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DESIGNING TACTILE EXPERIENCES FOR IMMERSIVE VIRTUAL ENVIRONMENTS

by
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Notes on style:

The work presented in this dissertation came about gradually and is in many cases the result of collaborations with other students, researchers, and industry professionals. We therefore use the scientific plural "we" to reflect the efforts of all parties involved. References to scientific resources are provided in the Bibliography chapter, with the use of DOIs where available. Online resources are referred to using URLs with their last date accessed and have been shortened to enhance readability and formatting. The style and typeset of this document is based on the typographical look-and-feel of "classicthesis v4.6", referenced in the Colophon.

Donald Degraen: *Designing Tactile Experiences for Immersive Virtual Environments*

Never refuse an invitation,
never resist the unfamiliar,
never fail to be polite, and,
never outstay the welcome.

Alex Garland, *The Beach*

ABSTRACT

Designing for the sense of touch is essential in creating convincing and realistic experiences in virtual reality (VR). Through haptic feedback, visual representations gain tangibility, which has been shown to positively influence task performance, realism, and a user's sense of presence. While previous work has explored a plethora of approaches to provide haptic feedback in immersive virtual environments (IVEs), developing effective and convincing tactile experiences still remains challenging. Reasons for this are manifold and include the high complexity of the haptic sense, an unfamiliarity with the domain of haptics in other fields, a high diversity of haptic interfaces, and a lack of understanding of the need for including the user's sense of touch. Our research contributes to the fields of VR and haptic design by investigating how real-world touch experiences can enhance the design of effective tactile experiences in IVEs. We propose different approaches that are aimed at creating experiences such that users would be able to receive an impression of the intended feedback during visuo-haptic exploration. Firstly, we investigate haptic reproduction through capturing and fabricating surface microgeometry. We show that fabrication processes can support the design of touch experiences inspired by real-world haptic information. Furthermore, we build upon procedural haptic design by generating and fabricating haptically-varying surface structures. We show that digital design processes are able to generate flexible and universal structures that directly influence tactile dimensions, such as roughness and hardness. By utilizing such structures in visuo-haptic settings, the range of material perception can be extended. Lastly, we investigate correspondences between different sensory modalities to enhance the design of tactile experiences. We show that correspondences between visual and haptic modalities are able to support a wide gamut of material and texture perception in IVEs. Moreover, we show that vocalizations can be used to transfer design intent into effective haptic experiences, while providing a rapid in-situ design process. Based on these contributions, this dissertation advances the fields of VR and haptic design by contributing knowledge to the question of how effective tactile experiences can be designed.

ZUSAMMENFASSUNG

Die Berücksichtigung des Tastsinns ist für die Schaffung überzeugender und realistischer Erlebnisse in der virtuellen Realität (VR) unerlässlich. Durch haptisches Feedback gewinnen visuelle Darstellungen an Greifbarkeit, was sich erwiesenermaßen positiv auf die Ausführung von Aufgaben, den Realismus und das Präsenzgefühl der Nutzer*innen auswirkt. Während frühere Arbeiten eine Vielzahl von Ansätzen von haptischem Feedback in immersiven virtuellen Umgebungen (IVUs) erforscht haben, bleibt die Entwicklung effektiver und überzeugender haptischer Erfahrungen eine Herausforderung. Die Gründe hierfür sind vielfältig und erstrecken sich von der hohen Komplexität des haptischen Sinns, der mangelnden Vertrautheit mit dem Bereich der Haptik, die große Vielfalt an haptischen Schnittstellen bis zu dem fehlenden Verständnis der Notwendigkeit für die Einbeziehung des Tastsinns der Benutzer*innen. In dieser Arbeit leisten wir einen Beitrag zu den Bereichen VR und haptischem Design, indem wir untersuchen, wie reale Berührungserfahrungen das Design effektiver, taktiler Erfahrungen in IVUs verbessern können. Wir stellen verschiedene Ansätze vor, die es Designer*innen ermöglichen, Erlebnisse so zu gestalten, dass die Nutzer*innen einen realistischen Eindruck des beabsichtigten Feedbacks während der visuell-haptischen Erkundung erhalten können. Zunächst untersuchen wir die haptische Reproduktion durch die Erfassung und Herstellung von Oberflächen mit Mikrogeometrien. Wir zeigen, dass Herstellungsprozesse, die durch haptischen Informationen aus der realen Welt inspiriert wurden, das Design von haptischen Erfahrungen unterstützen können. Darüber hinaus bauen wir auf dem prozeduralen haptischen Design auf, indem wir haptisch veränderliche Oberflächenstrukturen erzeugen und herstellen. Wir zeigen, dass digitale Designprozesse in der Lage sind, flexible und universelle Strukturen zu erzeugen, die taktile Dimensionen, wie Rauheit und Härte, direkt beeinflussen. Durch den Einsatz solcher Strukturen in visuell-haptischen Umgebungen kann die Bandbreite der Materialwahrnehmung erweitert werden. Schließlich untersuchen wir Zusammenhänge zwischen verschiedenen Sinnesmodalitäten, um die Gestaltung von taktilen Erfahrungen zu verbessern. Wir zeigen, dass Übereinstimmungen zwischen visuellen und haptischen Modalitäten in der Lage sind, eine breite Palette von Material- und Texturwahrnehmungen in IVUs zu ermöglichen. Darüber hinaus zeigen wir, dass Vokalisierung genutzt werden kann, um Designabsichten in effektive haptische Erfahrungen zu überführen und gleichzeitig einen effizienten In-Situ-Designprozess zu ermöglichen. Basierend auf diesen Forschungsergebnissen bringt diese Dissertation die Bereiche VR und haptisches Design voran, indem sie Erkenntnisse zu der Frage liefert, wie effektive haptische Erfahrungen gestaltet werden können.

PUBLICATIONS

During my research, I collaborated with a diverse set of researchers and professionals and gained valuable feedback and insights along the way. The work described in this thesis came about gradually, and is primarily based upon the following list of publications.

- **Donald Degraen**, Bruno Fruchard, Frederik Smolders, Emmanouil Potetsianakis, Seref Güngör, Antonio Krüger, and Jürgen Steimle (2021a). "Weirding Haptics: In-Situ Prototyping of Vibrotactile Feedback in Virtual Reality through Vocalization." In: *The 34th Annual ACM Symposium on User Interface Software and Technology.* UIST '21. Virtual Event, USA. DOI: 10.1145/3472749.3474797
- **Donald Degraen**, Michal Piovarči, Bernd Bickel, and Antonio Krüger (2021c). "Capturing Tactile Properties of Real Surfaces for Haptic Reproduction." In: *The 34th Annual ACM Symposium on User Interface Software and Technology.* UIST '21. Virtual Event, USA. DOI: 10.1145/3472749.3474798
- **Donald Degraen**, André Zenner, and Antonio Krüger (2019b). "Enhancing Texture Perception in Virtual Reality Using 3D-Printed Hair Structures." In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems.* CHI '19. Glasgow, Scotland UK. DOI: 10.1145/3290605.3300479

Beyond these publications, I was part of research in the field of haptic feedback and interaction in virtual reality, which led to the following publications.

- Dennis Wittchen, Katta Spiel, Bruno Fruchard, **Donald Degraen**, Oliver Schneider, Georg Freitag, and Paul Strohmeier (2022). "TactJam: An End-to-End Prototyping Suite for Collaborative Design of On-Body Vibrotactile Feedback." In: *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction.* New York, NY, USA. DOI: 10.1145/3490149.3501307
- Akhmajon Makhsadov, **Donald Degraen**, André Zenner, Felix Kosmalla, Kamila Mushkina, and Antonio Krüger (2022). "VRySmart: a Framework for Embedding Smart Devices in Virtual Reality." In: *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems.* CHI EA '22. New Orleans, LA, USA. DOI: 10.1145/3491101.3519717

- **Donald Degraen**, Anna Reindl, Akhmajon Makhsadov, André Zenner, and Antonio Krüger (2020a). "Envisioning Haptic Design for Immersive Virtual Environments." In: *Companion Publication of the 2020 ACM Designing Interactive Systems Conference*. DIS' 20 Companion. Eindhoven, Netherlands. DOI: 10.1145/3393914.3395870
- Marco Speicher, Christoph Rosenberg, **Donald Degraen**, Florian Daiber, and Antonio Krüger (2019b). "Exploring Visual Guidance in 360-Degree Videos." In: *Proceedings of the 2019 ACM International Conference on Interactive Experiences for TV and Online Video*. TVX '19. Salford (Manchester), United Kingdom. DOI: 10.1145/3317697.3323350
- Marco Speicher, Jan Ehrlich, Vito Gentile, **Donald Degraen**, Salvatore Sorce, and Antonio Krüger (2019a). "Pseudo-Haptic Controls for Mid-Air Finger-Based Menu Interaction." In: *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI EA '19. Glasgow, Scotland, UK. DOI: 10.1145/3290607.3312927
- Daniele Giunchi, Stuart James, **Donald Degraen**, and Anthony Steed (2019). "Mixing Realities for Sketch Retrieval in Virtual Reality." In: *The 17th International Conference on Virtual-Reality Continuum and Its Applications in Industry*. VRCAI '19. Brisbane, QLD, Australia. DOI: 10.1145/3359997.3365751
- André Zenner, Marco Speicher, Sören Klingner, **Donald Degraen**, Florian Daiber, and Antonio Krüger (2018). "Immersive Notification Framework: Adaptive & Plausible Notifications in Virtual Reality." In: *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI EA '18. Montreal QC, Canada. DOI: 10.1145/3170427.3188505

On these topics, we organized the following workshops and demos.

- Bruno Fruchard and **Donald Degraen** (2022). "Demonstration of Weirding Haptics: Prototyping Vibrotactile Feedback through Vocalization in Virtual Reality." In: *IEEE 7th VR Workshop on Sonic Interactions for Virtual Environments*. SIVE '22. Virtual, Online
- Oliver Schneider, Bruno Fruchard, Dennis Wittchen, Bibhushan Raj Joshi, Georg Freitag, **Donald Degraen**, and Paul Strohmeier (2022). "Sustainable Haptic Design: Improving Collaboration, Sharing, and Reuse in Haptic Design Research." In: *CHI Conference on Human Factors in Computing Systems Extended Abstracts*. CHI EA '22. New Orleans, LA, USA. DOI: 10.1145/3491101.3503734

- Florian Daiber, **Donald Degraen**, André Zenner, Tanja Döring, Frank Steinicke, Oscar Javier Ariza Nunez, and Adalberto L. Simeone (2021). "Everyday Proxy Objects for Virtual Reality." In: *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems.* CHI EA '20. Honolulu, HI, USA. DOI: 10.1145/3411763.3441343
- Florian Daiber, **Donald Degraen**, André Zenner, Frank Steinicke, Oscar Javier Ariza Núñez, and Adalberto L. Simeone (2020). "Everyday Proxy Objects for Virtual Reality." In: *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems.* CHI EA '20. Honolulu, HI, USA. DOI: 10.1145/3334480.3375165
- André Zenner, **Donald Degraen**, Florian Daiber, and Antonio Krüger (2020). "Demonstration of Drag:On - A VR Controller Providing Haptic Feedback Based on Drag and Weight Shift." In: *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems.* CHI EA '20. Honolulu, HI, USA. DOI: 10.1145/3334480.3383145

During my PhD research, I actively engaged in a wide range of collaborations, which include the fields of living media interfaces, gamification, and the Social Internet of Things.

- **Donald Degraen**, Hannah Hock, Marc Schubhan, Maximilian Altmeyer, Felix Kosmalla, and Antonio Krüger (2021b). "FamilyFlower: An Artifical Flower to Foster Distant Family Connections." In: *20th International Conference on Mobile and Ubiquitous Multimedia.* MUM 2021. Leuven, Belgium. DOI: 10.1145/3490632.3497833
- **Donald Degraen**, Marc Schubhan, Maximilian Altmeyer, and Antonio Krüger (2021d). "Hakoniwa: Enhancing Physical Gamification Using Miniature Garden Elements." In: *Academic Mindtrek 2021.* Mindtrek 2021. Tampere/Virtual, Finland. DOI: 10.1145/3464327.3464362
- Maximilian Altmeyer, **Donald Degraen**, Tobias Sander, Felix Kosmalla, and Antonio Krüger (2021). "Does Physicality Enhance the Meaningfulness of Gamification? Transforming Gamification Elements to Their Physical Counterparts." In: *Proceedings of the 33rd Australian Conference on Human-Computer Interaction.* OzCHI '21. Melbourne, VIC, Australia. DOI: 10.1145/3520495.3520500
- **Donald Degraen**, Marc Schubhan, Kamila Mushkina, Akhmajon Makhsadov, Felix Kosmalla, André Zenner, and Antonio Krüger (2020b). "AmbiPlant - Ambient Feedback for Digital Media through Actuated Plants." In: *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems.* CHI EA '20. Honolulu, HI, USA. DOI: 10.1145/3334480.3382860

- **Donald Degraen**, Felix Kosmalla, and Antonio Krüger (2019a). "Overgrown: Supporting Plant Growth with an Endoskeleton for Ambient Notifications." In: *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI EA '19. Glasgow, Scotland Uk. DOI: 10.1145/3290607.3312833
- **Donald Degraen** (2019). "Exploring Interaction Design for the Social Internet of Things." In: *Social Internet of Things*. Ed. by Alessandro Soro, Margot Brereton, and Paul Roe. Cham. DOI: 10.1007/978-3-319-94659-7_5

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ACRONYMS

2IFC	two-interval forced-choice
AD	analog-to-digital
AHF	active haptic feedback
AR	augmented reality
AV	augmented virtuality
BOOM	Binocular Omni-Oriented Monitor
C/D	control/display ratio
CAVE	Cave Automatic Virtual Environment
CC	crossmodal correspondence
DA	digital-to-analog
DIY	Do-It-Yourself
DOF	degrees-of-freedom
DPHF	dynamic passive haptic feedback
EMS	electrical muscle stimulation
EP	exploratory procedure
EPM	Extent of Presence Metaphor
ERM	Eccentric Rotating Mass
ETHD	encountered-type haptic devices
EWK	Extent of World Knowledge
FDM	Fused Deposition Modeling
FOV	field of view
HaXD	haptic experience design
HCI	human-computer interaction
HMD	head-mounted display
HX	haptic experience
IPT	Immersive Projection Technology
IVE	immersive virtual environment
JND	just-noticeable difference
LRA	Linear Resonant Actuator
MDS	Multidimensional Scaling
MLE	maximum-likelihood estimation
MR	mixed reality
nMDS	non-Metric Multidimensional Scaling
PHF	passive haptic feedback
PI	Place Illusion
Psi	Plausibility Illusion
RF	Reproduction Fidelity
SC	Sensorimotor Contingency
SLA	Stereolithography
SMA	shape memory alloy
UX	user experience
VE	virtual environment
VR	virtual reality

Part I

FOUNDATION

Every story starts with a beginning,
and every thesis with an introduction.

1

INTRODUCTION

In the following chapter, we illustrate the idea behind this dissertation through framing the challenge of understanding and designing tactile experiences in our visually dominated world. Next, we introduce the presented work and the research questions that guided our investigations, and provide a breakdown of the contributions made. We further elaborate on our research approach and methodology, and conclude the chapter with a general overview.

1.1 MOTIVATION

I remember the *feeling* of touching coral stone.

My wife and I visited the Hukuru Miskiy in Malé, one of the finest coral stone buildings still remaining in the world. Built in 1658, this ornate old mosque is a testament to the artistry of the Maldivian people, and a unique example of sea-culture architecture.

Modern technology allows me to share with others, to a certain degree, the experience of visiting this place. I can illustrate the complexity of the building and its intricate carvings with the pictures in Figure 1.1. Using video recordings, I would be able to share the experience of walking in its presence and emphasize the shape and size of the construction. A digital reconstruction would permit even further freedom to investigate the details hidden within its decorations, while state-of-the-art virtual reality (VR) technology would allow us to visually immerse ourselves into the enclosure's surroundings and explore its location and perhaps even understand its cultural importance. However, it still remains difficult to capture and share the tangible impression such an artifact provides.

Figure 1.1: The Malé Hukuru Miskiy. Here depicted, (left top) the view of the entrance taken from Wikimedia Commons (2018), (left bottom) touching the surface reveals intricate natural and carved features, and (right) detailed view of the stone's material.

To share such a physical experience, I could verbally state that when running a finger over the surface, the sensation of detailed engravings combined with naturally embossed features leaves a rough, yet polished impression, or that in its tropical climate, the boulders provide a refreshing temperature to the skin with a light sensation of wetness. Visual depictions, such as pictures or video recordings, help us to investigate surface colors and patterns, with reflections aiding in classifying the material somewhere in between smooth concrete and rough marble. As these insights alone do not communicate the entirety of the haptic experience, we remain left with a boiled down version of a complex perception. The intricate feeling of touching the coral stone walls remains difficult to fully understand without physical access to the material itself.

The story of the Hukuru Miskiy and its coral stone walls underlines that currently there is no straightforward way of capturing and sharing a physical *feeling*. This poses a challenge for immersive virtual environments (IVEs), where the sense of touch has been shown to be crucial in providing plausible and convincing experiences. Motivated by this, the work described in this dissertation investigates how to improve the design of tactile experiences for virtual settings. To this aim, we propose different approaches, such that users would be able to receive a realistic impression of the intended feedback during visuo-haptic exploration. Specifically, we investigate (1) haptic reproduction through capturing and fabricating surface microgeometry, (2) procedural haptic design by generating and fabricating haptically-varying surface structures, and (3) crossmodal correspondence by translating designers' vocalizations into vibrotactile actuation.

1.2 PROBLEM STATEMENT

Slowly, but surely, VR is integrating itself into our everyday technology stack. Whereas CAVE systems were directed to room-sized setups for projecting virtual content onto walls (Cruz-Neira et al., 1993), the advent of head-mounted displays (HMDs) provided a greater level of accessibility by allowing users to immerse themselves in compelling, virtually generated worlds from the comfort of their home (Sutherland, 1968). Compared to traditional human-computer settings, VR aims to close the gap between the world generated by the computer and the user's world by placing them inside the experience.

The goal of an IVE is to provide a convincing and plausible experience that provides the user with the illusion of being some place else than where they are physically located (Slater, 2009). On succeeding in this, the user builds a sense of presence, i. e., the qualia of *"being there"*, in this virtual setting. However, creating the illusion where the user accepts the presented virtual environment as the one they are in and fails to perceive the existence of a medium, remains a challenging task.

As humans, we integrate visual and haptic sensory information into a robust percept to understand the world around us (Ernst and Banks, 2002). When interacting with virtual scenes, high expectations need to be met, as the plausibility of the illusion presented to the user heavily relies on such multisensory integration (Slater, 2009). Therefore, both industry and research have focused to a higher degree on including the user's sense of touch. As a crucial element of an IVE, haptic feedback provides tangibility to visual representations, which has been shown to positively influence task performance, realism, and a user's sense of presence (Meehan et al., 2002; Sallnäs et al., 2000; Viciana-Abad et al., 2010).

The importance of haptic feedback is best illustrated by the effects of its absence. Without the sense of touch, we cannot tell if the clothes we wear are comfortable, if an object we are holding is light or heavy, or if a button we press responds to our action. Even when directly observing our hands, our fine motor-control ability would be greatly impaired, and it would even be challenging just to remain standing upright (Robles-De-La-Torre, 2006).

Commodity VR hardware mainly relies on augmenting visual information with simple vibrotactile actuation through rumble motors or linear actuators. While such mechanisms deliver a rudimentary approach to haptic feedback during interaction, they remain limited in the gamut of experiences they are able to communicate. In literature, a broader variety of haptic experiences to support a user's sense of touch can be found. A commonly used classification contrasts different haptic technology on whether they provide active haptic feedback (AHF) through computer-controlled actuators, passive haptic feedback (PHF) where passive objects are paired to their virtual counterparts to serve as tangible proxies (Insko, 2001; Nilsson et al., 2021), or mixed approaches such as dynamic passive haptic feedback (DPHF) (Zenner and Krüger, 2017) or substitutional reality (Simeone et al., 2015) aimed at combining the best of both worlds. Leveraging these methods, convincing haptic illusions can be created through passive physical props (Insko, 2001), rendering

Figure 1.2: A sample book to explore different fabrics.

kinesthetic feedback (Zenner and Krüger, 2017, 2019), or simulating texture and material properties (Heo et al., 2019; Lee et al., 2019; Romano and Kuchenbecker, 2012; Strohmeier et al., 2018, 2020; Visell et al., 2014).

However, developing effective and convincing tactile experiences for virtual environments remains challenging. While PHF approaches enable designers to build virtual experiences around real-world objects to provide highly realistic impressions, they require every user to have access to the same physical material. On the other hand, AHF approaches more easily allow to abstract haptic impressions through modeling and rendering methods. However, control signals for driving such devices often rely on manipulating low-level parameters such as frequency and amplitude, making it challenging to transfer such abstract parameters into understandable haptic effects (Schneider et al., 2017; Strohmeier et al., 2018). Furthermore, mixed approaches rarely make it beyond the conceptual phase, as they are commonly streamlined to solve specific problems and therefore not easily generalizable (Schneider et al., 2022). As underlined by related work, the field of haptic design is in need of universal design practices and guidelines to support haptic designers (Seifi et al., 2020a).

In this dissertation, we investigate different approaches for designing and creating tactile experiences for IVEs, with the aim to enable users to receive a realistic impression of the intended feedback during visuo-haptic exploration. Our work is partly inspired by existing methods for configuring real-world haptic features in our environment, such as the use of fabric sample books, see Figure 1.2. Through such collections, users receive a realistic impression of the visual and haptic features a material has to offer. We utilize this concept and abstract the visual from the haptic stimuli. Using different design approaches, we investigate methods to create tactile experiences, and evaluate the resulting visuo-haptic experience through perceptually motivated user studies.

