

Chapter Overview

Mechanoreception I | Mechanoreception II | **Thermoception** | Proprioception

Related Publication:
Therminator: Understanding the Interdependency of Visual and On-Body Thermal Feedback in Virtual Reality
CHI 2020

Arm | Abdomen | Liquids as medium | Controlled Experiment | VR

The previous chapters investigated somatosensory interaction with a focus on MECHANORECEPTION. However, looking at human perception, a significant part of sensing and interacting with the environment is linked to THERMOCEPTION, meaning the perception of temperature [DJ77; HJ06]. In recent years, research in HCI has emerged that applied thermal displays to a broad spectrum of applications, ranging from training environments, catastrophe simulation, gaming experiences, and even rehabilitation. Also, thermal feedback is used to enrich media, present notifications, and convey emotions, and other social aspects, such as well-being and comfort. However, while a huge part of thermal displays is focusing on *actively* touching objects with the hands, other body parts need to be considered as well, such as the head, arms, torso, or even the back. Still, the investigation of thermal feedback, especially in VR situations, is sparse compared to other haptic modalities.

The thermal property is one of the main material characteristics [ONY13; ONH16] as it indicates an object's functionality, affordance, or situation (see also Section 2.3). For example, grabbing a warm mug may be interpreted that the beverage inside having a good drinking temperature. However, if the mug feels hot, it may suggest that it remains precarious to drink or even touch it. Yet, temperature perception is not limited to these mere physical properties as it can also stimulate emotions, e.g., through hugs and caresses. Also, despite such rather direct feedback, users may have a specific mental model of how thermal properties feel. E.g., what would happen if thermal and visual stimuli do not match expectations? How might a person perceive hot ice cubes? Or a cold burning flame?

In this chapter, Thermoception will be explored. As a first step, an overview of relevant research from the fields of HCI, physiology, and psychology was used to derive a set of requirements for thermal actuation. Based on those, and in contrast to existing approaches, concepts of a liquid-based system were designed and implemented. Further, this chapter presents the results of an investigation with 25 participants to deepen the understanding of how persons perceive temperature with varying visual and thermal stimuli in VR. Therefore, the study explored how those stimuli do or do not fit, and, thus, may or may not match the expected mental model of temperature.

7.1 CONTRIBUTION STATEMENT AND RELATED PUBLICATION

This chapter is based on the following publication:

Sebastian Günther, Florian Müller, Dominik Schön, Omar Elmoghazy, Max Mühlhäuser, and Martin Schmitz. "Therminator: Understanding the Interdependency of Visual and On-Body Thermal Feedback in Virtual Reality." In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (*CHI '20*). New York, NY, USA: ACM, Apr. 2020, pp. 1–14. ISBN: 9781450367080. DOI: 10.1145/3313831.3376195

Contribution Statement: I led the idea creation, concept design, implementation, data analysis, and writing process. The former students *Dominik Schön* and *Omar Elmoghazy* supported building the prototype and implemented the study client application. *Florian Müller* consulted to and reviewed the design process, as well as provided his experience of statistical analysis. *Martin Schmitz* gave feedback on the writing process. *Max Mühlhäuser* supervised and supported the writing of the publication and gave valuable feedback during the design process.

❗ *Some contents of this chapter might contain verbatim parts of the aforementioned publication.*

7.2 Chapter Structure

The remainder of this chapter is structured as follows: After this introduction, a structured overview of related work is given in Section 7.3 which highlights relevant work among the fields of thermal feedback in HCI, AR, VR, and how existing work investigated interdependecies with visual sensation. Afterwards, this chapter presents a set of requirements for thermal haptic feedback in VR, followed by introducing the Therminator concepts and prototype (Sections 7.4 and 7.5). Sections 7.6 and 7.7 present the controlled experiment and its results that investigate the interdependency between thermal and visual stimuli, concluded by a structured discussion (Section 7.8). To further underline the possibilities of this work, Section 7.9 presents three example applications using the Therminator system. The chapter closes by a discussion of current limitations and future work (Section 7.10), as well as a concluding summary (Section 7.11).

7.3 Related Work

This section presents a structured discussion of relevant work in the field of thermal actuation. First, a summary of general thermal feedback in HCI is addressed. Then, projects that use thermal feedback in the context of AR and VR will be discussed in more detail. The third subsection gives an overview of research investigating relationships between visual and thermal stimuli. More details on the physiological background of Thermoception within the somatosensory system are found in Chapter 2.2.2.

7.3.1 *Thermal Feedback in HCI*

Thermal feedback in HCI is leveraged in a variety of different situations to enhance user experiences or to support interaction concepts. Hereby, the spectrum of applications is broad and ranges from applying temperature to tangibles [LTH18; Bal14], over supporting social multimedia experiences [AHB17; Hal+12], up to augmenting public spaces with heat spots to let strangers meet together at determined locations [Nar+09].

Thermal feedback can be divided into contact-based and non-contact-based approaches. While the latter uses peripheral actuation, contact-based approaches often rely on thermoelectric components. Hereby, thermal displays are typically embedded directly into existing and novel devices.

In an early work, Wilson et al. [Wil+11] explored thermal stimuli on the wrist, palm, and arm for augmenting mobile experiences, such as smartphones. Löchtefeld et al. [Löc+14] added thermoelectric Peltier elements to the back of a tablet computer, to enrich the experience while consuming videos and other media. In a later work, the authors also applied thermal feedback to game controllers to increase the atmosphere and render additional information cues for individual UI elements [Löc+17]. Similarly, Kotsev et al. [Kot+17] also used thermal feedback as a direct game element but attached the Peltier elements directly to the users' lower arm. Moreover, using temperature is not restricted to digital artifacts and can also be employed to make physical pieces of art and paintings more accessible for persons with visual impairments, as done by Hribar and Pawluk [HP11]. As such, those works already cover a broad spectrum of application scenarios.

However, thermal feedback is not limited to media augmentation. For example, Peiris et al. [Pei+19] embedded small Peltier elements into a wristband that can be worn as a companion device for smartwatches or may directly be included in future devices. Further, the authors present different possibilities for a thermal display, such as notifications, media augmentation, or even guidance purposes. In a similar work, Zhu et al. [Zhu+19] presented an even smaller approach where the thermoelectric elements were embedded into a ring. Tewell et al. [TBB17] focused on the guidance aspect of thermal cues in 2D maze navigation tasks while using a conventional array of Peltier elements attached to the arm.

In addition, a large body of research in HCI explored the usage of thermal feedback for conveying and perceiving emotions. In numerous works, Wilson et al. [WB17; WDB16; WFB16] and Iwasaki et al. [IMR10] used thermal displays attached to mobile devices, such as smartphones, to support different emotional states on the palm. Akiyama et al. [Aki+13] used thermal feedback to adjust the mood of users while listening to music. More recently, El Ali et al. [El +20] used a chest-worn Peltier element to increase arousal, as well as increase and decrease valence for voice messages.

While those approaches provide foundations for thermal feedback, most of them rely on power-consuming and rigid thermoelectric components that are limited for the use in larger systems. Also, those devices mostly focused on presenting thermal stimuli but did not investigate how such actuation can be affected by or can affect other senses.

7.3.2 *Thermal Feedback in Augmented- and Virtual Reality*

Thermal feedback in AR and VR is becoming more relevant as one of the missing links towards the ultimate displays [Sut65]. However, it is still one of the lesser investigated haptic modalities for virtual experiences. While there exists plenty of existing work, two main methods and concepts of how thermal feedback is applied to users can be found: a CONTACT-BASED and a NON-CONTACT-BASED actuation.

7.3.2.1 *Contact-Based Actuation*

With contact-based feedback, thermal displays are typically placed directly on the body. Peiris et al. [Pei+17] and Chen et al. [Che+17], for example, used thermoelectric Peltier elements and small fans mounted on the HMD to generate different temperatures on and around the head. In more recent work, the authors further investigated and presented an approach to creating a wetness illusion on the face by solely changing the applied temperatures [PCM18], similar to the non-VR investigations by Shibahara et al. [SS16]. In another work by Ranasinghe et al. [Ran+17], the authors mounted small fans to the HMD to create a cooling effect via wind stimuli and extended it with olfactory stimuli in a follow-up work [Ran+18]. Maeda et al. [MK19] used modular thermoelectric Peltier elements for the body to create a very localized thermal actuation, likewise to commercial VR suits, such as Teslasuit[1] that also utilized this kind of elements. Peng et al. [PPM17] placed thermoelectric elements on the wrist and explored the effect of passing through virtual items or digital avatars.

Again, as mentioned in the previous section, thermoelectric Peltier elements tend to provide only a very spatially localized, rigid, and

1 https://teslasuit.io/blog/teslasuit-climate-control-system/, last accessed 2020-01-08

power-consuming actuation with the necessity of active or passive cooling elements[2], where some even use a water-cooling [Rag+20; Sou+21]. To overcome the movement constraints, more recent approaches use more miniature Peltier or Thermoelectric Cooler (TEC) elements with smaller surfaces which are less restricting [Nii+20; Zhu+19; Kim+20a]. Lee et al. [Lee+20] even embedded them into flexible silicone materials to wear directly on the skin. Yet, the issues of requiring heatsinks, small actuation areas, or lower thermal transfer rates remain.

As a possible alternative, a few systems considered fluids as a medium that can be used for heating and cooling. For example, the Haptx glove[3] uses very small amounts of liquid to generate thermal stimuli. This allows for less restricted movements, however, it is focusing only on a small body part, namely the hand. Also, as a commercial product, it lacks a systematic investigation of thermal stimuli and their effects on visual stimuli. Likewise, Cai et al. [Cai+20] cycle water through a heating and cooling chamber to provide thermal feedback on the arm. While very similar to the concepts of this chapter, the authors focused only on the arm and did not investigate other body parts and the effects of visual influences. More recently, Liu et al. [Liu+21] designed an arm sleeve that uses a combination of liquids and pressure to create stroking motions. A completely different approach using liquids, but in form of vaporizing oils and solutions, Brooks et al. [BNL20] provided thermal stimuli through a trigeminal illusion. Thereby, users are exposed to an olfactory stimulation that tricks the human perception to feel warmer or colder, e.g., by using capsaicin or menthol fluids.

7.3.2.2 *Non-Contact-Based Actuation*

Besides a CONTACT-BASED actuation where thermal elements are directly mounted to body parts, there also exist NON-CONTACT-BASED thermal feedback. Most approaches are using infrared heating lamps for heating or fans for cooling. The advantage compared to contact-based solutions is the complete freedom of movement. The main disadvantage, however, is the less precise actuation as they mostly cover larger or complete parts of the body from a distance through a stationary setup. For example, Iwai et al. [IAS19] and Yoshikawa et al. [YIS13] combine projection-

2 http://www.heatsink-guide.com/peltier.htm (accessed March 01, 2022)
3 https://haptx.com/what-is-haptics-really-part-3-thermal-feedback/ (accessed March 01, 2022)

Citation	Warm	Cold	Head / Face	Neck	Dorsum (Back)	Thorax / Abdomen	Arm	Wrist	Hand / Finger	Technology	VR / AR / Projection
Brooks et al. [BNL20]	✓	✓	✓ *							☕	VR
Cai et al. [Cai+20]	✓	✓							✓	⚡	VR
Han et al. [Han+18]	✓	✓	✓							💡🌀	VR ⤢
Hülsmann et al. [Hül+14]	✓	✓								💡🌀	📦⤢
Iwai et al. [IAS19]	✓						✓		✓	💡	⏏⤢
Kim et al. [Kim+20a]	✓	✓							✓	⚡	VR
Lee et al. [Lee+20]	✓	✓							✓	⚡	VR
Liu et al. [Liu+21]	✓	✓					✓			💧	
Maeda and Kurahashi [MK19]	✓	✓					✓	✓		⚡	VR ⏏
Peiris et al. [Pei+17]	✓	✓	✓ *							⚡	VR
Peiris et al. [PCM18]		✓	✓ *							⚡	VR
Ragozin et al. [Rag+20]	✓	✓		✓	✓		✓			⚡	VR
Ranasinghe et al. [Ran+17]	✓	✓	✓	✓						⚡🌀	VR
Shaw et al. [Sha+19]	✓		✓ *			✓	✓		✓	💡	VR
Soucy et al. [Sou+21]	✓	✓						✓		⚡	VR
Weir et al. [Wei+13]	✓								✓		AR
Wilson et al. [Wil+11]	✓	✓					✓	✓	✓	⚡	📱
Xu et al. [Xu+19]		✓	✓	✓						🌀	VR ⤢
Yoshikawa et al. [YIS13]	✓								✓	💡	VR
Ch. 7: THERMINATOR	✓	✓				✓	✓			💧	VR

Table 7.1: Overview of related work that uses thermal feedback in AR, VR, or projection-based environments. Legend: ✓ featured, ☕ olfactory, 💡 heatlamp, 🌀 fans, ⚡ thermoelectric elements, 💧 liquids, ⤢ non-contact, ⏏ projection, 📦 CUBE system.

based visuals with a heating infrared-lamp for a thermal stimulus. Similarly, Han et al. [Han+18] use a profoundly sophisticated stationary system on the ceiling that also provides warmth through a heating lamp, plus additional coldness by a ventilating fan and evaporated liquids. In 2014, Hülsmann et al. [Hül+14] previously presented an ambient large-scale thermal system for a CAVE environment using arrays of fans and infrared heating lamps. Shaw et al. [Sha+19] used directed high-energy heating units behind mechanical shutters to regulate the thermal intensity and hotness during a simulated fire evacuation scenario in VR. However, as the system is located on a desk, it always actuates the facing side of the user, typically including the head and upper body. While those all use stationary systems, Xu et al. [Xu+19] designed a hybrid of a contact- and non-contact-based system. Here, the authors provided a cold stimulus to the neck of users through air vortexes in a non-VR environment without considering warm stimuli.

Summarizing, with regards to the presented works in this section, a large group is using contact-based methods relying on thermoelectric elements focusing on the actuation of the head, face, arms, or hands. Table 7.1 gives an overview of AR-, VR-, and projection-based related work and highlights their ability to create warmth or coldness, the actuated body parts, and the underlying technology. Further, the capabilities of the prototypical implementation presented later in this chapter (Section 7.5), called THERMINATOR, were added for comparison.

However, most of the work considering AR or VR, put a strong emphasis on just providing the thermal feedback or how it affects the users' presence. Yet, besides the technical setup, it remains unclear how such an actuation affects the user perception and how it may differ between different parts of the body.

7.3.3 *Mutual Interaction between Thermal and Visual Stimuli*

Investigating mutual interaction effects between varying haptic and visual stimuli is critical to fully understand how each aspect affects the other. While such effects with visual stimuli are already explored for EMS and vibrotactile-based haptics (e.g., Gehrke et al. [Geh+19]), there was no systematic evaluation of visual and thermal stimuli in VR. However, previous research showed that the thermal perception of visuals is highly related to learned and experienced mental models and vice-versa. For example, the psychological rubber hand illusion, an experiment where stroking a fake rubber hand feels like the own hand by Botvinick and Cohen [BC98; TH05], was modified for thermal stimuli. Kanaya et al. [KMY12] and Trojan et al. [Tro+18] conducted studies to investigate how the illusion of temperature on a rubber hand affects the thermal judgment of participants. In a different work by Takakura et al. [Tak+15], the authors took a look into changes in body temperatures while looking at different images. Thereby the authors observed that once the participants were shown a hot-looking video (pictures of a desert), their body temperature subtly decreased compared to a neutral control image. On the other side, when showing a video with colder appealing pictures of snow, the body temperature slightly increased. In a different work, Wang et al. [Wan+18] explored the effect of different colored walls inside buildings and how it affects temperature perception and comfort.

However, the perceived temperature also depends on the expectations of users and their mental models of thermal properties. Fenko et al. [FSH10] therefore described two factors that affect the subjective temperature perception: (1) LITERAL MEANING that aligns with the physical warmness, and (2) FIGURATIVE MEANING of an object related to "social activity, intimacy, and friendly atmosphere" (Fenko et al., 2010, [FSH10], p. 1331). For example, if a user should perceive a visual stimulus as a cold expected temperature, an object, entity, or environment is needed that suggests a *cold looking* property. To examine such mental models, Wilson et al. [WDB15] investigated distinct application areas where thermal properties are subjectively interpreted differently, such as digital contents, doorknobs, and social media. In a similar, but more abstract fashion, Löffler et al. [LTH18] conducted a user study to explore how congruent and incongruent physical properties of tangibles are affecting their participants' intuitiveness for interacting with them, including varying sizes, weights, and temperatures of the tangibles.

On the one side, visuals undoubtedly strongly affect the perception of temperature, even when no actual thermal stimulus is present. For example, Weir et al. [Wei+13] designed an AR application that augments a user's hand with virtual flames and smoke effects. Even though they did not render any thermal feedback, about a fifth of the participants reported an increased warmness on their hands just by seeing the virtual flames. A similar effect was observed by Hoffmann et al. [HPC00] for rehabilitation processes. Here, the authors distracted burn patients with a VR game without actual thermal feedback to subjectively reduce the patient's pain perception.

On the other side, pure thermal stimuli can also influence how users perceive the physical properties of objects, such as the wetness of clothes. For example, Shibahara and Sato [SS16] changed the temperature of fabric with an underlying Peltier element while participants had the impression that the still dry material turned wet. The same effect of wetness was also observed by Peiris et al. [PCM18] who embedded thermoelectric elements into a VR HMD.

Iwai et al. [IAS19] used projector-based visualizations and provided warm non-contact-based feedback through infrared projections directed to their participants to enhance social interaction and temperature perception. Further, the authors investigated how visual and thermal properties should interact with each other. They observed that the thermal intensity should always be high and the actuated surfaces, both visually and thermally, do not have to be identical, as the thermal resolution of the human perception is rather low. While this already provides useful insights into the psychophysical effects of warmth, the authors did not investigate how visual and temperature mismatches affect perception. Further, projector-based visualizations are mostly limited to 2-dimensional visualization and, in contrast to VR, are not fully immersive around the user.

In other previous experiments, Balcer [Bal14] and Ziat et al. [Zia+16] investigated how the perceived temperature of virtual objects is affected by their visual color appearance and varying thermal stimuli. During their experiments in a VR environment, the authors changed the color hues of their test objects between red and blue, which typically represent a warm and cold temperature respectively [ME26]. Yet, the actual temperature of the proxy objects was also altered between warm and cold and did not necessarily have to match the expected temperature of the participants. As a finding, the authors identified that non-matching stimuli resulted in longer reaction times than matching stimuli. However, while these findings already show possible effects due to the interdependencies of stimuli, the study focused on associated temperatures of colors without considering more sophisticated visual stimuli in the form of 3D visualizations. Further, the authors did not consider the influence on the participant's involvement and comfort.

In summary, mutual effects and the interdependency between visual and thermal stimuli are not new phenomena as they are essential for human temperature perception. However, there is no structured investigation yet that explores how those effects are perceived in VR environments and how they affect the users' involvement and comfort. Further, as one advantage of VR, it is possible to simulate mismatching stimuli and uncanny effects, such as a burning ice cube, which may result in even stronger interaction effects.

7.4 REQUIREMENTS

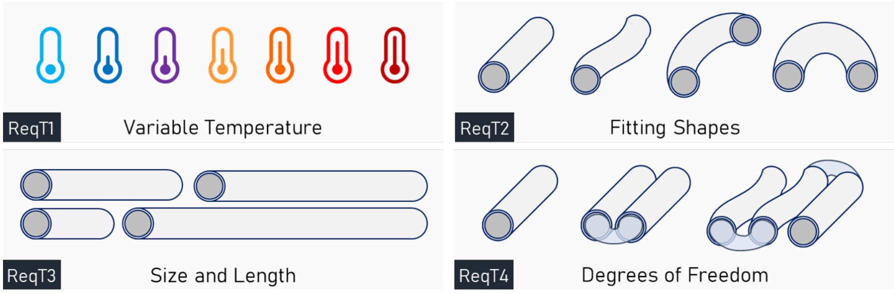


Figure 7.1: Requirements for a wearable thermal display: ReqT1. Variable Temperature, ReqT2. Fitting Shapes, ReqT3. Size and Length, ReqT4. Degrees of Freedom. The images already depict actuators in form of tubes, as they are used for the THERMINATOR system.

In the previous section, it was shown that localized thermal feedback offers a versatile spectrum of application scenarios, such as immersive interaction, media enrichment, or the transfer of emotions. While the requirements are different for each use case, some general requirements have to be considered if thermal feedback should be applied to wearable systems or VR applications. Besides the physical challenges when working with thermal displays [JH08], the complex anatomy and physiology of the human body require localized thermal stimuli that are flexible enough to adapt to specific anatomical shapes. For example, the arm has typically a narrow and cylindrical shape whereas the abdomen is a larger flat, or slightly convex surface. In the following, four requirements for the usage of thermal displays are given with an additional overview of how related work fulfills those.

REQT1. PROVIDE VARIABLE TEMPERATURE

The temperature should be variable and adjustable to fit changing situations, environments, or properties depending on the context. Depending on the use case, a thermal display would need the capabilities to render warm and cold temperatures (Figure 7.1 ReqT1)).

REQT2. SHAPES OF ACTUATORS MUST FIT BODY PART

Actuators ideally have to fit the shapes of each part of the body. The physiology of different parts of the body is typically largely varying. For example, body parts might be rather straight like the shin, more convex like the abdomen, or bent like the spine (Figure 7.1 ReqT2).

ReqT3. Provide custom size and length

An actuation should occur at an appropriate spot. Therefore, it is necessary that actuators can also be adjusted in size to cover as numerous purposes as possible (Figure 7.1 ReqT3).

ReqT4. Provide a good degree of freedom

Body parts vary in their dimensions, shapes, and size which also affects the degrees of freedom. Therefore, one requirement is to have movement restrictions coming from actuators by providing a high degree of freedom. For example, in order to let arms or legs bend and stretch freely (Figure 7.1 ReqT4).

	Peltier	**Air**	**Liquids**
ReqT1: Temperature	+	+	+
ReqT2: Shapes	o	+	+
ReqT3: Size and Length	o	-	+
ReqT4: Deg. of Freedom	-	+	o
Advantages	easy to deploy, based on electric energy, good thermal properties	non-contact based, highest movement flexibility	network of tubes are easy extendable, flexible, good thermal properties
Disadvantages	high power consumption, very localized, surfaces mostly flat, rigid, extensions are expensive	poor thermal properties, low precision	liquids need circulation and separate heating/cooling, water consumption

Table 7.2: Fulfillment of the requirements comparing the advantages and disadvantages of thermoelectric elements, air-based, and liquid-based systems.

7.5 Thermal concepts and system implementation

Based on the requirements (see Section 7.4), this section first introduces concepts for thermal actuation on the body. Then, a prototypical implementation of the concepts using a liquid-based approach, called Therminator, will be presented.

7.5.1 *Concepts*

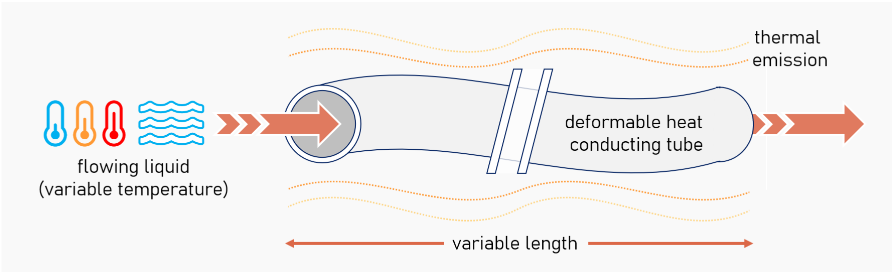


Figure 7.2: Concept of the THERMINATOR system which uses heat-conducting tubes that can be flexibly adapted to various shapes of different body parts. It allows fluids with adjustable temperatures to flow through the tubes.

7.5.1.1 *Limitations of Thermoelectric Elements and Air as Medium*

As shown in the related work section (Section 7.3), traditional approaches mostly use thermoelectric Peltier elements. While those are easy to deploy and inexpensive, they have some major drawbacks for the usage in AR/VR applications. Typically, their actuation is spatially very localized for small surfaces with about 1-5 cm edge length. Though it is possible to use thermally conductive carrier materials to extend the effective range, this can influence the thermal transfer performance and may result in lower actuation rates. Using multiple Peltier elements in an array, however, would yield a continuously decreased flexibility and rigidity with even higher power consumption. In addition, thermoelectric elements require active or passive cooling, e.g., through heatsinks[4]. This often hampers user movements, especially when much freedom is needed. As technology continuously improves, newer approaches use Peltier or TEC elements with smaller surfaces close to the size of a needle-head (e.g., [Nii+20; Zhu+19; Kim+20a]). This makes them less constraining and allows them to be embedded into silicon materials that act as a second skin [Lee+20]. However, this does not negate the issues of requiring heatsinks and providing only a small actuation surface, or the thermal properties are not fast enough. While air as the medium is a viable option, too, it suffers from low thermal conductivity and is mostly limited to non-contact-based systems that are insufficient for ac-

4 http://www.heatsink-guide.com/peltier.htm (accessed March 01, 2022)

tuating specific body parts, despite its maximum freedom of movement (e.g., [Hül+14; Han+18]).

7.5.1.2 *Liquids as Medium in a Tube System*

As an alternative to electrothermic elements and air, the advantages of liquids with different temperatures that flow through a network of deformable and thermally conductive tubes were considered (depicted in Figure 7.2). With regards to the aforementioned requirements, this approach is able to adapt to a variety of shapes and transfer temperatures directly to individual body parts with different anatomical properties. In the following, the liquid-based approach is discussed with regard to the requirements, while Table 7.2 gives an overview of the advantages and disadvantages of the three mentioned technologies.

The skin consists of a large network of thermal receptors that recognize temperature changes. Further, besides thermal characteristics, this network can warn for hot and too cold temperatures [JH08; ONH16], as well as to give a sense of pleasantness in ideal conditions [FSH10]. While the human capability to perceive temperature is very pronounced, for example, in differentiating surfaces through thermal properties [HJ06], the spatial resolution is limited [SM12]. Further, the temporal demand for temperature changes often does not apply to the users' expectations [Kot+17] which means that a thermal display should be able to adapt quickly to rapid temperature changes.

Therefore, liquids were considered a medium for a thermal display. For example, water has excellent thermal properties that can transfer temperature more effectively (WATER 0.59 W $\cdot m^{-1} \cdot K^{-1}$ compared to AIR 0.03 W $\cdot m^{-1} \cdot K^{-1}$). Further, there are several possibilities to modify the temperature of liquids (cf. Requirement REQT1). For example, by blending cold and warm liquid sources with a thermal mixing valve, or by changing the temperature directly via individual heating elements. This enabled to let liquids of any desired temperature to flow through the tubes. However, there are differences in how different individuals of different backgrounds or gender perceive the same temperature [GOH16], and the perception threshold changes over lifetime [SC98]. Research therefore showed [HWG52; HD99] that a lower boundary of 15 °C-17 °C and upper boundary of 45 °C-52 °C are typically avoid pain sensations (cf. NOCICEPTION in Section 2.2.4) associated with the thermoreceptors.