In our first approach, we investigate the case of haptic reproduction using digital fabrication. By capturing and replicating real-world information, we aim to create effective tactile experiences from known properties of the physical environment. To this aim, we built a photometric sensing technique able to capture the stable surface microgeometry of textures, and encode them into height map representations. Using this data as displacement maps, we fabricate physical surface samples, and investigate the tactile perception of these replicas in a psychophysical experiment. While a shift in perceived attributes underlined the haptic information was not fully reproduced, we see that our replication process is able to support a wide gamut of *feel* aesthetics. Furthermore, we applied this approach to passive haptic feedback in VR. By using our replicated structures as passive proxy objects, we overlaid them with different virtual representations, such as their original textures. From the results of a user study, we noted that in most cases, haptic dominance pushed perception in the direction of the replicated structures. However, we also observed that the addition of visual information allowed users to perceive a wide range of materials through visuo-haptic combinations.

Next, we look towards procedural design. By generating and fabricating 3D-printed hair-like structures, we explore how abstract haptically-varying samples can serve as versatile proxy surfaces for influencing texture perception in IVEs. In a user study, we found that visuo-haptic augmentations enhance haptic perception by making small variations in hair length distinguishable. When visual and haptic stimuli were rated higher in terms of matching, materials were more consistently recognized. Furthermore, as users actively make sense of mixed modalities, varying augmentations are able to cause perceptual switches, indicating the flexibility of this approach to support material perception in VR.

Lastly, we investigate design through crossmodal expression. As perceptual processes actively build our understanding of the world, perceptual representations stemming from different modalities are shared between the senses, and non-arbitrary associations between features of different stimuli are created. To understand these crossmodal correspondences between haptic and auditory features, we performed a user study where users were asked to vocally express haptic stimuli of a wide range of objects during interaction. Informed by these insights, we built a VR design tool that enables fast-prototyping of vibrotactile experiences using vocalizations. Using this tool, one can synchronously vocalize the intended vibrotactile experience of a virtual object during in-situ interaction with objects. This work presents a novel design concept for creating effective haptic feedback in VR.

1.3 RESEARCH QUESTIONS

Guided by previous considerations, our work aims to enhance the design of tactile experiences for IVEs. The main question guiding this work is as follows.

> **How can we utilize our understanding of real-world touch experiences to enhance the design of tactile feedback for immersive virtual environments?**

Specifically, our work considers different perspectives, which we break down into the following research questions.

RQ1: How can reproduction of real-world haptics enhance the design of tactile experiences for IVEs?

RQ2: How can procedural fabrication methods enhance the design of tactile experiences for IVEs?

RQ3: How can correspondences between different sensory modalities enhance the design of tactile experiences for IVEs?

With **RQ1**, we look towards appropriating experiences from real-life which designers are already intimately familiar with. We investigate this through two different approaches. Firstly, by capturing and reconstructing physical information from real textures, we investigate which tactile information is able to reproduce through replicating surface textures using additive manufacturing. This provides insights for future approaches to allow designers to capture and reproduce the haptics of real world experiences. Secondly, we investigate how tactile experiences can be expressed through vocalizations. This aims to extend our understanding of how haptic impressions can be communicated, and how systems can capture and render such vocalizations to simulate the designer's intent.

With **RQ2**, we look towards novel fabrication methods to support haptic feedback in immersive virtual environments. As the resolution of digital fabrication technology is already high enough to generate fine-grained surface variations, their usage for designing haptic artifacts lends itself to share and produce physical objects on demand. Specifically, we build upon previous work investigating passive haptic feedback, an approach where physical props are used as haptic proxies for virtual objects. By overlaying proxies with visual textures, we investigate how the visuo-haptic perception of tactile textures can be simulated. Our results underline that fabrication of proxy objects is able to extend the scalability and generalizability of PHF.

With **RQ3**, we look towards crossmodal correspondences, i. e., the notion that different sensory modalities share associations between common features. Specifically, we investigate how tactile impressions can be expressed through vocalizations, and which features of such vocalizations can be used to create vibrotactile feedback. To this aim, we present the results of a user study investigating user's vocalizations for a set of objects. Based on the insights gained, we built a design tool able to convert vocalizations into feedback mechanisms during interaction with virtual objects. A user study confirmed that this approach was able to transfer designer's intentions into effective haptic effects.

1.4 RESEARCH METHODOLOGY

In order to complete the research goals, our work first conceptualized and implemented novel design methods, utilized lab studies and semi-structured interviews to test hypotheses, and performed established statistical data analysis to frame discussions and conclusions.

CONCEPTUALIZATION The ideas presented in this dissertation started from a conceptualization phase. Often, ongoing discussions were built around the notion of fabric sample books, commonly used for deciding on material configurations while purchasing furniture. Their flexibility and ease of use remains an inspiration of which we aim to translate features to novel haptic design processes.

SEMI-STRUCTURED INTERVIEWS When further information was needed to proceed to the implementation phase, we conducted semi-structured interviews. Specifically, for Weirding Haptics in Chapter 8, we presented users with a varying set of objects and asked them to vocalize the haptic impression during interaction. Through a thematic analysis, we uncovered correlations between tactile qualities and features of users' vocalizations. These insights allowed us to proceed with a detailed and focused implementation.

IMPLEMENTATION Often, conceptualization was followed by implementation. For designing immersive virtual environments, we utilized the *"Unity Real-Time Development Platform"* (Unity Technologies, 2022). As a cross-platform game engine, it allowed us to easily create and test software to support user studies.

During projects in which fabrication methods were employed, a variety of programming languages and tools were used to achieve the goals of the project. Procedural generation of digital designs and digital reconstruction approaches were implemented through a combination of custom-built C++, C#, and Python applications and scripts. The final designs were manufactured using a variety of additive fabrication systems, including the Autodesk Ember and the Objet Connex 260 printers. Specifically, the silicone used for capturing micro-surface information in Chapter 5 was manually poured into laser cut molds designed in Inkscape.

LAB STUDIES Using the implemented tools, lab studies were organized to investigate the psychophysical perception of visuo-haptic experiences. For these studies, we implemented variations of established psychophysics study designs commonly used in the field of haptics and human-computer interaction (HCI). All studies employed *Semantic Differential Methods*, where users rated their subjective perception through fixed scales depicting principal tactile dimensions, e. g., hardness-softness, or roughness-smoothness. In Chapter 5, a *Similarity Estimation Method* inquired about the perceptual match between surface samples by asking users to provide their subjective matching rate for each presented pair.

Lastly, in Chapter 9, we took a more open study design to evaluate the Weirding Haptics framework. As users designed vibrotactile feedback through vocalizations and post-design parametric configuration, the resulting feedback was subjectively evaluated by asking users how well it matched their design intent.

DATA ANALYSIS All data analysis methods were informed by established work in the research fields of haptics, VR, and HCI. Based on the design of the user study, we utilized several approaches to evaluate initial hypotheses. For uncovering significant differences in subjective perceptual ratings, we performed statistical tests comparing different conditions. Furthermore, correlation tests were used throughout the work to assess consistency across participants' indications, or to uncover correlations between different tactile perceptual dimensions. Lastly, in order to fully understand the underlying aspects influencing users' perception, we looked towards specific analysis methods, such as Multidimensional Scaling (MDS).

As our studies involved the use of VR, we additionally investigated related concepts of user experience and presence. Therefore, we evaluated users' subjective experience through post-experiment SUS questionnaires (Slater et al., 1994). Combined with custom demographics surveys, these were used to relate analysis results to users' subjective experience and general background information.

1.5 CONTRIBUTIONS

The work presented in this dissertation represents several contributions to the fields of HCI, fabrication, and haptic design.

EMPIRICAL AND THEORETICAL CONTRIBUTIONS Parts of our work build upon PHF, an approach where physical proxy objects are paired with virtual objects to provide a sense of tangibility in IVEs. Commonly, these methods use a variety of props, including existing objects with desired properties, or more abstract polystyrene foam reproductions. While this easily allows communicating general shape, detailed tactile features, such as surface textures, remain difficult as each user needs access to the same material. As far as we know, we are first in investigating fabrication methods for designing more flexible proxy objects for detailed tactile feature replication in IVEs. Both through reproduction of real-world micro-surface geometries and procedural fabrication of haptically-varying surfaces, we show that additive manufacturing methods can support haptic design.

Through abstracting physical samples from their visual perception in visuo-haptic experiences, we contribute to research investigating visuo-haptic integration. Specifically, through designing tactile samples and overlaying them with visual information, we created a wide range of visuo-haptic combinations. Here, mismatching information stemming from different sensory modalities showed that users actively tried to make sense of different combinations and that adjectives were used to express conflicting stimuli. Moreover, in the case of 3D-printed hair-like samples, we saw that such abstract surface samples with varying tactile properties were able to support material impressions.

Our work builds upon previous understanding of crossmodal interaction. As different sensory modalities receive stimuli in multi-modal environments, non-arbitrary associations are built between features of different sensory sensations. In this context, we investigated correlations between real-world haptic experiences and user's vocal expressions. From our investigations, we saw that vocal features can express haptic perceptual qualities, and, moreover, can be used to design intended haptic effects using vibrotactile actuation.

TECHNICAL CONTRIBUTIONS During the work presented in this dissertation, several software tools were constructed to support user studies. As a specific contribution, we designed and released the *"Weirding Haptics"* framework for designing vibrotactile feedback while immersed in VR, available online (Degraen, 2021). This design tool supports off-the-shelf devices and aims to abstract from complex parameters to enable novice designers to design for haptic feedback. Built on the insights from our investigation of crossmodal correspondences, designers use their voices while manipulating virtual objects to vocalize the intended vibrotactile feedback, directly experience the result, and enables them to fine-tune their designs.

DESIGN CONTRIBUTIONS Lastly, part of our work builds upon an existing method, called *"GelSight"*, for capturing the micro-geometry of surfaces. This approach employs a transparent elastomeric silicone coated with a layer of reflective paint, of which the bidirectional reflectance distribution function (BDRF) is known. We contribute an implementation of a bench setup which uses this principle, based on the retrographic sensing method presented by Johnson et al. (2011). Our variation is focused on consistently capturing the highly detailed surface features from fabric samples.

1.6 THESIS OVERVIEW

The dissertation is structured as follows. In Chapter 2, we review the necessary background information on the field of haptic perception to understand how our sense of touch is used to understand the physical world around us. Chapter 3 continues with a related work overview on the field of immersive virtual environments and recent advances in haptic feedback. This is followed by review of literature involving the design of haptic experiences, in Chapter 4, which concludes by introducing our approach for building prototyping methods for haptic experiences.

The work described in Chapter 5 approaches the prototyping phase of haptic experiences from the perspective of appropriating real world information and was published in (Degraen et al., 2021c). Here, surface variations of a set of 15 textures were replicated using a retrographic sensing technique. The tactile perception of the photometrically reconstructed surface samples was examined in a psychophysical user study. Chapter 6, at the time of writing unpublished, builds upon this work by augmenting the replicated surface structures with visual stimulation in an immersive virtual environment. Through multisensory visuo-haptic stimuli, we investigated how the perception of the replicated structures varied in the presence of visual dominance. The method of applying procedural generation of tactile structures is elaborated in Chapter 7 and was originally published in (Degraen et al., 2019b). Here, the visuo-haptic perception of 3D-printed hair-like structures was investigated in a virtual setting to understand how parametric fabrication of abstract surface textures can build material perception. Furthermore, Chapter 8, investigates the vocalization approaches used to express tactile impressions, continued with Chapter 9, which introduces our method of in-situ prototyping of haptic feedback in VR. Chapter 8 and Chapter 9 were originally published in (Degraen et al., 2021a).

Finally, in Chapter 10, we conclude the dissertation, underline our major contributions and discuss potential future work.

Part II

BACKGROUND & RELATED WORK

Seeing is believing, but
feeling is the truth.

— Thomas Fuller

2

SENSES, SENSATIONS, AND PERCEPTIONS

Before delving into the world of immersive virtual experiences, we must first understand the fundamental mechanisms that build our sensory perception. In this chapter, we investigate the physiological and conceptual elements of our haptic perception, and address the means of investigating perception through psychophysical procedures. As perception in itself is a highly complex and interwoven process, we focus our review to the context of the work performed in this thesis, i. e., the perception of tactile experiences.

2.1 UNDERSTANDING PERCEPTION

As living creatures, we do not experience our external environment in a direct manner, but rather through the use of specialized organs (Schmidt, 1986, p. 1). For this, we have evolved *senses* to secure information from the world around us. Using a diverse range of receptors with varying distribution densities and quantities, sensory organs capture external stimuli as impulses which cause *sensations* to the nervous system. In turn, higher level cognitive processes called perceptual systems interpret this input, evoking *perceptions*.

Perception is an individual's interpretation of a sensation. Instead of being mere channels of sensation, Gibson (1983) was the first to posit that the senses are to be considered as systems for perception. This explicit distinction between sensations and perceptions carries with it certain implications. Rather than thinking of perception in terms of passive receptors and energies to stimulate them, we must consider perception as an active, investigative process. In this process, our interpretation of the state of the external environment results

Figure 2.1: Our sense of touch allows us to *be in touch* with others.

from a complex cognitive system distilling multiple sources of sensory information derived from different modalities. In turn, our interactions with the environment are guided by these perceptions. As the state of the environment changes through these actions, novel sensations are evoked, which restarts the iterative process commonly known as the *perception-action loop* (Ernst and Bülthoff, 2004).

In this work, we investigate methods to design understandable and effective tactile experiences for IVEs. These approaches start from comprehending how physical variations influence touch sensations, but also need to consider the contribution of visual perception through multisensory processes that integrate both senses into a robust percept.

2.1.1 *Haptic Perception*

Our sense of touch is arguably the most primitive of all senses. As the first to develop in the womb, it provides us with an intimate familiarity of the physical world around us (Montagu, 1986). It is an immediate, direct sense that demands proximity, and *"entails a conscious attention to sensation from the outside"* (Fretwell, 2020, p. 228). As a form of communication, it is an expressive and reciprocal modality able to convey affect, and enables people to *be in touch* with their environment and each other.

Touch is also a primal sense, crucial to embodied existence (Paterson, 2007, p. 1). Both in real and virtual environments, successful navigation and interaction highly depend on our touch perception (Robles-De-La-Torre, 2006). Without it, we cannot tell if the clothes we wear are comfortable, if an object we are holding is light or heavy, or if a button we press responds to our action. Even while directly observing our hands, our fine motor-control ability would greatly be impaired, making it challenging just to remain standing upright.

In this section, we discuss the physiology of touch perception and how it is used to explore tactile qualities of objects, such as textures.

2.1.1.1 *Physiology of Touch*

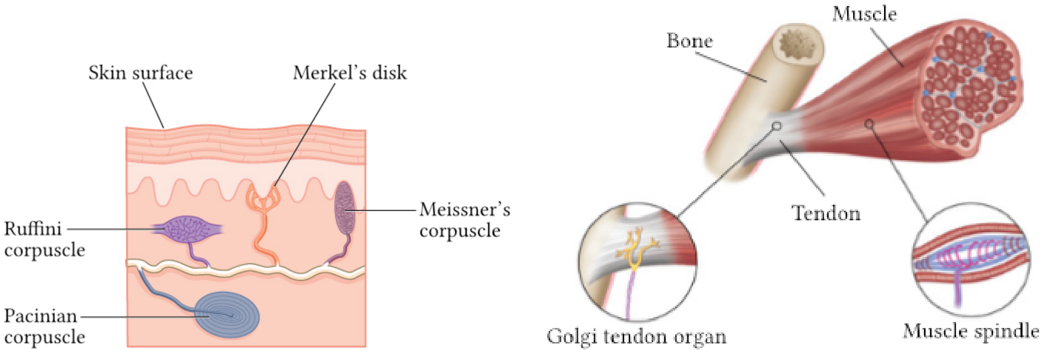
The sense of touch is also referred to with the term *haptic*. Originally coined by Dessoir, it draws an analogy to the terms of optic and acoustic, and aims to encompass different aspects of the sense of touch and its field of study (Grunwald, 2008, p. 22).

From a physiological perspective, our haptic perception is a complex constitution of multiple sensory systems stemming from an elaborate network of neural structures called the somatosensory system (McGlone and Reilly, 2010). It enables us to perceive a manifold of sensations, such as vibrations, temperature, and pain, as well as the position of our body and limbs. Our sense of touch not only informs us about external stimuli we come into contact with, but also investigates our own internal state. While we might not be mindful of all sensations, they build our worldly perception and enable us to act in an effective, efficient and safe manner.

Conceptually, our haptic system consists of two separate modalities, i. e., *cutaneous*, and *kinesthetic* senses (Lederman and Klatzky, 2009; McGlone and Reilly, 2010).

CUTANEOUS SENSES As the most versatile and extensive organ in our body, the skin captures afferent nerve impulses through embedded mechanoreceptors and thermoreceptors. Four submodalities of cutaneous senses that relay tactile, thermal, pain and pruritic (itching) sensations, are commonly recognized, with growing evidence of a fifth modality conveying positive affective (pleasure) properties of touch (McGlone and Reilly, 2010).

The tactile subsystem, of particular interest to this dissertation, subserves the perception of pressure, vibration and texture, through skin deformations resulting from contact with physical objects or external forces. Four different low-threshold mechanoreceptors innervating the glabrous skin are specialized to transduce mechanical forces impinging the skin into nerve impulses (Abraira and Ginty, 2013; Bolanowski et al., 1988; Johnson, 2001; Lederman and Klatzky, 2009; Wolfe et al., 2018). Visualized in Figure 2.2a, they are respectively the Pacinian corpuscles, Meissner's corpuscles, Merkel's disks, and Ruffini endings, and are essential for performing stable precision grasp and manipulation operations. Both Merkel's disks and Ruffini endings are slowly adapting receptors. Merkel's disks are highly sensitive to sustained pressure and very low frequencies (<~ 5 Hz), and are therefore able to transmit contact pressure to the brain and encode curvature and edges of explored surfaces during interaction. Ruffini endings, on the other hand, are sensitive to lateral stretching of the skin, and sustained downwards pressure, enabling them to detect object motion and force, and finger positioning (~ 100 Hz to ~ 500 Hz). Both corpuscles, i. e., Meissner's and Pacinian, are fast adapting receptors sensitive to temporal changes in skin deformation. Meissner's corpuscles specifically respond to low-frequency vibrations (~ 5 Hz to ~ 50 Hz) and transfer the image of skin motion, while Pacinian corpuscles respond to higher frequency vibrations (~ 50 Hz to ~ 700 Hz) and are highly sensitive to



(a) Cutaneous Receptors.

(b) Kinesthetic Receptors.

Figure 2.2: Diagrams respectively showing the mechanoreceptors, (a) inside the human skin, and (b) inside the muscles and tendons. Images respectively adapted from OpenStax (2021, fig. 5.21) and Walker (2011, p. 13, fig. 1.7).

transient signals. Of these receptors, Merkel's disks support pattern and form detection, and coarse texture perception, while Pacinian corpuscles perform fine texture perception.

During active exploration with our fingers, our cutaneous senses enable us to investigate the physical world around us. The information gathered by our mechanoreceptors is integrated to form our overall tactile perception. With incredibly high discriminatory power this allows us to assess a wide range of object qualities, including geometrical characteristics, e. g., overall shape and edge composition, material properties, e. g., hardness and roughness, and fine surface details, e. g., textures.

KINESTHETIC SENSES Besides innervated in the skin, mechanoreceptors are present, with varying densities, in our muscles, tendons, fascia, joint capsules, and ligaments (Jones, 2000; Proske and Gandevia, 2012). Stimulation of these receptors evoke kinesthetic sensations, i. e., sensations of body and limb movements.

Three different types of receptors, shown in Figure 2.2b, contributing to kinesthetic sensations are commonly described. The first two types of receptors are the spindle receptors innervated in muscle fibers. Here, primary spindle receptors are highly responsive to dynamic velocity and acceleration changes during muscle lengthening and contraction, while secondary spindle receptors respond to constant muscle length. Subsequently, primary spindle receptors signal the velocity and direction of muscle stretch or limb movement, whereas secondary spindle receptors inform about static muscle length or limb position. Found at the junction between muscle tendons and groups of muscle fibers, the Golgi tendon organs sense forces and all but the smallest muscle contractions. Additionally, cutaneous receptors contribute to kinesthetic sensations. Through stretching and deformation of the skin, skin-related information is essential for movement and position perception of our fingers. Kinesthetic perception not only allows us to understand our body and limbs, but supports in investigating kinesthetic properties of objects during physical manipulation.

Cutaneous and vestibular perceptions, i. e., the perception of balance, head position, acceleration and deceleration, are combined with kinesthetic perception to build proprioception (Oakley et al., 2000). Described as the perception of the position, state and movement of our body and limbs in space (Jones, 2000), it is essential for successful navigation and interaction in both virtual and real environments (Robles-De-La-Torre, 2006).

2.1.1.2 *Haptic Exploration*

Our haptic perception enables us to investigate and process physical properties of objects and surfaces for different purposes (Wolfe et al., 2018, p. 466). In *perception for action*, sensory input is utilized to prepare and guide interaction with objects and surfaces, while *action for perception* utilizes this sensory input to actively explore haptic properties of objects and surfaces. The latter is used by participants during studies in this dissertation to investigate and rate haptic qualities.

In terms of qualities that affect our perception, Gibson (1983, p. 135) distinguishes between tangible properties originating from geometrical variables, such as shape, surface variables, such as texture, and material variables such as weight. Similarly, Lederman and Klatzky (2009) classify them as material, geometrical and hybrid properties. Material properties relate to surface textures, compliance, and thermal qualities, while geometric properties generally comprise shape and size. Hybrid properties, such as weight, originate from a combination of an object's material and its structure.

Through grasping and manipulating objects and surfaces, we actively engage in the process of haptic exploration. This process is essential in measuring haptic properties and requires intentional movement to understand spatial relationships and layout, i. e., to *measure* our environment in terms of its haptic space (Paterson, 2007, p. 73). The process of assessing object properties and understanding how they combine to produce the whole, is also known as *haptic apprehension*, while the term *haptic recognition* is used to indicate the categorization of haptic properties.

Important in this context, are the manner in which objects or surfaces are explored, if active movement is involved, and if contact is made directly, or through the use of an intermediate tool.

PASSIVE VERSUS ACTIVE TOUCH Static contact allows us to perceive an object's temperature, and a coarse impression of its surface variations. During such passive touch, the impressive discriminative power of our fingers allows us to identify embossed dots down to 550 µm in diameter and a height of only 3 µm (Wang and Hayward, 2008). However, movement is essential to optimally investigate haptic properties (Katz and Krueger, 1989, p. 5). In the absence of relative lateral motion, texture discrimination becomes nearly impossible (Katz and Krueger, 1989).

During active exploration, the hand can *"grope, palpate, prod, press, rub, or heft"* (Gibson, 1983, p. 123), and is wielded as such to actively obtain sensations from the physical envi-

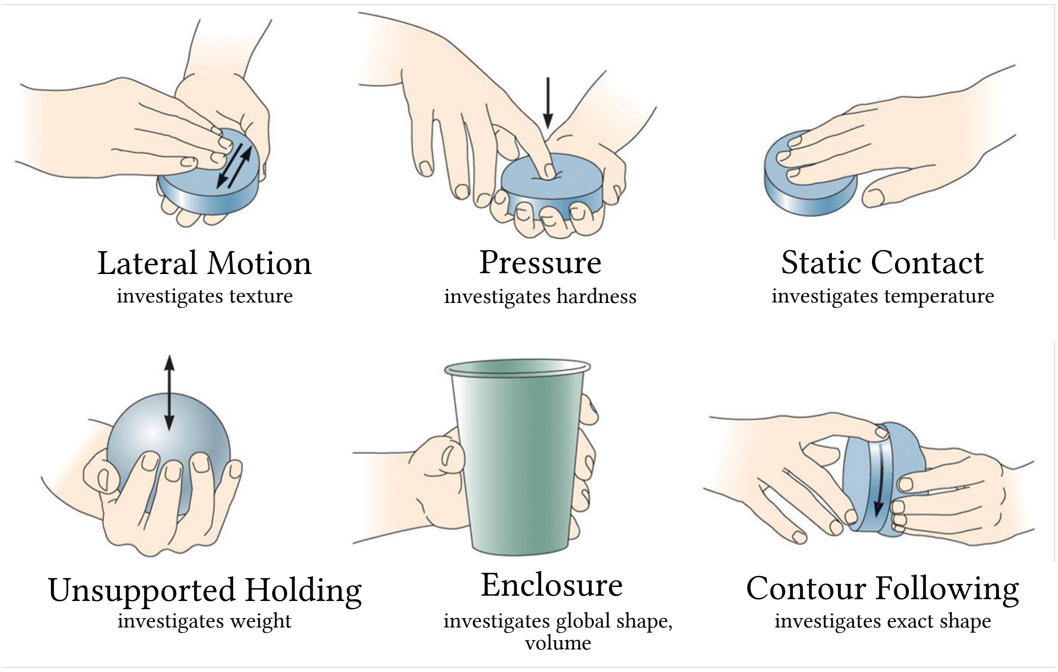


Figure 2.3: Exploratory Procedures as defined by Lederman and Klatzky (1987). Image adapted from Wolfe et al. (2018, p. 447).

ronment. As finger ridges interact with the underlying substrate they are in contact with, the resulting effect of pattern beating heightens our sensitivity. This increased temporal and spatial sensitivity allows us to discriminate sinusoidal gratings down to 13 nm in height (Skedung et al., 2013). When continuously exploring a surface formed of various bumps, we perceive them as vibrations that are appreciable up to 500 Hz with the highest sensitivity around 240 Hz (Israr et al., 2006).

The investigative difference between passive and active touch is also known as the *duplex theory* of tactile texture perception (Hollins and Risner, 2000). Therefore, in order to design effective tactile experiences, users have to be able to actively explore the world with their hands in order to fully appreciate physical impressions.

EXPLORATORY PROCEDURES The nature of contact, i. e., the manner in which and the duration of the exploration of an object, is tightly bound to the properties perceived (Lederman and Klatzky, 2009). Based on this understanding, Lederman and Klatzky (1987) investigate the typical movement patterns employed to engage in intentional exploration of haptic properties. These patterns, called exploratory procedures (EPs), are stereotyped movement patterns with certain characteristics that are invariant to others and highly typical. Each EP associated with an object property is executed spontaneously when information about that property is desired, and aims to optimize information uptake.

Depicted in Figure 2.3, the taxonomy of the set of basic EPs defined by Lederman and Klatzky (1987) is as follows.

- **Lateral Movement**: the skin is passed laterally across a surface to produce a shear force, to investigate *surface texture*;
- **Pressure**: force is exerted through, e. g., pressing into the surface, or bending or twisting the object, to investigate *compliance or hardness*;
- **Static Contact**: the skin is held in contact with the object's surface, to investigate *apparent temperature*;
- **Unsupported Holding**: the object is held while the hand is not externally supported, to investigate *weight*;
- **Enclosure**: the fingers or hands are molded closely to the object's surface, to investigate *volume and global shape*;
- **Contour Following**: the gradient of the object's surface or edges is traced during skin contact, to investigate *exact shape*.

Additionally, Lederman and Klatzky (1987) note the EPs of *function test* and *part movement* for compound objects that respectively perform a function, or consist of moving elements.

As specialized interaction patterns that maximize information intake about an associated object property, EPs are executed to optimize information apprehension for haptic perception (Lederman and Klatzky, 1987). Some EPs show compatibility to investigate haptic qualities other than their optimal associated property, e. g., contour following will also inform about an object's texture due to the presence of shear forces. However, other procedures are incompatible as they limit access to other properties, e. g., lateral motion to perceive texture does not transfer temperature information as static contact is required. Further work has underlined that some EPs can be executed together to investigate multiple object properties (Klatzky et al., 1987), e. g., by exerting pressure during lateral exploration both compliance and texture information can be acquired.

Additionally, EPs have been shown to adapt to what is known as the local context. For example, during exploration of an object expected to be rigid, greater force will be applied to determine compliance (Smith et al., 2002). Similarly, during roughness judgements, contact force will vary more for smoother samples than rougher ones (Tanaka et al., 2014).

From these insights, we note that lateral motion is of particular importance to allow users to investigate texture properties, while pressure is required for hardness evaluation.

DYNAMIC TOUCH Besides direct exploration, objects can be manipulated and wielded to interact with the world around us. Known as dynamic touch, this activity allows us to assess various object properties, including the kinesthetic properties of the manipulated object itself, and material properties of objects it comes into contact with (Gibson, 1983; Riley et al., 2002; Turvey and Carello, 1995). As the manipulated object affects the mechanoreceptors innervated in muscles and tendons during active wielding, the process can be employed

Figure 2.4: Through direct exploration (left), we are able to investigate tactile properties of objects and surfaces around us. In dynamic touch (right), we wield objects to interact with the world around us. Left image generated by the DALL-E 2 Engine, right image courtesy of Unsplash.

to assess mechanical qualities related to an object's moment of inertia and static moment, such as its length, width, and weight (Turvey et al., 1998). In VR, this effect has been used to simulate a wielded object's perceived weight and length (Zenner and Krüger, 2017), or its drag (Zenner et al., 2020; Zenner and Krüger, 2019).

When a wielded object comes into contact with other objects and surfaces, the resulting vibrations are transferred throughout the whole, e. g., though the use of a paintbrush as shown in Figure 2.4. Merely from these vibrations, it is possible to distinguish a variety of materials, such as wood, metal, and porcelain (Loomis and Lederman, 1986). Moreover, a surface texture's roughness is particularly well communicated during such manipulations. Such interactions have been simulated using computer generated vibrotactile actuation, e. g., for generating haptic textures when interacting with a slider (Strohmeier et al., 2018), for midair motion-to-vibration simulation (Strohmeier and Hornbæk, 2017), and even in perceptual modeling of fabricated styli (Piovarči et al., 2020, 2018).

In Chapter 9, we enable designers to create vibrotactile actuation through vocalizations while immersed in a virtual environment. Here, the controller is wielded as an intermediate actuator between the user and the virtual objects around them. Through dynamic touch, several haptic illusions can be perceived, including surface textures, length, and even complex interactions through sand or rocks embedded inside a virtual object.

2.1.2 *Visual Perception*

Where touch is considered as primal and direct, vision is a distant sense informing us about our surroundings (Hutmacher, 2019). It has the advantage of being able to easily recognize spatial relationships. However, these perspective mappings need to be learned to understand geometrical distances in the haptic space (Paterson, 2007, p. 73).

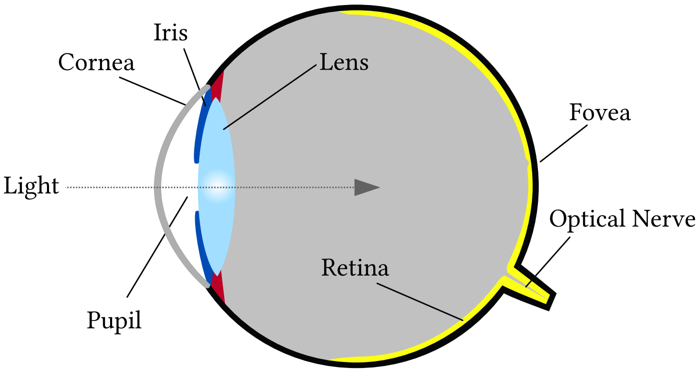


Figure 2.5: Diagram showing the human eye structure. Image recreated from Piovarči (2020).

As there is a subjective and cultural bias towards vision being the most important and complex of our senses, it has been studied to a much larger degree in research (Hutmacher, 2019). This has creates a self-reinforced scenario where more vision research is being performed, as present-day technology is better suited for studying vision than for studying other modalities. Consequently, VR technology has shown a great amount of progress in terms of visual acuity and resolution, and falls behind in terms of haptic technology.

In this section, we discuss the physiology of visual perception and how it is used to assess material and texture properties.

2.1.2.1 *Physiology of Sight*

Central to our visual perception is the sensory organ known as the eye (Wandell, 1995). The imaging components, shown in Figure 2.5, allow capturing light from its surroundings and transmit visual stimuli as electrical impulses through the optical nerves to the brain.

A transparent cover over the eyes, called the cornea, serves as a barrier between the inner eye and the outside world. Thanks to its dome shape, it aids in focusing incoming light. To adjust the amount of light entering the eye, the diameter of a small opening, called the pupil, is controlled through muscles connected to the iris. The iris is easily recognizable as the colored portion of the visible eye. Light is then focused by the lens directly onto the retina, where specialized photoreceptors respond to incoming light waves.

There are two kinds of photoreceptors, i. e., rods and cones, each with their own specialized functionality due to a specific wavelength sensitivity. Cones are highly sensitive to detail, provide tremendous spatial resolution, and are responsible for perceiving color. Rods, on the other hand, are sensitive to brightness, making them work well in low light conditions, and are responsible for perceiving objects' size, shape, and movement. Both rods and cones are connected to retinal ganglion cells, which converge through the back of the eye to form the optical nerve. A specific region on the retina called the fovea is densely packed with cone receptors, and the focal point of light projection from the lens where

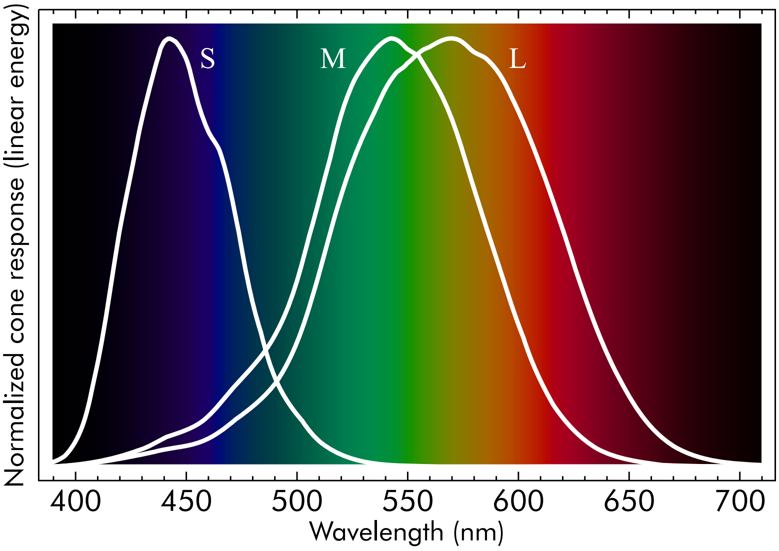


Figure 2.6: The human cone response as defined by Stockman and Sharpe (2000) plotted against the sRGB spectrum. Image from Wikimedia Commons (2009).

images are sharpest. Distributed throughout the remainder of the retina, rods build our perception in the periphery of our visual field and our sense of optical movements.

The following paragraphs detail on the visual perception properties of color and depth. Transferring these concepts into the virtual environment is key in creating effective and faithful visuo-haptic experiences.

COLOR PERCEPTION What is perceived as color, is an optical property defined by the wavelength of light entering our eyes (Hunt, 2004). To mediate color vision, three different types of cone receptors are present in the retina of the eye. Each receptor is sensitive to a specific wavelength, i. e., to short (400 nm to 500 nm), medium (450 nm to 630 nm), and long (500 nm to 700 nm) wavelengths, see Figure 2.6. They are also commonly referenced to as blue, green, and red receptors.

According to the trichromatic theory of color vision, all colors in the visible spectrum can be reproduced by combining different light sensitive cones. However, two visual stimuli with different spectral compositions can elicit identical neural responses in the brain, and thus be perceived as identical (Kingdom and Prins, 2016). These stimuli are called *metamers*, and are the result of photoreceptors responding to cumulative energy received from a broader range of wavelengths. Therefore, when reproducing colors, a predefined light source is used to change the spectral distribution of the illuminated surface to affect the perceived colors.

DEPTH PERCEPTION To understand spatial relationships in three-dimensional space, depth perception is mitigated through a variety of visual cues. A first set of cues are binocular cues that rely on the use of both eyes. For example, the slightly different positioning of each eye causes binocular disparity, i. e., slightly different views captured by each eye at the same time. During movement, this view disparity caused by interocular distance creates what is known as a parallax effect, where objects closer appear to move faster than objects further away. Furthermore, monocular cues relate to cues captured by a single viewpoint. Examples include linear perspective, where the conversion of seemingly parallel lines are perceived as depth, and partial overlap and relative sizing of objects, which hint at spatial positioning and sizing.

2.1.3 *Multisensory Perception*

As humans, we perceive the world through the use of multiple different sensory modalities. To understand how this influences our overall percept, this section provides an introduction into multisensory perception for the purpose of understanding sensory integration, crossmodal correspondences and conflicting visuo-haptic sensory information.

2.1.3.1 *Multisensory Integration*

Multisensory perception enables us to create robust internal representations of our environment (Ernst and Bülthoff, 2004). In the context of interface design, the addition of multimodal feedback has been shown to increase the intuitiveness of an interactive interface (Frid et al., 2019). Multimodal cues can increase the efficiency of sensory processing, and enable users to be more aware of ongoing events (Oskarsson et al., 2012). Moreover, when estimating object properties, the combination of cues stemming from different modalities tends to retain information better (Hillis et al., 2002).

The use of different sensory modalities can support the creation of perception in different manners (Ernst and Bülthoff, 2004). When different sensory channels receive complementary information, individual sensations are combined in the process of *sensory combination*. In *sensory integration*, redundant information from multiple sensory channels is integrated to create meaningful multisensory experiences.

Early investigations into intersensory cooperation, which focused on the visuo-tactile perception of surface texture details, found that bimodal visual and tactile sensory input is able to provide a higher level of accuracy in judgements of abrasiveness (Heller, 1982). However, when discrepant information is presented, a relative weighting of multiple sources of sensory information seemed to explain observers' judgements (Lederman and Abbott, 1981). In further investigations, a weighted averaging model described the nature of the intersensory integration process for both spatial density and roughness perception, with no fixed dominance hierarchy (Lederman et al., 1986).

More recently, sensory integration of visual and haptic stimuli was found to adhere to a statistical modelling process (Ernst and Banks, 2002). In a visual-haptic experiment, observers simultaneously looked at and felt two raised ridges. These ridges were presented sequentially, with one being the comparison stimulus where both the visual and haptic information was equal, and the other being the standard stimulus where a height difference was introduced between both sensory inputs. As the observers rated which modality's stimulus was taller, the visual modality was influenced by the addition of visual noise. From the psychometric results, it was shown that human observers may combine visual and haptic information in a manner similar to the statistical model of maximum-likelihood estimation (MLE). From this, the understanding follows that each modality's information is integrated as a weighted sum based on its reliability to form the entirety of the perception.

Multisensory perception not only influences how perception is built, but alters the manner in which each sense is utilized to acquire information. Klatzky et al. (1993) found that when objects can be viewed as well as touched, specialized EPs tend only to be executed when specific material properties are to be investigated. Visually salient textures, such as coarse sandpaper, will be unlikely to elicit haptic exploration. However, when the aim is to determine specific roughness information of the surface, the EP of lateral motion was performed explicitly.

2.1.3.2 *Visuo-Haptic Mismatching*

In the case of mismatching information, models for multisensory perception aim to predict the experience of an observer, and if the observer will notice any discrepancies, or if a unified percept is built.

The MLE model of multisensory integration dictates that a single modality is able to show dominance over others. This can be seen as a vetoing of a sensory modality to overcome conflicting inputs and still serve a successful and meaningful overall percept. Most commonly known, is the case of *visual dominance*, where visual information overrules other sensory input. In certain cases, visual dominance is so powerful in relation to touch that the very touch experience itself undergoes a change. As shown by Gibson (1983), distorting of an observer's vision can lead to the perception of curvature during visuo-haptic exploration of physically straight lines. This illusion was so strong that it remained, even when observers were instructed to dissociate the two sensory modalities.

For surface textures, the addition of haptic feedback has been shown to change the subsequent visual perception of surface slant (Ernst et al., 2000). Similarly, Kitahara et al. (2010) investigated mismatching visuo-haptic stimuli during surface texture exploration through lateral motion and edge perception through contour following. In a two-part study, an augmented reality setup was used to project different visual stimuli over physical surfaces and edges. For edge perception, they note that when the curvature radius became larger, the haptic sensation was duller, indicating the occupancy rate of visual stimuli increased.

In terms of haptic dominance, Beers et al. (2002) show that the reliability of haptic sensory information for proprioception can be increased. Their results support the optimal integration model, and underline that sensory weights are flexible, varying with experimental conditions, such as active versus passive movement, or direction. This shows that careful design of visuo-haptic experiences is able to reliably influence users' overall perception.

However, breaks in illusions drastically influence overall percept, as shown by Rock and Victor (1964). Here, authors used a transparent plastic as an optical lens to visually reduce the width of a small white square. During tactile exploration in the presence of a distorted image, observers were asked to draw a picture of the perceived shape. The ratio of the drawn square was clearly biased by visual perception and indicated a high level of visual dominance. As half of the participants became aware of the conflict, the dominance effect shifted, which led to a tendency to resolve the conflict in favour of the haptic perception.

2.1.3.3 *Crossmodal Correspondence*

As perceptual processes build our understanding of the world, perceptual representations stemming from different modalities are shared between the senses. This is known as crossmodal interaction and describes how the senses influence each other (Lin et al., 2021; Spence, 2011; Spence and Parise, 2012). For example, a new object being experienced without vision, can still be recognized visually based on features accessed through both vision and touch, such as size, shape, or texture (Dopjans et al., 2009; Wallraven et al., 2014).

A particular class of crossmodal interactions are non-arbitrary associations between features of different stimuli, known as crossmodal correspondences (CCs). Spence and Parise (2012) define them as *"a tendency for a sensory feature, or attribute, in one modality, either physically present or merely imagined, to be matched (or associated) with a sensory feature in another sensory modality"*. CCs serve to understand how sensory modalities relate to and influence each other, and have been documented between pretty much every pair of sensory modality (Spence, 2011). Showcased by the well-known 'rubber hand illusion' (Botvinick and Cohen, 1998), CCs can give rise to sensory illusions, as they might occur even without the presence of actual physical stimuli. These synaesthetic associations between the senses have been used in visuo-haptic illusions, e. g., through pseudo-haptic feedback (Speicher et al., 2019a), and are recognized as highly relevant future directions for the design of haptic interfaces (Haans and IJsselsteijn, 2006).

In Chapter 7, this dissertation looks towards CCs between the tactile perception of 3D-printed surface features and the visual perception of virtual textures. Through visuo-haptic associations of surface impressions, the design of visuo-haptic experiences for IVEs can be enhanced using personal fabrication methods.