7.5.1.3 *Shape, Size, and Arrangement*

When using liquids as a medium for heat conduction, the liquids have to be ensured in a closed system that can actuate different regions of the body without leakages. A network of tubes can enable such a high flexible actuation by using deformable interconnected tubes. Hereby, each actuator can be designed to match varying curvatures of the body (cf. Requirements REQT2-4), leading to straight, curved, or even bent shapes. Further to this, the total length of actuators is important. For example, having an actuator for the thigh compared to an actuator for the forearm, the tubes might be longer or larger.

This means that individual actuators must not be implemented as one large tube, but rather as an interconnected network of smaller tubes with fitting shapes for the specific parts of the body. As a consequence, the tubes must also be linked together using particularly elastic, flexible tubes so that liquids can flow from one actuator tube to the next. With this concept, each actuator is composed of a series of tubes that can be arranged in different configurations, e.g., horizontally, vertically, and diagonally.

7.5.2 *Actuators: Tube system*

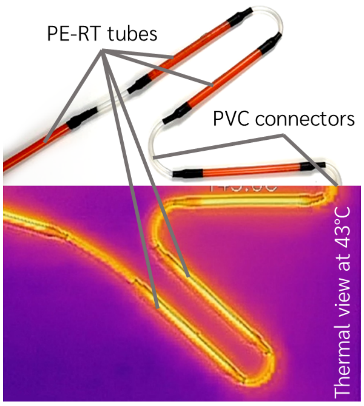


Figure 7.3: A picture of one actuator with the heat conduction PE-RT tubes in red and super flexible PVC connector tubes, together with a thermal camera view at 43 °C on the right side.

The tubes have to be flexible to adapt to different shapes and need to have a good thermal conductivity in order to transfer the temperature of the inner liquids to the user. Using this network of tubes instead of larger chambers guarantees a homogeneous distribution of the temperature to flow liquids at a constant rate. For example, due to the good thermal properties of mesh-like networks of liquids within tubes, NASA proposed its usage to cool down spacesuits for astronauts during their missions [Ize+15].

For the THERMINATOR system, tubes are needed in alignment with the introduced requirements in Section 7.4. In the beginning, different types of tubes and implementations were tested. For example, while *PVC* (*polyvinyl chloride*) tubes were highly flexible, they do not provide good thermal conductivity. Metallic pipes made from copper, however, have a very good thermal conductivity but are too rigid and cool down too fast. Providing both advantages, thermoplastic PE-RT TUBES (*polyethylene of raised temperature resistance*) turned out to have exactly such properties as their thermal conductivity is close to the thermal conductivity of water (WATER 0.59 $W \cdot m^{-1} \cdot K^{-1}$, PE-RT 0.43 $W \cdot m^{-1} \cdot K^{-1}$) and they are not too rigid. They are commonly used for professional thermal appliances, such as underfloor heating systems, and the outside temperature of the PE-RT tubes adapts to the internal temperature quickly in between 2-5 seconds, depending on the diameter of the tubes.

Typical PE-RT tubes have a high-pressure resistance of up to 1300 kPa at flow temperatures of up to 70 °C[5] which is largely sufficient for all imaginable HCI applications such high temperatures are above the tolerable maximum heat for on-body feedback [JH08; GOH16]. However, this also means that PE-RT tubes are not super flexible, e.g., compared to PVC tubes. However, they can be permanently deformed when applying very high heat, e.g., with a hot air gun, and bringing them into a new form. For THERMINATOR, tubes with a diameter of 12 mm were taken as this size allowed for a good tradeoff between flow and a bending radius of about 10 cm when re-shaped with heat.

To connect single PE-RT segments to a larger "grill"-like network that can be woven into a fabric, a bending radius of 10 cm, however, would still limit the applicability to different body parts. Further, as PE-RT tubes are mostly firm even after re-shaping, an actuator made solely from those elements would be not flexible enough. Therefore, the highly flexible PVC TUBES mentioned before that can be bent beyond were identified as practical to provide a connection for PE-RT tubes. Further,

5 `https://plasticpipe.org/building-construction/bcd-pe-rt.html` (accessed March 01, 2022)

PVC tubes have negligible thermal properties which allowed to use them as feeder and drainer for the actuator at body parts that should not be affected by temperature changes.

Therefore for THERMINATOR, the actuators were arranged in a *grill* like arrangement with a spacing of 5 cm spacing between each PE-RT segment. This arrangement represented a good coverage of any body part as the thermal resolution of the body is low [SM12; SC98] and also more energy-saving than having larger chambers for the liquids. Figure 7.3 depicts a detailed view of the actuators and their tube-based layout, as well as a thermal camera view showing the heat radiation at 43 °C.

While the tube-based system allows for a multitude of actuator layouts, two specific layouts were considered to actuate the arm and abdomen. They were selected due to their fit with the intended applications. For the arm actuator, the tubes were put inside a tight arm sleeve which ensured the contact of the heat-exposing tubes with the skin. For the abdomen actuator, the tubes were woven into a fabric shirt in a horizontal layout. Both actuators used 8 PE-RT tubes interconnected with PVC tubes and had a spacing of 5 cm between each PE-RT segment.

7.5.3 *Water Cycle and Temperature Mixing*

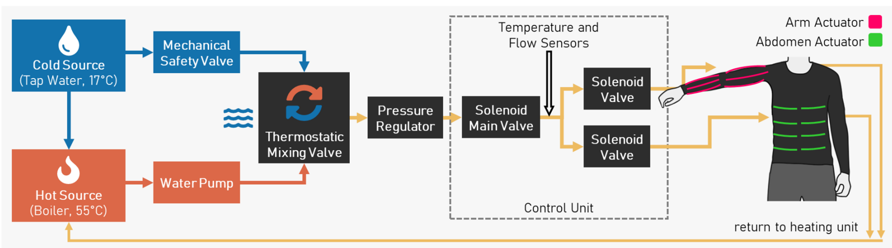


Figure 7.4: Schematic overview of the complete THERMINATOR system with two actuators. From left to right: A cold tap water source is used to supply a heating boiler. Both liquids with different temperatures are then mixed with a thermostatic mixing and regulated with a mechanical pressure regulator. The control unit can toggle electronic solenoid valves to release the mixed liquid to separate actuators. Further, a temperature and flow sensor are measuring the state of the system.

For supplying the actuators with a liquid that can change temperature, two sources of water were necessary. A cold water source to cool the liquid down and a hot water source to increase the temperature which was then mixed to reach a specific temperature. The cold water supply was a conventional household connection providing tap water at a constant rate of 17 °C. However, as there was no hot tap water source available, a boiler that heated 30 L of water to constant 55 °C was used. The water in the boiler had to be refilled before using the system and it took about 5 minutes before everything was ready.

Both water supplies were then connected to a mechanical thermal mixing valve that can be manually regulated between 18 °C and 48 °C to reach a certain temperature. However, as the hot water supply did not provide its own pressure to create a water flow, a pump (*Daypower WP-165*) had to be installed which carried the hot water from the boiler into the system with a throughput of up to 6 L/min. To increase sustainability and reduce the number of refills needed for the boiler, the warm reflux coming from the actuators was partially collected and reused. After both sources were mixed to reach a certain temperature, the flow was limited to a constant rate of 40 mL/s through a mechanical pressure regulating valve. This kept the pressure in the system low, reducing potential leakages, and still provided a high flow rate to power the actuators quickly.

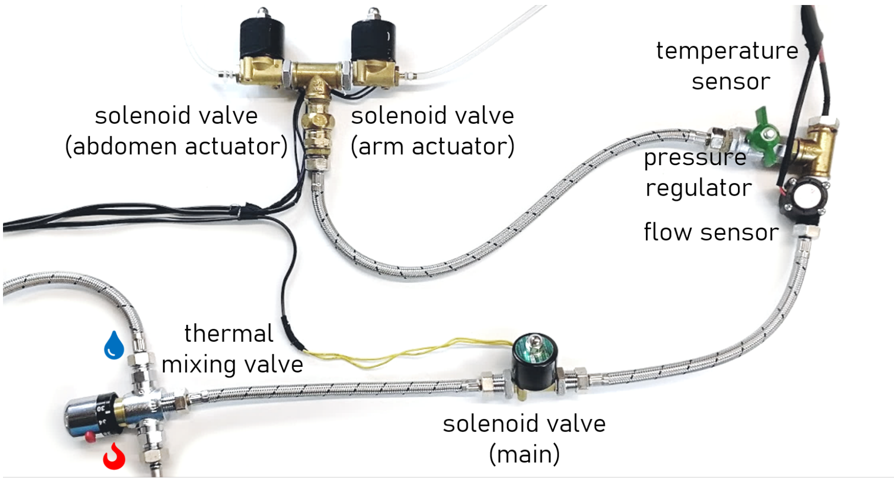


Figure 7.5: Overview of the implemented THERMINATOR system without the actuator tubes showing the thermal mixing valve, the solenoid valves, the pressure regulator, and the flow and temperature sensors.

To start and stop the actuation, and to allow for rapid emergency shutdowns if inevitable, the resulting pressure-reduced flow of the water was digitally controlled with a switchable solenoid valve. Further, to monitor the resulting temperature and internal flow rate at all times, a temperature and flow sensor was installed after the solenoid valve.

As the prototypical system should actuate two body parts, namely the arm and abdomen, two actuators were connected to the system with a Y-connector. Further, each actuator was then also enabled and disabled individually by separate solenoid valves. A schematic overview of the Therminator system is depicted in Figure 7.4. Figure 7.5 shows the final implementation of the system.

7.5.4 *Controlling the Actuation*

The prototypical system was built on top of the ActuBoard platform (as introduced in Chapter 9) for controlling the water pump, the solenoid valves, and reading out the data from the temperature and flow sensors. All data and commands are processed within a VR application built with the Unity engine[6] and abstracted with the ActuBoard C# API. While various VR systems were supported, Therminator was only tested with the HTC Vive and Valve Index. The experimenter could start and stop the actuation of each actuator individually and had an overview perspective of the whole VR scene and sensor data. The solenoid valves (*U.S. Solid USS2-SV00051*) and pump run (*Daypower WP-165*) on 12 V whereas the sensors and the ActuBoard was running at 5 V.

7.5.4.1 *System Performance*

The prototype is capable to change the temperature at a rate of 1.75 °C/s on average which fulfills the aforementioned concepts and requirements for a fast actuation. A full cycle to change the actuated temperature from cold(22.5 °C) to hot (42.5 °C) is possible in 12 s. Those rates were based on an intentional limitation of the flow rate at 40 mL/s for a constant actuation and to avoid a possible overshooting of the temperature which could negatively affect the study results. Similarly, this constant flow rate also helped to avoid any temperature loss and unintentional cooling effects after a short period of time. The rate was also selected to be in alignment with the physical properties of human skin which typically adapts to the temperature of the actuator in between 2 s to 5 s depending on the applied temperature differences.

6 https://www.unity.com/ (accessed March 01, 2022)

However, while this reduced flow and temperature change rate were intentionally achieved through the pressure regulation valve, it is possible to accelerate those rates through an overdriving of the valve for future experiments.

7.5.4.2 *Safety Measurements*

Each component used was checked multiple times to ensure high reliability and maximum safety standards. All electronic and power switching components were operated at most at 12 V and were connected to physical- and software-based emergency switches to turn off the system immediately in case of any malfunction. Both water supplies were secured behind separate mechanical and electronic solenoid valves, whereas the latter automatically stopped any flow when unpowered (NORMALLY-CLOSED VALVES). The temperature reaching a user was always limited as the mechanical bimetallic mixing valve never allowed too high or too cold temperatures. Further, before a user was using THERMINATOR, all actuators, the connecting tubes, and every other component were tested to quickly identify potential flaws or leakages within the system.

7.6 USER STUDY AND METHODOLOGY

Methodology Summary — within-subjects design

Controlled Experiment Lab Study	non-parametric analysis 3-way RM ANOVA Aligned Rank Transform	25 participants 12 female, 13 male 20 – 55 years

f(IV)
Thermal Stimuli (22.5° C – 42.5° C)
Visual Stimuli (five different visualizations)
Body Part (abdomen, arm)

f(DV)
Custom Questionnaires:
Perceived Temperature
Perceived Comfort
Involvement of Visual Stimuli
Involvement of Thermal Stimuli

This section presents the methodology of a controlled experiment assessing the interdependency between visual and thermal stimuli. The THERMINATOR prototype was used to provide the different temperature sensations, while users were *inside* a VR environment to experience different visual stimuli. In particular, the user study investigated the following research questions:

RQ1. How does the interdependency of thermal and visual stimuli affect the perceived temperature?

RQ2. How do the thermal and visual stimuli affect the involvement of users?

RQ3. How do the thermal and visual stimuli affect the comfort of users?

7.6.1 *Design and Task*

The study was performed as a within-subjects design. The conditions varied the THERMAL STIMULI, the VISUAL STIMULI in VR, and the actuated BODY PART as the three independent variable (IV) in a repeated-measures design. In total, five thermal stimuli, five VISUAL STIMULI, and two body parts were considered for the experiment, which resulted in $5 \times 5 \times 2 = 50$ conditions. The order of the THERMAL and visual stimuli was counterbalanced using a Balanced Latin Square design, while the order of the body part was always first the arm and then the abdomen or vice-versa. In the following, all IV are described in detail.

7.6.1.1 *Thermal Stimuli*

The THERMAL STIMULI varied five levels of applied temperature, centered around the mean neutral temperature of the human skin between 30 °C-36 °C [Par14; JH08]. To identify a proper neutral THERMAL STIMULUS used as the baseline, the epidermis temperature (*outermost layer of the skin*) of five individuals at a constant room temperature of 23 °C was measured at different times. As the surface skin temperatures of the test individuals always ranged between 31 °C and 33.5 °C, the neutral THERMAL STIMULUS was defined as its average at 32.5 °C. The pain threshold of the human for temperature was carefully taken into account when defining the upper and lower bounds for the THERMAL STIMULI [JH08; GOH16]. As such, the temperatures were varied in 5 °C steps, resulting in 22.5 °C, 27.5 °C, 32.5 °C, 37.5 °C, and 42.5 °C.

7.6.1.2 *Visual Stimuli*

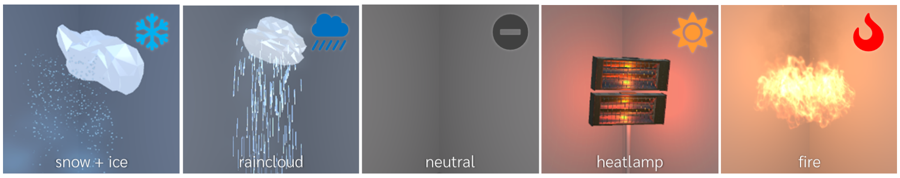


Figure 7.6: Five different VISUAL STIMULI based on their expected temperature from cold to hot. The Figure shows from left to right: very cold snow, cold rain cloud, a neutral stimulus with no visualization, warm heating lamp, hot fire.

The VISUAL STIMULI should incorporate different thermal mental models of users and be close to expected temperatures. As mentioned before, Fenko et al. [FSH10] classified the temperature expectations into their LITERAL MEANING that aligns with the physical warmness, and their FIGURATIVE MEANING related to "*social activity, intimacy, and friendly atmosphere*".

Therefore, to identify fitting visualizations that suggested different temperature expectations of users, informal interviews were conducted with seven individuals. All of them were asked about objects, entities, and situations in which they have different expectations about thermal appearances. Further, commonly used visualizations were observed from related work.

In each interview, the interviewees provided up to 20 different entities that propagate different temperatures. Based on those, they were then asked to describe and sort the expected temperatures of each on a continuous scale ranging from *very cold* to *very hot*. The resulting lists were then annotated with regard to their frequency of mentions and compared with their occurrences in related work. Matching entities, such as fire and flames or ice and snow, were grouped into one item according to similarities.

In a final step, the four most commonly mentioned items clustered into varying temperature expectations were ranked on a temperature scale (*very cold*, *cool*, *warm*, *very hot*). In addition, NO VISUAL STIMULUS was defined as the neutral baseline. As a result, this process led to the following five VISUAL STIMULI: a very cold SNOWFALL, a cold RAIN CLOUD, NO VISUALIZATION as neutral stimulus, a warm HEAT LAMP, and a hot BURNING FIRE. All five VISUAL STIMULI are depicted in Figure 7.6.

During the user study, those five different types of visualization were additionally altering the color temperature of the virtual room to 4500 K for warmer VISUAL STIMULI and 9500 K for colder VISUAL STIMULI. The neutral visual stimulus and between conditions, the color temperature reset to a neutral point of 6800 K. To avoid cross-effects of audio influencing the visual or THERMAL STIMULI, no visualization included any sound effects.

7.6.1.3 *Body Part*

Figure 7.7: A user wearing both, the abdomen and arm actuators. Green lines indicate the location of each thermally conductive PE-RT tube on the abdomen and pink lines on the arm. Gray lines indicate the flexible PVC tubes that connect each PE-RT tube with the main system.

For the experiment, two body parts were considered as IV: 1) the ABDOMEN and 2) RIGHT ARM. Both body parts cover a large part of the human body surface and, as such, have a large influence on the human thermal sensation [GOH16]. Moreover, while similar in surface size, both represent largely different anatomical properties which made an investigation of them particularly interesting. The abdomen resembles a central part of the human body and has a major influence on thermal comfort [AZH06]. The abdomen is typically covered evenly with a layer of fatty tissue on a larger surface that is very flexible as it lacks skeletal structures. The shape and form are mainly altered caused by the bending of the torso or by the rotation of the pelvis. In contrast, the right arm has a completely different anatomy and consists of an upper and lower part that is cylindrically shaped and predominantly stiff. Also, the temperature is perceived differently compared to other body parts [GOH16].

As both body parts have different anatomical properties, the actuators for them were carefully designed to ensure comparability between the arm and abdomen. Both actuators consisted of exactly 8 PE-RT tubes with a length of 15 cm and a spacing of 5 cm each. This allowed covering a comparable surface contact with a user's body to transmit the same amount of thermal energy. Figure 7.7 depicts a user wearing one actuator on the right arm and one actuator on the abdomen.

7.6.1.4 *Task and Dependent Variables (DV)*

To assess the influence of the THERMAL and VISUAL STIMULI as well as the actuated body part, the participants were situated in a VR environment. Hereby, the participants were simultaneously exposed to a combination of a visual and THERMAL STIMULUS at one of the given body parts until all possible combinations were presented. Each condition was presented for a total of 25 s once the target temperature was reached.

After each condition, the participants had to answer a questionnaire consisting of four questions using individual scales which represented the dependent variable (DV). The questions were targeted at the temperature rating of the THERMAL STIMULI, the thermal comfort, and the participants' involvement with regards to the thermal and VISUAL STIMULI. The first two items were based on previous studies by Arens et al. [AZH06] and directly investigate the temperature and comfort perception of participants. The latter two are based on the Witmer-Singer questionnaire [WS98] as derived by previous work done by Peiris et al. [Pei+17].

Q1. HOW DO YOU RATE THE THERMAL SENSATION?
: A 9-Points scale ranging from *very cold* to *very hot*.

Q2. HOW DO YOU RATE THE THERMAL COMFORT?
: A 6-Points scale ranging from *very comfortable* to *very uncomfortable*. As suggested by related work, there was no *neutral* level and the participants had to answer at least *just comfortable* or *just uncomfortable*.

Q3. HOW MUCH DID THE VISUAL ASPECTS INVOLVE YOU?
: A 7-Points scale ranging from *not involved at all* to *completely involved*.

Q4. HOW MUCH DID THE THERMAL ASPECTS INVOLVE YOU?
A 7-Points scale ranging from *not involved at all* to *completely involved*.

In a final questionnaire, the participants were asked to rate the overall experience of thermal feedback in VR on a 7-Points scale and provide qualitative feedback to the experimenter.

7.6.2 *Study Setup and Apparatus*

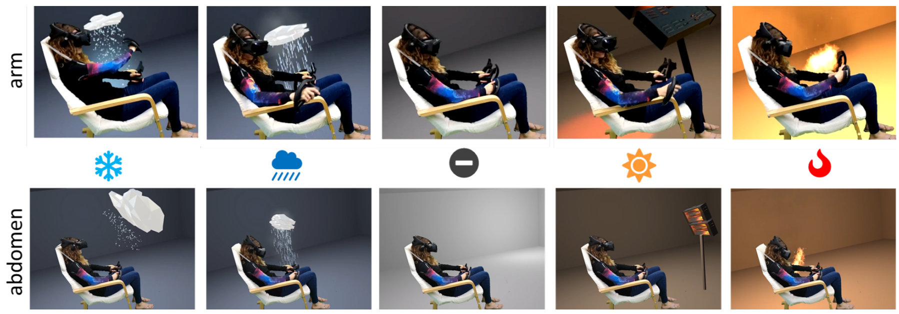


Figure 7.8: Stylized view of a participant in the Virtual Reality environment during the study. The top images depict the visualizations appearing on the arm, the lower images on the abdomen. The visualization are from left to right: Snow, Rain, Neutral, Heatlamp, and Fire.

The setup for the user study used a state-of-the-art VR setup (*Valve Index*) to render a high-quality virtual environment. Participants were asked to sit in a regular armchair wearing the Head-Mounted Display (HMD) and the two actuators for the abdomen and arm. Further, participants also were asked to wear a provided long-sleeve shirt (*100% cotton, 140* g/m^2) without other clothing under it to reduce any side effects due to different clothing and fabrics. Therefore, different sizes were provided to ensure the shirts fit tightly but do not constrain the participants in any way. For hygienic reasons, the shirts were washed regularly between two participants, and a separate designated dressing area was set up in another room to ensure full privacy.

Besides the actuators and HMD, participants were also equipped with two hand-held controllers and one additional VR tracker (*HTC Vive Tracker 2.0*) on each foot. This allowed for a more realistic depiction of the user immersed within the VR environment as limb movements were represented virtually. Therefore, inverse-kinematic was used and the VR scene showed the model of a gender-neutral human (designed with *MakeHuman*[7]) resting on a physical look-a-like armchair from the ego-perspective to provide a high level of detail.

As the experiment was focusing on the predefined thermal and VISUAL STIMULI, other stimuli that could interfere with the study were tried to be minimized. Therefore, the participants were situated in a large and neutral room in VR with dimmed lights and no specific details or furniture besides the armchair and a large screen in front of them. As mentioned before, the chair was used to locate the participant, while the large screen was only turned on after each condition to show the items of the questionnaire (see Section 7.6.1.4). The question on the virtual screen could be answered with the handheld controllers. To reduce distracting influences from the outside world, such as environmental noise, the participants wear situated in a lab with restricted access and had to wear the headphones of the HMD. Those were used for noise-cancellation and to provide neutral ambient music during the experiment which is well suited for concentration tasks [HHW14] at relaxing 60 bpm (*beats per minute*).

The participants were asked to stay within the virtual environment for the complete duration of the experiment besides a short break when switching body parts. However, they always could take breaks or stop the experiment at any time if needed. Though, none of the participants made use of optional breaks. Figure 7.8 shows a participant during the experiment while exposed to all five VISUAL STIMULI for the arm and abdomen.

7.6.3 *Procedure*

BEFORE THE STUDY: The participants were welcomed and introduced to the THERMINATOR system and concepts behind it. All necessary details were disclosed and the goal of the study was described. They were informed that all collected data, including personal information, were anonymized and used only for the experiment. Once the participant agreed and had no further initial questions, they were asked to fill out a demographic questionnaire, a consent form, and a privacy protection form.

7 http://www.makehumancommunity.org/ (accessed March 01, 2022)

Then, the participants were provided with long sleeve shirts of a fitting size and guided to the changing room. Afterward, when the participants returned, they were asked to sit down on the provided armchair and the experimenter assisted with putting on both actuators and mounting the additional trackers on their feet. When ready, participants had to put on the HMD and the hand-held controllers were given to them. Once the participants were comfortable, the study started with the first condition in a counterbalanced order.

DURING THE STUDY: The study either started with the abdomen or right arm as the first actuated body part. However, for both conditions, all combinations of the five visual and five THERMAL STIMULI were presented in a counterbalanced order. When the participants were ready, the first condition started. For each condition, the thermal mixing valve had to be adjusted to the target temperature. Once the system reached the target temperature, an additional countdown of 5 s started to provide enough time for the heat or coldness to be transmitted to the participant's body. After those 5 s, the current VISUAL STIMULUS was appearing and was located on the respective body part for another precisely 25 s. Then, the VISUAL STIMULUS was removed and the temperature of the system was reset to the neutral 32.5 °C again. The illumination of the VR room returned to the default state and the questionnaire was displayed on the virtual screen. To answer the questionnaire, the participants were asked to use the hand-held controller for their input. After answering all items, the next condition started.

Once all conditions for one body part were finished, the participants had to take a 5-minute break where they could put off the HMD and relax, until the study continued with the other body part. That being said, all participants were allowed to freely look around or move their arms and legs while remaining seated and being asked to not get up. Further, the participants were also invited to provide verbal feedback at any time.

AFTER THE STUDY: After completing all conditions, the experimenter helped the participants to take off the actuators before they were asked to change their clothes again in the separate clothing room. In a semi-structured interview and a post-questionnaire, the participants were asked for additional qualitative feedback, ideas, and comments. Overall, the whole procedure took about 90 minutes per participant.

7.6.4 *Participants*

In total, 25 individuals participated in the study (12 female, 13 male). All of them were between 20 and 55 years (M=30.28, SD=8.6). 9 of them had little or no experience with VR while 13 had minor experiences. Three participants stated to be regular or experienced VR users. Besides snacks and drinks, no compensation was provided.

7.7 RESULTS

In the following, the results of the controlled experiment are reported. At the beginning of the section, details of the analysis methods are given, followed by the quantitative analysis and qualitative feedback of the participants.

7.7.1 *Analysis*

For analyzing the data, a non-parametric analysis using a 3-way repeated-measures ANOVA was used. Since the questionnaires collected non-continuous data, the Aligned Rank Transform (ART) as proposed by Wobbrock et al. [Wob+11] was used to identify interaction effects. If the analysis revealed significant effects, a Tukey corrected pairwise t-test for posthoc analysis was performed. All effect sizes are reported as partial eta-squared η_p^2 using Cohen's classification [Coh88; Ric11]. Further, because of the ordinal nature of the data, the medians $\tilde{x}$ of the results are reported.