2.1.3.4 *Iconicity and Sound-Symbolism*

In visual, spoken or other modalities of communication, the term *iconicity* is used to indicate a relationship or resemblance between form and meaning (Lockwood and Dingemanse, 2015). Specifically, for spoken language, the term sound-symbolism is used to refer to associations between language sounds or vocal expressions, and perceptual or semantic

Figure 2.7: Onomatopoeia are commonly used in comics and graphical novels to communicate other perceptual events, such as the non-word *ptang* here used to depict a bullet hitting a metal can. Image from Kirkman and Moore (2004).

features (Lockwood and Dingemanse, 2015; Sidhu and Pexman, 2018). The research field of iconicity has been connected to CCs in studies investigating synaesthetic sound symbolism to capture mappings between form and meaning that cuts across sensory modalities, with speech sounds representing content from other modalities, such as the visual or tactile properties of objects (Ćwiek et al., 2022; Hinton et al., 1995).

In terms of speech, ideophones are words that depict sensory imagery and cover a wide range of domains, such as motion, texture, and even psychological states (Akita and Dingemanse, 2019). Onomatopoeia are well-known examples, that use written language for expressing sounds (Guynes, 2014). As shown in Figure 2.7, onomatopoeia are abundantly found in comics and graphical novels to express and emphasize ongoing events through the use of crossmodal interactions.

As a phonic modality of speech, onomatopoeia and mimetic words are able to communicate perceptual qualities such as the visual appearance of metal textures (Sakamoto et al., 2016; Yakata et al., 2013), tactile sensations (Schneider and MacLean, 2014; Watanabe and Sakamoto, 2012), or emotional qualities of those sensations (Watanabe et al., 2012), and can even be used to transfer embodied expertise (Hojo et al., 2014). Perhaps the most well known, is the *'bouba/kiki'* effect (Ćwiek et al., 2022; Ramachandran and Hubbard, 2003), where these non-words have consistently been associated with the visual spikiness of a shape, illustrated in Figure 2.8.

Iconic vocalizations have been shown to describe tactile sensations (Schneider and MacLean, 2014; Watanabe and Sakamoto, 2012), and to ground and communicate design intention (Arab et al., 2015; Brunet et al., 2013). While they show great potential for expressing tactile impressions, outside the cultural consistency of *'bouba/kiki'* effect (Ćwiek et al., 2022), vocalizations are highly dependent on the cultural background of the speaker (Sasamoto,

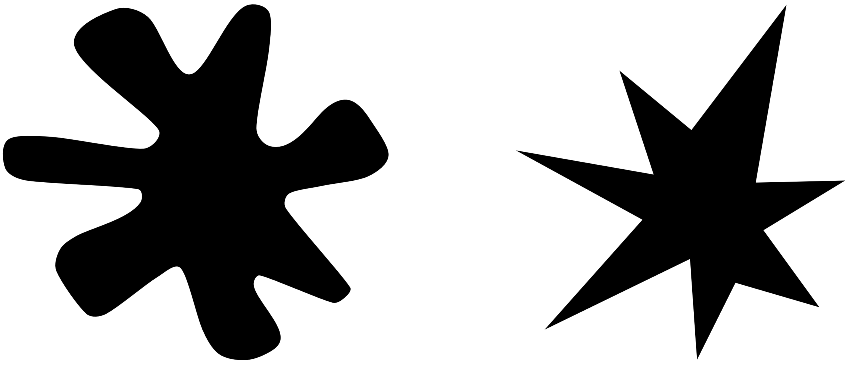


Figure 2.8: The bouba/kiki effect. Here, people overwhelmingly assign the non-word 'bouba' to the left shape and the non-word 'kiki' to the right shape (Ramachandran and Hubbard, 2003). Image adapted from Ćwiek et al. (2022).

2019). To abstract from these dependencies, research has focused specifically on the acoustic properties of vocalizations. For example, the pitch of sound has been associated with roundness (O'Boyle and Tarte, 1980).

In Chapter 8 and Chapter 9, this dissertation investigates the use of linguistic features of vocal expressions to enable an in-situ haptic design process in IVEs. One major inspiration for the use of vocalizations, is the work by Marino et al. (2017), where they have been used to sketch movement for a single degrees-of-freedom (DOF) robot. This resulted in an iterative and intuitive design process, with the use of phonetic features, such as amplitude and pitch, building more affective behavior in the robotic movements.

2.2 PSYCHOPHYSICAL INVESTIGATION

From an understanding of the basic constituents that make up our perception, we continue with an investigation of how perception can be studied through psychophysical procedures. The notion that touch has a psychological component was first established by Ernst Heinrich Weber, whose work is considered *"the foundation stone of experimental psychology"* (Fretwell, 2020, p. 229). His work described in *De Subtilitate Tactus* (Weber, 1834) and *Der Tastsinn und das Gemeingefühl* (Weber, 1846) was the first body of knowledge about human sensation based on experimental methods for measuring subjective experiences.

2.2.1 *Psychophysics*

The formal investigative tool to study associations between one's psychological state and the physical environment, was described by Weber's doctoral student Fechner (1860). He was the first to define the term psychophysics and defined it as *"[. . .] an exact theory of the functionally dependent relations of body and soul or, more generally, of the material and the mental, of the physical and the psychological worlds."*. With this proposition, he built the understanding that physical stimuli as received by the body and their interpretation by the mind are related through a function that can be unraveled through experimental studies.

In such psychophysical user studies, environmental stimuli are varied in order to influence the respective sensations by the sensory organs, which in turn influences users' perceptions. In order to build an understanding of the effects and their parametric range, users provide statements of their personal perception. Through these results, we specifically aim to know if a user can detect stimuli, describe their magnitude, differentiate between different (levels of) stimuli, or associate a stimulus with physical properties.

The remainder of this section provides an overview of the fundamentals of psychophysics, and details on the procedures and methods applied in studies in this dissertation.

2.2.2 *Experimental Components*

The outcome of a psychophysics experiment is typically a set of measures which reflect the particular question asked about sensory function (Kingdom and Prins, 2016, p. 12). To this aim, a number of experimental components needs to be carefully streamlined to achieve the experimental goal. These components are the *stimulus* being varied, the *task* the user needs to perform, the *method* defining the manner in which each stimulus is presented, the *measure* taken as rated by the user for each trial, and the *analysis* to process the measures.

One example in the study of vision is called the measure of a *contrast detection threshold*, and is defined as the minimum amount of contrast needed for a stimulus to be just detectable, see Figure 2.9. In one version of this experiment, the contrast between a specific patch and its background is varied in terms of luminance level. The contrast difference is known as the Weber contrast and the detection threshold is therefore the smallest value of Weber contrast needed to detect the patch. In each trial, the stimulus being presented to the user, is the patch at a certain luminance level.

For this study, different methods and tasks can be implemented. For example, in the *method of adjustment* the user is presented with a setup where they have the task to manually adjust the contrast until the stimulus is just visible. Alternatively, the user can be asked to perform a two-interval forced-choice (2IFC), where two consecutive stimuli are presented briefly on each trial. The user must then rate, for each trial, which stimulus contained a visible patch, which is scored as "correct" or "incorrect". For the standard 2IFC task, different methods can be used to select the contrasts presented on each trial. A preselected set of contrasts, e. g., by using a fixed amount of contrasts with fixed intervals, is known as the *method of constants*. Alternatively, an adaptive method, able to select the contrast on each trial based on previous trial responses, is able to shorten the duration of the experiment and defined the threshold with more accuracy.

Lastly, to interpret the results of the experiments, the data collected during the experiment need to be converted into measures through the selected analysis. For the the method of adjustment the final settings across users could be averaged to obtain the threshold, while

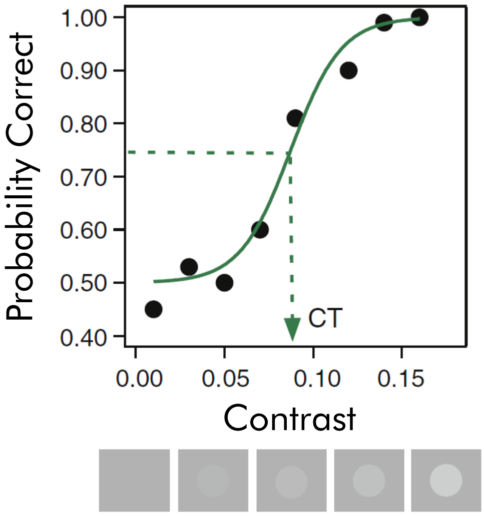


Figure 2.9: Example results for the contrast detection threshold study. The black circles represent the proportion of correct responses for each contrast level. The green curve is the best fit of a psychometric function, and the calculated contrast detection threshold (CT) is indicated by the arrow. Image adapted from Kingdom and Prins (2016, p. 13, fig. 2.2).

for the 2IFC procedure in conjunction with the method of constants, the proportion of correct data can be fitted to a function with a shape matching the data. Here, the fitting procedure is used to estimate the threshold as a proportion of correct indications, with a commonly accepted proportion of 75%.

The results of the fitting procedure present a functional model that describes the relationship between physical stimuli and human perception. It provides an understanding of the differential sensitivity to the stimulus in question, i. e., *detection* and *discrimination* thresholds (Gescheider, 1997). Here, the former describes the required intensity for a stimulus to be detected by a user, while the latter defines the required difference in intensity between two stimuli of the same modality for users to be able to detect a difference between both. The minimum amount of intensity variation to be detected is also known as the just-noticeable difference (JND).

Weber's law states that that JNDs are proportional to the baseline stimulus magnitude, which has been shown to remain valid for all sensory modalities (Kingdom and Prins, 2016, p. 228). This is illustrated in the contrast detection study, where the detection threshold of the patch is dependent on the luminance of the background. Fechner's law builds upon this and states that the underlying perceptual scale could be approximated by a logarithmic function (Kingdom and Prins, 2016, p. 228).

It is to be noted that during studies of human sensory perception, the *problem of subjectivity* arises (Schmidt, 1986, p. 1). That is, due to the fact that perceptions are highly personal, the responses given by users are affected by a number of subjective aspects. For example, an individual's internal state, such as their mood, or the context in which the investigation occurs, might influence perceptual ratings. Therefore, psychophysical experiments provide generalized assessments of stimuli and their effects, rather than absolute ratings.

2.2.3 *Procedures and Analysis*

To correctly address the experimental goal, the procedure applied during a psychophysics study needs to be tailored. Kingdom and Prins (2016, p. 32) present an initial classification scheme to guide experimenters in the abundance of available procedures.

Firstly, experiments can either be performance-based or appearance-based. Performance-based experiments measure something that affords a comparison in terms of aptitude, and are aimed to detect either thresholds, or other measures, such as accuracy or reaction times. Appearance-based experiments, on the other hand, measure the apparent magnitude of some stimulus dimension, and can detect perceived matching rates, i. e., point of subjective equality (PSE), perceptual scales, or other measures. Lastly, each procedure can either present the user with a forced-choice or non-forced-choice approach, where respectively the user is either forced in evaluating a limited set of stimuli for each trial, or has the freedom to indicate a value within a given range.

The work performed in this dissertation mainly addresses the class of appearance-based experiments, where the rated appearance is in fact a perceptual tactile property. Specifically, our work uses scaling assessments where users are asked to rate their subjective perception of a presented stimulus on a fixed scale addressing one perceptual feature. We further detail on two procedures implemented in the work in this dissertation, i. e., the *Semantic Differential Method* or *Magnitude Estimation*, and the *Similarity Estimation Method* or *Forced-Choice Paired Comparison*, and elaborate on analysis through *Multidimensional Scaling* (MDS).

SEMANTIC DIFFERENTIAL METHOD In the field of psychophysics, the *Semantic Differential Method* is also known as *Magnitude Estimation*, a non-forced-choice scaling procedure (Kingdom and Prins, 2016, p. 51). Using this approach, participants rate the perceptual properties of individual samples during each trial (Okamoto et al., 2013). Commonly, ratings provided by participants are selected from a fixed scale, e. g., a five or seven-point scale, with opposing pairs of adjectives, such as 'smooth' and 'rough'. Other implementations allow participants to rate stimuli using an open scale, where they provide any number that translates the perceived stimulus into a numerical result. As long as participants remain consistent in their assessments, data normalization will yield robust results. Lastly, it is also possible for participants to assess a presented stimulus through using a magnitude proportional to a modulus, e. g., 50% of the baseline. Originally devised by Osgood et al. (1957), this method was first applied to study tactile perception by Yoshida (1968).

The data obtained allows for mostly straightforward statistical analysis to interpret fundamental perceptual ratings. However, the results remain limited by the scale descriptions used, and can therefore lead to unextracted perceptual dimensions. Therefore, the labels should be chosen such that they cover all potential dimensions. In most of our studies, we use this procedure to assess different tactile dimensions of surface samples, and to evaluate the matching rate between perceived stimuli stemming from different modalities.

SIMILARITY ESTIMATION METHOD Using the *Similarity Estimation Method*, also know as the *Forced-Choice Paired Comparison* (Kingdom and Prins, 2016, p. 50), participants rate the perceived similarity of paired samples (Okamoto et al., 2013). While different implementations exist, commonly such methods fall within one of three groups, i. e., ratio judgment, grading, and visual analog scaling. During ratio judgements, for each trial participants estimate the relative perceptual distance between two presented samples using arithmetic values. For grading methods, a fixed scale, e. g., a seven-point Likert scale, is used to rate the similarity between two samples. Lastly, for visual analog scaling, the relative distance between samples is rated through placing a mark on a line with endpoints representing two perceptual extremes, e. g., "opposites" and "identical".

The data obtained is commonly analysed through a Multidimensional Scaling (MDS) analysis, which we further elaborate on below. In Chapter 5, we utilize the *Similarity Estimation Method* combined with a variation of MDS to generate a perceptual space for understanding distances between original and replicated surface samples.

MULTI-DIMENSIONAL SCALING To investigate semantic meaning and associate perceived stimuli with physical phenomena, it is possible to generate a *perceptual space*. This is a multidimensional embedding of stimuli in which their perceived dissimilarity represents their Euclidean distance. From the data obtained through the *Similarity Estimation Method*, similarity ratings can be converted into a symmetrical dissimilarity matrix. Using this, MDS performs an ordination resulting in an r-dimensional space where each sample is placed such that the original distances between samples are optimally obtained (Kruskal, 1964; Torgerson, 1952). In our work, we utilize non-Metric Multidimensional Scaling (nMDS), a rank-based approach that substitutes the original distance data with ranks. This method has been shown to fit human similarity data more consistently than classical metric MDS, and is therefore commonly applied in the field of haptics (Cooke et al., 2006; Culbertson et al., 2013; Vardar et al., 2019).

A drawback of the MDS method is that the resulting space has an indeterminate orthogonal rotation, meaning that individual axes never correspond to individual psychophysical dimensions. To ensure interpretation of the obtained results, commonly a perceptual space is related back to other obtained measures, such as physical measurements or other perceptual assessments. For example, Vardar et al. (2019) utilized a Procrustes analysis to transform perceptual spaces generated from visual and haptic similarity assessments of tactile samples, to a 3-dimensional space of physical measurements. In our work, we follow a similar approach and transform a 3-dimensional space of physical sample measurements to a perceptual space to understand which physical features influence tactile perception.

2.3 MATERIAL AND TEXTURE PERCEPTION

The tangible world around us consists of a highly diverse set of objects and surfaces with varying material and geometrical qualities. As our eyes capture their appearance and our fingertips reach into contact, individual sensations are integrated into judgements of physical, functional, and multisensory properties (Fleming, 2017). In turn, we effortlessly use these impressions evaluate and resolve further interactions.

With this dissertation, we aim to improve on the design of tactile experiences for IVEs. To understand how effective tactile experience are constructed from variations of physical qualities, both in terms of haptic and visual stimuli, we detail on the perceptual dimensions that elicit material perception.

2.3.1 *Perceptual Investigations*

As different physical features are integrated into judgments of textures and materials, research has given much attention to the principal perceptual dimensions of touch. This line of work aims to minimize the dimensions that build tactile perception into a set of discrete descriptors. Common to these approaches is the use of MDS methods to construct perceptual spaces from user's subjective ratings of a given set of samples. Relating the resulting axes back to physical measurements or individual assessments provides insights of the underlying factors that cause their differences in perceptions.

In one of the earliest approaches, Yoshida (1968) applied a semantic differential method to study the tactile perception of a set of 50 samples varying in texture, shape, size and material. In the presence of vision, each sample's haptic perception was rated using a set of 20 qualities on a seven point scale. A correlation analysis between the semantic differential ratings revealed four main factors influencing perception. Here, the first factor represented the perception of heaviness and coldness, the second indicated smoothness and wetness, the third depicted hardness, while the fourth differentiated haptic and visual impressions. Furthermore, MDS indicated opposite material clusters of fibers and metals, separated by physical properties of mass, thermal conductivity, plasticity and hardness.

Similarly, Hollins et al. (2000, 1993) aimed to reduce physical features into a minimum set of descriptors. Using a set of 17 diverse stimuli, such as sandpaper, wood, velvet, cork, participants were asked to describe their tactile impressions using adjectives. A MDS approach revealed major axes to correspond to the description of roughness (smooth vs. rough) and compliance (hard vs. soft), while minor axes were attributed to frictional properties (sticky vs. slippery) and temperature (warm vs. cold). Moreover, as these dimensions were found not to be orthogonal, cross-correlations between attributes exist.

Using the results of a free sorting study with 124 texture samples, Bergmann Tiest and Kappers (2006) performed MDS and noted that their material space was four-dimensional. As their set of samples was of higher order than previous studies, they posit that 'less-important' haptic differences were able to surface, through highly detailed distinctions made by participants. Their perceptual space shows a 'horseshoe' shape, which may indicate that the haptic material space cannot be represented as a simple Euclidean space. Furthermore, through embedding mechanical qualities of compliance and roughness into the perceptual space, correlations between the dimensions were apparent, however, not completely aligned. From their results, they note that roughness had a highly strong effect on perception, but perceptual dimensions were tangled across features.

In a further investigation, Vardar et al. (2019) conducted two psychophysical experiments using a set of 10 real surfaces from the Penn Haptic Texture Toolkit (Culbertson et al., 2014c), with the first investigating their visual perception, and the second their haptic perception. From the similarity ratings collected from participants, two perceptual spaces were generated from the respective studies. Additionally, physical measurements were calculated from accelerometer and force measurements during an experimenter's fingertip exploration of the surfaces. From these measurements, hardness was estimated through calculating the spectral centroid during tapping, roughness through the vibration power during sliding, and stickiness through the kinetic friction coefficient. Using Procrustes analysis, the perceptual spaces were linearly transformed to fit the physical measurements space. From these results, authors note that vision and touch rely on congruent perceptual representations, and therefore both modalities are perceived similarly, but judged separately.

In Chapter 5, we similarly construct a perceptual space from similarity assessments taken during a user study. Using a Procrustes analysis, we relate this space back to physical measurements taken from our set of 3D-printed surface samples to assess how the replication and fabrication process influence tactile perception. This provides further insights into the perceptual dimensions of fabricated surfaces, and serves as an initial investigation to more accurately reproduce the haptics from real surfaces.

2.3.2 *Psychophysical Dimensions*

The tactile perception of textures and materials is commonly decomposed into a total of four psychophysical dimensions, i. e., roughness, hardness, warmness, and friction (Bergmann Tiest, 2010; Loomis and Lederman, 1986; Okamoto et al., 2013). Here, the dimension of roughness is generally accepted to be the main contributor of tactile perception, and is often attributed as a complex composite dimension which can be further divided into macro- and micro-roughness. The latter dimension of friction is also understood as the stickiness dimension, and additionally involves sensations of moistness or dryness.

In order to understand how to improve on the design of tactile experiences, we evaluate samples through user studies investigating their psychophysical dimensions, and their matching rate with visual stimuli. To this aim, the remainder of this section provides an overview of each property separately, and concludes with an overview of interactions between them.

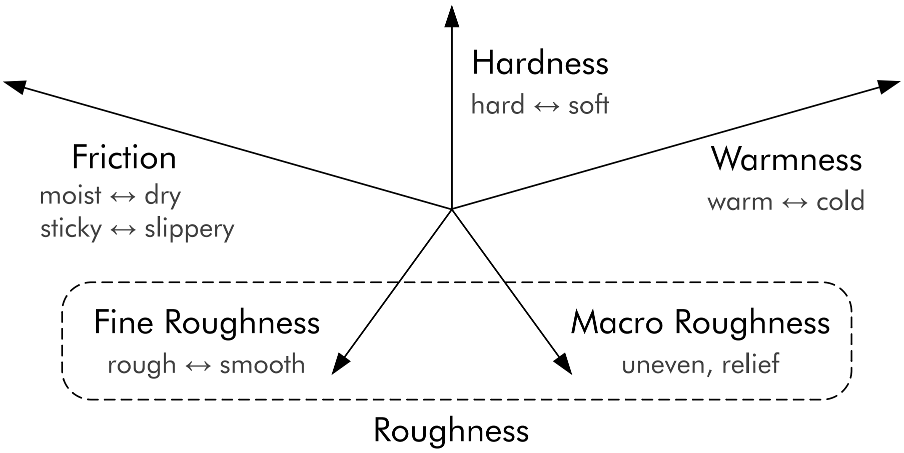


Figure 2.10: The psychophysical dimensions of tactile textures, as proposed by Okamoto et al. (2013) through an in-depth review of studies investigating the tactile dimensionality of physical properties of textures and materials.

2.3.2.1 *Roughness/Smoothness*

Attributed as the most important feature for discriminating haptically explored surfaces, roughness is the most studied dimension of tactile perception (Bergmann Tiest, 2010; Bergmann Tiest and Kappers, 2006; Hollins et al., 2000, 1993; Okamoto et al., 2013). Physical roughness refers to height differences on the surface of an object, and can be measured and expressed in different ways. In Chapter 5, we determine the physical roughness of surface texture samples by calculating the root-mean-square of the reconstructed height fields, which is based on a common approach in manufacturing processes (Black, 2019).