7.7.1.1 *Q1 Perceived Temperature*

The analysis with regards to the perceived temperature showed significant effects for the visual with a large effect size ($F_{4,92} = 13.36, p <.001$, η_p^2=.37). Post-hoc tests confirmed significant differences between al-

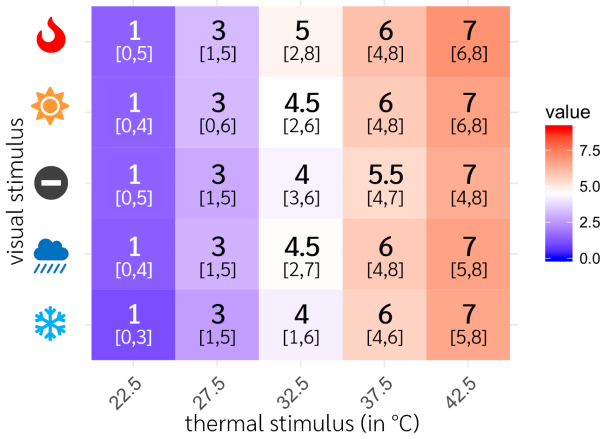


Figure 7.9: The results of the participants' responses to the perceived temperatures in a heatmap matrix visualization. The X-axis shows the five different THERMAL STIMULI in degrees Celsius, the Y-axis is the five VISUAL STIMULI. The big numbers indicate the median ratings, the numbers in brackets the minimum and maximum. The colors indicate a lower (blue) or higher (red) perceived temperature.

most all VISUAL STIMULI (ice-rain, p <.001; ice-heatlamp, p <.001; ice-fire, p <.001; rain-none, p <.05; heatlamp-none, p <.05; fire-none, p <.001). The analysis also identified significant effects for the THERMAL STIMULI with a large effect size ($F_{4,92} = 347.79, p < .001$, η_p^2=.94). Here, the post-hoc tests confirmed significant differences between every THERMAL STIMULUS (all p <.001).

Further, the analysis indicated significant effects for the body part ($F_{1,23} = 5.1, p < .05$, η_p^2=.18) which are confirmed by the posthoc tests (*arm-abdomen*, p <.05). Significant interaction effects were also revealed between THERMAL STIMULI and body part ($F_{4,92} = 7.06, p < .001$, η_p^2=.23) with a large effect size. Figure 7.9 depicts the medians for each condition, including the minimum and maximum ratings. While the medians for each temperature level are mostly identical, the VISUAL STIMULI affect the distribution of the ratings.

7.7.1.2 *Q2 Perceived Comfort*

The analysis revealed significant effects of the THERMAL STIMULI on the perceived comfort with a large effect size ($F_{4,92} = 25.57, p < .001$, η_p^2=.53). Post-hoc tests confirmed significant differences between all temperature levels besides 27.5-42.5, 32.5-37.5, and 32.5-42.5 (all p <.001). Further, the given feedback of the participants indicate that extreme tempera-

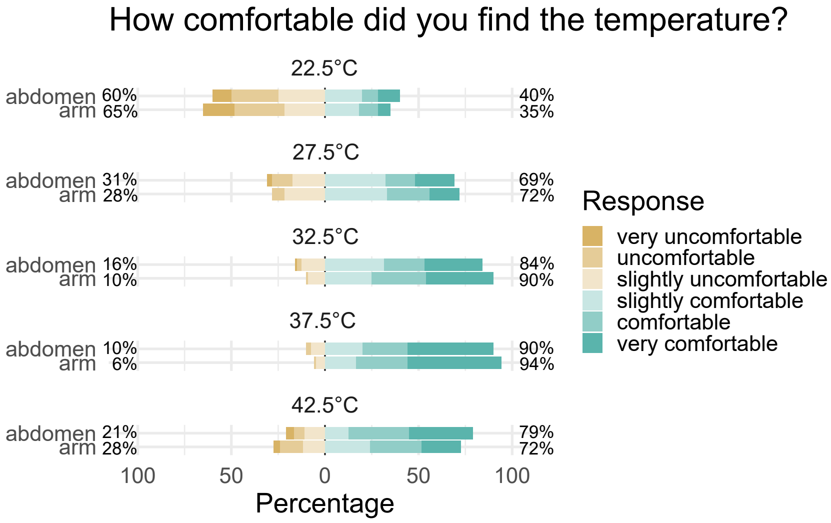


Figure 7.10: Comfort rating of the participants with regards to the THERMAL STIMULI (from *very uncomfortable* to *very comfortable*). Each temperature level is further divided to depict the results for both individual body parts.

tures closer to the cold and hot pain thresholds have a negative impact on the participants' level of comfort (22.5 °C: both body parts $\tilde{x} = 2$-uncomfortable, 27.5 °C: both body parts $\tilde{x} = 3$-slighty uncomfortable, 32.5 °C: both body parts $\tilde{x} = 4$-slighty comfortable, 37.5 °C: arm $\tilde{x} = 4.5$-(very) comfortable and abdomen $\tilde{x} = 4$-comfortable, 42.5 °C: arm $\tilde{x} = 3$-slightly uncomfortable and abdomen $\tilde{x} = 4$-comfortable). While there were no significant effects for the body part or the visualization, the analysis revealed significant interaction effects between the THERMAL STIMULI and body part with a large effect size ($F_{4,92} = 4.94, p < .01$, $\eta_p^2 = .17$), as depicted in Figure 7.10.

7.7.1.3 *Q3 Involvement of Visual Stimuli*

The analysis of the VISUAL STIMULI involvement on the perceived temperature showed significant differences for the visualization with a large effect size ($F_{4,92} = 85.31, p < .001$, $\eta_p^2 = .79$). Post-hoc tests confirmed significant differences between all levels and the neutral visualization for the VISUAL STIMULI (all $p < .001$).

There were significant effects with a medium effect size for the THERMAL STIMULI ($F_{4,92} = 3.22, p < .05$, $\eta_p^2 = .12$). Post-hoc tests further con-

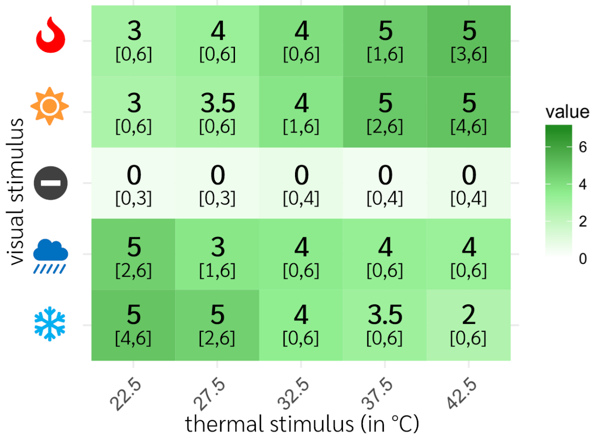


Figure 7.11: The results of the participants' responses to the visual involvement in a heatmap matrix visualization. The X-axis shows the five different THERMAL STIMULI in degrees Celsius, the Y-axis is the five VISUAL STIMULI. The big numbers indicate the median ratings, the numbers in brackets the minimum and maximum.

firmed significant differences between (27.5 °C-37.5 °C, p .<05 and 27.5 °C-42.5 °C, p .<05).

The analysis also revealed significant interaction effects between visual and THERMAL STIMULI with a large effect size ($F_{16,268} = 23.18, p <.001$, η_p^2=.50), which are depicted in Figure 7.11. In addition, the minimum and maximum ratings given for each condition were included. No significant effects with regards to the body part could be identified ($F_{1,23} = 11.81, p >.05$).

7.7.1.4 *Q4 Involvement of Thermal Stimuli*

With regards to the involvement of the THERMAL STIMULI on the perceived temperature, the analysis revealed significant effects with a large effect size ($F_{4,92} = 19.24, p <.001$, η_p^2=.46). The post-hoc tests confirmed significant differences between the majority of the temperature levels (22.5 °C-27.5 °C, 22.5 °C-32.5 °C, 27.5 °C-37.5 °C, 27.5 °C-42.5 °C, 32.5 °C-37.5 °C, and 32.5 °C-42.5 °C; all $p <.001$).

Interestingly, the analysis revealed significant differences for the visualization ($F_{4,92} = 13.38, p <.001$, η_p^2=.37) and could confirm interaction effects between visual and THERMAL STIMULI with a large effect size ($F_{16,368} = 14.41, p <.001$, η_p^2=.39). As depicted in Figure 7.12, the median rating as well as the minimum and maximum ratings show

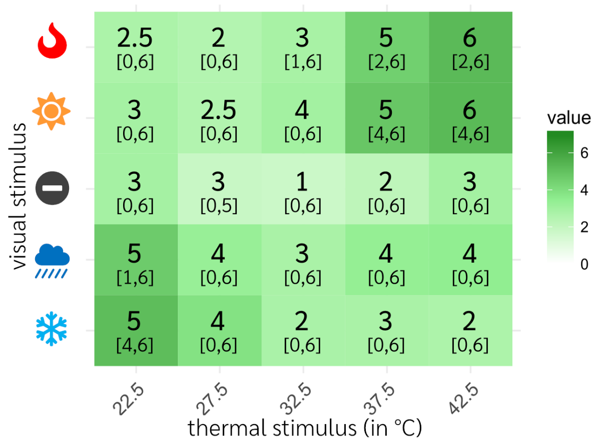


Figure 7.12: The results of the participants' responses to the thermal involvement in a heatmap matrix visualization. The X-axis shows the five different THERMAL STIMULI in degrees Celsius, the Y-axis is the five VISUAL STIMULI. The big numbers indicate the median ratings, the numbers in brackets the minimum and maximum.

differences with regards to the presented visuals. Additionally, the analysis revealed significant differences for the body part with a large effect size ($F_{1,23} = 14.78, p <.001$, η_p^2=.39). Post-hoc tests confirmed significant differences between *arm* and *abdomen* ($p <.001$).

7.7.2 *Post-Questionnaire: Overall Experience*

The results of the post-questionnaire showed that the majority of participants generally agreed on a very positive experience ($\tilde{x} = 6$, 7-Points scale).

7.7.3 *Qualitative Feedback*

In alignment with the post-questionnaire, the consensus of the participants was very positive and is further underlined by the qualitative feedback. The participants described the THERMINATOR concepts as "*interesting idea*" (P1, P22), "*funny simulation*" (P24), and "*cool idea with great potential*" (P21). One participant reported it was a great experience to dive into a virtual world with thermal feedback (P19). P20 highlighted the "*different and rapidly changing temperature possibilities*", while

P10 remarked that the appearance of the VISUAL STIMULI was very well synchronized.

The general consensus was that the THERMAL STIMULI felt "*realistic*" (P14), "*especially at very high or low temperatures*" (P9). The provided temperatures were "*very well recognizable*" (P14). While P10 said that all temperatures were "*very pleasant and did not feel disturbing at all*", most participants described the warmer stimuli as preferable (P7, P9, P11, P17, P18), and more distinguishable than the colder ones (P10). As the quantitative analysis confirmed, participants perceived cold temperatures generally as more unpleasant (P2, P17, P19, P20). Yet, two participants stated the system could even provide colder temperatures (P4, P10), and one participant also asked for "*more heat while burning*" (P24).

The 3D models of the VISUAL STIMULI were minimalistic, and their appearance was based on the thermal expectations of users. Participants, therefore, described the visualizations as "*appropriate and fitting for the experience*" (P4). In particular, a larger number emphasized the effects and the "*immersive experience when the perceived temperature corresponds to the expectations from the visual and personal experiences*" (P3, P5, P12). For example, P24 stated that "*it felt more realistic if the thermal feedback matched*". One participant (P25) even explained that they "*have goosebumps during the snow effect while perceiving a cold temperature*". Yet, on the other side during conditions where a VISUAL STIMULUS did not match the expected THERMAL STIMULUS, participants felt "*more uncomfortable or uncanny*" (P24, P1, P8), as the "*discrepancy between perceived and visually expected temperature was too high*" (P23).

Taking a look at VISUAL STIMULI, participants were typically able to interpret them very well to different levels of anticipated temperatures (P4). However, although all visualizations were carefully selected concerning their different temperature expectations, participants showed two different conceptions of the raincloud visualization. While the original intention was a colder rainy day with a rain shower, some participants were more "*reminded of a warm shower*" (P11). Also, two participants mentioned that the overall visualizations could have shown more "*wow effects*" (P14, P16). However, this was intentionally avoided since this could have interferences and might be too distracting from the actual experiment.

For future improvements, participants suggested that "*the experience may be enhanced by appropriate sound effects*" (P15, P20), which were intentionally omitted to avoid cross-effects with aural stimuli. While no questions during the experiment were directly asking for the wearing comfort of the actuators, no participant reported negative impacts that go further than already having the cable of the HMD attached. However, this was also not reported as problematic since the experiment was completely conducted while participants had to sit in the armchair. To summarize, the additional feedback supported the quantitative findings and helped to better understand them.

7.8 DISCUSSION

The results of the questionnaires and the additional feedback could show interdependencies and interaction effects between thermal and visual stimuli. In particular, mismatches between an expected and the actual temperature lead to interesting results which are discussed in the following.

7.8.1 *Thermal Stimuli Overwrite Visual Stimuli*

The analysis of the data revealed significant effects on the perceived temperature. Taking a closer look at the median results of Q1 (see Figure 7.9), the thermal stimuli still had the highest influence on the perceived temperature. For example, even a fire visualization was perceived as cold when a cold thermal stimulus was provided. Similarly, the snow visualization did not feel cold when a warm thermal stimulus was applied.

While this very dominant result was not expected to this degree, it highlights the importance of thermal stimuli for more realistic experiences. However, the results also showed that visual stimuli are not completely neglected. In particular, two things have to be investigated in more detail: the perceived temperature 1) at non-matching stimuli, and 2) at a neutral thermal stimulus.

Considering non-matching stimuli, such as the *fire* visualization at 22.5 °C or the *snow* visualization at 42.5 °C, only marginal effects compared to matching conditions could be observed. However, taking the distribution of the perceived temperature ratings into account, a trend to more broadened minima and maxima for non-matching stimuli was found. Further, with regards to the neutral thermal stimulus (32.5 °C), the influence of visualizations on the perceived temperatures was more visible. For example, the *fire* visualization has a significantly higher temperature rating than the *snow* visualization which indicates that a purely visual stimulus without thermal stimulus can influence the perceived temperature of participants.

However, supported by the qualitative feedback (see Section 7.7.3), the temperature expectations of visualizations need to be considered as well. Even though the five visualizations with different temperature expectations were carefully selected before conducting the experiment, the *raincloud* visualization was interpreted as *warm shower* rather than *cold raindrops*.

For future VR applications, immersion, presence, and realism might largely benefit from thermal feedback as visualizations alone are not able to stimulate the THERMOCEPTIONin the same quality as without, even though the effects of visualizations in combination with thermal stimuli can never be completely neglected.

7.8.2 *Congruent Stimuli Increase Involvement*

The experiment revealed significant effects concerning the involvement of the visualizations and thermal stimuli. The analysis revealed that the more closely temperature expectations of a visualization and the actual thermal stimulus were, the higher the involvement of each participant was. Interestingly, those involvement ratings of the visual and thermal stimuli were expected to be completely opposing. For example, considering a *snow* visualization with a warm thermal stimulus of 42.5 °C, the initial assumption was that the visual stimuli would be more involving than the thermal ones. However, both leveled on a similarly low rating ($\tilde{x} = 2$) and the opposite effect was observed: More matching stimuli that fitted the expectations of participants increased the median ratings for the involvement of both stimuli. This effect is depicted in the lower left and upper right quadrants of Figure 7.11 and Figure 7.12). Further, participants described during their qualitative feedback that matching stimuli felt more involving compared to non-matching combinations which sometimes were perceived as uncanny or surreal.

When applying a neutral visual stimulus (*no visualization*), the results confirmed no involvement for the visualization as expected. However, considering the involvement of the thermal stimuli, similar low median ratings for all levels as for visual stimuli that did not match the expectations could be observed. As a consequence, even though thermal stimuli had a major impact on the perceived temperature (see Section 7.8.1), they only slightly affected the involvement if there was no visual stimulus given.

Focusing on the actuated part of the body, the experiment only indicated significant differences for the thermal involvement but not for visualizations. This might result from the fact that temperature expectations of visualizations often apply to the whole body instead of single body parts. However, further investigation would be necessary to give a precise answer to this.

7.8.3 *Comfort depends on Thermal Stimuli*

Comfort is highly important for the acceptance of a system and the stimuli. The experiment showed significant effects with temperatures that are closer to the neutral skin temperature (32.5 °C) and slightly warmer temperatures (37.5 °C) as they felt more comfortable. Contrary, temperatures in the close range to the minimum and maximum were mostly perceived as uncomfortable (see Figure 7.10). However, as the experiment limited the thermal stimuli to a range between 22.5 °C to 42.5 °C to avoid any pain sensations, most participants reported that the warmest stimulus at 42.5 °C still felt comfortable and pleasant, thus, could be even warmer. In contrast, the coldest stimulus (22.5 °C), which was about 10 °C lower than the neutral skin temperature [JH08; Par14] and approximated the pain threshold of 17 °C [HWG52; HD99], was often described as very chill and almost completely was rated as uncomfortable. Although the intervals of temperature changes were always of the same size of ± 5 °C and ± 10 °C respectively, the experiment revealed that cold stimuli were typically perceived as more intense than higher temperatures which is also in alignment with existing research [SC98].

In addition, the analysis revealed significant differences in the level of comfort between the body parts. Supporting existing research [SC98], limbs are generally better in their THERMOCEPTION compared to the abdomen which perceives temperature with less sensitivity.

7.9 EXAMPLE APPLICATIONS

Besides investigating the mutual interaction between visual and thermal stimuli where participants were situated in a resting position on a chair, example applications were created to see how users would behave while having the ability to move. Further, the example applications can provide insight for future scenarios. In this section, we highlight three different use cases, where thermal haptic feedback can enhance an immersive and engaging VR experience.

Figure 7.13: Three example applications showcasing situations for the usefulness of thermal feedback: a) a firefighting simulation, b) a hot tropical game environment, and c) a challenging snowball game in a cold landscape.

7.9.1 *Firefighting Simulation*

Crisis simulation and training environments are emerging scenarios for VR. For example, emergency forces, such as firefighters or first-responders, can train their abilities and perform rescue operations within realistic but harmless and safe environments (e.g., [Sha+19]). In the application described here, the user also takes the role of a firefighter who is located in a building that is on fire (see Figure 7.13 a). As a task, the user has to extinguish all flames to stop the fire from spreading.

The THERMINATOR system is used to simulate the heat coming from the flames to increase the realism towards real-world training. During the whole simulation, a warm stimulus occurs on the abdomen of the user and the temperature increases the closer the user stands next to a fire source. However, the user can use the game controller as a fire hose and the temperature will decrease the more flames are extinguished. Once all flames are successfully cleared, the temperature will return to a neutral stimulus.

7.9.2 *Pirates in the Sun*

The second application aimed to provide varying thermal stimuli on the arm and abdomen at the same time. Hereby, the user is supposed to be a pirate at the beach of an isolated tropical island as depicted in Figure 7.13 b. All around the island and in the shallow water are hidden treasures in form of precious gems that the player has to find. To obtain them, the player needs to track sparkling spots in the surroundings and dig for them using the game controller.

While the task is relatively easy, the thermal feedback is used to give a sense of the tropical and humid environment at high temperatures. Therminator's abdomen actuator is used to warm up the player's body when walking in the sun, and to cool down a bit when spending some time in the shades of the palm trees. The arm actuator, in contrast, is lowering the temperature on the arm intensively when the player reaches out for a gem in the water. This combines two different stimuli at the same time: a warm overall body temperature and a cold arm resulting from the water. As a side effect, the combination of a cold stimulus and the water visuals, a sense of liquid on the arm can be observed, similar to [PCM18; SS16]. However, further studies are needed to fully understand how much this affects the realism and overall experience.

7.9.3 *Angry Snowman*

The last example application should demonstrate sudden temperature changes in the body. In contrast to the first two applications, the user is located in an already cold snow-covered landscape which is the home to an enchanted snowman (depicted in Figure 7.13 c). Unfortunately, the snowman does not appreciate guests in his realm and starts to throw snowballs at the player. The player can evade them by freely moving around the scenery and counteract by throwing snowballs back. However, if the player gets hit, the system cools down the abdomen and recovers slowly until it reaches a more neutral temperature again. When the player is holding a snowball in his hand, the arm experiences a cooling sensation that may recede when a snowball is thrown.

7.10 LIMITATIONS AND FUTURE WORK

THERMINATOR demonstrated how thermal haptic feedback can be realized using liquids and investigated the interdependency between visual and on-body thermal feedback. Alongside the mentioned benefits, limitations remain, offering an opportunity for future work.

7.10.1 *Other Body Parts*

For the experiment, the focus was on two body parts with different properties, namely the abdomen and arm. However, as discussed earlier, other body parts should be considered as well to identify if similar body parts behave similarly, such as the legs, back, or head, or if system changes are necessary. For example, thermal stimuli on the face could be perceived as more intense than for the rest of the body as the thermal response varies for different regions of the body [GOH16].

Furthermore, to exclude possible cross effects, both body parts were investigated separately. Yet, it is not clarified how users perceive the temperature feedback on different body parts at the same time. For example, actuating individual body parts alongside different thermal stimuli from several actuators could result in similar effects as the thermal grill illusion [CB94].

7.10.2 *Other Visual Stimuli and Combinations*

The visual stimuli for the experiment were carefully selected resembling five different levels with regard to users' temperature expectations. While those were mostly seen by the participants as intended, the RAINCLOUD visualization was sometimes perceived differently as some participants were reminded of a warmer shower instead of cold raindrops.

As the visualizations represented only a small selection of the imaginable spectrum of temperature-prone images, it would be interesting to also investigate other visual stimuli and combinations of them at the same time. Similar to simultaneously actuating multiple body parts, a mix of visual and thermal stimuli can yield further insightful results.

7.10.3 *Wearability and Sustainability*

The wearability is currently limited as it was not the main focus of this work. However, it was considered in the discourse about the Therminator concept throughout its design process. During the experiment, users did not describe the tubes as restricting any further than the regular HMD cables. However, this was probably less of an issue since the participants were seated for the whole duration. Further, during the three example applications, while not systematically evaluated, users seemed to move around mostly unconstrained, similar to the scenarios investigated in the second study of Chapter 8.

At the moment, the system relies on external sources of water with a high throughput of liquids. For example, this could be reduced in a future version by having a full reusable circle of the liquids in a closed system, similar to Goetz et al. [GOC20] that used smaller chambers with heating and cooling capabilities. Mobility could be further improved by making the system more compact. Further, a pressure-based approach with smaller amounts of liquids in a backpack or hidden in a suit could be promising. Though, this would require more power-demanding heating and cooling units to keep the system fast enough for situations with rapid temperature changes.

As a beneficial side-effect, reducing the required flow would also increase the sustainability of the prototype. While some of the re-flux during the experiments was already reused if the output temperature was at least at 32 °C, the colder outflows could not be recirculated, as this would either cool down the boiler considerably or heat the cold water source temperatures higher than the lowest thermal stimulus. However, excess (cold) water could be re-collected to increase sustainability. For example, it was partly used for watering plants in the institute and the landscaped areas outside the building during the summer, where the study took place.

7.10.4 *User Acceptance and Use-Cases outside the Lab*

The main intentions of the experiment were to investigate the feasibility of a liquid-based thermal display and how visual and thermal stimuli mutually interact with each other. While this chapter already presented three demonstration applications of how such a system can be embedded into real-world scenarios, the prototypical system remained less wearable as discussed in the previous section. However, future systems require a strong user acceptance to deploy such concepts for other scenarios, such as supporting training environments, weather simulations, or rehabilitative therapies that would need a life-like representation of temperature. Although those additional developments are highly interesting and this chapter provides a broad but detailed overview of thermal feedback, a future miniaturization process and following studies on the acceptance are beyond the scope of this work.

7.11 Conclusion

In this chapter, the importance of thermal feedback in the context of somatosensory interaction was highlighted. The elaborated concepts based on a systematic analysis of related work formed the foundation for the development of a novel prototypical system based on the thermal conduction of fluids. Using this approach, interactive applications can recreate the environment in a more immersive and detailed way, allowing users not only to see and hear virtual worlds but also to perceive the thermal properties.

Additionally, in the presented user study, these concepts were examined in more depth to better understand the influences of thermal stimuli on visual stimuli and vice versa. Participants were presented with combinations of different thermal and visual stimuli, which at times were more and at times less matching. It was found that temperature perception was more influenced by thermal than by visual stimuli. Still, visual stimuli also influenced the temperature perception and were able to slightly shift the sensory response. At the same time, although cold thermal stimuli were more unpleasant, the combination of incongruent thermal and visual stimuli showed a measurable decrease in comfort, whereas a matching sensation could particularly increase the participants' involvement.

In summary, this underlines the importance of considering the full spectrum of somatosensory interaction, including the presented Thermoception, for a lifelike simulation and stimulation of physical properties in virtual environments.

Part IV

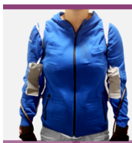
PROPRIOCEPTION AND KINESTHESIA

8

PROPRIOCEPTION: KINESTHETIC ACTUATION OF THE BODY

Chapter Overview

Mechanoreception I | Mechanoreception II | Thermoception | **Proprioception**



Related Publications:
PneumAct: Pneumatic Kinesthetic Actuation of Body Joints in Virtual Reality Environments
DIS 2019

Body | Arms | Kinesthetic Feedback | Proprioception | Controlled Experiment | VR

The previous chapters have examined parts of the somatosensory system that represent direct touch and contacts that were mostly affected by external stimuli. Although these stimuli can be perceived as continuous movements along the body (cf. Chapter 6), another part of the somatosensory system is the sensation to determine the spatial position and motion of individual body parts, the so-called PROPRIOCEPTION. Therefore, the PROPRIOCEPTION, and KINESTHESIA respectively [Tay09], is responsible for perceiving the own position of the body by static forces, such as gravity, on the muscles, joints, and tendons, but also the motion by dynamic forces [PG12; Tay09; Dou97]. As such, "PROPRIOCEPTION is critical for maintaining posture and balance" (Dougherty [Dou97], Sec. 2.1).

However, to explicitly trigger PROPRIOCEPTION, especially for perceiving the motion of a body part, it is necessary to elicit *kinesthetic* feedback which will be the focus of this chapter. While the previous Chapter 5 on PRESSURE-BASED MECHANORECEPTION already introduced concepts for more intense actuations, this chapter uses a similar pneumatic-based approach but to explicitly move body parts through external forces. For example, when users in a virtual environment should be actively moved in response to the environment (*dynamic forces*). This can range from smaller notification-like actuations to guide attention, to stronger forces that move the user's entire body, such as a "grab and pull" of another (virtual) person or environmental forces such as strong headwinds or explosions. Likewise, it is also essential to reproduce *static forces*, for example, to provide a counterweight when the user wants to pick up a virtual object. Further, it can be also differed between a more rough actuation that is particularly useful for sudden actions (also in form of active warnings in hazardous situations), recoil, resistance, and movements in general and a more precise but subtle actuation that would result in more exact motions. While both concepts are useful, this work focuses on the rougher actuation fitting the demands of VR applications, and as this also reduces safety risks since users can safely counteract an actuation.