Perceptually, roughness is dependent on the height differences of a surface texture, the spatial period and spacing of its variations, and its material friction coefficient. Specifically, perceptual roughness can be subdivided into macro- and micro-roughness, respectively mediated through two distinct channels, i. e., spatial variations of coarser surfaces, and vibrations mitigated by fine-structured surfaces. This is supported by the *duplex theory* of texture perception, which states there is a difference between passive (or static) and active touch perception of tactile textures (Hollins and Risner, 2000), see Section 2.1. Namely, during static touch, the impressive discriminative power of our fingers allows us to identify embossed dots down to 550 µm in diameter and a height of only 3 µm (Wang and Hayward, 2008). However, during active exploration, our sensitivity to surface textures is increased even further. The finger ridges interact with the underlying substrate, and the resulting effect of pattern beating heightens our sensitivity, which allows us to discriminate sinusoidal gratings down to 13 nm in height (Skedung et al., 2013). During such continuous exploration of a surface, height variations are perceived as vibrations, leading to a perceived roughness associated with the respective amplitude, weighted with the frequency response of the Pacinian receptors (Bergmann Tiest, 2010). These vibrations are appreciable up to 500 Hz with the highest sensitivity around 240 Hz (Israr et al., 2006). These insights provide a basis for the design of tactile roughness for both passive structures and active vibrations.

Additionally, perceptual roughness is also dependent on the spatial and temporal context (Kahrimanovic et al., 2009). For example, a surface that is felt just after a smooth surface has been explored, feels rougher than the same surface when it is felt just after a rough surface has been felt. This effect has been found to work both ways, meaning it is not caused by fatigue in the receptors, but of processes at a higher level. Additionally, while exploring different surfaces with the index and the middle finger, a rougher surface under the middle finger will cause the surface under the index finger to feel smoother. Therefore, in terms of perceptual studies investigating roughness, counterbalancing and consistent surface exploration remain essential.

2.3.2.2 *Hardness/Softness*

Hardness or compliance is the second most attributed perceptual dimension of tactile textures (Bergmann Tiest, 2010). Physically, hardness can be expressed through an object's stiffness, i. e., the ratio between the force that is exerted onto it and the resulting displacement. Here, stiffness is dependent on the object's dimensions, meaning a thick narrow object can be compressed more than a thin wide object of the same material when the same force is applied. Compliance can also be expressed through a material's *Young's modulus*, i. e., the ratio between pressure (force per unit area) and relative displacement (the displacement divided by the original length). This method is independent of the object's dimensions for so called linear materials. Alternatively, the spectral centroid of a recorded acceleration signal when tapping an object can be used to discriminate hardness (Culbertson et al., 2013; Vardar et al., 2019). In Chapter 5, we build upon the first approach and measure the physical hardness of surface texture samples by recording the indicated weight on a load cell when multiple stacked layers of the surface with a uniform height were compressed with a fixed displacement (Panetta et al., 2015).

Perceptually, compliance can be investigated through either pressing down on, or tapping a surface with one finger, or through squeezing an object between fingers. From these interactions, about 90% of information comes from surface deformation cues, while the remaining information stems from kinesthetic (force and displacement) cues. Discrimination values are commonly expressed in terms of Weber fractions, i. e., the ratio of the just-noticeable difference (JND) to the intensity of the stimulus. With both kinesthetic and cutaneous cues present, discrimination is possible down to Weber fractions of ($\sim$ 15%), while only cutaneous cues during passive pressure lead to Weber fractions of ($\sim$ 50%). This underlines the need for appropriate haptic exploration methods during user studies to ensure perceptual ratings of hardness are consistently investigated.

2.3.2.3 *Warmness/Coldness*

Warmness or coldness still remains an underexplored dimension of tactile perception. Physically, it is directly related to material properties of heat capacity and thermal conductivity, and the geometry of the object in question (Bergmann Tiest, 2010). Modeling approaches describe coldness by cooling the finger along a curve, and generally show a shape similar to exponential decay. In our work, we did not consider physical measurements of coldness.

Perceptually, coldness is investigated through direct contact with a surface. Discrimination experiments explore coldness perception in relation to a material's contact coefficient, its thermal diffusivity, or its heat transfer rate. Depending on the chosen method, thermal parameters for discrimination ranges from about 40% to 200% or more. As there is a direct relation with the material in question, coldness perception can be used to identify different materials. When comparing real surfaces to replicated counterparts, or investigating matching rates between fabricated samples and virtual objects, coldness perception can give way to discrepancies in the perception of tactile surfaces. While we do not normalize or control for perceptual coldness, we take these indications in consideration to assess how discrepancies are perceived and how much they contribute to the general percept.

Interestingly, while physical coldness is independent of room temperature, it directly influences perceptual coldness. Generally, heat transfer rate upon contact is larger for thicker stimuli, meaning a thinner object will be perceived warmer. However, from a room temperature of around 34 °C and higher a reversal phenomenon takes place, where thinner stimuli will be perceived colder than thicker ones (Bergmann Tiest and Kappers, 2008).

2.3.2.4 *Friction (Slipperiness/Stickiness, Moistness/Dryness)*

Similar to coldness, research involving the haptic perception of slipperiness is still in its early stages, and remains underexplored. Slip is caused by the relative motion between the fingertip and the surface. Physically, slipperiness is related to the friction between the material and the skin during exploration (Bergmann Tiest, 2010). Frictional force works in the opposite direction of the applied motion, and depends on the speed of movement. Here, the *coefficient of friction* is the ratio between the frictional force and the normal force. It is important to distinguish stickiness from adhesiveness, where the latter is defined by attractive forces between an object's surface and a probe, commonly caused by compounds or properties other than a surface's geometry or material. In our work, we classified slipperiness in texture samples through measuring static friction. Here, we recorded the angle of inclination a fixed object on top of the surface would start a movement (Kurtus, 2005).

During fingertip exploration, slip perception provides tactile cues of the relative speed and the relative orientation (Salada et al., 2004). Such cues are important during dexterous object manipulation (Khurshid et al., 2017), as well as recognizing surface texture information (Salada et al., 2005). For conscious perception of slipperiness of surfaces, movement is essential to ensure accurate perception. During exploration, slipperiness is perceived through both kinesthetic and cutaneous channels, whereas the latter is mediated by rapid adapting mechanoreceptors, i. e., Meissner or Pacinian corpuscles, depending on whether the slip of a single dot or a textured surface is perceived, respectively. While humans are able to perceive different levels of slipperiness quite accurately, fundamental research has not yet determined a perceptual model of slip perception.

Similarly, moistness perception remains an open challenge for research. Interestingly, there is no physiological basis for moistness detection in humans, as the human skin does not have the ionotropic receptors required for hygrosensation (Filingeri, 2015). It is commonly accepted that moistness perception is regulated through integration of tactile and temperature sensations, however no perceptual model has been determined. In our work, we choose not to include investigations into moistness perception, as all surface samples used were not regulated or controlled in terms of wetness.

2.3.2.5 *Interactions*

Furthermore, interactions between different tactile perceptions exist (Bergmann Tiest, 2010). As a rougher material might grip the skin on the finger more due to the surface variations present, perceived slipperiness is potentially rated differently. Visa-versa, a surface with a high coefficient of friction might be considered rougher due to a learned association between both perceptions. Similarly, a more compliant surface will create a larger contact area between the finger and the surface, potentially influencing heat transfer and friction.

In our work, we noted an interaction between a surface's compliance and its roughness and stickiness perception. As 3D-printed surface samples were less compliant than their textile originals, during interaction the substrate beneath the finger was less likely to deform during exploration. This potentially influenced roughness and stickiness perception, as harder surfaces emphasized variations in their micro-geometries.

2.3.3 *Material Perception*

Materials are an integral part of what defines objects (Fleming et al., 2015, 2013). For example, a screwdriver made out of butter will most likely not perform the same as one made from metal. Material identification and classification is essential to understand object affordances.

In order to perceive materials and their properties, vision plays an essential part (Fleming, 2017). Through a feedforward process of visual perception, low-level vision extracts local image features, such as the responses of spatio-temporal filters tuned to different orientations, spatial frequencies, and colors. These low-level image measurements are processed into mid-level surface computations, i. e., estimating material properties, followed by high-level recognition processes, i. e., recognizing materials. Mid-level vision is thought to create a high-dimensional feature space for describing different materials, such as estimates of surface properties, e. g., glossiness, or texture, and potentially also physical properties, e. g., hardness, or roughness.

When exploring surfaces and objects, multi-modal investigations are used to understand their textures and materials. As material perception is built through sensory integration processes, research has investigated how different modalities correlate to each other. In terms of roughness, Bergmann Tiest and Kappers (2007) found that the visual correspondence with the physical ordering was approximately of the same level as the haptic correspondence. Analogously, investigations of softness determined that there is a high overall perceptual correspondence between haptically or visually exploring materials (Cavdan et al., 2021). Moreover, in terms of affective properties, visual, auditory, and tactile evaluations have been shown to correlate for material properties of wood (Fujisaki et al., 2015).

In our work, we build visuo-haptic experiences through combining tactile impressions with visually overlaid textures. Through user studies, we investigate if the presented illusion builds a successful material perception, or if both controlled modalities are conflicting. In parts of our work, we ask users to describe the sensation and perception they acquire, which we examine to understand the perceived materials, their underlying material properties, and also the affective qualities communicated by each combination. This allows us to understand the dominant modality and its respective sensations, and additionally hints at how users make sense of mismatching impressions.

2.4 CONCLUSION

The subject of interest in this work lies with the sense of touch, arguably our most primitive sense. Touch sensations arise from mechanoreceptors innervated in our skin, muscles, and tendons. Through different patterns of haptic exploration, touch allows us to explore physical objects and surfaces around us to understand their tactile and kinesthetic properties, such as their hardness or weight.

Designing for the sense of touch presents a multi-modal challenge. As humans, we experience the world around us through different senses. Our perceptual processes integrate perceptions from different sensory modalities to create robust internal representations. Even when mismatching information occurs, these processes aim to make sense of our environment, which might lead to one modality showing dominance over the other. Moreover, perceptual representations stemming from different modalities are shared between the senses, which might lead to crossmodal correspondences, i. e., non-arbitrary associations between features of different stimuli, such as sound-symbolic words in language.

In order to design effective tactile experiences, we must understand how to study them. This is done using psychophysics, the formal investigative tool for examining the relationship between the physical world and one's psychological state. Using this tool, different procedures and analyses allow us to understand when a sensation is perceived and how it compares to other sensations of the same, or even different, modality. Moreover, by investigating semantic meaning and associating perceived stimuli with physical phenomena, it is possible to generate perceptual spaces that visualize differences between stimuli.

Of particular interest to this work, is the perception of materials and textures. Whereas an object's material is defined by the matter it is made of, its texture is defined by the composition of its surface properties. Perceptions of materials and textures are built through different psychophysical dimensions that are investigated using varying exploratory procedures. During lateral motion, surface variations give rise to perceptions of (macro and fine) roughness, and friction, applying pressure investigates an object's hardness, while static contact enables us to investigate the dimension of warmness. In turn, these individual perceptions are integrated and combined with visual qualities to successfully build material perception. Previous work has established methods and procedures to study the perception of different material and texture properties, providing us with the foundation to investigate the design of tactile experiences in IVEs.

Cyberspace. A consensual hallucination experienced daily by billions of legitimate operators, in every nation.

— William Gibson, *Neuromancer*

3

IMMERSIVE VIRTUAL ENVIRONMENTS

In the following chapter, we introduce the field of virtual reality (VR), provide an overview of its history and current technology. To understand how different design aspects of virtual environments contribute to a user's perception, we further detail on the concepts of immersion and presence. With our aim to design effective tactile experiences for virtual settings, we investigate the current state of haptic feedback for virtual environments.

3.1 VIRTUAL REALITY

Somewhere along the line, we made a rock think[1]. Combined with a pinch of curiosity, a grain of creativity, and decades of engineering, we have arrived at the point where highly complex calculators can stimulate different human senses to present artificially generated magical illusions. While this is a great oversimplification, in essence, VR technology is merely a modern instrument to capture and present our imagination (Jerald, 2016, p. 15).

The term virtual reality, first coined by Jaron Lanier (Jerald, 2016, p. 26), refers to *"a computer-generated digital environment that can be experienced and interacted with as if that environment were real"* (Jerald, 2016, p. 9). As users experience the virtual world presented to them, they immerse themselves in the ongoing events through different perceptual senses,

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[1] ben (@daisyowl) on Twitter: "if you ever code something that "feels like a hack but it works," just remember that a CPU is literally a rock that we tricked into thinking" - https://bit.ly/3v1JW6e

Figure 3.1: A History of Virtual Reality with (left) an artistic representation of experiencing imaginary worlds through the use of fictional goggles in "Pygmalion's Spectacles" (Weinbaum, 1935), and (right) Morton Heilig's Sensorama (Heilig, 1992).

commonly the visual, auditory and haptic channels. The aim is to present a plausible illusion that feels realistic to the user, one wherein they can act accordingly (Slater, 2009).

In this work, we aim to enhance the user's virtual experience through the design of effective tactile feedback for IVEs. To understand how this builds upon VR technology, we first address its history, the concepts of immersion and presence, and take a look at the current state of VR and common application areas.

3.1.1 *A Montage of Virtual Reality*

Anything that we want to go from just a beginner to a pro, you need a montage.[2]

A "Brave New World" by Aldous Huxley was in part a response to significant technological advances that were changing the world at the time. Early on in the novel, there is mention of the *feelies*, a movie theater experience that includes smell and touch, on top of traditional sight and sound sensations. As an experience that pulls its viewer into the events displayed on screen, it paved the way for immersive VR.

One of the earliest mentions of a model for VR resembling what it is approaching today, dates back to 1935 with the short story titled "Pygmalion's Spectacles"[3]. Here, Weinbaum (1935) describes a pair of goggles that allow its wearer to experience *"a movie that gives one sight and sound [. . .] taste, smell, even touch."*, artistically depicted in Figure 3.1. Through the inclusion of multiple sensory modalities, the protagonist not only visually and audibly discerns a beautiful forest with the *"curiously lovely pipings and twitterings"* of birds, but also experiences *"[a] faint, deliciously sweet perfume breathed against him"*. The events occur interactively as the wearer is able to speak to the "shadows", or characters, presented to them while the story is *"[. . .] all about [the wearer]"*. However, as the protagonist inspects

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[2] *Montage* from Team America

[3] Project Gutenberg's Pygmalion's Spectacles by Stanley Grauman Weinbaum — https://bit.ly/3xbDASU

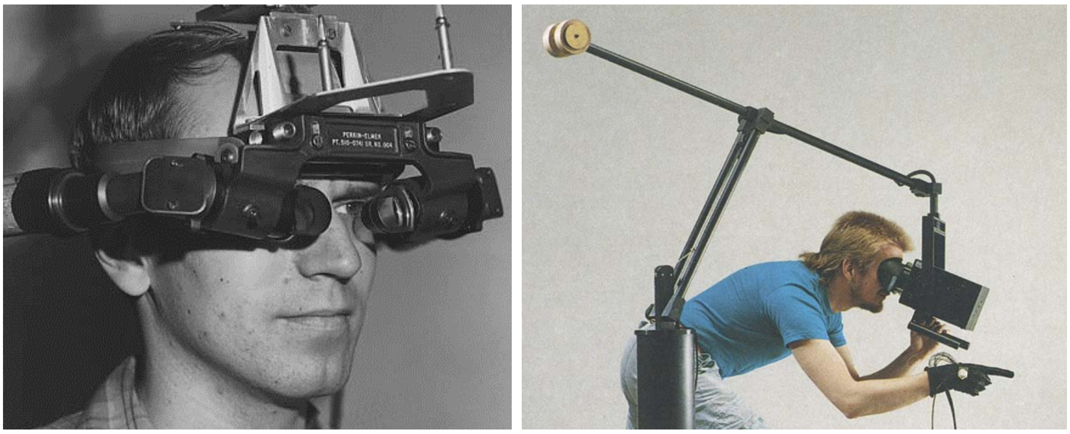

Figure 3.2: A History of Virtual Reality with (left) the “Sword of Damocles” Sutherland (1968), and (right) Binocular Omni-Oriented Monitor (BOOM) from (Bryson, 1992).

the floor, he notes that *“[t]o his eyes the ground was mossy verdure; to his touch it was merely a thin hotel carpet.”*. Interestingly, this early depiction deals with a number of actual research interests, such as breaks in immersion through sensory mismatches, the importance of plot and interactivity, and even (cyber-)sickness after exiting the illusion (all though the latter was also mitigated due to the protagonist’s alcohol abuse).

The technical origins of VR date back to the early 1800s with the use of stereoscopic photography (Jerald, 2016, p. 15). Through binocular disparities, i. e., the presentation of two slightly different images projected into each eye respectively, the stereoscope served the illusion of depth perception and three-dimensional structure. Combined with the rise in popularity of film, this set the stage for technology to serve human imagination at a deeper level. In the mid 1900s, innovation moved beyond static image presentation. The “Sensorama”, depicted in Figure 3.1, was created by a cinematographer by the name of Morton Heilig (Heilig, 1992). With the idea to fully immerse a person into a film-like experience, it provided stereoscopic color displays with a wide field of view, stereo speakers, a tilting chair with vibrations, as well as smell generators and fans to simulate wind.

Arguably the pivoting point for VR, was the concept of the “Ultimate Display” by Sutherland (1965). Touching on ideas presented in “Pygmalion’s Spectacles”, this conceptual display would be able to stimulate reality to a point that the viewer would not be able to tell the difference between the virtual and the real world. Sutherland (1968) later went on to demonstrate the first head-mounted display (HMD) that used head tracking and computer-generated imagery. As the contraption was too heavy for a person to wear comfortably on their head, the device had to be suspended from the ceiling. Dubbed the “Sword of Damocles” (Sutherland, 1968), it was named after the story of King Damocles who, with a sword hanging above his head by a single hair of a horse’s tail, was in constant peril.

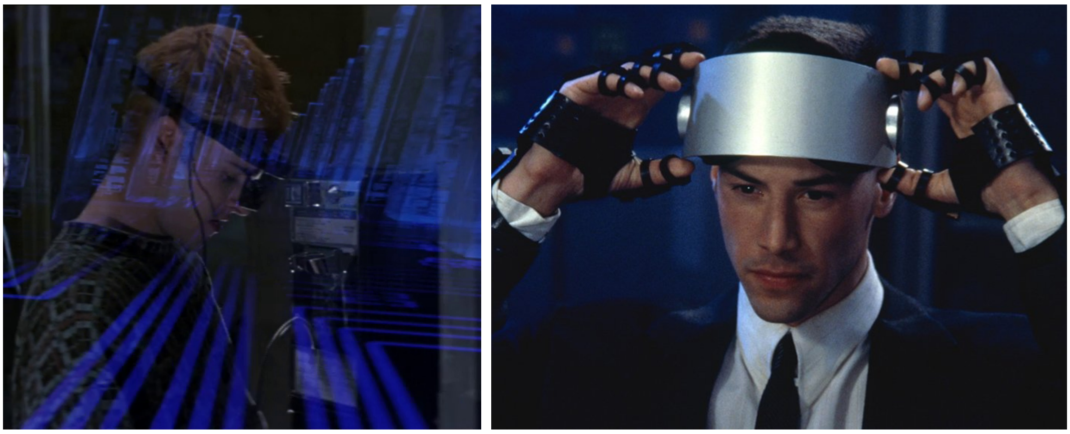

Figure 3.3: A History of Virtual Reality with (left) an immersive virtual file system in the movie "Hackers" (Softley, 1995), and (right) a fictional HMD with gloves for interaction in the movie "Johnny Mnemonic" (Longo, 1995).

In the late 1980s and 1990s, a burst of innovations pushed the field of VR beyond its borders, such as Janon Lanier's EyePhone 1 and EyePhone HRX[4], and the NASA VIEW system[5]. The inclusion of haptic feedback was being recognized through custom built simulator setups and glove-based technologies. In research, different form factors for scientific visualization applications were being explored, with notable examples including the Binocular Omni-Oriented Monitor (BOOM) (Bryson, 1992) and the Cave Automatic Virtual Environment (CAVE) (Cruz-Neira et al., 1993). However, these systems remained high in cost and posed too many disadvantages compared to advances made for HMDs. In popular culture, the entertainment industry started implementing VR technology, such as arcade machines built by The Virtuality Group[6], and Nintendo's Virtual Boy 3D Gaming Console[7]. For the film industry, VR provided a new channel of inspiration, as showcased by movies such as "Hackers" (Softley, 1995) and "Johnny Mnemonic" (Longo, 1995), see Figure 3.3.

During the so called *VR winter* in the early 2000s, VR was given little media attention (Jerald, 2016, p. 27). However, research continued to investigate novel approaches, with a high focus on human-centered aspects. With the fame of the Oculus Rift Kickstarter, mainstream media started picking up the topic of VR again, as it suddenly became a more affordable and attractive technology. Nowadays, we have reached the point where both visual and auditory modalities have undergone long iterations leading to high innovations. As applications are extending themselves into the direction of more diverse haptic feedback, and some even consider oldfactory or gustation experiences, the future of VR technology is certainly multimodal. However, there still remains a long road ahead.

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[4] VPL Research — https://bit.ly/3L2BdHV

[5] The Virtual Interface Environment Workstation (VIEW) by NASA — https://go.nasa.gov/2ptyAWs

[6] Virtuality — https://bit.ly/3d18zKt

[7] Virtual Boy by Nintendo — https://bit.ly/3Rvj2go

Figure 3.4: VR technologies with (left) a user inside a Cave Automatic Virtual Environment (CAVE) from Wikimedia Commons (2001) and (right) this dissertation's author enjoying a cup of coffee while wearing a head-mounted display (HMD).

3.1.2 *The State of Virtual Reality*

Since "Pygmalion's Spectacles" and the early days of stereoscopic photography, VR has evolved in numerous ways. From a technological point of view, the visual and auditory output modalities have received most of the attention. However, both research and industry are realizing the importance of the multimodal aspect that makes (or breaks) the virtual experience. To understand how current approaches serve the senses, we detail on several aspects of their technical realization and provide an overview of general application areas.

3.1.2.1 *Serving the Senses*

A VR system consist of a technical setup that simulates (parts of) the virtual environment through different output modalities. Common approaches combine visual and auditory sensations, and are often augmented with haptic feedback through vibrotactile actuation. While olfactory and gustatory stimulation sometimes find their way into the spotlight, their practical usage remains rare.

VISUAL The most straightforward method in bringing a virtual scene to life, is through Desktop VR or mobile systems, where respectively standard desktop monitors and handheld devices render a specific viewpoint (Anthes et al., 2016). Here, the use of stereoscopic glasses can support depth perception to further support the presented illusion. Fish Tank VR systems build on desktop approaches through tracking a user's head in order to provide a more natural way for visual inspection (Ware et al., 1993).

A second class, called Immersive Projection Technologies (IPTs) (Bowman and McMahan, 2007), visualize the virtual environment using large projections onto walls or screens. Through spatial combinations, this method gives rise to omni-directional screen setups, or

Cave Automatic Virtual Environments (CAVE) (Cruz-Neira et al., 1993) see Figure 3.4. The size of these approaches increases the user's field of view (FOV), and provides an increased freedom of movement within the real environment. However, they remain costly both in terms of technical and space requirements, and can therefore rarely be found outside of research or specialized settings.

By bringing the display closer to the user's eyes, we reach the class of head-based displays (Muhanna, 2015). Shown in Figure 3.2, the Binocular Omni-Oriented Monitor (BOOM) was an early implementation which combined close to the eye stereoscopic view rendering with positional head tracking for data visualization and inspection (Bryson, 1992). However, the success of the head-mounted display (HMD) (Sutherland, 1968), shown in Figure 3.4, quickly overtook most methods due to a better trade-off between cost and user experience. The success of the Oculus Rift Kickstarter[8] in 2012 revived the VR scene, and paved the way for large investments by big tech companies (Jerald, 2016, p. 27). Nowadays, we find state-of-the-art systems, such as the HTC Vive[9], the PlayStation VR headset[10] and the Meta Quest[11], which provide an all-around setup including visual and auditory modalities, often augmented with haptic feedback through vibrotactile actuation.

AUDITORY In terms of auditory feedback, most methods can be combined with either static speakers, or through the use of headsets, which can be separate devices or integrated into the headset. The challenge lies with providing spatially varying audio that mimics natural sounds waves emanating from a 3D-point in space. To this aim, many setups already include spatial audio solutions, and both software[12,13] and hardware[14] rendering based approaches exist that allow for easy integration with common platforms.

HAPTIC Commercial solutions for haptic feedback rely on two technical approaches, i. e., force-feedback and vibrotactile actuation (O'Malley and Gupta, 2008, p. 36). In the former, devices, such as haptic joysticks, are able to block movement and provide additional counter force to an interface controlled by the user. However, due to the need of high exertable force, these approaches usually remain limited to non-portable interfaces, making them less attractive for VR haptics where freedom of movement is often preferred.

Therefore, VR systems commonly rely on portable controller interfaces, which simulate a wide range of haptic sensations through vibrotactile actuation. Using this approach, signals are generated through low level manipulation of amplitude, frequency, and timing (Wang et al., 2019). As can be expected, the mapping of such rudimentary vibrations from complex virtual interactions, such as object collision or texture exploration, is often highly limited.

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[8] Oculus Rift Kickstarter by Oculus — https://bit.ly/3xc22Ue
[9] VIVE by HTC Corporation — https://bit.ly/3Bt3Bj1
[10] PlayStation VR by Sony — https://bit.ly/3TV9n49
[11] Meta Quest by Meta — https://bit.ly/3B6tjZ9
[12] Spatial Audio for Cinematic VR and 360 Videos by Facebook Technologies — https://ocul.us/3cYVXn6
[13] VIVE 3DSP Audio SDK by HTC Corporation — https://bit.ly/3Bs45pv
[14] VRWorks Audio by NVIDIA Corporation — https://bit.ly/3cYcSX9

Figure 3.5: VR interfaces with (left) commonly used controllers with basic vibrational feedback, and (right) gloves by SenseGlove able to exert forces onto the user's fingers (© SenseGlove).

While still the standard in commercial VR approaches, controller vibration lacks vividness and surroundedness to present the user with a plausible experience (Wang et al., 2019).

Gradually improvements find their way onto the consumer market. For example, during interaction, the Valve Index controllers[15] are tied to the user's hand. Combined with grab detection, users can throw and release virtual objects by 'releasing' the controller. Recently, PlayStation introduced adaptive triggers in their DualSense controller[16] to provide haptic feedback through force resistance, an interface further investigated by Stellmacher (2021) and Stellmacher et al. (2022). Furthermore, glove-based interfaces, such as the SenseGlove[17] or the Manus VR gloves[18] support more realistic touch interactions, while suit-based interfaces, such as the TactSuit[19], extend the bodily range of haptic feedback.

The sense of touch is central to the work in this dissertation, and therefore of special interest. In the field of haptics, different approaches have been illustrated to serve tactile experiences both in and outside VR. In Section 3.3, we provide a deeper review into different methods, and include their advantages and disadvantages.

OLFACTORY While research has attempted to classify primary odors that can be used for constructing more complex smells, arbitrary scent generation remains highly challenging (Nakaizumi et al., 2006). The psychological dimensions of human odor perception are still an outstanding issue in olfactory research, and there is a lack of a comprehensive and generally accepted classification (Kaeppler and Mueller, 2013).

Practical implementations using olfactory stimulation usually remain application specific, such as in the "Sensorama" by Morton Heilig (Heilig, 1992). In research, olfactory stimulation

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[15] Index Controllers by Valve — https://bit.ly/3Bq2bpB
[16] DualSense Wireless Controller for PS5 by Sony — https://bit.ly/3RyDCwd
[17] SenseGlove — https://bit.ly/2Aokbcg
[18] Manus Virtual Reality Gloves by Meta — https://bit.ly/3DabbR1
[19] TactSuit X40 by bHaptics — https://bit.ly/3d1YeOk

Figure 3.6: VR Olfactory and Gustatory experiences, with (left) simulating the smell of a field (© OVR Technology), and (right) an immersive gastronomy experience by Aerobanquests RMX (© Mattia Casalegno[20]).

has been explored through delivering vapors near or in the nostrils (Amores and Maes, 2017; Covington et al., 2018; Ranasinghe et al., 2018), through statically positioned systems using fans (Nakaizumi et al., 2006), through bubbles (Seah et al., 2014), or even using ultrasound arrays (Hasegawa et al., 2018). Additionally, through utilizing the properties of certain scents, such as the coolness of mint or hotness of peppers, olfactory stimulation has been shown to support illusions of environmental temperature (Brooks et al., 2020).

However, these methods have yet to find their way onto the consumer market. One face-mounted approach, called the Feelreal mask[21], was conceptualized for providing an attachable solution for HMDs to generate scents. With a total available set of 255 available scents, this device would generate complex smells from 9 embedded aroma capsules. However, in 2020 the project was placed on hold indefinitely[22]. A similar technology called INHALE, presented by OVR Technology[23], utilizes scent cartridges during virtual meditation and training sessions, see Figure 3.6. However, the product is focused towards enterprise, corporate, and federal applications, and therefore not available for private consumers.

GUSTATION Gustation approaches show a similar trend to olfactory methods. While research has investigated generalizable methods, such as direct stimulation of the tongue to simulate the sense of taste through thermal (Karunanayaka et al., 2018) or electrical (Ranasinghe and Do, 2016; Ranasinghe et al., 2012) means, their general application remains limited. To this date, no practical consumer devices exist.

However, gustation has been combined with VR in specialized scenarios. One example can be found with Aerobanquets RMX[24], see Figure 3.6, an immersive gastronomy experience

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[20] Mattia Casalegno — https://bit.ly/3eF3UhX
[21] Feelreal Multisensory VR Mask by Feelreal — https://bit.ly/3QzJCn4
[22] Feelreal Kickstarter — https://bit.ly/3xdLBXr
[23] OVR Technology — https://bit.ly/3eDimXs
[24] Aerobanquets RMX — https://bit.ly/3Qq3cCg

loosely based on the Futurist Cookbook (Marinetti, 2014), the (in)famous Italian book of surreal recipes and fantastical dinners published in 1932. A similar concept is Tree by Naked[25], where projection mapping techniques are combined with HMD systems to provide users with multisensory virtual dining and tasting experiences.

SOFTWARE RENDERING To simulate interactions and render the virtual environment, commonly 3D engines are employed in VR setups. Software frameworks, such as the Unreal Engine[26], Unity[27], or Ogre3D[28], allow designers to construct and define their virtual scenes and render them on HMDs. In our work, we commonly employed Unity for building scenes with integrated study logic, while 3D-modeling tools, such as Blender[29], aided in constructing 3D-models for both printing and virtual rendering.

3.1.3 *Application Areas*

While far from perfect, VR is able to present unique experiences to which users react strongly (Bowman and McMahan, 2007). With unprecedented freedom to create immersive simulated environments, specific applications are able to support scenarios that would otherwise be too expensive, too hazardous, or even impossible to achieve in the real world. Consequently, practical implementations of VR can be found in a highly diverse collection of applications and scenarios.

Medical applications of VR have been shown to support phobia and anxiety treatments (Powers and Emmelkamp, 2008). By exposing patients to a simulated environment that evokes their specific fear, or presents them with a highly stressful scenario, the therapist is able to guide them to bring the fear to a manageable and reasonable level. Examples include treatment of panic disorders (Botella et al., 2007), post-traumatic stress disorder (Difede and Cukor, 2007), or specific phobias, such as arachnophobia (Garcia-Palacios et al., 2002), acrophobia (Rothbaum et al., 1995), or aerophobia (Baños et al., 2002).

Another prominent domain can be found with simulation and training environments to lower risk and potential harm. For example, applications such as VR FireTrainer[30] aim to educate users in the use of fire extinguishers and guide them through fire scenarios. Similar approaches have been used in aerospace scenarios for pilot training (Council, 1995, p. 392), in military scenarios for urban combat infantry training (Council, 1995, p. 413), and in medical scenarios for training doctors to recognize brain-dead patients (Kockwelp et al., 2022), or for simulating dental surgery (Wang et al., 2019).

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[25] Tree by Naked in Yoyogi Park — https://bit.ly/2wsIBtn

[26] Unreal Engine by Epic Games — https://bit.ly/3TXAHyF

[27] Unity Real-Time Development Platform by Unity Technologies — https://bit.ly/3RMNBhP

[28] OGRE Open Source 3D Graphics Engine by Ogre3D — https://bit.ly/3Uo8WFZ

[29] Blender by The Blender Foundation — https://bit.ly/3eHjHNi

[30] VR FireTrainer by Vobling — https://bit.ly/3qopU35

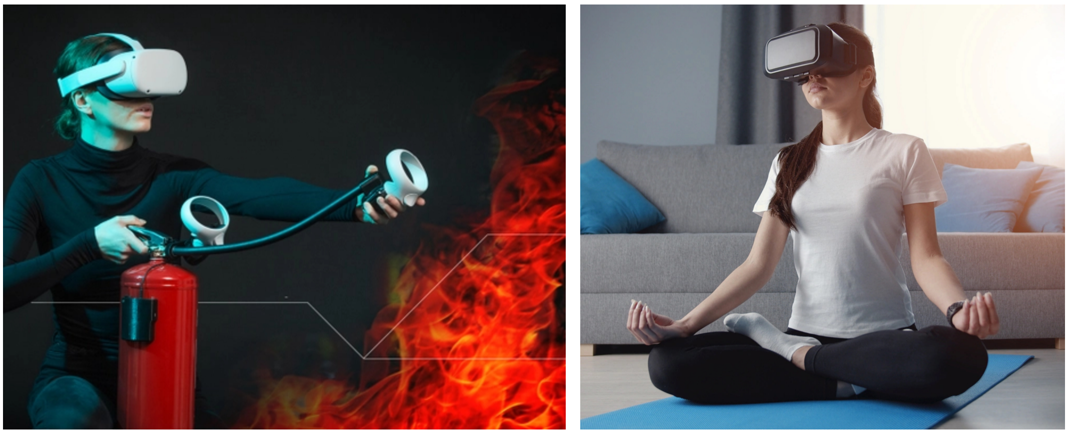

Figure 3.7: Example Application Scenarios for VR, with (left) a virtual fire scenario (© VR FireTrainer by Vobling), and (right) a user meditating in VR (© Samsung[34]).

Both for preservation and education, VR has made its way to the field of cultural heritage (Bekele and Champion, 2019). As historical artifacts and heritage sites are often too delicate to be exposed to an uncontrolled environment, VR provides the ideal opportunity to enrich visitor's experiences. Moreover, in combination with 3D-scanning approaches, digitization of cultural artifacts enables future knowledge transfer, e. g., through platforms such as Open Heritage[31].

Arguably, a main driver for VR technology can be found in the entertainment industry. With an average of 132 million active monthly users in 2021[32], the *Steam* gaming platform noted that around 2.05% (or around 2.5 million) of these users have any type of compatible VR system[33]. The importance of this area is therefore not to be underestimated.

The work in this dissertation aims to enhance tactile experiences for VR. Through different design approaches, we enable designers to more easily create feedback mechanisms that align with their intentions. As visuo-haptic experiences become more realistic and plausible, the different application scenarios benefit from our techniques.

3.2 BUT WHAT IS REALITY?

Real objects and environments have an actual physical existence and can be observed directly, while virtual objects and environments require mediating technology to be viewed and manipulated. They therefore only exist *"in essence or effect, though not actually or in fact"*[35], i. e., virtually. Whereas the term VR is used to indicate technology able to mitigate the virtual, a highly diverse set of technologies able to blend both representations together

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[31] Open Heritage by Google — https://bit.ly/2XmXaY2
[32] 2021 Year in Review by Steam — https://bit.ly/3QvUuCy
[33] Hardware and Software Survey by Steam — https://bit.ly/2JIFtzJ
[34] VR Games for Mindfulness by Samsung — https://bit.ly/3RLzTuQ
[35] Definition of 'virtual' by Wiktionary — https://bit.ly/3QsoIpX

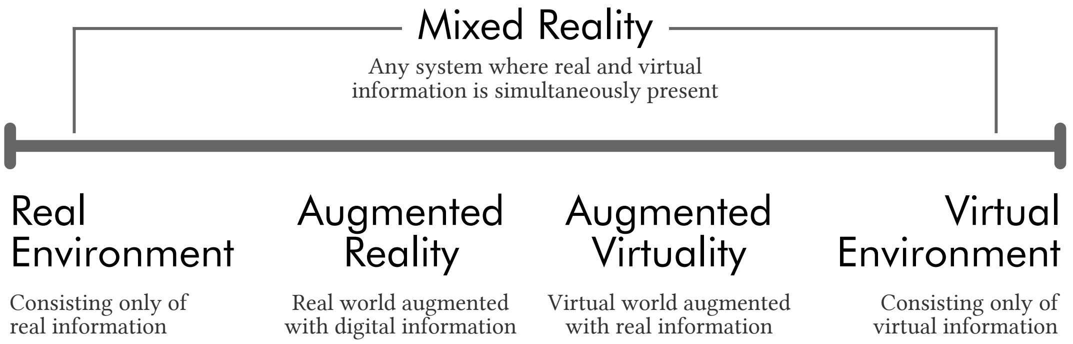

Figure 3.8: The Virtuality Continuum. Image adapted from Milgram and Kishino (1994).

to a varying degrees, exist. To understand this spectrum and mitigate ongoing discussions, Milgram and Kishino (1994) propose the *Virtuality Continuum*, depicted in Figure 3.8.

The presented classification contrasts the absolute real environment with the fully immersive virtual environment (VE) on opposite sides of a continuous spectrum. In between these two extremes, the class of mixed reality (MR) technology encompasses any and all systems where both real and virtual information is simultaneously present. Within this region, a further distinction is made between augmented reality (AR) and augmented virtuality (AV). The former presents any case where an environment, grounded in real world depictions, is augmented with digital information. An example of such a technology would be a see-through HMD that is able to project computer generated graphics onto the view of physical objects. Analogously, the case of AV portrays experiences based in virtual representations that are augmented with real world information. For example, a virtually generated world augmented with a projection of a user's real hands to enhance virtual interaction.

Furthermore, the full taxonomy proposes the dimensions of the Extent of World Knowledge (EWK), the Reproduction Fidelity (RF), and the Extent of Presence Metaphor (EPM). To illustrate the varying capabilities of different MR technologies, the EWK depicts the level of comprehension of the real world. Here, this understanding consists of the knowledge of the location of real objects, i. e., the *where*, and the knowledge about the objects themselves, i. e., the *what*. Both the RF and EPM dimensions deal with the issue of realism for MR displays, where the former deals with a technology's visual quality, the latter represents the level of immersion or presence that is offered.

While the taxonomy presented by Milgram and Kishino (1994) initially focused on classification of visual technologies, the underlying concepts remain valid for other modalities, such as the auditory, haptic, gustation, and olfactory. In the context of this dissertation, our work deals with visual and haptic technology in the MR space. As we will see in Section 3.3, the two-dimensional extension of the *Virtuality Continuum* which includes the haptic domain, as presented by Jeon and Choi (2009), will be of particular importance.

3.2.1 *Building a Virtual Illusion*

In classical human-computer settings, the user's world and the world generated by the computer are separate, making the link between both one that is from the outside in (Witmer and Singer, 1998). In virtual environments, this link is one from the inside out, where two separate entities, i. e., the user and the computer, become closer connected. As the user acts from within the virtual environment, the computer's world and the user's world become one, making the experience more meaningful. The task of a VR system is to provide the user with sensory experiences that simulate the state of the virtual environment, with the aim of providing a convincing experience that is able to persuade the user of its reality.

Slater (2009) defines a distinct difference between two orthogonal concepts of IVEs, namely, Place Illusion (PI) and the Plausibility Illusion (Psi). PI is defined as the qualia of *'being there'*, i. e., the feeling of being in a place depicted by the virtual environment, while Psi is the illusion that the events occurring inside the virtual environment are real, even though one realizes they might not be. When these illusions occur, users believe that what is happening in the virtual scene is what is actually happening to them, and therefore will behave and interact realistically, i. e., a *'response-as-if-real'* (RAIR).

Central to these illusions, are the concepts of *immersion* and *presence* (Slater et al., 1996; Slater and Wilbur, 1997). Their definitions show resemblance to the conceptual divide between objective physical stimuli and subjective sensations and perceptions in psychophysics (Fechner, 1860), see Section 2.2. Whereas immersion is an objective quality of a system, the level of presence is a user's perception of the portrayed environment.

3.2.2 *System Immersion*

Slater and Wilbur (1997) define immersion as *"the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding, and vivid illusion of reality to the senses of a human participant"*. As an objective system quality, immersion has the potential to engage users in the experience, while being independent of the user utilizing the system (Jerald, 2016, p 45). To measure immersion, several elements have been defined:

- **Extensiveness**: the range of sensory modalities presented to the user, e. g., visual, auditory, and haptic;
- **Matching**: the level of agreement between the presented sensory modalities;
- **Surroundness**: the extent of cues being panoramic, e. g., the visual field of view;
- **Vividness**: the quality of the stimuli, e. g., visual resolution;
- **Interactability**: the level of influence a user's actions has over the whole of the environment;

- **Plot**: the story.

An analogous definition, by Slater (2009), characterizes the level of immersion by the Sensorimotor Contingencies (SCs) it supports. Here, an SC refers to the actions that we know to carry out in order to perceive, for example, moving your head and eyes to change gaze direction, or bending down and shifting head and gaze direction in order to see underneath something. The SCs supported by a system define a set of valid actions that are meaningful in terms of perception within the virtual environment depicted. Based on SCs, authors define what they call first-order systems that are similar to everyday reality, and second-order systems that can be simulated with first-order systems.

As both the terms of immersion and presence have been ongoing topics of discussion in literature, Nilsson et al. (2016) provide an overview of their usage in literature. They state that it seems reasonable to distinguish between four general views of immersion, i. e., immersion as a property of the system used to present the virtual world, immersion as a perceptual response to that system, immersion as a response to an unfolding narrative, the characters inhabiting the story world, or the depiction of the world itself, and immersion as a response to challenges demanding the use of one's intellect or sensorimotor skills. Based on these insights, they define a three-dimensional taxonomy of existing conceptualizations. Here, system immersion is the term that deals with properties of the system, narrative immersion is the subjective response to the experience's narrative, and challenge-based immersion is the subjective response to challenges presented.

The idea behind immersion is to provide an objective level of sensory fidelity a system is able to generate (Slater, 1999). Optimizing and enhancing a VR system for its immersion, is therefore able to benefit the user's experience through a measurable and understandable approach. While one of the main research focus points of immersion is to increase the user's level of presence, as we will see in the next section, recent approaches posit that immersion benefits more aspects, such as a user's spatial understanding, increased peripheral awareness, or increased information bandwidth (Bowman and McMahan, 2007).