> *"Typically, a haptic interface stimulates cutaneous and kinesthetic sensory channels through force feedback that varies depending on a user's limb movements."*
>
> G. Robles-De-La-Torre, 2006 [Rob06]

This chapter, therefore, investigates how *static* positions and *dynamic* forces for PROPRIOCEPTION can be achieved through a kinesthetic actuation. First, requirements and concepts for the actuators are discussed, which are capable of contracting and stretching different body parts at their joints through external forces. In a second step, these concepts were implemented in a prototypical system, called PNEUMACT, based on pneumatic actuation and investigated in a first study to determine their influence on the angle between the upper and lower arm at the elbow joint under different actuations. In particular, different inflation durations and patterns were examined, and how pronounced the influences on the arm movement of the 24 participants were. Subsequently, three VR sample applications were designed, which could represent the different static and dynamic forces in specific scenarios, i.e., two entertainment applications and an exergame. On this basis, a second user study was conducted in which 12 participants were asked to compare the active kinesthetic feedback concerning immersion, realism, and enjoyment with state-of-the-art controller-based vibrations and a no haptics baseline.

This chapter is based on the following publication:

Sebastian Günther, Mohit Makhija, Florian Müller, Dominik Schön, Max Mühlhäuser, and Markus Funk. "PneumAct: Pneumatic Kinesthetic Actuation of Body Joints in Virtual Reality Environments." In: *Proceedings of the 2019 on Designing Interactive Systems Conference*. New York, NY, USA: ACM, June 2019, pp. 227–240. ISBN: 9781450358507. DOI: 10.1145/3322276.3322302

Contribution Statement: I led the idea creation, concept design, implementation, performed the data analysis, and writing process. The former student *Mohit Makhija* supported building the initial pneumatic-based prototypes and supported the conduction of the user studies. The former student *Dominik Schön* supported the implementation of the Virtual Reality application of the second study. *Florian Müller* and *Markus Funk* consulted to and reviewed the design process, contributing with their experience, and also assisted with the statistical analysis of the data. *Max Mühlhäuser* supervised the project and writing process.

❗ *Some contents of this chapter might contain verbatim parts of the aforementioned publication.*

8.1 CHAPTER STRUCTURE

The remainder of this chapter is structured as follows: After the introduction, an overview of related research is given in Section 8.2.2. Based on this, concepts for kinesthetic feedback in order to trigger the PROPRIOCEPTION were derived and implemented in a prototypical system using a pneumatic approach (Sections 8.3 and 8.4). In a next step, the applicability of the systems were investigated in a first user study, showing the effects of different inflation durations and patterns (Sections 8.5 and 8.6). As proof-of-concept, three example applications were designed (Section 8.7) and deployed for a second user study that investigated the immersion, realism, and enjoyment when using kinesthetic feedback (Section 8.8). Section 8.11 further discusses the limitations of both studies together with potential future work. Section 8.12 summarizes and concludes the chapter.

8.2 REQUIREMENTS AND RELATED WORK

This section provides an overview of requirements for kinesthetic actuation related to PROPRIOCEPTION and KINESTHESIA, followed by a review of relevant related work.

8.2.1 *Requirements*

REQP1. SUPPORT FOR DIFFERENT INTENSITIES
: The intensity of a kinesthetic actuation should always adapt to the specific use case and preferably be as accurate as possible, which includes the intensity itself but also the duration of the actuation. Therefore, these properties must be adjustable, so that both, lighter and stronger feedback, becomes feasible.

REQP2. CONSIDER DIRECTION OF ACTUATION
: A kinesthetic actuation always requires a direction in which a body part is moved. While some joints have many degrees of directional freedom, such as the shoulder, the elbow joint has only two possible directions, either in extension or contraction direction. Therefore, an actuation must always consider the range of possible directions of motion and degrees of freedom of a joint or body part.

REQP3. ADDRESS STATIC AND DYNAMIC FORCES
: The PROPRIOCEPTION involves two sub-areas, namely static and dynamic forces, which are essential for body position and body movement. Therefore, any work must determine precisely which of the two areas should be addressed, or if they both should be covered.

REQP4. SUPPORT DIFFERENT BODY PARTS
: As with all types of haptic interaction, the physical location of the body parts that will be actuated is important. Therefore, it should always be considered which body parts are required for a specific use case and how these can be brought into motion in a meaningful sense.

REQP5. SUPPORT DIFFERENT ENVIRONMENTS

Depending on the use case, the environment must also be taken into account. While kinesthetic actuation has been long known, for example, through exoskeletons that help users gain more strength in a work context or support rehabilitation progress, modern AR/VR environments can also benefit, where stimulating Proprioception can improve immersion, presence, and realism. Therefore, it is necessary to consider in which environment - real, augmented, or virtual - a kinesthetic actuation will be applied.

REQP6. SUPPORT FOR DIFFERENT DEVICES

Not only the actuation itself is important, but also the devices used to achieve kinesthetic actuation, for example through exoskeletons, EMS, or artificial muscles. For some applications, fixed setups are sufficient, while others have special requirements for wearability, such as in the context of AR/VR. Therefore, the kinesthetic actuation must be provided by compatible devices.

REQP7. BE AWARE OF PAIN THRESHOLDS

Kinesthetic actuations are usually stronger than other types of haptic feedback due to their ability to actively set the body in motion. Consequently, these actuations must be indeed powerful enough for their intended purpose, but neither too intense nor exceeding the natural limits of the human body to avoid causing pain or any harm.

8.2.2 *Related Work*

Kinesthetic Feedback that stimulates the Proprioception has a distinct role within the somatosensory system. While there exist several approaches that provide tactile stimuli that can be perceived and interpreted by users to achieve guidance or result in the movement of the body, such as done through the vibrotactile stimuli of TactileGlove in Chapter 4 and other motion guidance approaches related to traditional Mechanoreception (cf. Section 4.3), the following focuses on active kinesthetic actuation through the use of (1) mechanical actuations, such as exoskeletons, (2) pneumatic actuation, such as Pneumatical Artifical Muscle (PAM), and (3) Electrical Muscle Stimulation (EMS). In addition, the most relevant work is highlighted in Table 8.1 with regard to the aforementioned requirements.

	ReqP1. Intensity	ReqP2. Direction	ReqP3. Static / Dynamic	ReqP4. Body Part	ReqP5. Environment	ReqP6. Device Type
Auda et al. [APS19]	✓	⇲	🏃	LEG	VR	⚡ EMS pads
Bergamasco et al. [Ber+94]	✓	⇲ ⤢	🏃	ARM	📱	⚙ exoskeleton
Chang et al. [Cha+18]	✓	↻	🏃	HEAD	VR	⚙ HMD
Chen et al. [Che+16]	✓	↻	🏃	ARM	RW	⚙ sleeve
Connelly et al. [Con+10]	✓	⤢	🏃	FINGER	VR	♿ 💨 glove
Das et al. [Das+18]	✓	⇲ ⤢ ↻	🏃 🧍	WRIST	VR	💨 sleeve
Frisoli et al. [Fri+09]	✓	⇲ ⤢ ↻	🏃	ARM	VR	♿ ⚙ exoskeleton
Goto et al. [Got+18]	✓	⇲ ⤢ ↻	🏃 🧍	WRIST	RW	💨 sleeve
Gu et al. [Gu+16]	✓	⇲ ⤢	🏃 🧍	HAND	VR	⚙ exoskeleton
Kon et al. [KNK17]	✓	↻	🏃	HEAD	VR	💨 ⚙ HMD
Lopes et al. [LBB13]	✓	⇲	🏃 🧍	ARM	📱	⚡ smartphone
Lopes et al. [LIB15]	✓	⇲	🏃 🧍	ARM LEG	VR	⚡ EMS pads
Lopes et al. [Lop+18]	✓	⇲ ⤢ ↻	🏃 🧍	ARM	AR	⚡ EMS pads
Maimani and Roudaut [MR17]	✓	⊘	🧍	ARM	VR	💨 vacuum pads
Moon et al. [Moo+06]		⇲	🏃	FINGER	📱	💨 glove
Pfeiffer et al. [Pfe+15]	✓	⇲	🏃	LEG	RW	⚡ EMS pads
Pohl et al. [PHR17]		⊘	🧍	BODY	RW	💨 vacuum pads
Polygerinos et al. [Pol+13]	✓	⇲	🏃 🧍	FINGER	RW	♿ 💨 glove
Sakoda et al. [Sak+18]	✓	⇲	🏃	ARM	RW	💨 sleeve
Tsoupikova et al. [Tso+09]		⤢	🏃	FINGER	VR	💨 glove
PNEUMACT	✓	⇲ ⤢	🧍 🏃	ARM	RWVR	💨 jacket

Table 8.1: Overview of selected related work in the field of PROPRIOCEPTION and KINESTHESIA. Legend: ✓ fulfilled requirement, ⇲ contraction / ⤢ extension / ↻ rotation / ⊘ restriction, 🧍 static / 🏃 dynamic, 📱 screen / RW Real World, ⚡ Electrical Muscle Stimulation (EMS) / ⚙ mechanical / robotic, 💨 air / pneumatic, ♿ accessibility. *Note: The table excludes ReqP7 since all work provide measurements to avoid pain.*

8.2.3 *Mechanical Actuation and Exoskeletons*

An external actuation for kinesthetic feedback through mechanical devices, such as exoskeletons, is probably the most common method. Hereby, exoskeletons are existing for a long time to assist users and, while such devices typically do not counteract any motion, they still kinesthetically support movements. Already in 1971, Fick et al. [Fic71] patented a full-body exoskeleton to support workers in performing heavy tasks. Although this was still early work and a bulky device, more modern systems have become more lightweight. For example, Frisoli et al. [Fri+09] presented an exoskeleton for upper-limb rehabilitation in a virtual environment, while Bergamasco et al. [Ber+94] already presented one of the first arm-located exoskeleton for telepresence. Thereby, the authors could not only kinesthetically actuate the user but also record the arm movements and replay them through the mechanical forces. Similarly, exoskeletons are typically very powerful and are often used to support walking and lower-limb movements, as surveyed by Dollar et al. [DH08].

One disadvantage, however, is the typically high costs for such devices. Therefore, Gu et al. [Gu+16] created an inexpensive exoskeleton for the hand that provided force feedback in VR. Chen et al. [Che+16] designed a motion guidance sleeve using strings as a form of artificial muscles to create active forearm rotations. However, this work only focused on rotational forces and did not consider any extension or flexion motion. And although those newer approaches consider VR as a use-case, the application of exoskeletons for this specific area was already investigated before as, for example, reviewed by Stone in 2001 [Sto01].

Other mechanical approaches are not based on exoskeletons but use specialized controller-based devices to provide kinesthetic feedback. Zenner et al. [ZK17], for example, created a tube-like handheld device that could shift a weight inside a plastic tube to alter the weight distribution to increase the immersion and realism in VR when holding objects in the hand. While not providing active movement of body parts, the work showed how weight distribution could affect the proprioceptive sensation. In a follow-up work by Zenner and Krüger [ZK19], the authors designed a controller device that could change its air resistance and provide a similar weight shift to increase realism in VR. Chang et al. [Cha+18] mounted two motors on the sides of an VR HMD to create a torque effect that resulted in active head movements. Similarly, but relying on the hanger effect that subconsciously results in head movements due to skin shear deformations, Kon et al. [KNK17; Kon+18a] used small inflatable cushions on the head to actuate the user in VR.

8.2.4 *Pneumatic Actuation*

While the aforementioned approaches are often using electromechanics, other works are based on pneumatic approaches, for example in form of Pneumatical Artifical Muscle (PAM) [CMG95; Dae+02]. In this case, the force is coming from strong pneumatic actuations in order to support users' movements, e.g., while walking or doing sports [Oga+17; Sak+18]. Yet, besides these pneumatic-based exoskeletons, other research investigated how pneumatics and compressed air is suitable for kinesthetic actuations and Proprioception, similar to various approaches for pressure-based feedback as discussed in the earlier Section 3.2.0.1 of the Mechanoreception chapter.

Most commonly, research investigated this type of actuation in the form of gloves or wristbands. While Raitor et al. [Rai+17], for example, investigated hand rotations and translation by using pneumatic patterns in a wearable wristband similar to other motion guidance approaches (cf. Section 4.3), other work used active kinesthetic actuations. In earlier work, Moon et al. [Moo+06] compared a glove using PAM with more conventional hydraulic-based approaches for VR. Similarly, Das et al. [Das+18] and Goto et al. [Got+18] also used PAM-based devices to create wrist movements, particularly flexion, extension, pronation, and supination. Often, these types of gloves are interesting for rehabilitation, particularly from strokes, in order to regain the ability to move single fingers [Con+09; Con+10; Koe+04; Pol+13]. Thereby, some work further combined these ideas with VR environments, such as presented by Laver et al. [Lav+11] or Tsoupikova et al. [Tso+09]. However, while these are undoubtedly useful and show the potential of pneumatic-based actuations, their focus was purely on rehabilitation for hand movements, while immersive and realism aspects or other body parts were not covered.

Although Proprioception research in this topic mostly focuses on the movement of certain body parts or joints, there also exists work that aimed to do the opposite by inheriting movements, e.g., as done by Pohl et al. [PHR17], or even limiting a user's motion completely, e.g., as investigated by Maimani et al. [MR17] who were using vacuumized actuators to give a sense of being frozen in VR. However, the kinesthetic motion of body joints through pneumatic actuations in VR remained underexplored.

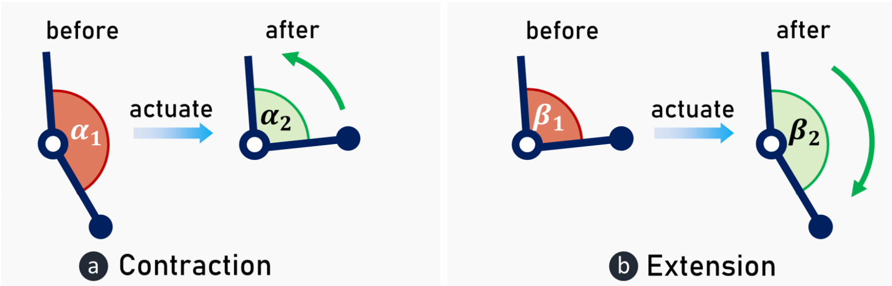


Figure 8.1: Actuation concept for body joints: (a) contraction, and (b) extension movements. α indicates the angle change for a concentric contraction, while β indicates an eccentric contraction.

8.2.5 *Electrical Muscle Stimulation (EMS)*

In the last years, more approaches were using EMS for active kinesthetic feedback and stimulation. Therefore, EMS devices use surface electrodes that create muscle tension through electric impulses which then affect body movements. For example, Pfeiffer et al. [PDR16] designed a EMS platform to easily create wearable devices to evaluate kinesthetic concepts, for example by placing electrodes on the legs for pedestrian guidance and obstacle avoidance [Pfe+15]. Similarly, Auda et al. [APS19] used EMS on the legs to also subtly modify the walking direction for an infinite walking redirection experience in VR. Further, Lopes et al. investigated various use-cases for EMS-based actuations. In earlier work, the authors used it for force feedback and to provide physical contact that is able to manipulate the user's motion [LBB13; LIB15]. In follow up works, Lopes et al. [Lop+18; Lop+17] extended these concepts to AR/VR environments, e.g., for gaming purposes. Thereby, the resulting kinesthetic feedback was used to create the impression of weight and counterforces or was capable of actively limiting or enhancing the user's motion.

8.3 KINESTHETIC ACTUATORS: CONCEPTS

In order to address the proprioceptive sensation of humans, muscles have to be kinesthetically stimulated. Hereby, proprioception mainly relies on the trigger of two receptors: (1) Golgi tendon organs, and (2) muscle spindles [DBD20; Kaa12]. Both are responsible for detecting stretches and changes in the length of muscles to detect the movement

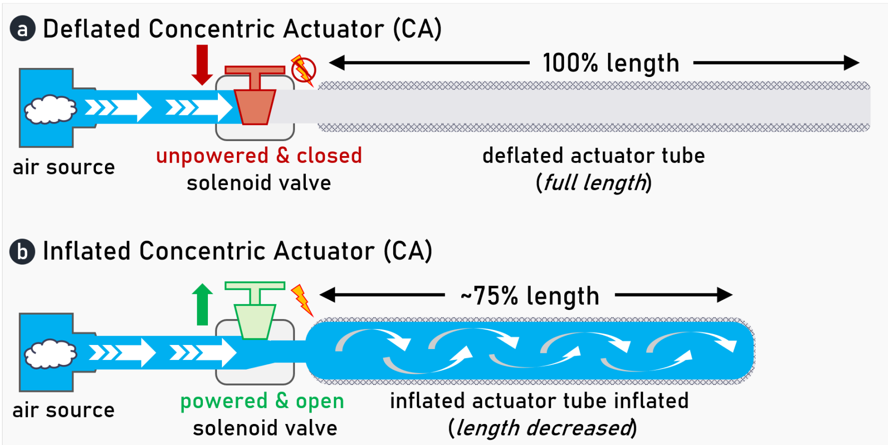


Figure 8.2: Concept of the Concentric Actuators (CA) based on a Pneumatical Artifical Muscle (PAM). (1) In the deflated state, the magnetic solenoid valve is closed and the air from the compressor cannot flow through. As soon as (2) the solenoid valve is powered, it allows the compressed air to pass and the actuator inflates. Due to the outer mesh around the inner tube, the entire actuator cannot expand indefinitely in width but will reduce its length resulting in a contraction.

and position of individual body parts, however, muscle spindles are usually seen as most responsible for kinesthetic sensation [PG12] (see also background Section 2.2.3). As consequence, to actuate body joints, it is necessary to provide both, contraction and extension of the muscle, to fully support both motion directions. In terms of (sport) medicine, this type of movements are typically referred as a *concentric* (shortening of muscle) and *eccentric* (lengthen of muscle) contraction [New+83]. Therefore, two kinds of actuators have to be considered: (1) a Concentric Actuator (CA) that decreases the angle of a body joint, and (2) Eccentric Actuator (EA) that does the opposite motion.

8.3.1 *Concentric Contraction Actuator (CA)*

Limbs and body joints, in general, have to be contracted in order to provide one direction of kinesthetic feedback. This can be either done by external forces or through exoskeletons. While both approaches require large setups or may hinder movements, some exoskeletons make use of a PAM [CMG95; Dae+02]. The concepts of a PAM, also known as *McKibben muscle*, were already invented in the 50s [CH96;

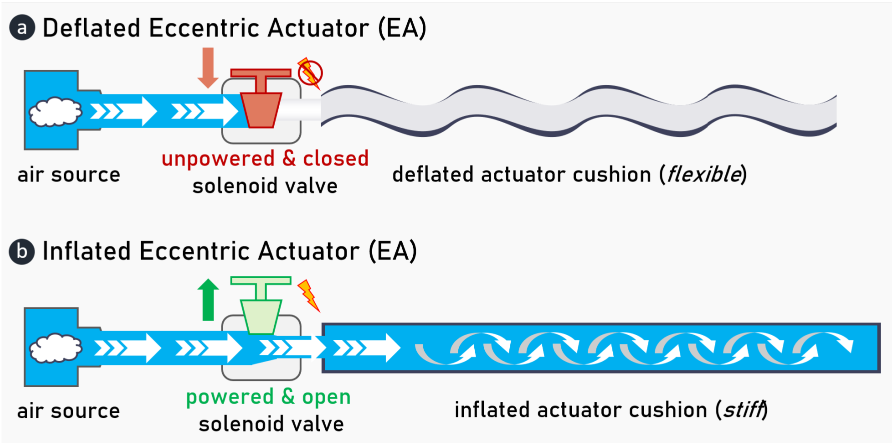


Figure 8.3: Concept of the Eccentric Actuators (EA) based on pneumatic inflation of air cushions. (1) In the deflated state, the magnetic solenoid valve is closed and the air from the compressor cannot flow through, leaving the cushion flexible. As soon as (2) the solenoid valve is powered, it allows the compressed air to pass and the actuator inflates which results in a more stiff cushion, able to push body parts.

KCH99; TL00] and allow to replicate the behavior of biological muscles through pneumatic actuation [CH96; KCH99].

Therefore, a flexible tube is enclosed in a slightly larger mesh sleeve. If compressed air inflates the inner flexible tube, it expands in width but is limited in the full expansion through the outer mesh sleeve. At the same time, the tube contracts in length resulting in a *pulling* of both ends. While this can be used in exoskeletons, it can also be applied directly to a body joint by mounting it to two different body parts linked by the joint, e.g., the forearm and upper arm. The basic concept of the CA is depicted in Figure 8.2.

8.3.2 *Eccentric Contraction Actuator (EA)*

Contrary to the contraction of a body joint, the full kinesthetic feedback also requires the possibility for an extension or stretching motion. While this could be achieved with a PAM as well, it would require sophisticated placements and anchoring on the body which may still constrain other movements. Therefore, inflated cushions similar to the cushions presented in Chapter 5 but placed directly on the inner apex or bending point of a body joint would result in a forced extension of the joint, such

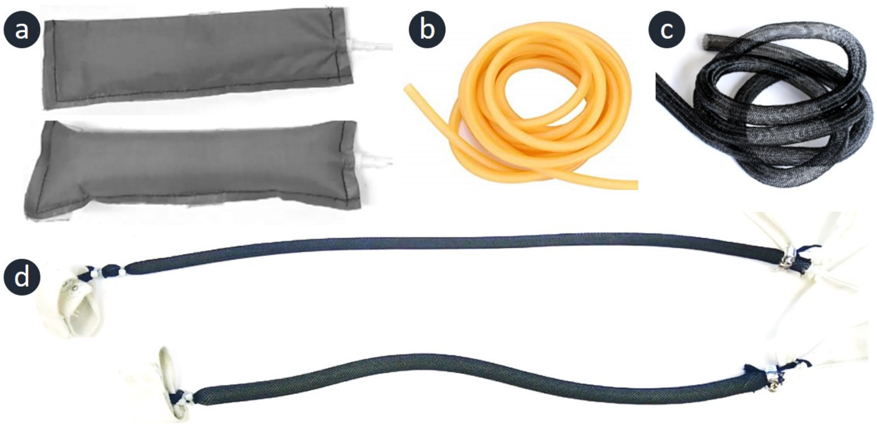


Figure 8.4: The final actuator design of the (a) EA and (d) CA in their inflated and deflated states. Further, (b) depicts the used inner latex rubber tube and (c) the outer mesh as used for the CA.

as the crook of the elbow. If air inflates the actuator cushion, it causes a push to the attached body parts and, thus, results in an increased angle of the body joint. The concept of the EA is depicted in Figure 8.3.

8.4 PNEUMACT SYSTEM

The implementation of the aforementioned concepts will be referred as PneumAct and explained in the following.

8.4.1 *Actuators*

Both types of actuators, the CA and EA, had to be implemented differently as described in the previous section.

CONCENTRIC CONTRACTION ACTUATOR (CA)

The design of the CA was based on a *McKibben* Pneumatical Artifical Muscle (PAM) [CH96]. Therefore, a 50 cm long latex rubber tube with a 0.8 cm diameter was used for the inner inflatable tube as this was identified to be a suitable length for the typical arm length of adults (see Figure 8.4b). For the outer mesh sleeve, a slightly broader diameter of 1.0 cm was chosen to fit the rubber tube (see Figure 8.4c). Once the actuator was inflated, its length decreased by 24 % (12 cm) and almost doubled in diam-

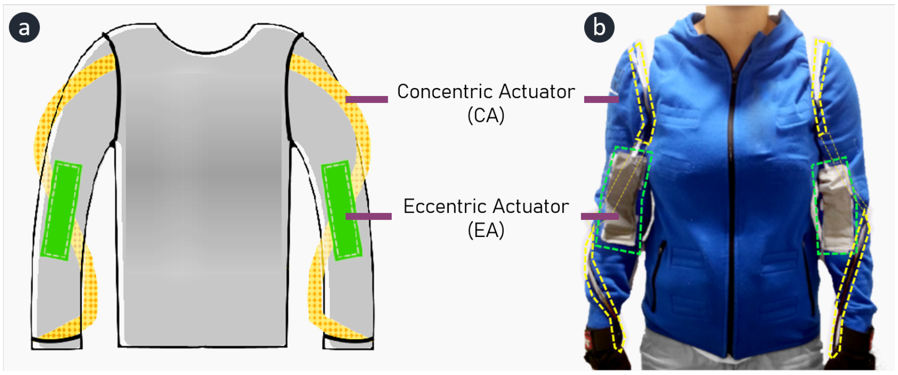


Figure 8.5: The PneumAct jacket as (a) concept and (b) the final prototype. The Concentric Actuators were attached to the outside of the jacket and wrapped around the arms (yellow). The Eccentric Actuators were located at the crooks of the elbows (green).

eter (1.5 cm) to create a full contraction. Due to the nature of a PAM, this design creates strong forces with a maximum of 150 N (approximately 15 kg pulling force). An CA in its deflated and inflated state is shown in Figure 8.4d.

ECCENTRIC CONTRACTION ACTUATOR (EA)

Contrary to the other type of actuators, the EA was made of a synthetic fabric that was cut into rectangular shapes. Then, it was folded and stitched on the sides to create an air cushion. Additional glue on the sides reduced air leakage. However, it still was enough permeable to ensure that once the actuation would be stopped, the cushion would deflate. For the inflation, small 3D-printed connectors were located on one side of the cushion, able to connect to 4 mm PVC tubes. The final design of one EA had a total size of 17.5 cm × 5.5 cm and could inflate to a maximum width of 3.5 cm. An EA in its deflated and inflated state is shown in Figure 8.4a.

8.4.2 *Wearable Jacket*

For increased wearability and more mobility, the heavy solenoid valves and control unit were located further away from the user and connected to the actuators through 5 m long PVC tubes. In addition, all actuators were attached to a regular cotton jacket for a faster setup. Therefore, both CAs were attached to the shoulder with a strap on one side, and

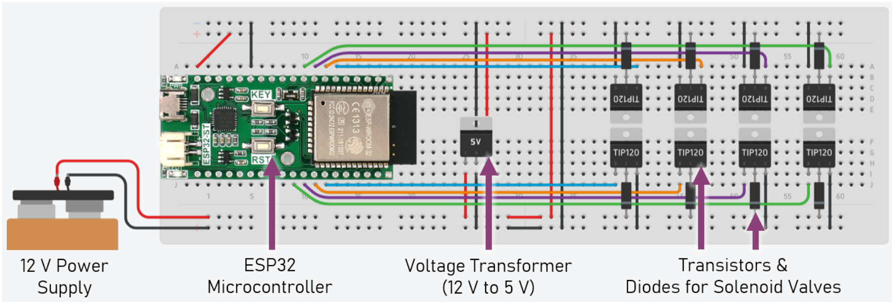


Figure 8.6: Schematic of the electronic components of the system controller. It shows the 12 V power supply, the ESP32 microcontroller, the voltage transformer, the transistors, and diodes for the solenoid valves, as well as the respective wiring. *This Figure uses breadboard view graphics from fritzing.org, licensed under CC Attribution-ShareALike (CC BY-SA 3.0).*

to the wrist or the hand on the other side. The EA were located on the crooks of the elbows with *hook-and-loop* fastener for more precise positioning. Hereby, all actuator placements were suitable for varying arm sizes. However, while the tubes going to the jacket are very flexible and long for a largely free movement, the system is still not completely mobile (this will be further discussed in Section 8.11). Figure 8.5 depicts a concept of the jacket and the final prototype as used in both user studies.

8.4.3 *System Controller*

In order to control the actuation, a custom system was built that used an ESP32 microcontroller which received commands either via a Bluetooth or USB serial connection to regulate the airflow of the actuators. Therefore, eight normally-closed magnetic solenoid valves (*U.S. Solid JFSV00051*, 12 V) were connected to each actuator with flexible PVC tubes and an air distributor. The distributor was made of metal and was used to distribute the airflow coming from an air compressor (*Einhell TH-AC 200/24 OF*, maximum 8 bar, 800 kPa). A mechanical valve was used to limit the maximum pressure of the air compressor to 5 bar (500 kPa). Further, an additional solenoid valve acted as the main valve to regulate the overall airflow, while another one was used to release excess air from the system.

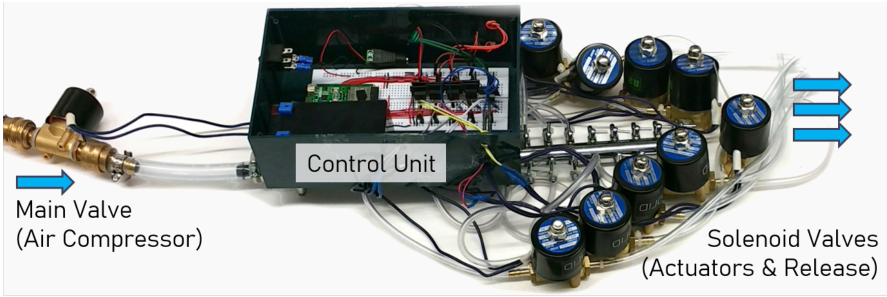


Figure 8.7: Controllable components of the PNEUMACT system showing the main valve for the air compressor and the custom control unit with connected solenoid valves for the actuators.

To switch all solenoid valves, MOSFET transistors (*IRLZ34NPBF*) were used. Additional safety diodes (*1N4007*) were also added to protect the hardware from reverse voltage spikes and currents. All actuators could be controlled automatically through dynamic in-application events or manually using a Unity compatible *C#* interface. A schematic of the system controller is depicted in Figure 8.6. All electronic components of the final prototypical system are depicted in Figure 8.7.

The experience gained from designing and realizing this prototype informed the general prototyping concept presented in Chapter 9, called ACTUBOARD. Further, the concepts for a pneumatic actuation were also used for the evaluation of PRESSURE-BASED MECHANORECEPTION in Chapter 5.

8.4.4 *Safety Measurements*

The maximum airflow was mechanically regulated to 5 bar (500 kPa). This allowed for a powerful actuation, but that could always be counteracted by users. Also, forces were only applied in natural movement directions preventing overshooting. Additional hardware- and software-sided emergency switches were included to rapidly release air from the system in case of unexpected behaviors. During the studies, it was also ensured that no obstacles were in close range of the participants. Further, all actuations were strong but not strong enough to overshoot the natural movements of a body joint, e.g., overstretching the elbow.

8.5 USER STUDY I: EFFECTS OF INFLATION DURATION AND PATTERN ON CHANGE OF ANGLE - METHODOLOGY

Methodology Summary		within-subjects design
Controlled Experiment Lab Study	Repeated-Measures ANOVA Shapiro-Wilk & Mauchly Bonferroni-corrected pairwise t-tests	24 participants 10 female, 14 male 21 – 35 years

f(IV)	*f(DV)*
Inflation Duration Inflation Pattern Type of Actuator (CA/EA)	Change of the Arm Angle

This section presents the methodology of a first controlled experiment assessing the influence of different inflation DURATIONS and PATTERNS on the angle of body joints. In particular, both types of actuators, the CA and EA were used on the left and right arms of 24 participants to measure changes in the angle of the elbows. The user study investigated the following questions:

Q1. How does the inflation DURATION affect the angle?

Q2. How do different inflation PATTERNS affect the angle?

8.5.1 *Design and Task*

A within-subjects design was used for the user study to evaluate the changes in the angle on the users' arms as DV. As IV, the inflation DURATION and inflation PATTERN were varied in a repeated-measures design. The DURATION described how long the solenoid valves were open for inflating the actuators, and the PATTERN indicates if the inflation is continuous or in short intervals[1]. However, as the two types of actuators, CA and EA, rely on different concepts, they were investigated independently but with similar levels for both IVs. Therefore, participants performed all combinations, but conditions were always grouped by arm side and type of actuator. The IVs were further counterbalanced using a

1 The intervals are representing inflation bursts that are given in the format *XX-YY* where *XX* refers to a single inflation time and *YY* the pause between the inflations. Each interval's single inflation time was then summed up to match the total inflation duration

Balanced Latin square design and between trials, there was a random pause between one and three seconds to enforce a surprise effect of the actuation. The following sections describe the levels of the individual IVs in-depth with respect to the type of actuator.

8.5.1.1 *Levels of Concentric Actuator (CA)*

The CA had four levels for the inflation duration: (1) 100 ms, (2) 200 ms, (3) 300 ms, and (4) 400 ms. Informal pre-tests indicated only minor inflations that were too weak for a full actuation below 100 ms. Further, 400 ms turned out to be a maximum for a full inflation of the PAM.

Level	contin.	50-50	50-100	100-50	100-100
Pattern	■■	■—	■——	■■—	■■——

Table 8.2: The five levels of the inflation pattern while using the CA. ■ represents a single inflation time of 50 ms and — an interval pause of 50 ms.

The inflation pattern of the CA had five levels: (1) continuous, (2) 50-50, (3) 50-100, (4) 100-50, and (5) 100-100. The first number always indicates a single inflation (burst) time of an interval while the second numbers indicate the pause in between. A pattern was always repeated until the sum of all single inflations were equal to the total inflation duration of the current condition. The inflation patterns of the CA are depicted in Table 8.2.

Each condition combination was repeated six times with three repetitions on the left arm and three on the right. This resulted in a total of $4 \times 5 \times 6 = 120$ trials for the CA.

8.5.1.2 *Levels of Eccentric Actuator (EA)*

To compensate for the different behaviors of both types of actuators, the IV levels of the EA had to be slightly altered. As for the inflation duration, three levels were defined: (1) 50 ms, (2) 100 ms, and (3) 200 ms. Again, the lower threshold was set to the minimum duration that was required to have any effect on the actuation which lay at 50 ms. For the maximum duration, anything above 200 ms was found to have no additional effect.

Level	contin.	25-50	25-100	50-50	50-100
Pattern	■■	■——	■————	■■——	■■————

Table 8.3: The five levels of the inflation PATTERN while using the EA. ■ represents a single inflation time of 25 ms and — an interval pause of 25 ms.

For the inflation PATTERN, five levels were defined: (1) CONTINUOUS, (2) 25-50, (3) 25-100, (4) 50-50, and (5) 50-100. Likewise, as before, the first number indicates a single inflation duration while the second number indicates the pause until the next inflation interval. Concerning technical limitations of the magnetic solenoid valves that require at least 20 ms to open and 30 ms to close, a minimum single inflation time of 25 ms was chosen, as well as a minimum of 50 ms for the pauses. As before, the repetitions of an interval for each PATTERN were further fitted to match the inflation DURATION. All inflation PATTERNS of the EA are depicted in Table 8.3.

Each condition combination was repeated six times with three repetitions on the left arm and three on the right. This resulted in a total of $3 \times 5 \times 6 = 90$ trials for the EA.

8.5.2 *Task and Dependent Variable (DV)*

During the study, the participants had to wear the PneumAct actuators on both arms. However, only one actuator on one side was active at the same time until all conditions for this combination were completed. During all conditions, the experimenter assured the safety of the participants (cf. Section 8.4.4). Further, in each condition, participants had to bring their arms into relaxed starting positions while standing. This was a downwards position during CA and an angled arm during EA conditions. The participants were further instructed to not counteract at the beginning of an actuation as the actuation occurred suddenly. However, they were allowed to stop the arm movement when they thought the actuation was finished. The inflation was kept for one second and the participants had to remain the angle as good as possible until the air was released again. Thereby, the angle between forearm and upper arm was measured as DV. Afterward, the participants had to return the arm to the starting position.

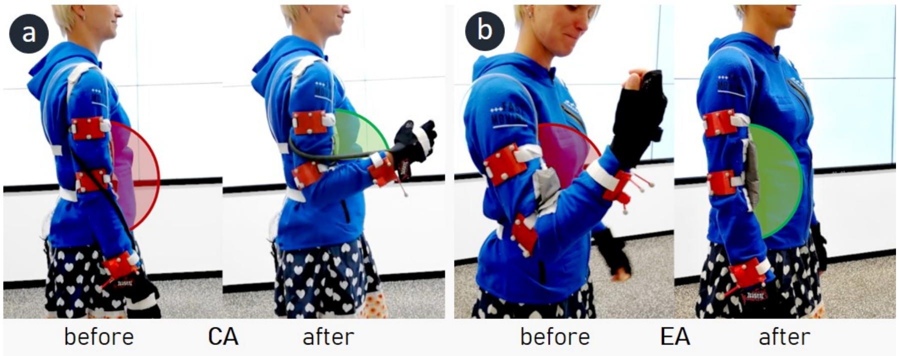


Figure 8.8: A participant wearing the PneumAct jacket with both actuators during the first user study. The pictures show both actuators, the (a) Concentric Actuator (CA) and (b) Eccentric Actuator (EA) before (left) and after an actuation (right).

8.5.3 *Setup and Apparatus*

The apparatus was based on the PneumAct jacket described in Section 8.4. Hereby, the CA were attached tightly but comfortably to the shoulder and wrists of participants, while the EA were located on the crooks of the elbows as shown in Figure 8.5.

To measure the angle between the forearm and upper arm, an optical tracking system with retro-reflected markers was used (array of six OptiTrack Flex 3). For an accurate measurement, markers were attached to the side of the upper arm, elbow, and center of the forearm using custom 3D-printed mounts. In addition to the angle, a timestamp, the current condition, and repetition number were logged. Before starting the study, it was ensured that all actuators and trackers were not restricting any movements and were placed firmly. Figure 8.8 depicts the setup.

8.5.4 *Procedure*

BEFORE THE STUDY: The participants were welcomed and the experimenter gave a short introduction to the concepts and introduced them to the PneumAct jacket. Further, they were informed of the safety precautions and data protection policy which had to be signed by everyone before beginning the study. Also, a demographic questionnaire including the age, gender, dominant hand,

and arm length (measured by the experimenter) had to be filled out. Once participants had no further questions, the experimenter assisted by putting on the jacket and assuring that all actuators were in place.

DURING THE STUDY: In each condition, a participant had to start by standing on a marked spot that was reliably tracked by the optical cameras. Then, depending on the active actuator, participants either had to leave their arms hanging downwards comfortably with approximately 180° between the forearm and upper arm during CA conditions, or angled during EA conditions. However, they were asked to not apply any counterforce or pressure on the arms.

Once ready, the trials for the respective arm and type of actuator started. For each trial, one arm of the participants was actively bent or stretched by the system and participants should try to let the motion happen naturally. After one second of holding, the air was released from the actuators and participants had to return to the starting position to start the next trial. When all trials for one arm and type of actuation were over, participants had to take a short break and then continued with the next combination.

AFTER THE STUDY: After finishing all conditions and trials, the experimenter helped to remove the jacket and actuators. Participants were also invited to give additional qualitative feedback throughout the study and engaged to do so at the end. Overall, the whole procedure took 40 minutes per participant.

8.5.5 *Participants*

In total, 24 individuals participated in the study (10 female, 14 male). All of them were between 21 and 35 years (M=26.0, SD=3.6). All of them had a right dominant hand with an average arm length of 55 cm (SD=4.6 cm), measured from the top of the shoulder to the wrist. Besides snacks and drinks, no compensation was provided.

8.6 USER STUDY I: RESULTS

In the following, the results of the controlled experiment are reported. At the beginning of the section, details of the analysis are presented, followed by the quantitative analysis and qualitative feedback of the participants.

8.6.1 *Analysis*

For analyzing the data, a repeated-measures ANOVA was used. First, the data was tested for normality using Shapiro-Wilk's test and checked for violations of the sphericity assumption using Mauchly's test. If the latter was the case, a Greenhouse-Geisser correction was performed to adjust the degrees and freedom and report the ϵ value. For posthoc analysis, Bonferroni corrected pairwise t-tests were performed. The analysis will further report the effect size as small, medium, or large, using Cohen's classification and the eta-square value η^2 [Coh88]. Also, the results will include the Estimated Marginal Mean (EMM) as the estimated influence of individual factors [SSM80].

8.6.1.1 *Concentric Actuator Results*

The analysis revealed a significant effect of the inflation DURATION with a large effect size ($F_{1.68,38.76}$=101.53, $p < .001$, $\epsilon = 0.562$, $\eta^2 = 0.188$). Post-hoc tests showed a significant increase of the angle between DURATIONS of 100 MS, 200 MS, and 300 MS (all p <.01). However, no significant effects were found between 300 MS and 400 MS (EMM $\mu = 43.4\,300$, $\sigma_{\overline{x}} = 3.12\,300°$, EMM $\mu = 44.3\,400$, $\sigma_{\overline{x}} = 3.12\,400°$, p >.05).

Significant effects were also identified for the PATTERN with a small effect size ($F_{2.46,56.64}$=16.05, $p < .001$, $\epsilon = 0.616$, $\eta^2 = 0.02$). Regarding the difference of angle, post-hoc tests showed that a CONTINUOUS inflation always resulted in a smaller mean angle difference than inflations with a same DURATION but different PATTERN. Further, it was observed that PATTERNS with short bursts of 50 ms (50-50 and 50-100) resulted in the largest angles differences (p <.001 for both and also the CONTINUOUS PATTERN). All measurements and results for the CA (as depicted in

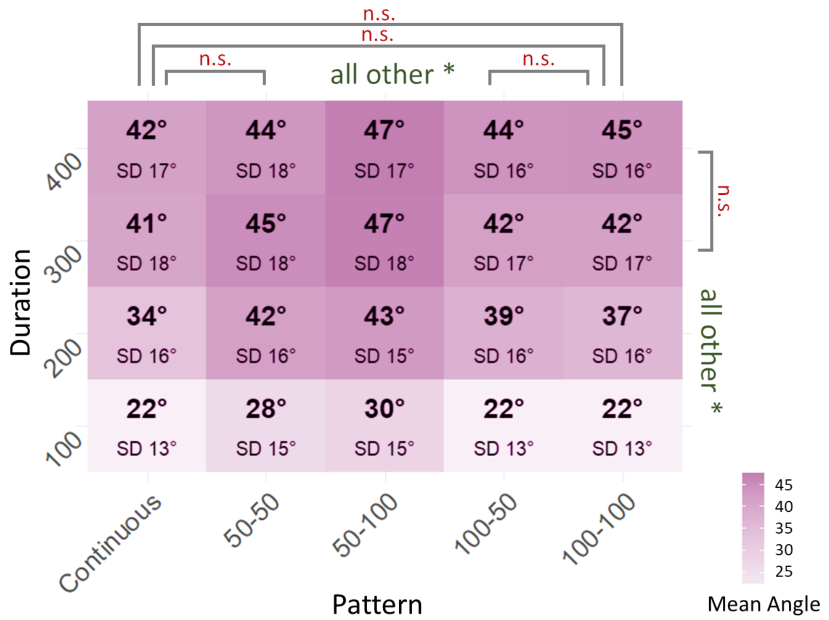


Figure 8.9: Angle differences after actuation for different inflation DURATIONS and PATTERNS of the CA. All conditions were significant (marked with *) except those marked with *n.s.*.

Figure 8.9) highlight which patterns and durations are resulting in which specific angles that can be used for other applications.

8.6.1.2 *Eccentric Actuator Results*

The analysis revealed significant effects for the DURATION with a large effect size ($F_{1.19,27.42}$=74.29, $p < .001$, $\epsilon = 0.596$, $\eta^2 = 0.235$). Post-hoc tests confirmed significant increased angles for longer DURATIONS (EMM $\mu = 13.7 50$, $\sigma_{\overline{x}} = 4.1 50°$, EMM $\mu = 29.6 100$, $\sigma_{\overline{x}} = 4.1 100°$, EMM $\mu = 42.3 200$, $\sigma_{\overline{x}} = 4.1 200°$; all p <.001).

The analysis could also identify significant effects for the inflation PATTERNS with a small effect size ($F_{2.1,48.4}$=46.79, $p < .001$, $\epsilon = 0.526$, $\eta^2 = 0.046$). Similar to the CA, post-hoc tests revealed significant larger resulting angles between CONTINUOUS inflations and PATTERNS using an interval (p <.001). Again, more rapid PATTERNS (25-50 and 25-100) resulted in the significantly largest differences of the angle (all p <.001). All measurements and results for the EA (as depicted in Figure 8.10) highlight which patterns and durations are resulting in which specific angles that can be used for other applications.

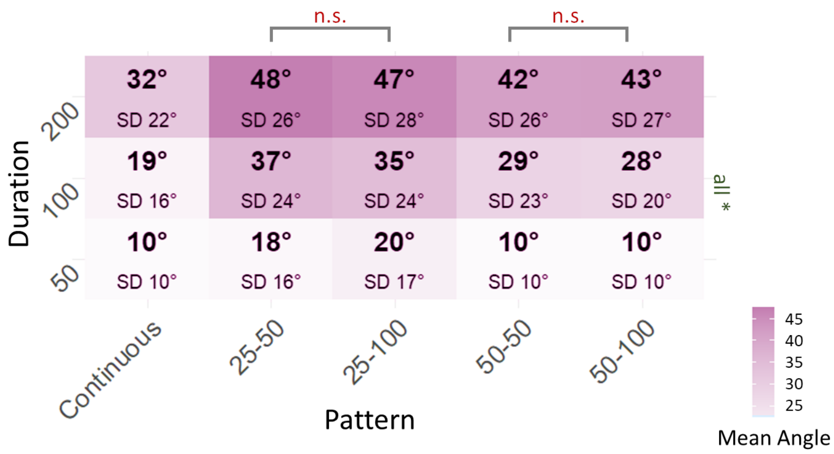


Figure 8.10: Angle differences after actuation for different inflation DURATIONS and PATTERNS of the EA. All conditions were significant (marked with *) except those marked with *n.s.*.

8.6.2 *Qualitative Feedback*

During the study, participants were asked to give additional qualitative feedback to get further insights on the performance of the kinesthetic actuation. Overall, participants were interested in the system and highlighted the general idea of the kinesthetic actuation (P2, P5, P7, P14) which was easy to follow for them (P1).

Taking a look at the inflation PATTERNS, most participants preferred the CONTINUOUS actuation as it "*felt more natural*" (P3, P10). However, some participants (P17, P18) stated that interval inflations were more intuitive to reaching a certain position that they thought to be the target of the actuation. P17, for example, said "*it tells me to continue the motion rather than just pushing me in a direction*". Two other participants even described the inflation intervals as a "*robotic feeling*" (P1, P7) which was a fun way for them to simulate artificial movements.

As comfort is essential for the acceptability of a system, participants were asked to describe the wearability. Almost every participant stated that it was pleasant or not disruptive. P2 even described that the EA "*feels like a soft bicep massage*", while P18 stated that the CA feels "*funny and cool*". Though, more critical voices explained that the CA was not feeling very comfortable and sometimes applied too much pressure on the triceps (P10, P12). On the other side, the EA felt too soft and did not provide enough pressure for some participants who reported also performing a lot of sports, thus, having more defined muscles on the arm (P1, P19). Also, as the jacket was unisized, larger participants reported that it was too tight (P4, P11).

8.6.3 *Discussion on Inflation Duration and Pattern*

This first user study was supposed to give insights on the overall performance of the PneumAct concepts and how both types of actuators affect the angle between the forearm and upper arm. Thereby, the variation of the inflation duration and pattern resulted in different angles but also in different interpretations of how the actuation was perceived by users. This section discusses those findings concerning the aforementioned results.

8.6.3.1 *Longer inflation durations result in larger angles*

While it seems rather obvious at first sight, longer inflation durations resulted in larger changes in the angle. However, taking a closer look, the user study helped to identify which duration leads to which angle. Also, the analysis revealed that while there are significant differences between the shorter actuation durations, there is not much difference between the longer ones (i.e., 300 ms and 400 ms with the CA).

This allows for designing future applications that can directly provide kinesthetic feedback which enforces certain motions of the users' arms. For example, longer and stronger (i.e., longer inflation durations or more intense patterns) actuations could be used for error feedback or as active prevention from reaching hazardous objects in critical situations. Shorter actuations, in contrast, could be used to *nudge* a person for guidance.

8.6.3.2 *Continuous Patterns are preferable*

While differences in the angle were often similar for the same inflation durations, the patterns influenced the characteristics and perception of the motion. Typically, continuous inflations were perceived as more natural and preferred by participants. However, while there were some significant differences, intervals with different pause lengths had only a minor effect on the resulting angle if the inflation duration is the same (e.g., 50-50 and 50-100 of the CA). Nevertheless, non-continuous PATTERNS still can be useful for specific applications. For example, if the actuation should replicate a shaking for notifications or coming from (virtual) avatars in VR, or as described by participants when trying to create artificial sensations such as feeling to be a robot. Also, non-continuous PATTERNS were seen to be more precise by some participants. However, as none of them knew a specific target angle, this statement could not be validated through the analysis.

8.6.3.3 *Interval Patterns affect Perception*

Taking a look at intervals, the angle difference did not differ much from the CONTINUOUS inflations. However, intervals made participants believe the actuation was more precise, even though they did not know if there was a target angle. Further, it was described to be more unnatural and artificial which made them think to have almost robotic arms, similar to work done by Kurihara et al. [Kur+14]. As such, the attention users paid to the artificial motion could be leveraged to influence the perception in a way that they also pay more attention to a certain event linked to the kinesthetic feedback. For example, it could represent notifications similar to strong vibration patterns known from mobile phones, or even used for VR applications where participants have to play a certain role, such as a robot.

8.6.3.4 *Concentric Actuation is perceived stronger*

While the design of both types of actuators is different, the CA was perceived as a stronger actuation. Indeed it was observed that it was harder to counteract the strength of a CA than the EA, which could also come from the typical strength differences of the primary muscles involved (biceps and triceps). However, the EA still resulted in similar angle changes for longer DURATIONS as the CA.

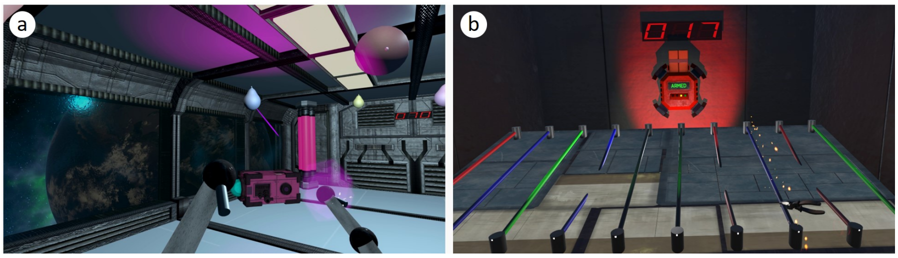


Figure 8.11: Screenshots of the first two example applications: (a) Robots in Space and (b) Wire Cutting.

8.7 EXAMPLE APPLICATIONS

Based on the findings of the previous user study, three example applications for VR were designed to further investigate the possibilities of the rougher kinesthetic feedback: (1) Robots in Space, (2) Wire Cutting, and (3) a Weight Lifting Exergame. All three applications used the lessons learned about inflation durations and patterns fitted to different scenarios, such as sudden motions, force feedback, artificial movements, recoil, and the simulation of varying weights. All of the following applications were implemented using the *Unity* game engine and the *SteamVR* platform. The *HTC Vive* system was used for the HMD and tracking. All three applications were evaluated in a second user study that is described in Section 8.8.

8.7.1 *Robots in Space*

The first application was a game situated in an abandoned space station. The player had to take the role of a rusty robot whose sole purpose was to *pop* balloons floating around the station. Therefore, the player had two virtual lasers that were controlled by the VR controllers to shoot balloons. While real lasers would have of course no actual recoil, the game was designed to provide kinesthetic feedback through the CA to push the arms slightly back after each shot. Hereby, the player could charge a laser by holding the trigger for a longer period, resulting in a stronger actuation. Further, as the player was supposed to act like a robot, the game used the EA to have short intervals of inflations that should represent the rusty artificial movements of the robot's joints, similar to Kurihara et al. [Kur+14]. In addition, vibrotactile feedback coming from the VR game controllers could be enabled to provide the same effects but through a different modality.

That being said, the goal of the game was to *pop* as many balloons as possible in a given period of time. If all balloons were *popped* in time, the player won, otherwise, the game was lost. A screenshot of the application is shown in Figure 8.11a.

8.7.2 *Wire Cutting Game*

A second application should highlight the usage of PneumAct during dangerous situations and sudden unexpected events. Hereby, the user was located in a small unpleasant room and had to avoid a timed explosion of a device. To do so, the user was provided with pliers to cut different colored wires on a console in front. If the correct wires were cut, the explosion was avoided. However, if a single wrong wire was cut or the time ran out, the explosion was triggered, resulting in a sudden impact force on the user. This force was implemented by inflating the EA fast and long, pushing the arms back.

To increase the difficulty and tension, the user did not know the correct wires beforehand. However, wrong wires were indicated by small visual sparks once the user reached out for them with the pliers. In addition, the CA gave subtle flinches through short inflations which were intended to simulate small electric shocks. Optional vibrotactile feedback was used similarly and started to heavily vibrate during an explosion or provided subtle cues when being close to a wrong wire.

As a small extra, once all correct wires were cut, a firework animation was presented to the user that also triggered the EA to provide short subtle intervals of explosions in the distance. A screenshot of the application is shown in Figure 8.11b.