In our work, we focus on the design of tactile experiences for virtual environments. With the inclusion of appropriate haptic feedback, we aim to increase the VR system's immersion through increasing its extensiveness and matching rate to optimize the user's experience.

3.2.3 *Feeling Presence*

Similar to how physical stimuli are interpreted into sensations and perceptions, immersive qualities of a VR system provide stimuli that are perceived and interpreted by the users during their experience. This experience commonly aims to support a user's sense of presence, a subjective sensation equating to the feeling of *"being there"* (IJsselsteijn et al., 2000). Originating from the term *telepresence*, presence is a psychological state of the user built through different illusions (Jerald, 2016):

- **Being in a Stable Spatial Place**: this illusion is a subset of the *place illusion*, where the user feels as if they are in the environment presented to them (Slater, 2009). Here, sensory modalities need to agree such that the user acts as if stimuli originate from the real world;
- **Self-Embodiment**: the perception that the user has a body within the virtual world. Famously illustrated by the rubber hand illusion (Botvinick and Cohen, 1998), this illusion can provide a compelling perception that virtual elements, regardless of their resemblance to real body parts, are part of the user's body;
- **Physical Interaction**: this illusion provides the user with a realistic sense of being able to act in the virtual environment, while receiving appropriate feedback from their actions;
- **Social Communication**: the perception of social presence, where the user feels they are truly communicating with other characters in the virtual environment.

The probability of presence occurring is a function of the system's level of immersion and the user. In terms of system qualities, several aspects, such as the addition of multisensory feedback (Goncalves et al., 2020), have been shown to significantly improve the occurrence of presence. Similarly, in terms of user factors, qualities such as the meaningfulness of the experience (Hoffman et al., 1998), are essential.

While different factors influence presence, it is first and foremost not guaranteed to occur (Cummings and Bailenson, 2016; Jerald, 2016, p. 46). Additionally, presence as a user's psychological state depending on the experience, is not a static concept. As the user experiences the virtual environment, breaks in presence might occur. For example, a subpar behavior of the system, such as low update rates or noticeable *bugs*, will create unrealistic scenarios affecting the user's experience (Barfield and Hendrix, 1995). Similarly, a user experiencing presence while observing the virtual events in a passive manner, might suddenly be pulled out of the illusion when attempting to investigate virtual objects and noticing the absence of haptic feedback.

To understand how a system and its different aspects can be optimized for presence, a user's presence can be measured with different system configurations in user studies. For this several approaches have been proposed, including physiological measures (Meehan et al., 2002), behavioral measures (Usoh et al., 1999), subjective questionnaires (Baren and IJsselsteijn, 2004; Usoh et al., 2000), and counting breaks in presence (Slater and Steed, 2000). Similarly, factor analytics can provide deeper insights into the level at which each aspect of the user's experience contributes (Schubert et al., 2001).

As our work directs itself to the design of tactile feedback, it remains important to evaluate the user's experience. Through subjective user presence, we are able to assess if the sensory modalities presented provided a sufficiently meaningful and convincing experience.

3.3 HAPTIC FEEDBACK

Haptic feedback involves stimulating the sense of touch, one of our most dominant and informative senses (O'Malley and Gupta, 2008, p. 25). As we have outlined in the previous sections, including the sense of touch in virtual experiences is essential to support effective and intuitive interaction strategies, and to support the user's sense of presence. Through different haptic feedback methods, such as active actuation or passive proxy objects, virtual objects gain a sense of tactility. By creating realistic tactile impressions, IVEs provide plausible visuo-haptic experiences for immersed users.

In this work, we aim to enhance the user's virtual experience through the design of effective tactile feedback. To frame our contributions, we briefly provide an overview of the field of haptics, frame relevant taxonomies, and detail further on both active and passive approaches for building tactile experiences in virtual settings.

3.3.1 *Haptic Interfaces*

Research in the field of haptics dates back to as early as the 1920s (Gault, 1927). Here, vibrotactile actuation was used to investigate sensory substitution of audio signals. More recently, the development of haptic interfaces was driven by the need for remote manipulation tasks, e. g., for handling materials in the context of the nuclear energy industry (Sheridan, 1992). Through force-reflecting arms, users haptically interface with remote environments to perform physically dangerous tasks. For similarly critical scenarios, haptic interfaces found their way into training scenario, e. g., in the context of aviation (Cook, 1965). In scientific visualization environments, force-feedback was used to increase the perception of data models (Brooks et al., 1990).

Currently, haptic devices can be found in a wide range of applications (Hayward et al., 2004), such as in games for enhancing the user's experience, in arts and music for enabling different means for creating and sketching, and in the field of engineering for supporting computer-aided design tasks.

3.3.1.1 *Haptics in VR*

Classical haptic interfaces involve the use of haptic displays, i. e., mechanical devices capable of simulating touch sensations through applied forces and vibrations. To serve their purpose, these types of haptic interfaces need to fulfill a set of basic tasks (Council, 1995, p. 172). Firstly, through sensing mechanisms, an interface needs to be able to measure the motion, i. e., position, velocity, and possibly acceleration, and the contact forces at the point of interaction with the user. These measurements are used as input variables for the computational system that models interactions with virtual objects and calculates the resulting output contact forces and positioning variables. Using these output variables, the haptic interface mechanically adjusts its internal actuators accordingly in order to simulate the appropriate haptic feedback to the user. This process is called *haptic rendering*, analogous to the term visual rendering, and creates a bidirectional exchange of information between the interface and the user (Hayward et al., 2004; Salisbury et al., 1995). In order to calculate output signals during this process, the environment may be represented through a model allowing for computational solving of its underlying equations (Hayward et al., 2004). This model may be developed from first principles, or parameterized to represent only certain desired aspects (MacLean, 1996).

In a virtual environment, the haptic interface provides the tactile or kinesthetic connection between virtual objects and the user (Adams and Hannaford, 1999; Council, 1995, p. 161). Using this interface, users have the ability to mechanically interact with the environment through pushing, pulling, feeling, and manipulating objects in the virtual space. As visually simulated objects take on actual physical properties, such as mass, hardness, and texture, users are able to utilize their manual dexterity for fine interactions.

The haptic interface aims to support different types of haptic interactions (Council, 1995, p. 172). Firstly, through free motion users experience the environment without making physical contact with objects, resulting in the absence of haptic feedback. During active exploration, users might engage in contact involving unbalanced resultant forces, such as pressing an object with a finger pad. Lastly, through interactions such as squeezing an object in a pinch grasp, the haptic interface needs to simulate contact involving self-equilibrating forces. An important further distinction within these interactions can be made on the basis of whether the interaction is performed directly or through the use of a tool.

Besides the challenges of rendering haptic feedback, haptics in VR needs to take care of visual alignment, in terms of temporal and spatial qualities, such that the presented haptic information is in line with the virtual information observed by the user.

3.3.1.2 *Classifying Haptic Approaches*

Throughout the years, haptic technology has evolved and diversified greatly, resulting in various classification methods to differentiate between existing realizations.

From a perceptual point of view, a haptic interface can either provide tactile or kinesthetic feedback (Srinivasan and Basdogan, 1997). The form factor of a haptic device can be either portable (or holdable) or non-portable (O'Malley and Gupta, 2008; Wang et al., 2020).

A similar classification considers if the device is grounded to the user or not, i. e., grounded versus ungrounded devices (Jerald, 2016, p. 38), depicted in Figure 3.9. Grounded devices can further be divided into devices that create a kinesthetic link between the point of contact with the user and the environment, i. e., world-grounded, between the point of contact with the user and a different location on the user's body, i. e., body-grounded, or those that are directly affixed to the point of contact with the user, i. e., wearable (Culbertson et al., 2018; Pacchierotti et al., 2017).

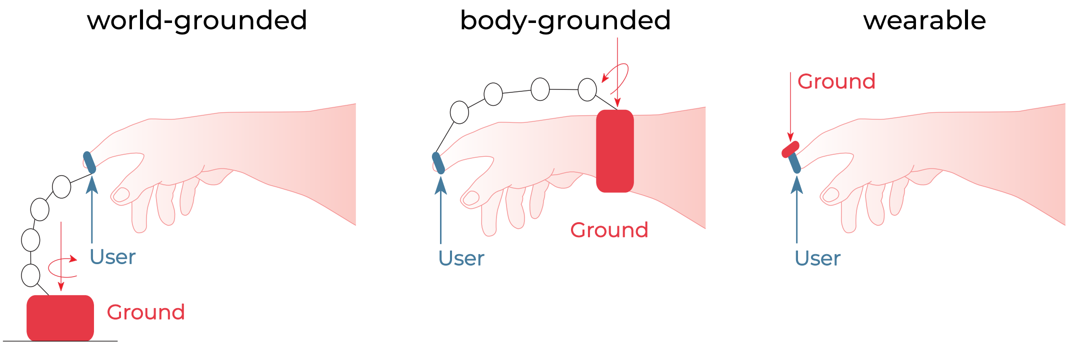

Figure 3.9: Classification of Grounded Interfaces (Culbertson et al., 2018). Here, different groundings (red) and user contact points (blue) are illustrated to differentiate between (left) world-grounded, (middle) body-grounded, and (right) wearable interfaces. Image adapted from Culbertson et al. (2018).

Furthermore, the technical realization of a device's actuation method can be differentiated, e. g., electrical motors, voice coil actuators, or pneumatic interfaces (Wang et al., 2019, 2020). Recent methods, such as ultrasonic feedback, provide an additional category where no direct contact is needed between the device and the user (Rakkolainen et al., 2021).

In the context of this dissertation, we elaborate further on taxonomies relevant to the contributions made to the field of haptic feedback in IVE.

ACTIVE VERSUS PASSIVE With the rise in popularity of VR, a more diverse set of approaches has found itself into haptics research. A common classification contrasts active and passive approaches. Whereas active haptic feedback (AHF) relates back to the classical understanding of the haptic interface as detailed above, passive haptic feedback (PHF) relies on passive objects, or props, to serve as physical proxy objects, or proxies, for virtual representations (Hinckley et al., 1994; Insko, 2001; Nilsson et al., 2021). One can draw an analogy between PHF and a computer mouse in the standard desktop setting. While the mouse does not render forces to simulate haptic sensations, it provides a tangible interface for the user to control digital events (Hayward et al., 2004). In a virtual environment, PHF builds upon this through pairing passive proxies with virtual objects to provide a sense of physicality to the virtual space. Through its inherent physical properties such as its shape, material, and weight, a haptic proxy provides haptic feedback for its registered virtual object (Lindeman, 1999).

Both extremes have their advantages and disadvantages. Active methods are considered generalized approaches (MacLean, 2008). Using haptic rendering algorithms, AHF converts virtual interactions into actuating forces. This implies that approaches require embedded electrical components, and functional software models to calculate device specific actuation from digital simulations. Due to the complexity of touch, both hardware and software limitations might cause detailed haptic interactions to feel unrealistic. While PHF methods

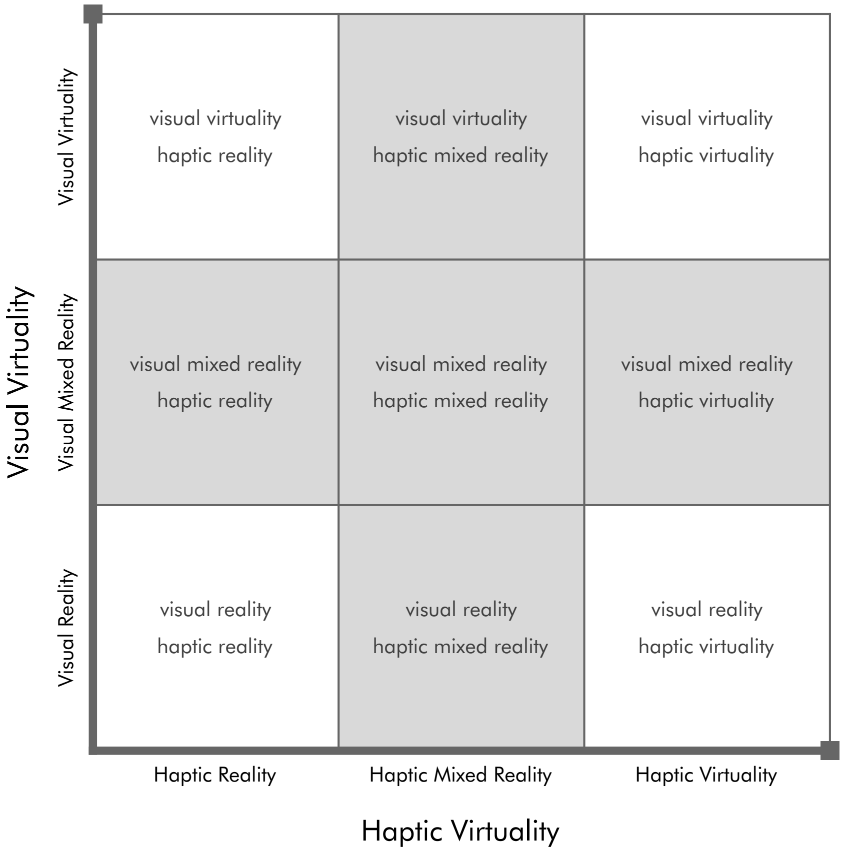

Figure 3.10: The Haptic Virtuality Continuum. Image adapted from Jeon and Choi (2009).

remain unburdened of integrated technology and the need for complex rendering methods, they tend to lack in terms of scaling. For example, a virtual environment with a large set of diverse objects will easily become unmanageable as the amount of required proxies increases drastically.

HAPTIC VIRTUALITY CONTINUUM Building upon the *Virtuality Continuum* (Milgram and Kishino, 1994), the *Visuo-Haptic Reality-Virtuality Continuum* splits the haptic and the visual dimensions into two separate axes. Each axis contrasts the extreme conditions of pure reality depictions to virtual simulations, while the case of mixed approaches separates both, see Figure 3.10.

On the left side of the *Haptic Virtuality* dimension, the case of *haptic reality* is plotted. This area incorporates PHF, where passive props are used to serve as tangible proxy objects (proxies) to provide haptic impressions to the user. Parts of this dissertation contribute to this area to replicate and simulate tactile touch experiences. Specifically, through fabrication technologies, physical objects with varying tactile properties are created. After baseline examinations of these objects in the area of *visual reality*, they are later used as proxies in VR by overlaying them with visual information in the use case of *visual virtuality*.

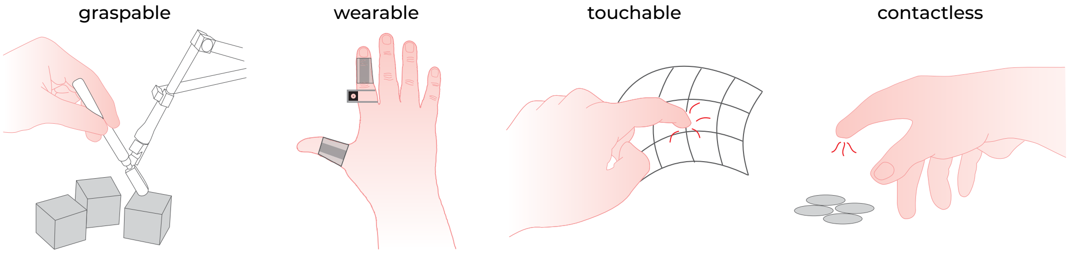

Figure 3.11: Classification of Haptic Interfaces (Ariza Nuñez, 2020; Culbertson et al., 2018). Here, different approaches are differentiated based on how the user interacts with them, i. e., (left) graspable, (left middle) wearable, (right middle) touchable, and (right) contactless interfaces. Image adapted from Culbertson et al. (2018).

The right side of the *Haptic Virtuality* dimension depicts the case of *haptic virtuality*. Here, AHF finds itself through computer-controlled actuators are used to apply active forces to the user's skin or muscles in order to simulate haptic sensations. Parts of this dissertation contribute to this area by investigating a rapid prototyping process for designing tactile touch experiences while immersed in the virtual environment. Specifically, this work, situating itself in the *visual virtuality* area, makes use of crossmodal expressions through vocalizations to allow in-situ creation of vibrotactile feedback.

To combine the best of both worlds, the case of *haptic mixed reality* visualized in the center of the *Haptic Virtuality* dimension, utilizes both real world and generated impressions to simulate touch sensations.

3.3.2 *Active Haptic Feedback*

To simulate tactile experiences, a plethora of devices have found their way to virtual experiences. Here, we review existing approaches and structure them using the haptic interface classification as presented by Culbertson et al. (2018), and additionally consider the class of contactless interfaces as suggested by Ariza Nuñez (2020). An overview of this classification is depicted in Figure 3.11.

In this section, we aim to be as inclusive as possible. While most of the presented methods fall under the category of AHF, some are considered to be hybrid or dynamic approaches that rely on both active and passive approaches. We indicate this when necessary, and reiterate their relevance to passive approaches in the next section.

3.3.2.1 *Graspable Interfaces*

Using either world-grounded or ungrounded approaches, *graspable* systems are able to provide kinesthetic or tactile sensations. Users interact with such systems through either grasping or holding the device to explore virtual information.

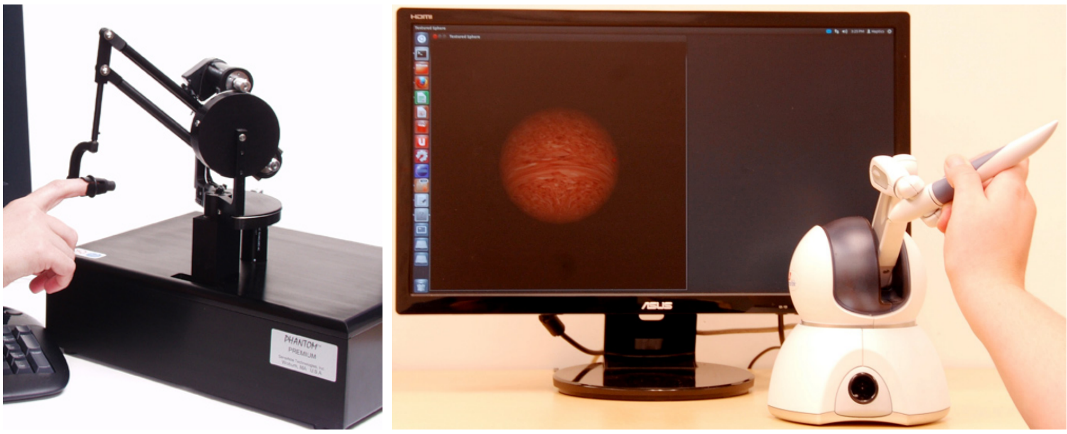

Figure 3.12: Examples of World-Grounded Haptic Interfaces, with (left) the PHANToM premium configured with a thimble end-effector (© 3D Systems, previously Sensable Technologies), and (right) a SensAble Phantom Omni with a pen-based interface used for exploring virtual textures from Culbertson et al. (2014b).

WORLD-GROUNDED World-grounded interfaces typically provide kinesthetic (or push-pull forces), which allow users to push onto them (and be pushed back) through a held tool. Such interfaces create a connection between the point of feedback, e. g., the user's finger, and a fixed point in the environment (Culbertson et al., 2018). Through this link, kinesthetic sensations are provided through force-feedback mechanisms, while tactile sensations are generated through simulating the kinesthetic component of the experience. From a design perspective, haptic feedback is realized through either admittance or impedance. Here, the former mode measures forces exerted by the user onto the master device and controls displacement and/or velocity of the device to simulate virtual sensations, while the latter measures displacement and/or velocity imposed by the user and controls the force applied by the device. Whereas admittance control devices are able to apply large forces, impedance control devices are typically smaller and lower in cost.

A prominent category of world-grounded devices can be found in the class of *pen-based masters* (O'Malley and Gupta, 2008). With a compact workspace, these haptic interfaces provide up to six degrees-of-freedom through arms driven by actuating motors. Interchangeable end-effectors allow users to interface with the device through different configurations. For example, thimble attachments support focused feedback onto the user's finger, while pen-like interfaces simulate tool and probe interactions. One of the earliest examples is the family of PHANToM devices (Massie and Salisbury, 1994), illustrated in Figure 3.12.

With the addition of vibrotactile actuation using linear voice-coil motors, such interfaces have been used to simulate both kinesthetic and cutaneous interactions with virtual environments (Iwata, 1993), and to replicate tool-based interaction with varying surface textures in telepresence scenarios (McMahan and Kuchenbecker, 2009a,b). In terms of tactile perception, they are able to render interactions with virtual objects to simulate different tactile dimensions of objects and textures, such as shape, roughness, hardness, and friction (Culbertson and Kuchenbecker, 2017; Shin and Choi, 2018, 2020).

Other world-grounded devices, include robotic arm systems, such as the HapticMaster (Van der Linde et al., 2002), and string-based force displays, such as the SPIDAR (Sato, 2002). Using different end-effectors, such devices provide localized feedback to the user's fingers (Endo et al., 2009). While perceptions of object properties such as global shape can be expressed, these methods are generally too crude for detailed tactile sensations.

UNGROUNDED Ungrounded graspable interfaces are held by users and provide kinesthetic feedback through generating inertial forces, or tactile feedback through stimulating the mechanoreceptors innervated into the skin. Handheld interfaces, such as controllers, are tracked in three-dimensional space and allow users to interface with the virtual environment while providing freedom of movement. In commercial VR systems, controllers, such as those depicted in Figure 3.5, commonly utilize vibrotactile feedback using embedded actuators such as Eccentric Rotating Mass (ERM) vibration motors, Linear Resonant Actuators (LRAs), piezoelectric motors, or voice coil actuators. While such mechanisms deliver a rudimentary approach to haptic feedback during interaction, basic vibrotactile actuators remain limited in the gamut of tactile experiences they are able to provide.