8.7.3 *Weight Lifting Exergame*

Besides pure entertaining games, kinesthetic feedback and affecting the Proprioception of persons can be used for training situations or motion

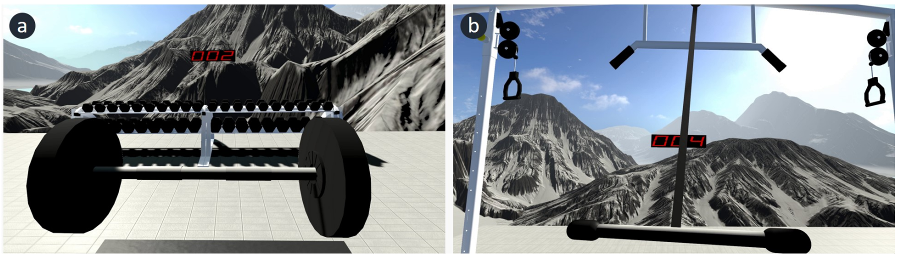


Figure 8.12: Screenshots of the exergame example application, showing the weight (a) lifting and (b) pulling exercises.

guidance. Therefore, a third application was designed as an exergame in VR where users could perform two sports exercises in a virtual gym.

For the first exercise, users should train their biceps by lifting a weight in form of barbell curls. Hereby, the EAs were inflated to simulate a counterforce once the user wanted to lift the barbell. To simulate different weights, the inflation duration and pattern were modified which provided in total three different intensities.

Similarly, for the second exercise, users should train their triceps by pulling down the handle of a cable pull. During this exercise, the CA were used to simulate the counterforce that was applied when pulling the handle, again, with three different intensity levels by varying the inflation duration and pattern.

As such exercises typically require proper training equipment, the barbell's and cable pull handle's physical shape was recreated by using a one-meter long pipe. To track the pipe realistically, one VR controller was mounted to the left side, while the second controller was mounted to the right to provide an even balance of the handle. In addition, the vibrotactile feedback of the controllers could be enabled to provide haptic feedback for downward arm movements during the pulling exercise, and upward arm movements during the lifting exercise. Two screenshots of the exergame showing both exercises are depicted in Figure 8.12.

Methodology Summary | within-subjects design

Controlled Experiment Lab Study	non-parametric analysis Friedman's test Wilcoxon Rank-Sum tests	12 participants 4 female, 8 male 21 – 32 years

f(IV) Type of Actuation: Kinesthetic Vibrotactile Combined No-Haptics	***f(DV)*** Questionnaires: Level of Immersion Level of Realism Level of Enjoyment

8.8 USER STUDY II: PNEUMACT IN VIRTUAL REALITY APPLICATIONS - METHODOLOGY

After designing the three example applications as introduced in the previous section, a second user study was conducted to identify how the kinesthetic feedback affected the immersion, level of realism, and enjoyment of users in VR. As a baseline, controller-based vibrotactile feedback and no-haptics were compared. Summarizing, the following research questions were investigated:

RQ1. How can a KINESTHETIC actuation positively affect the level of immersion, realism, and enjoyment?

RQ2. How does a KINESTHETIC actuation compare to VIBROTACTILE stimuli and NO-HAPTICS?

RQ3. How does a KINESTHETIC actuation affect the experience when combined with VIBROTACTILE stimuli?

8.8.1 *Study Design and Task*

The study was performed using a within-subject design, measuring the levels of IMMERSION, REALISM, and ENJOYMENT, as well as the SUPPORT of the different types of haptic feedback as the DV. Therefore, participants were invited to play all three aforementioned applications with four different TYPES OF ACTUATION as IV: (1) KINESTHETIC feedback, (1) VIBROTACTILE feedback, (3) COMBINED feedback, and (4) NO-HAPTICS baseline.

In order to assess the aforementioned items, the following questions were asked after each condition on 5-Point scales ranging from *not at all* to *very much*. Thereby, the second and third questions are based on related work done by Lopes et al. [Lop+18].

1. How immersed have you been in the VR experience?
2. How would you define the level of realism?
3. How much did you enjoy the experience?
4. How much did the additional feedback support you during the task?

8.8.1.1 *Task*

Participants had to test all three applications successively four times with one of the active TYPE OF ACTUATION for each repetition. Therefore, a total of 3 applications × 4 types of actuation = 12 repetitions had to be conducted. To avoid learning effects, the order of the four conditions was counterbalanced using a Balanced Latin Square. During each condition, the participants could freely explore the VR environment of the current application and try to fulfill the individual tasks. Further, participants could repeat an application as often and for as long as they preferred to try out all aspects before continuing with the next condition.

8.8.2 *Setup and Apparatus*

Again, the apparatus was based on the PneumAct system for the KINESTHETIC feedback as described in Section 8.4. Both CA were attached tightly but comfortably to the shoulder and wrists of participants, and the two EA were located on the crooks of the elbows as before.

The VR applications were exactly those that were described in Section 8.7. All participants used a state-of-the-art HMD (HTC Vive) with the respective game controllers. The controllers were used for interacting with the VR environments, as well as for VIBROTACTILE feedback. During the exergame (cf. Section 8.7.3), an additional pipe was used for resembling the handles of the weights.

8.8.3 *Procedure*

BEFORE THE STUDY: Participants were welcomed and introduced to the study. Therefore, they were briefed about the applications but without much detail to keep them exploring during the study. The participants afterward received explanations on the VR hardware and the PNEUMACT system including safety instructions. If they had no further questions, they had to sign a consent form and fill out a demographic questionnaire including information about their age, gender, and VR experience. Once ready, the experimenter assisted with putting on the hardware with regards to the current TYPE OF ACTUATION and also asked the participants to wear provided headphones to reduce background noises.

DURING THE STUDY: All participants had to play all three applications in random sequences for each TYPE OF ACTUATION together. As soon as all three applications for one feedback method were finished, participants were asked to answer the provided questionnaire. During all conditions, participants could freely explore the VR applications and try out all aspects without constraints. However, while they could repeat any task as often as they wanted, they were always asked to succeed in each task at least once.

AFTER THE STUDY: As soon as participants tried all four TYPES OF ACTUATION for all three applications, they could put off the hardware. During unstructured interviews and a final questionnaire afterward, participants were invited to give further feedback on the experiences, as well as to rank the TYPES OF ACTUATION. Overall, one session took about 60 minutes for each participant.

8.8.4 *Participants*

In total, 12 participants (4 female, 8 male) between 21 and 32 years were recruited (M=29, SD=3.5). Three of them never tried VR before while eight had used it at least a few times. One user expressed to be a regular VR enthusiast. Besides snacks and drinks, no compensation was provided.

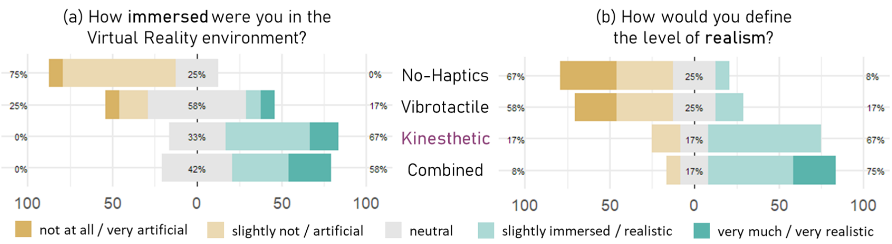


Figure 8.13: Participants' responses to the levels of (a) immersion and (b) realism during the second user study.

8.9 USER STUDY II: RESULTS

In the following, the results of this second controlled experiment are reported. At the beginning of the section, details of the analysis methods are given, followed by the quantitative results and qualitative feedback of the participants.

8.9.1 *Analysis*

A non-parametric analysis of the questionnaires' results was performed, using Friedman's test to reveal significant effects. If tests indicated significance, Bonferroni-corrected Wilcoxon rank-sum tests for the pairwise posthoc analysis were performed. Because of the ordinal nature of the data, the median values $\tilde{x}$ will be reported.

8.9.2 *Level of Immersion*

The analysis indicated significant effects ($\chi^2(3) = 21.84$, $p < .001$) of the participants' IMMERSION rating. Hereby, the best immersion ratings were observed for conditions using KINESTHETIC feedback. Post-hoc tests revealed significant different immersion ratings between the NO-HAPTICS baseline ($\tilde{x} = 2$) and a KINESTHETIC actuation ($\tilde{x} = 4$, $p <.001$), as well as with COMBINED feedback ($\tilde{x} = 4$, $p <.001$). There were no significant effects between KINESTHETIC and COMBINED feedback ($p >.05$), as well as for all VIBROTACTILE conditions ($\tilde{x} = 3$, all $p >.05$). The responses are visualized in Figure 8.13a.

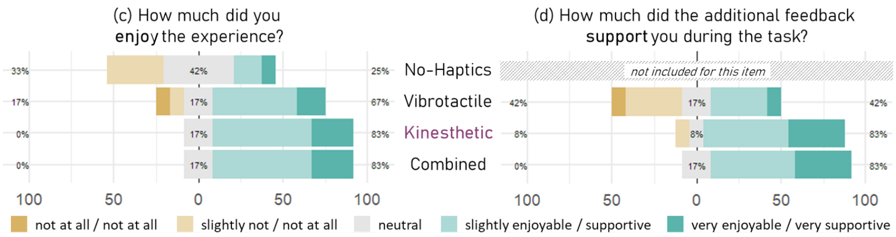


Figure 8.14: Participants' responses to the levels of (a) enjoyment and (b) support during the second user study. The SUPPORT question did not include the NO-HAPTICS baseline.

8.9.3 *Level of Realism*

The analysis indicated significant effects for the level of realism ($\chi^2(3) = 22.45, p < 0.001$). Post-hoc tests revealed that there is a significant higher rating for realism between KINESTHETIC ($\tilde{x} = 4$) and NO-HAPTIC feedback ($\tilde{x} = 2$, p <.05), as well as between COMBINED ($\tilde{x} = 4$) and NO-HAPTIC feedback (p <.01). While VIBROTACTILE was rated similar compared to the NO-HAPTIC baseline (both $\tilde{x} = 2$), there were only significant effects compared to COMBINED feedback (p <.05). The responses are visualized in Figure 8.13b.

8.9.4 *Level of Enjoyment*

The analysis revealed significant effects for the participants' enjoyment rating ($\chi^2(3) = 9.80$, $p < .05$). Pairwise comparisons further showed significant higher enjoyment ratings while having KINESTHETIC feedback enabled (KINESTHETIC: $\tilde{x} = 4$) compared to NO-HAPTICS ($\tilde{x} = 2$, p <.05). This was also the case between NO-HAPTICS and COMBINED feedback ($\tilde{x} = 4$, p <.05). However, no significant interaction effects were identified between VIBROTACTILE ($\tilde{x} = 4$) and NO-HAPTIC nor KINESTHETIC feedback (both p >.05). The responses are visualized in Figure 8.13c.

8.9.5 *Support of the Actuation during the Task*

For the analysis of the support of the additional feedback modalities, the NO-HAPTICS conditions were excluded. The analysis indicated significant effects ($\chi^2(3) = 23.26$, $p < .001$). However, the post-hoc analysis did not reveal any interaction effects. All three feedback methods had similar median ratings (KINESTHETIC and COMBINED: $\tilde{x} = 4$, VIBROTACTILE: $\tilde{x} = 3$). The responses are visualized in Figure 8.13d.

8.9.6 *Ranking of Actuation Types*

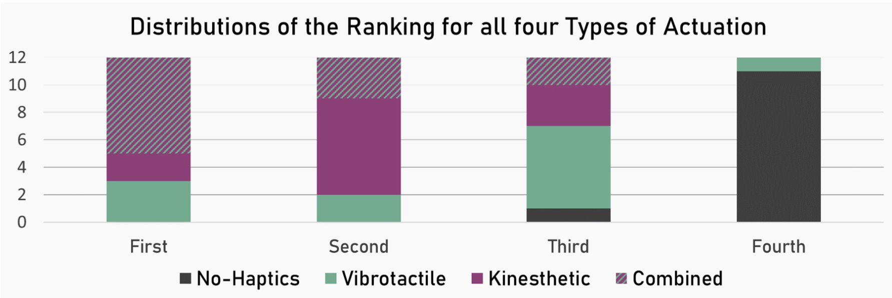


Figure 8.15: The distribution of the ranking of all four actuation types, sorted from best to worst.

In a final questionnaire, the participants were asked to rank the TYPES OF FEEDBACK from best to worst. As expected, the NO-HAPTIC baseline performed the worst ($\tilde{x} = 4$). Although the VIBROTACTILE feedback was generally rated as good, it only ranked third place compared to the others ($\tilde{x} = 3$). However, while conditions with KINESTHETIC feedback performed better ($\tilde{x} = 2$), the COMBINED feedback was ranked as the best TYPE OF ACTUATION ($\tilde{x} = 1$). The complete distribution of all rankings is shown in Figure 8.15.

8.9.7 *Qualitative Feedback*

To better frame the quantitative measurements and for additional feedback, participants were asked to provide verbal feedback throughout the study, noted down by the experimenter, as well as through unstructured interviews afterward. Generally, participants were enthusiastic about the KINESTHETIC actuation. They enjoyed the active forces (P10, P12) and described it as an "*interesting concept*" (P6). Especially the CA was positively highlighted (P10, P11, P12) and participants described them as a practical addition with a stronger force than imagined before (P5, P6).

During the *wire cutting* game, participants appreciated the idea of "*getting actively warned before cutting a wrong wire*" (P7), and that it "*almost felt realistic as if the wires are powered*" (P8) while having KINESTHETIC feedback. Further, such direct feedback made the game easier for some participants (P6, P9, P12), in particular, compared to the NO-HAPTIC baseline (P2, P12). Two participants also mentioned the "*effect of surprise at the moment of explosion*" as the KINESTHETIC actuation confronted them with directed force (P2, P3). However, one participant criticized that it now "*does all the work [for me]*" (P11).

The *robots in space* game was perceived as fun and shooting lasers with both, KINESTHETIC and VIBROTACTILE feedback, was well received (P5, P9). Though, one participant found the stuttering inflations that were supposed to provide a robotic feeling while moving as "*annoying*" (P11).

While the first two applications were mostly positively received, the exergame had mixed receptions. Although some participants appreciated that a KINESTHETIC actuation gave a "*good impression of counterforce*" (P1, P2, P5, P11), some others felt that the weights were "*too artificial*" (P4, P6) or just "*not heavy enough while doing the exercises*" (P7).

When asking for comparisons between the KINESTHETIC and VIBROTACTILE feedback, most participants preferred either the KINESTHETIC or COMBINED actuation (P7, P9, P11). For example, P3 missed on-body feedback during the VIBROTACTILE condition, and P12 missed the additional challenge without KINESTHETIC counterforces. However, one participant reported that although "*the pneumatic (KINESTHETIC) actuation was very intense and useful* (during the exergame), *for playing the other games, vibration seemed sufficient*" (P6).

With regards to technical aspects of the PNEUMACT system, one participant appreciated the "*synchronous interaction between games and jacket*" (P4), whereas two others criticized that the KINESTHETIC actuation should apply faster (P2, P7). In summary, most participants appraised the positive effects of a KINESTHETIC actuation, and, supported by the aforementioned analysis, the concepts worked even better COMBINED with VIBROTACTILE feedback of the game controllers.

8.10 DISCUSSION ON KINESTHETIC FEEDBACK IN SYNERGY WITH VIBROTACTILE ACTUATION

While the findings from the first study with regards to the effects of inflation durations and patterns were already discussed in Section 8.6.3, the second study was focused on the actual performance of such kinesthetic feedback during different VR applications.

As supported by the analysis, the additional kinesthetic actuation could result in higher realism, enjoyment, and immersion ratings compared to controller-based vibrotactile stimuli and the no-haptics baseline. Yet, this was somewhat expected beforehand, since the sample applications were specifically designed for scenarios that benefit from a kinesthetic actuation. However, the vibrotactile stimuli were already found to be adequate for some of the scenarios, resulting in relatively high ratings during the evaluation. Although kinesthetic actuation creates a more immersive experience in many areas, vibrotactile stimuli will not be replaced in the intermediate-term given their low implementation cost and ease of placement on different parts of the body. Moreover, it is important to understand that one technique does not entirely exclude the other and it is important to find synergies in how different haptic components can interact with each other. Hereby it seemed to be sufficient to just have any vibration during the combined condition, while for vibrotactile-only, the feedback appeared to be requiring a more sophisticated actuation that would be able to completely replicate a realistic sensation. In this manner, the results for conditions with combined kinesthetic actuation and vibrotactile stimuli were reported to be in fact higher than the isolated stimuli.

8.11 LIMITATIONS AND FUTURE WORK

The concepts, system, and studies come with some limitations that can be addressed for future iterations and discussed in the following.

8.11.1 *Other Body Parts*

In both studies, the elbow joint between the upper arm and forearm was considered. While this proved the overall idea and concept of such an actuation, other body parts need to be considered as well for the future. For example, the legs with their knee joints respectively might behave similarly to the arms. As such, it could be interesting to investigate how participants would react when they are forced to sit or get up, or even to be guided on a certain path, similar to EMS based approaches [PDR16; Pfe+15]. However, those encompass the *quadriceps* which is typically larger and stronger than the arms' *biceps* and *triceps* [Ric97]. This means that the actuators might need stronger forces or even different designs to avoid motion constraints. In particular, body parts with different anatomical properties, such as the back or shoulder, would require such adjustments. Yet, the back would be interesting to investigate as kinesthetic feedback might help for posture correction and rehabilitation. Another example would be an actuation of the hands or even each finger. This would require much smaller actuators, however, could be probably implemented with a weaker air supply, e.g., through small membrane pumps.

8.11.2 *Wearability*

The design for the actuators was kept flexible to fit the different sizes of the participants. However, this increased the setup as each actuator had to be carefully placed in the correct position and to provide the same actuation for each participant. Individualized actuators could increase wearability and reduce initial preparation steps. Similar to the PneumoVolley prototype (see Chapter 5), the prototype relied on a large peripheral air compressor that provided the actuators with air through long tubes going to the participants. This allowed for mostly unconstraint movements during the VR sessions, however, might reduce the freedom of the participants during more *active* scenarios.

To overcome this limitation, future prototypes could use small gas-filled cartridges or mechanical pumps that distribute the air from a separate air-filled container to an actuator, as also described in the limitations section of the Mechanoreception chapter 5.8.3. However, while the pressure-based actuation only required to fill small cushions that can be inflated rapidly, the presented actuators in this chapter require much stronger forces and used actuators with a larger volume. As another option, fixed ports leading to compressed air - to which a pneumatic-based system can be easily coupled - could be installed in stationary setups, such as 4D cinemas or VR arcades.

8.11.3 *Motion Guidance*

The field of motion guidance is a particularly interesting application area for kinesthetic feedback. Motion guidance can guide users to perform a specific action or to assist in learning new movements (e.g., [Che+16; Sch+12; Els+21]). The presented kinesthetic feedback within the scope of this chapter could provide another level for such guidance, however, further studies are necessary to see how it affects the training or learning effects of users.

8.11.4 *From Kinesthetic Actuation to Proprioception*

This chapter presented novel methods for kinesthetic and motion actuation. Such actuation allows to actively engage users to perform specific motions or movements. Further, while this stimulates proprioceptive receptors and afferents through Kinesthesia, it needs more investigations on how such kinesthetic actuation affects the proprioceptive sensation of body position. For example, how such actuations can be used to make a user aware or unaware of the own motion while at the same time overriding the own Proprioception, similarly to *redirected walking* research [Ste+08; Ste+10; APS19].

8.12 CONCLUSION

In this chapter, interaction concepts that activate the Proprioception by using kinesthetic feedback were investigated. Considering human physiology, technologies, such as Pneumatical Artifical Muscle (PAM) for concentric and the pressure-based actuators as described in Chapter 5 for eccentric actuation, were leveraged to create kinesthetic actuators that can actively elicit body movements. Further, to get a comprehensive picture of the parameters required for the actuators, taking the arm as an example, an initial user study was conducted to assess how different actuation patterns and durations affect the deflection around the arm joint. Based on the findings, these insights were adapted in three VR example applications that employed both types of actuators. In a second user study, the effects of the kinesthetic feedback on immersion, realism, and enjoyment in the three VR applications were assessed and compared with vibrotactile feedback and a no-haptics baseline.

As part of the results, it was shown that vibrotactile actuation was typically insufficient for realistic sensation, while the kinesthetic actuators could improve immersion, realism, and overall experience. Further, with consideration of the somatosensory interaction, the findings of this chapter also illustrated the importance of combined stimuli, as a pairing of kinesthetic and vibrotactile feedback resulted in even more promising effects, even though vibrotactile actuation alone would primarily affect only the Fine Mechanoreception.

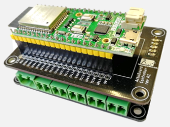
Part V

PROTOTYPING

9

ACTUBOARD: AN OPEN PROTOTYPING PLATFORM FOR ACTUATORS

Chapter Overview: Platform Contribution



Related Publications:
ActuBoard: An Open Rapid Prototyping Platform to integrate Hardware Actuators in Remote Applications
EICS Tech Note 2021

Rapid Prototyping | Open Source | Off-the ShelfActuators | Hardware Platform

In the previous chapters, a variety of prototypes were designed and developed to evaluate novel interaction concepts. Each prototype was unique since each one had to serve the evaluation of a specific type of somatosensory stimuli, in particular for vibrotactile, thermal, kinesthetic, or pressure-based actuations. Although these prototypes addressed different stimuli, their purpose always remained the same: a haptic actuation on the body. Thereby, the initial steps to achieve this common goal, despite different setups, were mostly similar or even identical from an electronic perspective, and providing stimuli for the somatosensory system requires the control of suitable actuators. Yet, also outside of the scope of this thesis, the design, and communication with hardware devices plays a crucial role in the whole field of prototyping in HCI, for example for mobile devices, wearables, and smart home appliances that have to drive actuators. In this chapter, a novel prototyping platform is presented that was designed and developed to support the implementation of haptic devices to easily control actuators, called ActuBoard.

While through the emergence of accessible tinker platforms, such as Arduino [1] or Teensy[2], and tool-assisted circuitry designers [Lo+19; AGF17; Wu+19], prototyping has already become a lot easier and faster, but it typically still requires basic knowledge of electrical engineering [Boo+16; Mel+16]. Also, repetitive steps at the beginning of each process have to be performed over and over again before researchers can focus on the investigation of interaction concepts and techniques.

1 https://www.arduino.cc/ (accessed March 01, 2022)
2 https://www.pjrc.com/teensy/ (accessed March 01, 2022)

Thus, ActuBoard was designed as a rapid prototyping platform to minimize those initial and repetitive steps for controlling actuators. Drawing from the experiences gained during the development of TactileGlove and PneumAct, the requirements for a unified toolkit were derived and resulted in the ActuBoard platform that provides (1) quick assembly, (2) less preparation work, and (3) better catering to the needs of non-tech-savvy users compared to traditional approaches. Therefore, this platform is not intended to replace existing prototyping platforms, such as Arduino or Gadgeteer, or deny their usefulness. Its purpose is to provide a specific alternative allowing for rapid prototyping of actuator-based devices with special attention paid to the needs of somatosensory stimuli, including additional software interfaces for applications in AR/VR or other environments. Throughout this dissertation, the versatility of ActuBoard could be shown as it was used as the basis for the development of the Therminator, PneumoVolley, and Smooth as Steelwool prototypes, and actively supported each step in their design processes. Further, ActuBoard was published as an open source to support other researchers who already built upon in creating novel systems for haptic actuation. Summarizing, ActuBoard has the following core features:

Flexible and Versatile: A high versatility of off-the-shelf components with no constraints to pre-defined or proxy modules.

Plug-And-Play Connection: The support of actuators with up to 24 V. No necessity to write a single line of firmware on the microcontroller. All hardware-related addressing is handled by the underlying framework.

Application Support and Communication Interface: Ready-to-use C# and serial communication interfaces for fast integration into own applications.

Inclusion of non-tech-savvy users: Less preparation work and electrical engineering knowledge are necessary as breadboarding and soldering of circuitry is not required.

Open Source: All hardware details and software implementations were published as Open Source[3].

3 https://git.tk.informatik.tu-darmstadt.de/sebastian.guenther/actuboard-public (accessed March 01, 2022)

9.1 CONTRIBUTION STATEMENT AND PUBLICATION

This chapter is based on the following publication:

Sebastian Günther, Florian Müller, Felix Hübner, Max Mühlhäuser, and Andrii Matviienko. "ActuBoard: An Open Rapid Prototyping Platform to integrate Hardware Actuators in Remote Applications." In: *Companion Proceedings of the 13th ACM SIGCHI Symposium on Engineering Interactive Computing Systems*. EICS '21 Companion. New York, NY, USA: Association for Computing Machinery, 2021. DOI: 10.1145/3459926.3464757

Contribution Statement: I led the idea creation, conceptual design, requirements definition, implementation supervision, and writing. The former student *Felix Hübner* shared his experiences of electrical engineering and carried out the Printed Circuit Board (PCB) design process under my supervision. *Florian Müller* and *Andrii Matviienko* assisted with the writing process. *Max Mühlhäuser* supervised the design and writing process.

❗ *Some contents of this chapter might contain verbatim parts of the aforementioned publication.*

9.2 CHAPTER STRUCTURE

The remainder of this chapter is structured as follows: Based on a review of existing platforms and relevant research, requirements for an actuation platform are defined in Section 9.3. The design and implementation of the platform is then presented in Section 9.5, followed by an example workflow comparing ActuBoard with traditional prototyping methods. In Section 9.6, existing projects relying on the platform are presented. Afterward, Sections 9.7 and 9.8 discuss the limitations and potential future work, as well concluding the chapter.

9.3 REQUIREMENTS AND RELATED WORK

Working with prototypes and hardware tinkering is essential for many projects. While there is a huge community that released a large body of open source platforms, toolkits, and systems to make the development of prototypes easier, all of them have individual requirements or focus on certain aspects that were more or less suitable for the prototypes presented in this work. Therefore, as a first step, experiences of past projects and related work were gathered (e.g., [Boo+16; Mel+16; VSH10; Mar+14; BH10; BH22; Min+12; Vil+15; SK10]) which resulted in the following seven requirements that were essential for future prototypes in the field.

REQA1. EMPHASIZE OFF-THE-SHELF COMPONENTS

Haptic prototypes often need to support off-the-shelf components as custom actuators would tend to be time-consuming and cost-inefficient to produce. Further, tinkers should not be restricted by pre-defined components that only work with certain platforms, meaning the range of supported actuators should be broad as possible, also including differing electronic specifications, such as a power supply beyond the typical 3.3 or 5 V.

REQA2. PROVIDE PLUG-AND-PLAY

To effectively reduce repetitive hardware steps, simplicity of the configuration is desirable and minimal knowledge about hardware or electrical engineering should be required. Therefore, a plug-and-play approach has to allow for a direct connection of actuators in a way that developers do not have to take care of circuitry protection and handling during unexpected failures.

REQA3. REQUIRE NO FIRMWARE CODING

Likewise to the plug-and-play requirement, a developer should not spend additional time writing repetitive boilerplate code or need to be concerned about low-level firmware programming. Therefore, an actuator platform should already provide firmware that can handle any off-the-shelf actuator component.

REQA4. PROVIDE AN COMMUNICATION INTERFACE

Besides repetitive firmware code, prototypes typically need to have additional communication interfaces if they are driven by external applications, such as VR environments running on faster hardware. Therefore, providing an easy communication interface that can be included in existing or new applications with minimal effort, reduces the overall demand for boilerplate code. At best, such an interface is abstracted, platform-independent, and flexible to changing requirements.

REQA5. BE SMALL, MOBILE, WIRELESS

A beneficial requirement for a prototyping platform is to be as compact, lightweight, and mobile as possible. Hence, prototypes should stay sufficiently small while making them amenable to mobile and wearable applications due to their form factor. As more and more AR and VR applications are focusing on mobile and wearable aspects, a wireless connection should be available to reduce the amount of wiring and increase flexibility.

REQA6. BE AFFORDABLE

Prototypes typically are going through many iterations and often can not provide the same robustness as commercially available products. Further, high costs would result in a high burden to reproduce a platform due to a low cost-efficiency. Therefore, one requirement for a platform within the scope of this work is to be low-cost and affordable.

REQA7. PROVIDE DEBUGGING INTERFACES

Although using the platform is supposed to be less error-prone, there will be always steps that require the debugging of components. Either because an actuator could be broken or the whole system is malfunctioning. Therefore, proper debugging interfaces should be available to allow developers to quickly identify issues or to even faster try out certain aspects by just controlling an actuator through a debug tool.

REQA8. EMBRACE SOMATOSENSORY INTERACTION

An additional requirement, particularly in relation to this thesis, is the consideration of somatosensory interaction. Therefore, all stimuli that are related to the somatosensory system, including Fine Mechanoreception, Pressure-based Mechanoreception, Thermoception, and Proprioception, should be supported by the platform or at least offer suitable control for this group of actuators.

9.3.1 *Prototyping Platforms*

Over the last two decades, a multitude of tinker and prototyping platforms have been established, which were especially accelerated due to the advent of the Arduino ecosystem in 2005 [Kus11] and groundbreaking research work [Lee+04]. Thereby, two main types of platforms have emerged: (1) low-level, and (2) component-based platforms.

Low-level platforms typically provide high flexibility that allows developers to fully control an almost infinite amount of actuators and sensors. Apart from the popular Arduino platform and its forks and derivates, other accessible microcontroller systems were established and offer accessible hardware interfaces, such as the ESP family[4], Teensy, or Photon[5], all up to more specialized educational-focused platforms, such as Micro:bit[6] [Sen+17; Aus+20] or TinkerForge[7]. However, with high flexibility and freedom, complexity increases and may constrain inexperienced users. Similarly, the components often require at least breadboarding of electric parts or even soldering.

As one solution, component-based or module-based systems tried to fill those gaps by finding a trade-off between flexibility and simplicity through pre-defined plug-and-play components. Popular ecosystems hereby are the Seeed Grove[8] and Microsoft Gadgeteer platforms [VSH10]. Their advantage lies in their easy-accessible modules that can be linked to the main controller and, for example in the case of Gadgeteer, easily integrated into high-level applications. However, such modules also typically are higher priced than regular counterparts, and often not all desired functionalities, i.e., when requiring more uncommon types of actuators, may be available. While those platforms can also address standard off-the-shelf actuators through breakout modules, it again requires the same effort as low-level platforms.

Another requirement that is often not met, is that existing platforms typically focus on prototypes that are solely based on the microcontroller itself. This means that external applications that could control a prototype would still require some kind of communication interface

4 `https://www.espressif.com/en/products/devkits` (accessed March 01, 2022)
5 `https://docs.particle.io/photon/` (accessed March 01, 2022)
6 `https://microbit.org/` (accessed March 01, 2022)
7 `https://www.tinkerforge.com/` (accessed March 01, 2022)
8 `https://www.seeedstudio.com/category/Grove-c-1003.html` (accessed March 01, 2022)

to be written. Single-board computers, in contrast, provide direct interfaces for input and output, such as Raspberry Pi[9], Banana Pi[10], or BeagleBoard[11]. Though very powerful, they are to date still not able to run demanding graphic intensive VR applications.

The presented systems are of course just a subset of a large number of existing prototyping platforms. However, as summarized in Table 9.1, all existing platforms introduce specific advantages but none of them provided all the features that were completely satisfying for designing the prototypes required within the scope of this thesis. More flexible platforms, such as Arduino, inevitably introduce more complexity for users. Less complex platforms, such as Gadgeteer, sacrifice flexibility for simpler usage. And yet, both require the coding of firmware or communication interfaces. In particular, these compromises often impose a constraint on the rapid development of systems that involve the exploration of interaction concepts rather than hardware tinkering, or that have a limited scope that cannot be equipped with off-the-shelf components without a great deal of effort (e.g., using breakout boards). Table 9.1 highlights the features of common prototyping platforms compared to the presented requirements that were defined for ActuBoard.

9.3.2 *Prototyping in Research*

In addition to commercial and open-source prototyping platforms, research, tinker, and the industry introduced several toolkits and systems that allow for specialized prototyping. Some of them are allowing the planning and creation of virtual prototypes [Gar03; ALV14], providing tool-based circuit designers [Lo+19; AGF17; Wan+16], or even AR and VR supported tools [Kel+18; Kim+20b]. However, for a haptic actuation or tangibles, physical hardware prototypes are necessary. Therefore, some related work used custom tangibles for the exploration of interaction concepts (e.g., [Led+12; Gal+16; Lec+16]) or use proxy modules to create low-fidelity prototypes [Wu+19]. While fast in their domain, those are limited to the features provided by each device. Similar to the Grove and Gadgeteer platforms [VSH10], research proposed hardware toolkits with pre-defined sets of actuators (e.g., [Lee+04; SK10; Vil+15; Min+12; BH10]). However, this also leads to the same drawbacks of

9 https://www.raspberrypi.org/ (accessed March 01, 2022)
10 http://www.banana-pi.org/ (accessed March 01, 2022)
11 https://beagleboard.org/ (accessed March 01, 2022)

Requirement	**ActuBoard**	**Arduino**	**ESP32**	**Grove**	**Gadgeteer**	**Raspberry PI**
ReqA1: Off-the-Shelf components	✓	✓	✓	1	1	✓
ReqA2: Plug-And-Play	✓	-	-	✓	✓	-
ReqA3: No Firmware Coding	✓	-	-	-	✓	-
ReqA4: Communication Interface	✓	-	-	-	✓	✓
ReqA5: Small, Mobile, Wireless	✓	✓	✓	✓	✓	✓
ReqA6: Low Cost and Affordable	2	✓	✓	3	-	✓
ReqA7: Debugging	✓	✓	✓	✓	✓	✓
ReqA8: Somatosensory Interaction	✓	✓	✓	✓	✓	✓

Table 9.1: Requirements comparison of ActuBoard to commonly used tinkering and hardware platforms.

1 Possible with breakout modules but then in conflict with Req2. **2** Currently no mass production, thus, higher initial costs. **3** Available pre-configured components are more expensive than the same regular off-the-shelf electronics.

having a limited amount of pre-defined modules and no support for plug-and-play off-the-shelf actuators. Others use custom platforms for (capacitive) sensing of user input but can not control actuators, i.e. they are restricted to sensing input [Gro+13; Sch+21].

Further, from a software perspective (e.g., [Lin+19]), there are some published tools to support the actuation of vibrotactile feedback [Mar+14; PAB13; Nor16], or other haptic feedback [Del+18; SPV14; PRR10]. Thus, the focus of this work is on creating interaction behaviors and mapping actuator responses during specific events, but not on creating prototypes themselves.

To summarize, existing tinkering platforms and related work presented interesting and powerful tools that made prototyping easier than ever before. However, they are mostly aiming for high versatility with a focus on creating hardware devices, thus, lacking special attention to the easy usage of actuators for somatosensory interactions. As a consequence, the respective chapters of this thesis could provide a larger picture of what aspects are essential when working with hardware actuators and none of the aforementioned platforms could completely fulfill the introduced requirements. Further, while they all share low entry barriers by abstracting the direct work with just a microcontroller, most of them still require longer learning phases and basic knowledge of electrical engineering that can draw important time from the actual investigation of interaction concepts.

9.4 ACTUBOARD CONCEPTS

Based on the aforementioned requirements, concepts were elaborated for designing an effective and user-friendly platform that is also accessible to non-tech-savvy users. As a foundation for this, a powerful controller must be available, which takes care of the addressing of individual actuators. This controller needs to have sophisticated firmware so that a tinker does not need to write any additional hardware code (ReqA3). Furthermore, in order to be user-friendly, the hardware platform should be capable of communicating directly with a remote application (ReqA4), either wired or wirelessly, e.g. via the most common interfaces, USB and Bluetooth (ReqA5). Again, to be as convenient as possible for the user, a communication interface or API should be provided which is easy to integrate and understand, e.g. through a serial interface or libraries for high-level programming languages, such as C# that is common for AR/VR applications. Further, additional debugging can be provided by using flexible serial interfaces or separate utilities (ReqA7).

Similarly, to reduce the effort in electronics, off-the-shelf components should be supported (ReqA1; more details on types of actuators in the next Section 9.4.1), by already providing all electronic circuitry, such as resistors or safety diodes, to drive the actuators, allowing all actuators to be easily connected via plug-and-play (ReqA2). To be as versatile as possible, a further separation of the controller and the plug-and-play ports is advisable. Here, single or multiple hubs may be connected to a single controller and host a certain number of actuators as desired (ReqA2). On top of that, this will also allow a smaller size of the entire system for just a few actuators (ReqA5), but modular extensibility for larger quantities.

All these concepts of course also assist in providing a quick and uncomplicated integration for modern AR/VR applications and thus also offer

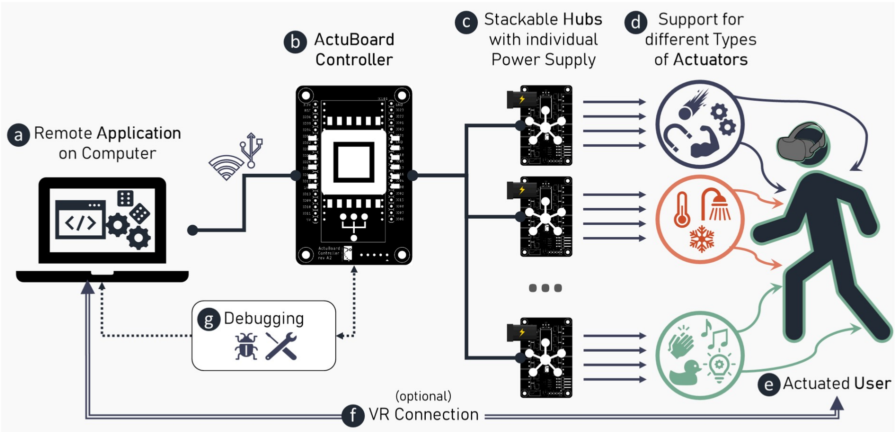


Figure 9.1: Concept and architecture of the ActuBoard platform: (a) An application is running on a regular computer using the provided software interface and connected to the (b) ActuBoard controller, responsible for handling the addressing of actuators. Therefore, (c) coupled and stackable Hubs with individual power supplies provide plug-and-play support for a large number of (d) different types of hardware actuators. These can work stand-alone or directly (e) actuate a user, for example, while (f) in a VR environment. Further, (g) a possibility for debugging is provided.

haptic interaction for such environments. For an architectural image illustrating the concepts, see Figure 9.1.

9.4.1 *Supported Types of Actuators*

Considering off-the-shelf components, the following two complementary types of actuators are supported by ActuBoard: (1) discretely controlled, and (2) continuously controlled actuators.

DISCRETELY CONTROLLED ACTUATORS

This type of actuator is the most basic as they mostly have only one or a few distinct states. This ranges from an active or disabled state of an actuator, such as a basic on/off property of a lamp, to setting discrete states, such as different levels of an electric lift.

CONTINUOUSLY CONTROLLED ACTUATORS

A large number of actuators are not limited to binary states (e.g., on and off) but have a continuous range of different states. Those can be vibrotactile actuators which are controlled by their frequency, the speed of DC motors, or the intensity of electrothermal Peltier elements.

Additionally, in the context of this thesis, the support for actuators that are suitable for use in the field of somatosensory interaction has to be emphasized (ReqA8). Since off-the-shelf components are already considered, a large part of this type of actuator is already included. For example, controlling valves for air supply for pressure-based feedback is possible (cf. Chapter 5 and 8), controlling of pumps (cf. Chapter 7) or modulating the intensity of vibration motors (cf. Chapter 4 and 6). Likewise, other components that were not employed in this work but apply to somatosensory interaction can be actuated, such as thermoelectric Peltier elements, EMS units, or ultrasound modules.

9.4.2 *Pipeline and Workflow*

As a result of considering the aforementioned requirements and based on the concepts, the workflow necessary to use hardware actuators reduces compared to traditional approaches. As visualized in Figure 9.2, with both approaches it is first necessary to identify the specifications of the actuators. However, while the traditional approach would require a deeper understanding of all technical requirements, only the voltage would be necessary for ActuBoard. More critical and time-consuming, however, are the following steps of traditional approaches where the electronic setup has to be performed, including the selection of correct electronic components, such as fitting resistors, the wiring (and soldering) of the circuitry, coding microcontroller firmware to handle the actuators, and coding of a communication interface on the microcontroller and a remote application. With ActuBoard, these repetitive hardware steps and coding of boilerplate code are minimized as only the actuators have to be connected using a plug-and-play approach and the communication interface has to be imported to the application. In conclusion, the ActuBoard concepts reduce initial setup steps and, further, decrease the required knowledge of electrical engineering.

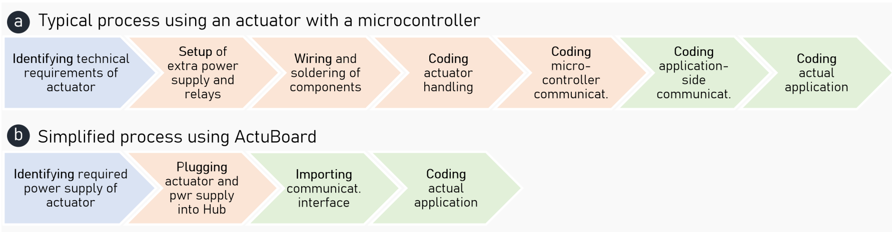


Figure 9.2: Comparison of the typical pipeline on how to connect and control actuators with a traditional approach and with ActuBoard. (a) The traditional process requires more manual wiring, soldering, and setup, as well as writing a communication interface to control actuators. (b) ActuBoard reduces those efforts by a plug-and-play approach directly addressing the usage of actuators. The colors of each step represent the preparation (blue), hardware (orange), and application (green) phases.

9.4.2.1 *Example Workflow*

Before discussing the implementation details, this simplified example should illustrate how prototyping with ActuBoard differs from traditional approaches. Therefore, this conceptual example was intentionally selected to show a use-case outside of somatosensory interaction to be easy to follow, while more specific sample applications that were built on top of the ActuBoard will be presented later in this chapter (Section 9.6).

In this example situation, Alice wants to automatically water her plants. Therefore, she already designed a web application that receives and processes weather information. However, she still needs an actuator that releases water to the plant pot when the application identifies a very hot day. For this, she found a magnetic solenoid valve as most suitable and attaches it to a water source.

With a traditional approach, she now has to check all specifications of the valve, needs a proper microcontroller, an additional power supply for the valve, and a transistor and resistor to switch the valve. Also, a safety diode is recommended to ensure that individual components are protected from currents. Though, this requires a lot of wiring, soldering, and most importantly: time. And still, the communication interface between the microcontroller and her application is missing.

In contrast, when using ActuBoard, Alice only needs to find the appropriate solenoid valve and plug the valve together with a fitting power

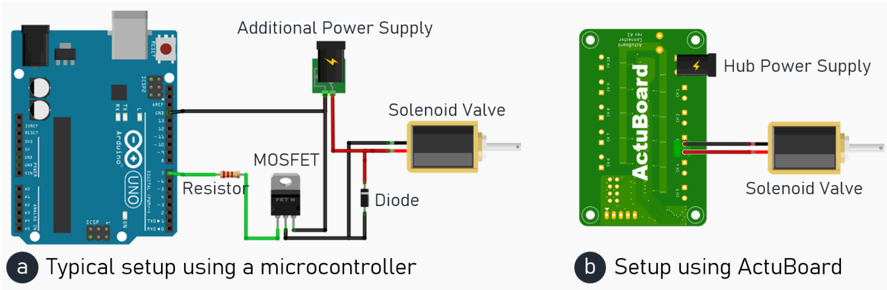


Figure 9.3: Example workflow to connect and actuate a solenoid valve when using (a) a traditional method with an Arduino and required electronic components, and (b) ActuBoard where the solenoid valve can be directly plugged-in. *This Figure uses breadboard view graphics from fritzing.org, licensed under CC Attribution-ShareALike (CC BY-SA 3.0).*

supply into an ActuBoard Hub. Further, for communication only importing the provided interface is necessary. There is no need to delve into technical details, yet she has full control over a large part of commercially available actuators she wants to use. Even if she plans to water more than one plant or use different valves, she just has to get them and plug each directly into the ActuBoard instead of repeating the time-consuming steps and writing boilerplate code. Both methods for this example are depicted in Figure 9.3.

9.5 ACTUBOARD PLATFORM: IMPLEMENTATION DETAILS

In the following, the implementation details of ActuBoard are presented, based on the previously introduced concepts. Thereby, the most important design decision was the separation of two main components: (1) the Controller, and (2) Hubs.

The Controller is managing the addressing of actuators, as well as the communication through a serial interface. The Hubs are stackable, interconnected extension boards that allow to host up to ten actuators each. Every Hub further provides a separate power plug to supply the connected actuators. The Controller delegates commands to each Hub via an I^2C interface with a maximum of 12 Hubs connected. Figure 9.4 a depicts a 3D rendering of the platform, while Figures 9.4 b and c shows the final device with the ActuBoard Controller and connected Hubs. As ActuBoard was planned as open-source from the beginning, the

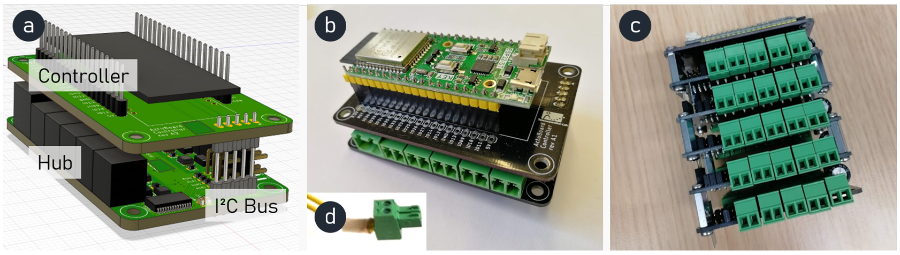


Figure 9.4: The ActuBoard platform shown as (a) 3D rendering, (b) final prototype with one Controller and one connected Hub, and (c) with a total of five attached Hubs. For a convenient method to connect actuators, (d) small connector plugs were used.

source code, hardware schematics, and every other necessary information to build and use the platform are available in a public GIT repository[12].

9.5.1 *ActuBoard Controller*

The Controller manages the addressing of the actuators and is responsible for the serial communication with an external application. For compatibility reasons, an ESP32 microcontroller with full Arduino library support[13] was embedded on the PCB, as it provides powerful processing capabilities and already supports USB, Bluetooth, and WiFi interfaces (Figure 9.4 b). Further, the ESP32 comes with an I^2C interface bus which is used for the communication with the Hubs (see Section 9.5.2). In addition, the I^2C bus is used for supply pins, shared clock data, and an additional output enable/disable channel to toggle all actuators simultaneously by demand. As the main actuation of ActuBoard happens through the Hubs via the I^2C interface, the default I/O pins of the underlying ESP32 controller remain unassigned and can be used for different purposes if needed, such as the controlling of more complex actuators, sensors, and other input electronics.

12 https://git.tk.informatik.tu-darmstadt.de/sebastian.guenther/actuboard-public (accessed March 01, 2022)
13 https://github.com/espressif/arduino-esp32 (accessed March 01, 2022)

9.5.2 *ActuBoard Hubs*

The HUBS are custom PCB that host up to ten actuators each. All of the actuators are connected via a plug-and-play approach as shown in Figure 9.4 d. The HUBS are communicating with a CONTROLLER using an I^2C bus with the lower 4 bits of the address pins as base ID. The base ID for each HUB has to be within the range of 0 to 11, settable through jumper pins. Further, the bus is used for addressing each actuator on a HUB ranging from port IDs between 0 and 9. In total, this results in up to 12 addressable HUBS and a maximum of 120 actuators for one ACTUBOARD device. An example with five connected HUBS on one CONTROLLER is depicted in Figure 9.4 c.

To drive the actuators, each HUB uses 16-channel LED drivers (*PCA9635PW*) with a fixed PWM frequency of 97 kHz and a 8-bit resolution. An additional group PWM is used for setting a blinking pattern for actuators at a frequency of 190 Hz. This allows for an on/off pattern with intervals between 24 Hz and 1/10.73 s. Further, each channel uses high-side MOSFETs (*CSD17579Q3A*) with a current of up to 11 A and a RS_{ON} of less than $30m\Omega$. Additional safety diodes are used to protect the components from potential inductive loads. This also makes it possible to have one power input for each HUB to cope with different power requirements of up to 24 V.

9.5.3 *Communication Interface*

As one of the main requirements, ACTUBOARD has to communicate with external applications that may run power-demanding applications, such as VR. Therefore, a communication interface had to be implemented which is simple to integrate and directly controls actuators (cf. Figure 9.2). Therefore, ACTUBOARD provides an easy-to-use serial communication that comes with all necessary commands and instructions, such as setting a single or multiple actuators to certain PWM values or enabling and disabling all ports. Also, commands to enable a *blinking* of actuators (automatically toggle actuators on and off periodically), list all IDs of connected HUBS, and toggling additional debug messages are implemented.

Command Description	Command	Length	Channel	PWM	Interval	Boolean	Example
Set single Channel PWM	S		0-119	0-255			S01FF\r
Read single Channel PWM	R		0-119				R01\r
Set n Channels to 1 PWM	m	0-119	len × ch	0-255			m03010203FF\r
Set n Channels to n PWM	n	0-119	len × ch	array			n020102C0D0\r
Set blinking Interval	I				0-255 × 41.6 ms		I10\r
Set blinking Duty Cycle	i				int/256		i40\r
Set blinking to single Channel	G		0-119			0/1	G0101\r
Set blinking to n Channels	g	0-119	len × ch			len × 0/1	g0201020101\r
Enable / Disable Output	O					0/1	O01\r
List connected Hubs	L						L\r
Toggle Debug Mode	D						D\r

Table 9.2: Available serial commands for controlling actuators. Each begins with a unique identifier, followed by instruction and payload in 2-Byte Hex notation. The example column shows how each command should be formated to be correctly interpreted. The response to each command is '\r' = 0x0D on success or 'BEL' = 0x07 on error. Abbreviations: ch = channel, len = length, int = interval.

As the communication between application and actuators has to be fast to mitigate any delay, the serial communication BAUD rate is set to 115200 and instructions are as short as possible. Therefore, each command consists of 1 Byte for the command type (e.g., S for setting a single actuator), 2 Bytes for the actuator ID (including the address of the Hub and actuator port), and 2 Bytes for the PWM value. Some more complex commands, such as setting multiple channels with different PWM values at once, are similar but use 4 Bytes more for each addressed actuator and additional 2 Bytes for the number (length) of the actuators. A complete list of all commands and instructions including examples are shown in Table 9.2.

Besides the serial interface that works with any platform and can be controlled through a terminal (command-line interface), an additional C# library is available. This library allows for using the serial commands in the same way as through a terminal but also with easy-to-read wrapper methods. Further, it is completely .NET 3.5 compatible to be used in applications using the Unity engine as it is one of the most used engines for VR[14].

14 based on an official Unity statement https://twitter.com/unity3d/status/1256256504098947080

9.5.3.1 *Debugging*

For uncomplicated debugging, two interfaces are available. The first method to connect directly to an ActuBoard is a serial connection where users can monitor the state of individual ports and the current status of the Controller. The second method is a standalone software tool that is based on the provided C# library. It comes with a clean user interface that allows sending custom commands, as well as all pre-defined commands to the ActuBoard. Through an included terminal-like output panel, additional debug information from the microcontroller can be displayed.

9.6 illustrative sample of applications using actuboard

The ActuBoard platform was based on the demand for a rapid prototyping solution that can control a variety of actuators without much learning effort. In particular, a special focus was on the somatosensory interaction that evolves around Thermoception, Fine Mechanoreception, Pressure-based Mechanoreception, and Proprioception. Often, more technically inexperienced users, such as undergraduate students or designers, first had to get familiar with engineering before being able to work on interaction concepts. For example, during the development of PneumAct, the involved individuals had to learn which MOSFETs and resistors are necessary and how to communicate with an Arduino or ESP32 microcontroller. This took a long time until the prototype was ready to use and always delayed the important user studies. Based on this experience, the ActuBoard was created and already used in the following projects:

pressure-based mechanoreception: pneumovolley
: For PneumoVolley, the airflow coming from a strong air compressor had to be controlled to provide a pressure-based actuation on the head. Therefore, a total of six magnetic solenoid valves could be automatically inflated to provide realistic feedback of head contact with a volleyball in a VR game. More detailed implementation details can be found in Section 5.4.

stroke sensations: smooth as steel wool
: In Smooth as Steelwool, small solenoid valves had to be actuated

in order to control the pressure intensity of the silicone cushions hosting the textures with different roughness. Further, it was used to control the vibrotactile array that was used for one of the baseline comparisons. More detailed implementation information can be found in Section 6.5.2.

THERMOCEPTION: THERMINATOR

In this project, ActuBoard was used to support the thermal actuation that used liquids with different temperatures in a system of tubes on the body of the participants. Therefore, solenoid valves were controlled to regulate the liquid's flow and to control the connected water pump to provide warm and cold stimuli. More detailed implementation information can be found in Section 7.5.

FINE MECHANORECEPTION: VIBROMAP

This was the first project that was using ActuBoard outside the scope of this thesis, named VibroMap by Elsayed et al. [Els+20b]. While there exist multiple research papers that investigated phantom sensations and their effectiveness with regard to the minimum and maximum distance between two vibrotactile actuators, there was no systematic comparison for phantom sensations on different body parts and orientations. Elsayed et al. [Els+20b], therefore, conducted two user studies to investigate the Fine Mechanoreception with vibrotactile stimuli on the wrist, lower arm, upper arm, back, torso, thigh, and leg in a transverse and longitudinal orientation. Hereby, ActuBoard was used to control ten vibration motors that created the illusion of continuous motion on each body part.

PRESSURE-BASED MECHANORECEPTION: HAPTIC GLOVE

Again outside the work of this thesis, ActuBoard was also used during a lecture at the *Telecooperation Lab, Darmstadt*, highlighting its accessibility for novice users. In these projects, students designed a glove that provided haptic pressure-based feedback through small silicone bladders on the fingertip. ActuBoard helped to create a quick prototype and to perform a user study comparing its effects with vibrotactile feedback. This work was not published.

PROPRIOCEPTION AND KINESTHESIA: PNEUMACT

While ActuBoard was not used in this project, it was the predecessor for it. This means the PneumAct prototype could be easily replaced with the ActuBoard platform, for example, to control the Pneumatical Artifical Muscle (PAM).

Further Application Scenarios

While the above examples show actual implementations, the potential use-cases are not limited to them. The modular design provides the opportunity to use different types of off-the-shelf actuators with varying electronics and to address them in a variety of scenarios. While the previous projects mostly used ActuBoard for haptic feedback in VR, similar situations in AR are possible. Further, EMS-based force feedback or tangible interaction are promising domains. Thanks to a small form factor, the platform could also directly be embedded in Internet of Things (IoT) devices. Moreover, as the platform is easy to learn and can help to rapidly implement prototypes, it shows potential for educational purposes to learn tinkering or the use of actuators, before having to understand much technical detail in a top-down approach, similar to existing educational platforms from different areas [Wal+20; BH10; Lec+16].

9.7 LIMITATIONS AND FUTURE WORK

ActuBoard is a novel prototyping platform with a special focus on hardware actuators and somatosensory interaction. However, some limitations are addressable for future improvements.

9.7.1 *Support for Input Components and Sensors*

As actuators are typically output (from a device perspective), ActuBoard currently only provides plug-and-play support for these types of components, i.e., controlling actuators and similar electronic parts. However, the support for input components, such as buttons or sensors, remains limited. While it is possible to connect such components directly to the free I/O pins of the underlying ESP32 embedded on the Controller (see 9.5.1), it requires similar efforts as using a traditional tinkering approach.

9.7.2 *Support for Actuators with internal Logic*

Another current limitation is the type of actuators that can be handled. ActuBoard only runs actuators that do not have internal logic, e.g., stepper motors requiring separate motor drivers. Yet, similar to input components, those can still be linked with the Controller's ESP32 as all I/O pins remain unreserved.

9.7.3 *Direct Communication between multiple ActuBoards*

As an additional extension for ActuBoard, a wireless intercommunication between multiple devices could leverage its potential for distributed IoT capabilities, or to support multilayered haptic devices that can automatically actuate based on the state of others.

To summarize, as highlighted by the projects that were already based on the ActuBoard platform, it was shown how it already enables fast prototyping that covers most of the application areas needed, including the design of haptic devices interacting with the somatosensory system. Moreover, all information is published as open-source to allow others to improve the current design for more individual purposes.

9.8 CONCLUSION

The initial aim of the ActuBoard was to enable the design of sophisticated prototypes for user studies that operate a variety of actuators in order to present and evaluate haptic stimuli. However, the applicability of ActuBoard is more extensive as it can be also used as a foundation for a large number of other application areas, such as controlling haptic entertainment systems in 4D cinemas, improving home automation, educating students, or driving actuators for virtual training or gym environments (see also Section 10.2). As the previous chapters on somatosensory interaction have underlined, reliable prototypes were essential for the investigation of interaction concepts of any kind. However, despite similar experimental setups, the initial steps in designing prototypes like this were often repetitive and, thus, cost time and effort needed for the actual experiments.

Therefore, in this chapter, a rapid prototyping platform called ActuBoard was introduced that contributes to (1) quick assembly, (2) less preparation work, and (3) better catering to the needs of non-tech-savvy users for prototyping. Thanks to a simple plug-and-play approach, which can accommodate up to 120 actuators of various designs and electronic requirements through stackable Hubs, as well as provided software interfaces for communication, the development process for the prototypes built in this work and were based on ActuBoard could be drastically reduced. Further, to share the benefits of this actuation platform with the community, all materials have been released as open-source and are freely available for replication.

9.8.1 *Public Repository*

All materials, sources, examples, renderings, libraries, and interfaces of ActuBoard can be found online in a public repository at `https://git.tk.informatik.tu-darmstadt.de/sebastian.guenther/actuboard-public`.

Part VI

OUTLOOK AND CONCLUSION

10 CONCLUSIONS

This thesis proposes novel interaction approaches for a haptic actuation of the somatosensory system in HCI. Therefore, this work contributes interaction concepts and techniques, based on the individual challenges and requirements of Fine Mechanoreception, Pressure-based Mechanoreception, Thermoception, Proprioception, and Kinesthesia for applications in HCI and their contributions to the user experience as described with attributes like immersion, presence, realism, pleasantness, or their mutual interaction with other stimuli. Further, a rapid-prototyping platform called ActuBoard was designed to address the special challenges when working with actuators for haptic feedback.

Therefore, a total of eight systematic user studies and controlled experiments have been conducted with individual prototypes that were designed to create a variety of haptic stimuli, such as vibrations, pressure-based feedback, hot and cold temperatures, and kinesthetic motion, in order to actuate the participants. In these studies, the perception of these haptic stimuli, their use for guidance purposes and remote assistance tasks, their effects on immersion, presence, and realism in VR, their pleasantness, and even their potential to alter the sensory perception, depending on the parameters of the actuation or their interaction with other stimuli, were investigated. For example, how thermal stimuli can influence the expected temperature perception of visualizations, or how combining kinesthetic actuation with subtle vibrotactile feedback can further enhance the user experience.

This final chapter summarizes the main contributions in Section 10.1, followed by sharing visions for potential concepts of future systems leveraging the findings of the presented interaction concepts in Section 10.2 and concluding remarks in Section 10.3.

10.1 SUMMARY OF CONTRIBUTIONS

The contributions of this thesis addressed the interaction with the somatosensory system from an HCI perspective as follows:

10.1.1 *Mechanoreception*

This was investigated in three chapters, each contributing to a specific aspect: (1) Fine Mechanoreception, (2) Pressure-based Mechanoreception, and (3) the combination of both for stroking stimuli.

10.1.1.1 *Fine Mechanoreception*

(1) First, the Fine Mechanoreception was examined and interaction concepts were presented for using vibrotactile stimuli for guidance and remote assistance tasks. Therefore, a glove with multiple vibrotactile actuators named TactileGlove was designed. In a first user study, the ability of users to interpret and recognize different vibrotactile cues on the hand, based on the guidance metaphor and resolution of actuators, was systematically investigated. In a second exploratory user study, the guidance concepts were further explored for remote assistance tasks, showing the potential for future applications.

10.1.1.2 *Pressure-based Mechanoreception*

(2) The second chapter then contributed by investigating interaction concepts for Pressure-based Mechanoreception. Hereby, the focus was on stronger actuations based on pneumatic inflation of air cushions that are able to create force feedback beyond a vibrotactile actuation. Therefore, a prototype was designed that used compressed air for inflating flexible air cushions located on the body and could rapidly inflate to simulate impacts, called PneumoVolley. In a conducted user study, this novel form of pressure-based feedback was then applied to the head and demonstrated the potential for creating a more enjoyable and realistic experience in a VR environment.

10.1.1.3 *Stroke Stimuli*

(3) In a third chapter, this thesis contributed a combination of the two previous chapters for stroke stimuli. Hereby, concepts for creating a moving touch stimulation with different rough textures were presented. In particular, this chapter investigated how the perception of roughness in VR is affected by the interaction of haptic stimuli and the roughness expectations of different visualizations. Therefore, a first study was conducted to identify a broad range of suitable items, followed by a second user study that assessed how participants perceive haptic stroking stimuli in a VR environment, and how the perception is affected when the shown visualizations do not necessarily match. As an important result, it was shown that a large selection of haptic stimuli is not always needed if the roughness comes close to the visual expectation of users.

10.1.2 *Thermoception*

The second part contributed novel interaction concepts and techniques addressing the Thermoception. The proposed ideas were based on a thermal actuation using liquids in a cycle that could provide warmth and coldness to the body, called Therminator. As a proof-of-concept, a prototypical system was designed and a user study was conducted to investigate the perception of temperature in a VR environment. Besides the involvement within VR of users, the study particularly assessed how the Thermoception is affected by combining thermal and visual stimuli while the presented stimuli might not match. As part of the results, this chapter could show how the experience of the thermal stimuli has the capability to override visual expectations.

10.1.3 *Proprioception and Kinesthesia*

The third part contributed to the understanding of Proprioception and Kinesthesia by introducing concepts for actuation of body parts around their joints, called PneumAct. Using two types of actuators, a body movement could suddenly be initiated. The first type of actuator is similar to the previously described pressure-based actuators and caused an extension at a joint by inflating an air cushion. The second type of actuator is based on the idea of a Pneumatical Artifical Muscle (PAM), in which the inflating of a latex tube enclosed in mesh fabric reduced its length and caused a contraction comparable to a real muscle. In two user studies, the concepts were evaluated to determine their effects on the angle of the motion and their potential to enhance immersion, realism, and enjoyment in VR environments. While the results could show that a kinesthetic actuation already increases all of those effectively, the combination of a kinesthetic actuation was found to be even more effective when combined with a vibrotactile stimulation.

10.1.4 *ActuBoard*

Another contribution of this work is the design of a rapid prototyping platform, called ActuBoard. This platform was created as a result of the required prototypes of this thesis and is, therefore, based on their requirements and those from haptic devices of related work. It was designed for experienced and non-tech-savvy makers to support the creation process of haptic devices and to easily operate hardware actuators without repetitive and cumbersome setup and the need for extensive knowledge in electrical engineering. Further, to underline its capabilities, ActuBoard was used as a basis for several projects within and outside of the scope of this thesis and released as an open-source to support the tinkering and HCI community.

10.2 INTEGRATION AND FUTURE WORK

This thesis investigated a wide spectrum of haptic stimuli linked to the somatosensory system and how they affect human perception. These included the different aspects of Fine Mechanoreception, Pressure-based Mechanoreception, Thermoception, Proprioception, and Kinesthesia. In summary, each of the chapters presented prototypical setups to achieve these novel experiences and proposed varieties of example applications. While some of these were conceptual, others, such as the PneumAct or PneumoVolley concepts, were also evaluated in user studies with respect to their presence and user experience in immersive VR environments.

While further research is necessary to fully understand every aspect of haptic research in HCI and how haptic stimuli can be created for realistic experiences, this section illustrates and discusses how the findings of this thesis contribute to the overall picture of haptic feedback and how future systems and applications can benefit from the concepts and results. Therefore, potential application areas will be outlined in the following, which integrate the aforementioned contributions in (1) entertainment, (2) training, (3) exercising and rehabilitation, and (4) telecooperation environments. On top, the design and realization of all of these potential application areas can be supported by the presented ActuBoard platform.

10.2.1 *Entertainment and Gaming*

The entertainment and gaming industry continues to be a driving force for innovative technologies. Here, leisure activities like these are appealing to all age generations, ethnicities, and social backgrounds, given that their primary objective is to entertain, as well as to convey knowledge through edutainment. While conventional games usually relied purely on visual and auditory output, recent years [Oro+12] and also this thesis have shown how haptic elements can make the experience of various domains more immersive and more enjoyable.

For many years, people could mostly try out such immersive experiences by visiting 4D cinemas [1] that provides a collective experience among the visitors. Here, people are able to experience movies or even interactive stories with special effects, such as temperature, vibrating seats, or fog. Similarly, some public arcades have game machines that feature vibrating plates or other haptic capabilities, such as replicates of motorbikes or plane cockpits that mimic the motion of their real-world counterparts. Yet, most often this experience is limited to dedicated theaters and in the case of the 4D cinemas, lesser interactive features. However, besides these collective or public locations that entertain larger groups, there exist also more individual home entertainment systems. While traditional gaming consoles or mobile gaming platforms mostly provide only vibrotactile feedback within controllers, the advent of consumer-level VR helped to create more interactive worlds that

1 https://www.hollywoodreporter.com/news/general-news/will-4d-ever-catch-802627/ (accessed March 01, 2022)

are already increasing the immersion and presence just by their visual quality.

Today, most VR systems display virtual worlds with a high degree of realism, thanks to incredible improvements in display quality, graphics performance, and powerful software engines. Similarly, sound effects, spatial audio, and voice quality have been brought to near perfection by integrating multiple small high-quality speakers directly into the HMD around the user's ears. But again, haptic feedback is mostly limited to vibrotactile feedback coming from handheld controllers while other stimuli affecting the whole body - that are known from the aforementioned 4D cinemas - are still almost non-existent for the consumer market.

While haptic components are of course not entirely new, for example, there already even exist commercial vests, such as Tactsuit, KOR-FX, or the neosensory vest, that offer tactile feedback, the introduced concepts and results of this thesis provide the basis to improve future devices in terms of their efficiency and effects on enjoyment, immersion, and realism in particular. For example, the findings of Therminator (Chapter 7) or Smooth as Steelwool (Chapter 6) highlight how haptic perception affects the visual perception and vice versa. So it was shown as part of this thesis that a convincing actuation of roughness requires only a few or even just two gradations rather than a large number of different textures, or that temperature gradations need to be less complex to achieve a wide range of perceptible differences. In the Proprioception and Kinesthesia chapter (8), it could also be demonstrated how multimodal feedback in the form of kinesthetic actuation in combination with vibrotactile feedback significantly increases the enjoyment, by making the virtual environment feel much more realistic.

In this work, significant discoveries have been made about novel methods to affect the entire somatosensory system for further enhancements of immersion and realism beyond state-of-the-art vibrotactile actuations. Moreover, the experiments have revealed that a very precise and accurate actuation, which attempts to reproduce reality one-to-one, is often not necessary. Instead, a subset can be adequate as long as the perceptual differences are strong enough. In the end, it will be feasible to reduce the size of complex haptic devices in order to make them more wearable and mobile.

10.2.2 *Training and Professional Instruction*

In the context of professional instructions, there are complex combined sequences of actions and operations in which both, trainees and experienced personnel, are trained. The primary objective is to internalize safety risks in controlled and safe environments to proactively minimize them during real emergency operations. In addition, repeating common procedures to be better prepared in case of emergency can be optimized through specific training in lifelike, but safe training environments. This also includes simulations of unusual events and the risk-free practice of alternative strategies. For example, firefighters must always be well prepared for severe fires or a disaster that endangers not only the lives of individuals but also the lives of rescuers.

To prevent being surprised by unexpected events in these situations, constant professional training sessions are essential. This means that if the actual incident cannot be controlled, then it is vital to learn how to respond to it. Supervised training sessions and seminars in which real fires or hazards are practiced in difficult terrain are, of course, very effective, realistic, and generally safe. But such real-world training is very costly, requires a great effort in preparation, is usually tailored to specific situations, and is time-consuming to conduct. As an alternative, virtual training, for example in VR or AR environments, can be a more cost-efficient but still effective method of training. Therefore, the contributions of this thesis help to render these environments and simulations more lifelike, as VR-based training with realistic haptic feedback support initial training or the familiarization of concrete applications and intermediate steps.

More precisely, virtual training can be started or repeated at any given point, while strictly physical training often requires beginning from the beginning or does not allow for complete repetitions. Taking the firefighting example, the outcomes from the Thermoception chapter can help to provide localized heat according to the situation. Similarly, the insights from the Pressure-based Mechanoreception chapter as well as Proprioception and Kinesthesia chapter are useful to simulate leaking pressure from gas pipes or entire pressure waves impacting the body. Findings from the Mechanoreception section might be used to realistically depict contact with individuals in distress.

10.2.3 *Fitness and Rehabilitation*

While the two previous sections focused on the rendering of haptic stimuli to provide a realistic representation of environments, the findings of this thesis apply to other domains as well. One of these is rehabilitation and fitness applications, where the emphasis is on performing repeatable movements that require precise feedback. From physiotherapy, where specific exercises and movement sequences are used to improve health, to personal fitness training in a gym or at home, where exact exercises provide a more effective training success.

In particular, the findings from the Fine Mechanoreception chapter add to motion guidance research. By using expressive vibrotactile stimuli on the hand, this research demonstrated how to instruct movements in order to reach specific targets. Transferring the concepts to other body parts, in the same way, might result in a complete actuation of the body, which could subtly support posture correction. Furthermore, as demonstrated in the chapter on Proprioception and Kinesthesia, external force can be used to generate simulated weights of training equipment, such as barbells. In other words, an entire training environment can be virtually recreated and, thanks to haptic actuation, also physically challenge the athlete's body. According to the particular configuration, different training intensities are feasible and individually adjusted to personal needs.

In the field of Thermoception, it is also conceivable for conventional fitness training that a system like Therminator can actively improve the performance of a person by reducing the level of fatigue in the body through cooling down the body (e.g., like [Weg+12]). Combined with TactileGlove and PneumAct it is therefore in fact possible that an entire gym together with a virtual coach (guide) and a set of training equipment can be modeled in a space-saving, cost-effective, and highly personalized way in AR or VR under close-to-reality conditions. Moreover, additional training performance could be achieved, for example through an enforced handicap using strong kinesthetic counterforces while performing exercises.

10.2.4 *Telepresence and Telecooperation*

Remote communication, telepresence, and telecooperation have been a hot topic in HCI for decades. Thereby, research and industry are exploring new concepts to bridge physical distances digitally and virtually, ranging from basic audio transmissions over video conferencing to fully immersive VR environments where attendees communicate and interact as lifelike as possible. While the research for this is not new, especially the last two years have shown through the Corona pandemic that firstly, there is a great need for interactive tools and secondly, despite great advances in everyday life, we are largely not going beyond established video conferencing technology. Even though interesting applications for interaction have become available to the general public thanks to modern VR technologies, such as Mozilla Hubs[2], VRChat[3] or Meta's Horizon Workrooms[4], the acceptance remains rather low.

One reason for this is very likely the scarcity of VR devices among the masses, as well as the extra effort required to put on a HMD that also blocks out the physical world. Perhaps another reason is that existing commercially available VR telepresence applications generally lack the haptic aspects. This will certainly change in the future as haptic devices will become more available and usable, however, until then, research must continue to explore methods of using them effectively and conveniently for end-users.

The findings of this thesis also support the advancement of telepresence and telecooperative applications in terms of haptics. Future systems can benefit from this in several ways. For example, with the findings from SMOOTH AS STEELWOOL (Chapter 6, it was demonstrated how haptic strokes can generate appropriate stimuli that may be used for interpersonal interaction such as caressing. With the findings on PRESSURE-BASED MECHANORECEPTION (Chapter 5), physical touching or hugging is also conceivable, as well as the findings in the area of FINE MECHANORECEPTION (Chapter 4). Furthermore, this chapter additionally showed how vibrotactile cues for use in remote collaboration tasks can support collaborative teamwork over a distance (Section 4.9). Together with the insights gained from the THERMOCEPTION chapter (Chapter 7), also body

2 https://hubs.mozilla.com/ (accessed March 01, 2022)
3 https://hello.vrchat.com/ (accessed March 01, 2022)
4 https://about.fb.com/news/2021/08/introducing-horizon-workrooms-remote-collaboration-reimagined/ (accessed March 01, 2022)

and ambient temperatures might be actively communicated, which for instance would also arise during non-remote interaction. Moreover, the studies presented in the chapter on Proprioception and Kinesthesia (Chapter 8) can be useful for the use in telepresence, too, since external forces can be generated, such as active interventions from a remote side by guiding the other person's hand.

Summarizing, the presented haptic concepts are of course just a fraction of what might be feasible for telepresence in the future. Yet, this thesis contributes to how these concepts affect the haptic perception with respect to the somatosensory system and demonstrated how future applications might address them.

10.3 CONCLUDING REMARKS

In conclusion, this work demonstrated the importance of a deep understanding of haptic perception for HCI from different perspectives that go beyond the purely neurological, physiological, and psychological views on the somatosensory system, particularly the Fine Mechanoreception, Pressure-based Mechanoreception, Thermoception, as well as Proprioception and Kinesthesia. Although great progress has been made in the last years, there is still research necessary before a holistic actuation will arrive in everyday life to fulfill Sutherland's vision of an ultimate display [Sut65]. And yet, while this vision might still seem distant, this thesis could contribute to getting a step closer by providing novel concepts and findings on somatosensory interaction.

LIST OF PUBLICATIONS

The main contributions of this thesis have been peer-reviewed and published at international renown conferences. Some contents of this thesis might contain verbatim parts of the respective publications, highlighted at the beginning of each corresponding chapter. An additional overview of them, can be found in Section 1.5.

In the following, all relevant publications done by me as first-author are listed, followed by a list of other publications where I have contributed to as co-author.

PUBLICATIONS DIRECTLY RELATED TO THIS THESIS

[Gün+18a] Sebastian Günther, Sven Kratz, Daniel Avrahami, and Max Mühlhäuser. "Exploring Audio, Visual, and Tactile Cues for Synchronous Remote Assistance." In: *Proceedings of the 11th PErvasive Technologies Related to Assistive Environments Conference*. New York, NY, USA: ACM, June 2018, pp. 339–344. ISBN: 9781450363907. DOI: 10.1145/3197768.3201568.

[Gün+19] Sebastian Günther, Mohit Makhija, Florian Müller, Dominik Schön, Max Mühlhäuser, and Markus Funk. "PneumAct: Pneumatic Kinesthetic Actuation of Body Joints in Virtual Reality Environments." In: *Proceedings of the 2019 on Designing Interactive Systems Conference*. New York, NY, USA: ACM, June 2019, pp. 227–240. ISBN: 9781450358507. DOI: 10.1145/3322276.3322302.

[Gün+18b] Sebastian Günther, Florian Müller, Markus Funk, Jan Kirchner, Niloofar Dezfuli, and Max Mühlhäuser. "TactileGlove: Assistive Spatial Guidance in 3D Space through Vibrotactile Navigation." In: *Proceedings of the 11th PErvasive Technologies Related to Assistive Environments Conference*. New York, NY, USA: ACM, June 2018, pp. 273–280. ISBN: 9781450363907. DOI: 10.1145/3197768.3197785.

[Gün+21] Sebastian Günther, Florian Müller, Felix Hübner, Max Mühlhäuser, and Andrii Matviienko. "ActuBoard: An Open Rapid Prototyping Platform to integrate Hardware Actuators in Remote Applications." In: *Companion Proceedings of the 13th ACM SIGCHI Symposium on Engineering Interactive Computing Systems*. EICS '21 Companion. New York, NY, USA: Association for Computing Machinery, 2021. DOI: 10.1145/3459926.3464757.

[Gün+20a] Sebastian Günther, Florian Müller, Dominik Schön, Omar Elmoghazy, Max Mühlhäuser, and Martin Schmitz. "Therminator: Understanding the Interdependency of Visual and On-Body Thermal Feedback in Virtual Reality." In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (*CHI '20*). New York, NY, USA: ACM, Apr. 2020, pp. 1–14. ISBN: 9781450367080. DOI: 10.1145/3313831.3376195.

[Gün+22] Sebastian Günther, Julian Rasch, Dominik Schön, Florian Müller, Martin Schmitz, Jan Riemann, Andrii Matviienko, and Max Mühlhäuser. "Smooth as Steel Wool: Effects of Visual Stimuli on the Haptic Perception of Roughness in Virtual Reality." In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (*CHI '22*). New York, NY, USA: ACM, Apr. 2022. ISBN: 978-1-4503-9157-3/22/04. DOI: 10.1145/3491102.3517454.

[Gün+20b] Sebastian Günther, Dominik Schön, Florian Müller, Max Mühlhäuser, and Martin Schmitz. "PneumoVolley: Pressure-based Haptic Feedback on the Head through Pneumatic Actuation." In: *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (*CHI EA '20*). New York, NY, USA: ACM, Apr. 2020, pp. 1–10. ISBN: 9781450368193. DOI: 10.1145/3334480.3382916.

OTHER PUBLICATIONS

In addition to the aforementioned publications that are the foundation of this thesis, I have been contributing to several other publications as first- and co-author.

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LIST OF TABLES

ACRONYMS

IV	independent variable
DV	dependent variable
HMD	Head-Mounted Display
AR	Augmented Reality
VR	Virtual Reality
AR/VR	Augmented- and Virtual Reality
IoT	Internet of Things
HCI	Human-Computer Interaction
TCT	Task Completion Time
RTLX	Raw NASA-TLX
EMS	Electrical Muscle Stimulation
PAM	Pneumatical Artifical Muscle
EMM	Estimated Marginal Mean
ART	Aligned Rank Transform
EMM	Estimated Marginal Mean
IQR	interquartile range
PWM	Pulse-Width Modulation
CA	Concentric Actuator
EA	Eccentric Actuator
AI	Artificial Intelligence
TEC	Thermoelectric Cooler
PCB	Printed Circuit Board
RHI	Rubber Hand Illusion
SMA	Shape Memory Alloy
PWM	Pulse-Width Modulation
CAMI	Coated Abrasive Manufacturers Institute

LIST OF THIRD-PARTY MATERIALS

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Figure 2.1 is taken from the medical gallery of Blausen Medical 2014 [Bla14], licensed under CC BY 3.0 (`https://creativecommons.org/licenses/by/3.0/`).

Figure 6.1 contains a cleaning sponge model (`https://sketchfab.com/3d-models/sponge-97aee64edf0c4521b82416f3b30c61ce`) and a wooden branch model (`https://sketchfab.com/3d-models/lowpoly-stick-01-9a8ffae22f0846ba895f09d08ff97d82`) from SKETCHFAB, both licensed under CC BY 4.0 (`https://creativecommons.org/licenses/by-sa/4.0/`). The toothbrush, small rock, and spoon models are licensed under the *TurboSquid 3D Model License* (`https://blog.turbosquid.com/turbosquid-3d-model-license/`). The silk cloth model is licensed under the *cgtrader Royalty Free License* (`https://www.cgtrader.com/pages/terms-and-conditions`). The hand model is from the MakeHuman project, licensed under CC0 (`https://creativecommons.org/publicdomain/zero/1.0`).

Figure 6.7 contains a screenshot of a body model and two depictions of a hand, all from the MakeHuman project, licensed under CC0 (`https://creativecommons.org/publicdomain/zero/1.0`). The hand model is also included in the chapter overview image of Chapter 6 (CC0).

Figures 5.1c, 5.3c, 7.6, 7.8, 7.13, 8.11, and 8.12 contain screenshots of different models from the Unity Asset Store (`https://unity3d.com/legal/as_terms`).

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ERKLÄRUNG

Hiermit erkläre ich, die vorgelegte Arbeit zur Erlangung des akademischen Grades Doktor rerum naturalium (Dr. rer. nat.) mit dem Titel

Somatosensory Interaction: Investigating Mechanoreception, Thermoception, and Proprioception for On-Body Haptic Feedback

selbständig und ausschließlich unter Verwendung der angegebenen Hilfsmittel erstellt zu haben. Ich habe bisher noch keinen Promotionsversuch unternommen.

Darmstadt, 18. März 2022

Sebastian Günther, M.Sc.