To investigate how vibrotactile experiences can be extended, Strohmeier et al. (2018) used a vibrotactile actuated rod to simulate haptic textures during midair interaction. Their work underlines that the coupling between the action and the provided feedback is able to alter the user's interpretation of the experience, leading to more material-like experiences in the case of translation and rotation mappings in their case. Similar findings were noted in our work called *Weirding Haptics* (Degraen et al., 2021a), as we found that the in-situ design of effective vibrotactile feedback heavily relied on spatial and temporal factors that influence the interpretation of the experience.

Another approach can be found with asymmetric vibrations to create virtual force illusions. First introduced by Rekimoto (2013), Culbertson et al. (2016) used this approach to induce ungrounded pulling sensations through asymmetric skin displacement. Building on this, *Grabity* simulates weight and grasping sensations when lifting virtual objects (Choi et al., 2017). Furthermore, in combination with vibrotactile texture feedback, pseudo-forces can result in the sensation of dynamic mass behavior inside a manipulated virtual object (Tanaka et al., 2020). In our work, a similar effect was created by participants through vocalizing the design of vibrotactile actuation (Degraen et al., 2021a). Specifically, by shaking a virtual cube, spatially and temporally aligned vibrations served the virtual illusion of smaller objects moving inside the enclosure.

In combination with real world objects, such as those used in PHF approaches, vibration augment objects' perception. Jeon and Choi (2009) illustrate this effect using a world-grounded setup to modulate the stiffness of perceived objects during tool interactions, while Hachisu et al. (2012) present a custom tool for free interaction. Such method uses active

Figure 3.13: Examples of Ungrounded Graspable Interfaces, with (left top) surface normal simulation with *NormalTouch* and (left center) texture simulation using a pin array with *TextureTouch* (Benko et al., 2016), (middle top) slip simulation with *RollingStone* (Lo et al., 2018), (middle center) altering the perceived hardness of real objects using active transient vibrations (Choi et al., 2021), (right top) dexterous finger interaction using *TORC* (Lee et al., 2019), (left bottom) surface texture simulation using *Haptic Revolver* (Whitmire et al., 2018), (middle bottom) dynamic hardness and roughness using a brush-like interface in *HairTouch* (Lee et al., 2021), and (right bottom) object shape simulation using *Grabity* (Choi et al., 2017).

transient vibrations, i. e., high-frequency vibrations superimposed on interaction events, such as tapping (Kuchenbecker et al., 2006). In combination with visual manipulation of virtual objects during interaction, this effect can provide reliable and convincing alterations of objects' perceived softness (Choi et al., 2021), and can enable high-dexterity finger interaction in controller setups (Lee et al., 2019).

Direct stimulation of a user's finger allows for more focused and localized tactile feedback during interaction. For example, *NormalTouch* actuates a force-sensing platform using servo motors to simulate shape and geometry (Benko et al., 2016). While aligning the controller to a virtual object, the local surface normal is used to alter the platform's height and angle in order to faithfully render the surface at the point of touch. Following a similar concept, *TextureTouch* utilizes a 4 × 4 pin array to render surface variations (Benko et al., 2016), while *PoCoPo* positions the pin interface in the palm of the user's hand to simulate virtual object shapes (Yoshida et al., 2020). Lastly, *RollingStone* focuses on slip feedback by using a single slip taxel to influence users' perception of roughness and slipperiness (Lo et al., 2018).

Another category of ungrounded devices are those that simulate physical properties by altering the state of the controller (Nilsson et al., 2021; Zenner and Krüger, 2017). Known as dynamic passive haptic feedback (DPHF) devices, their usage can be found for both kinesthetic and tactile perception. For example, the *Shifty* device alters the position of an internal weight to change the center of mass of the held controller to simulate virtual objects with different lengths, weights, center of mass, and inertia (Zenner and Krüger, 2017). Similarly, the *Drag:on* device manipulates the state of two hand fans to simulate rotational inertia felt by the user during interaction (Zenner and Krüger, 2019).

In terms of tactile perception, such approaches can be used to render virtual objects' size and shape (Sun et al., 2019), and surface texture properties by directly presenting materials underneath the user's finger (Whitmire et al., 2018), or through altering the angle and stiffness of the hairs on a brush-like interface (Lee et al., 2021). The latter builds upon our work, where we fabricate hair-like structures with varying lengths and investigate their tactile perception in combination with virtually overlaid materials (Degraen et al., 2019b).

3.3.2.2 *Wearable Interfaces*

Wearable devices are attached to or worn on the user's body. Here, kinesthetic feedback is provided through body-grounded approaches, while tactile methods include vibrotactile feedback, lateral skin stretch, normal skin deformation, or electrical skin, muscle, or tendon stimulation. We provide a brief overview of interfaces focusing on tactile experiences. For a detailed overview of available technologies, we refer the reader to the work of Pacchierotti et al. (2017) and Ariza Nuñez (2020).

BODY-GROUNDED Body-grounded haptic interfaces are affixed to the user's body to provide forces from different grounding locations using kinesthetic links (Nisar et al., 2019), see Figure 3.14. Similar to world-grounded interfaces, virtual collisions are used to calculate impedance forces to limit the user's movements.

For tactile experiences, a first category of devices can be found with hand exoskeletons, which are able to actively restrict finger movements to simulate dexterous interactions in telepresence or virtual environments (Ben-Tzvi and Ma, 2015; Blake and Gurocak, 2009; Bouzit et al., 2002; Gu et al., 2016; Ma and Ben-Tzvi, 2015). Often impedance mode is applied using braking mechanisms which allows to render spring-like forces (Burdea et al., 1992), or to simulate a virtual object's shape (Choi et al., 2016; Hinchet et al., 2018). Here, the addition of vibrotactile feedback is able to extend tactile perception upon contact, while the addition of a world-grounded link is able to provide a sense of weight while lifting objects (Choi et al., 2017). The latter approach has been proposed to be integrated dynamically to overcome the limitation of body-grounded approaches being unable to restrict users' movements relative to the real world (Steed et al., 2020).

Figure 3.14: Examples of Body-Grounded Haptic Interfaces, with (left) finger and hand strings simulating a virtual statue with *Wireality* (Fang et al., 2020), (middle) the *Wolverine* device connecting a user's thumb to other fingers (Choi et al., 2016), (right top) a hand exoskeleton with active motors (Blake and Gurocak, 2009), (right bottom) a more compact hand exoskeleton using electrostatic brakes (Hinchet et al., 2018).

Body-grounded interfaces can also come in a controller form-factor. For example, the *CLAW* device uses a force impedance approach to provide force feedback and actuated movement to the user's index finger for simulating grasping, touching, and triggering actions (Choi et al., 2018). Here, potential tactile experiences take the form of compliance, volume, and texture rendering. Similarly, the *CapstanCrunch* device provides adjustable friction to render haptic compliance in response to grasping (Sinclair et al., 2019).

HAND-WORN AND FINGER-WORN To directly stimulate the skin on the user's fingertip, wearable devices, such as gloves and thimbles, focus on vibrotactile actuation or skin stimulation through mechanical stretching or deformation, for simulating tactile properties.

Commercially available VR gloves, such as the one depicted in Figure 3.5, rely on vibrotactile actuation to simulate virtual interactions. The use of vibration motors in such a form factor has been investigated in perceptual experiments (Muramatsu et al., 2012), and has been shown to serve texture discrimination (Martinez et al., 2016), and shape recognition (Giannopoulos et al., 2015). Similar approaches include low-powered electromagnetic actuators to render spatial haptic patterns in virtual settings (Vechev et al., 2019), or shape changing mechanical actuators for rendering virtual shapes (Tsai et al., 2022).

Alternatively, finger-worn devices are directly be attached to the user's finger, and mechanically stretch or deform the skin region underneath the fingertip to provide localized tactile sensations (Pacchierotti et al., 2017). Such devices are able to provide normal indentation of the fingertip using moving platforms, pin-arrays, pneumatic systems, or ribbon belt systems, to simulate surface contact, curvature, vibrations, and mass (Bianchi et al., 2016; Frediani et al., 2014; Gabardi et al., 2016; Minamizawa et al., 2007a,b; Perez et al., 2015;

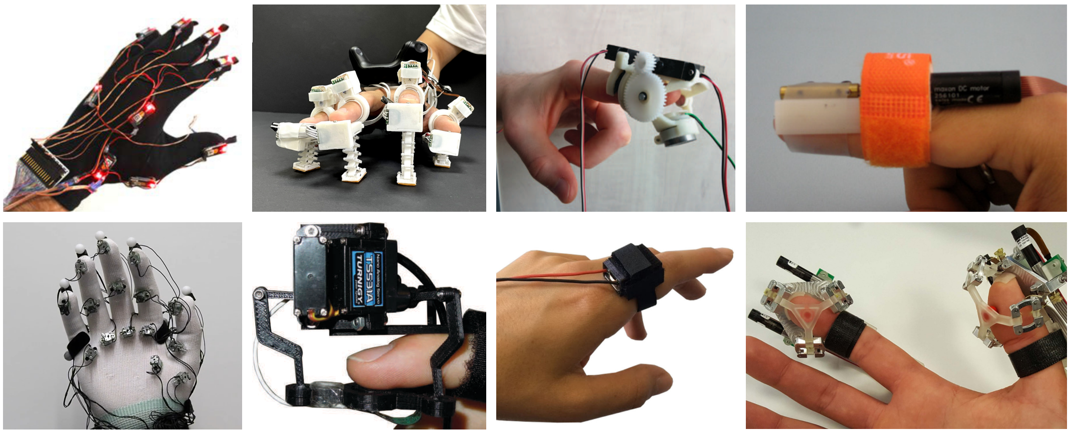

Figure 3.15: Examples of Hand-Worn and Finger-Worn Interfaces, with (left top) a vibrotactile glove (Martinez et al., 2016), (left bottom) low-powered electromagnetic actuators in *TacTiles* (Vechev et al., 2019), (left center top) shape changing mechanical actuators in *FingerX* (Tsai et al., 2022), (left center bottom) an actuating surface platform for softness rendering (Perez et al., 2015), (right center top) virtual shape and surface feature rendering (Gabardi et al., 2016), (right center bottom) a vibrotactile ring (Gaudeni et al., 2019), (right top) virtual mass rendering through shearing with *GravityGrabber* (Minamizawa et al., 2007a), (right bottom) virtual object interaction using a tactor on a motion platform (Schorr and Okamura, 2017).

Prattichizzo et al., 2013; Solazzi et al., 2010). In combination with Peltier elements, such interfaces are able to serve temperature perception (Murakami et al., 2017).

Through shearing forces applied to the skin using tactile arrays, or actuating pins called *tactors* (tactile actuators), tactile properties such as softness, and friction can be simulated (Caldwell et al., 1999; Frediani et al., 2014; Han et al., 2020; Solazzi et al., 2011). Combined normal platforms and tactors serve the perception of mass, stiffness, and friction (Schorr and Okamura, 2017), while dual rotating motors are able to provide slip sensations (Tsagarakis et al., 2005). Moreover, Teng et al. (2021) present a foldable approach able to serve both real world and virtual sensations in mixed reality environments.

Alternatively, ring-like devices actuate the user's finger muscles and skin while leaving the fingertip free for interaction. Here, normal and shearing forces can be applied to the finger to simulate virtual object interaction (Pacchierotti et al., 2016), while vibrational forces serve displacements, pressure sensations, and texture patterns (Ariza Nuñez, 2020; Ariza Núñez et al., 2015; Gaudeni et al., 2019).

ELECTRICAL STIMULATION To provide appropriate forces, body-grounded interfaces often employ tethered motors and complex mechanisms attached to the user's hands or fingers, which might limit flexibility and dexterity, and impact user experience. An alternative approach is to directly stimulate the user's skin, muscles or tendons using electrical current.

Figure 3.16: Examples of Interfaces using Electrical Stimulation, with (left top) an electro-tactile finger interface (Hummel et al., 2016), (left bottom) on-skin electric actuation in *Tacttoo* (Withana et al., 2018) next to a combination of mechanical and electrical actuation in *FinGAR* (Yem et al., 2016), (middle) EMS applied to the user's forearm (Lopes and Baudisch, 2017a), and (right) EMS for simulating heavy objects in VR (Lopes et al., 2017).

Direct stimulation of the user's muscles and tendons is known as electrical muscle stimulation (EMS). Originally used in the field of medicine for rehabilitation purposes, EMS has drawn the attention of HCI research due to its potential to pack strong mechanical actuation into a compact form factor (Hassan et al., 2017; Lopes and Baudisch, 2017a,b). Through active muscle stimulation, EMS generates involuntarily movements, and mimics kinesthetic feedback (Lopes and Baudisch, 2017a,b; Tamaki et al., 2011), which has the potential to increase perceived presence and realism in virtual settings (Khamis et al., 2019).

When localized on the arm, such feedback is able to generate strong physical forces while the hands remain unencumbered (Lopes et al., 2018), and can provide the sensation of resistive forces to simulate virtual walls and objects' weight perception (Lopes et al., 2017). Through back of the hand stimulation, more dexterous actuation enables users to perceive forces applied to individual fingers (Takahashi et al., 2021). Moreover, EMS experiences can be enriched with vibrotactile actuation, e. g., to mimic the sensation of being hit (Lopes et al., 2015a), or with body-grounded braking mechanisms to increase the feedback's accuracy in terms of dexterity by individually actuating fingers while avoiding unwanted oscillations (Nith et al., 2021). During object interaction, EMS has been used to extend the affordances of objects, e. g., by informing how to interact with the object before interaction even takes place (Lopes et al., 2015b).

In terms of tactile experiences, electro-tactile interfaces use electrodes which directly apply currents to the user's skin to stimulate the innervated mechanoreceptors (Kajimoto, 2016; Yem and Kajimoto, 2017). Such stimulation is interpreted as mechanical vibrations, and is able to deliver varying tactile sensations with high acuity using a wide frequency range (Solomonow et al., 1977). Direct stimulation of the user's fingertips has been illustrated to provide pressure sensations (Visell, 2009), improve grasp experiences in IVEs (Hummel

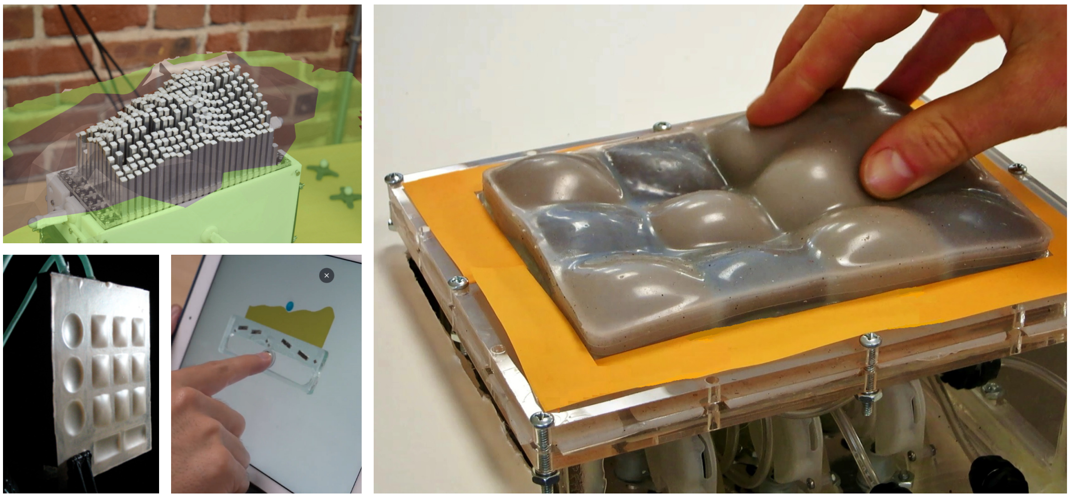

Figure 3.17: Examples of Touchable interfaces, with (left top) *ShapeShift*, a pin array interface (Siu et al., 2018), (left bottom) a pneumatic tangible interface (Harrison and Hudson, 2009), (left middle bottom) *MagnetoHaptics*, a magnetic haptic interface (Ogata, 2018), (right) a shape changing haptic surface using particle jamming (Stanley et al., 2016).

et al., 2016), and even to manipulate the perception of tactile features (Yoshimoto et al., 2015). Moreover, such interfaces can come in lightweight form factors that can be fabricated (Kato et al., 2018; Withana et al., 2018), and combined with other approaches such as mechanical stimulation (Yem et al., 2016).

3.3.2.3 *Touchable Interfaces*

Touchable devices are encountered-type haptic surfaces that are explored by the user by reaching out for them. Able to provide kinesthetic or tactile sensations, their rendering includes surface shapes, tactile properties, and mechanical properties, which can be providing through either mechanical vibrations, friction modulation, or surface shape and property changes (Wang et al., 2019, 2020).

Similar to vibrotactile feedback in other approaches, surface vibrations are able to communicate tactile features through direct contact or using tool based interactions. For example, Ban and Ujitoko (2018) render vibrotactile stimuli during pen interaction to simulate surface textures of prerecorded real surfaces.

In the case of friction rendering, tactile touch displays use either electrostatic feedback, or squeeze-film effects (Wang et al., 2019). In the former case, electrostatic feedback between the surface and the user's finger is modulated based on the normal force of the touching point to create attraction forces (Bau et al., 2010). Devices using the squeeze-film effect generate a thin air film by applying high frequency vibrations. Through modulating frequency and intensity, the fictional coefficient is altered, which influences the contact force between the user's finger and the surface to simulate textures (Marchuk et al., 2010).

Using two-dimensional tactile arrays, highly detailed micro roughness sensations can be simulated through electro-tactile feedback (Kajimoto, 2011). Alternatively, one can use shape changing surfaces which physically alter their topological composition to serve tactile sensations. Such devices render surface information through mechanically actuated pin arrays (Siu et al., 2018), and deformable crust interfaces (Rosen and Nguyen, 2005). Additionally, pneumatic systems have been used to inflate two-dimensional air chambers for generating tactile interfaces (Harrison and Hudson, 2009), and are able to create surface deformations using particle jamming (Follmer et al., 2012; Stanley et al., 2016; Stanley and Okamura, 2015), which can be combined with vibrotactile feedback mechanisms to create soft haptic interfaces (Brown and Farkhatdinov, 2020). Lastly, using magnetic forces, magnetic interfaces are able to provide programmed resistance for tangible interfaces (Ogata, 2018), and can be combined with magnetorheological fluids to serve haptic feedback on multitouch screens (Jansen et al., 2010).

3.3.2.4 *Contactless*

Contactless devices provide sensations that do not require direct contact between the user and the device. With the aim to provide a large area of actuation, such interfaces remove the need for a graspable interface, or on-body device placement. Commonly, such approaches provide midair tactile sensations to a specific region of the user's body, but are unable to provide kinesthetic sensations due to their limit in applied forces. Stimulation using these approaches is done either through manipulation of airflow, generation of magnetic fields, or actuation through acoustic means.

AIRFLOW In order to manipulate airflow, directed fans or exhaust systems using compressed air are able to provide contactless haptic feedback in VR. Here, direct stimulation onto the user's head, allows to simulate virtual airflows (Rietzler et al., 2017). In terms of tactile experiences, the *AIREAL* device allows users to sense objects and textures midair through projecting air vortices directly onto the user's skin (Sodhi et al., 2013). A similar approach, illustrated by Tsalamlal et al. (2014), blows air onto the user's hand to provide tactile stimulation, while a robotic structure is used to reposition the jet.

MAGNETIC Using a magnetic mixture applied to the user's arm hair, Boldu et al. (2019) investigate tactile stimulation through magnetic actuation. In a study using an actuated two-dimensional magnet, authors found that users showed a low discriminative accuracy, particularly for shape recognition. However, such actuation was associated with more positive and calming emotions. A wearable version of their method significantly improved on the magnetic mixture used, and increased recognition rates (Boldu et al., 2020).

ULTRASONIC A highly promising approach for contactless tactile experiences are acoustic actuation methods (Rakkolainen et al., 2021). Such feedback is provided through gener-

Figure 3.18: Examples of Contactless Tactile Interfaces, with (left) the *UltraHaptics* device for ultrasonic fingertip stimulation (Carter et al., 2013), (right top) the *AIREAL* device manipulating airflow (Sodhi et al., 2013), and (right bottom) magnetic stimulation of body hairs in *M-Hair* (Boldu et al., 2019).

ating focused ultrasonic soundwaves using arrays of ultrasonic speakers (Carter et al., 2013; Iwamoto et al., 2008). Through manipulating the spatial properties of the output, i. e., focal point position, and the temporal properties of the soundwaves, midair ultrasonic haptics are able to directly stimulate the skin, and even actuate small objects (Ochiai et al., 2014).

Using a head-mounted setup, ultrasonic haptics are able to enrich digital user interfaces in VR (Sand et al., 2015). Through skin actuation, approaches for rendering volumetric shapes (Long et al., 2014) and two-dimensional polygons (Korres et al., 2017; Korres and Eid, 2016) have been explored. However, shape recognition rates generally remain low (Rakkolainen et al., 2021; Rutten et al., 2019).

In terms of surface textural qualities, ultrasound devices have been used to generate macro-scale texture properties, such as gratings, to simulate roughness (Freeman et al., 2017). Additionally, through generating ultrasonic tactile features from digital texture graphics, the simulation of macro- and micro-roughness has been explored (Beattie et al., 2020). However, these approaches still remain in their infancy, and therefore need to significantly improve in terms of actuation force and haptic rendering (Rakkolainen et al., 2021).

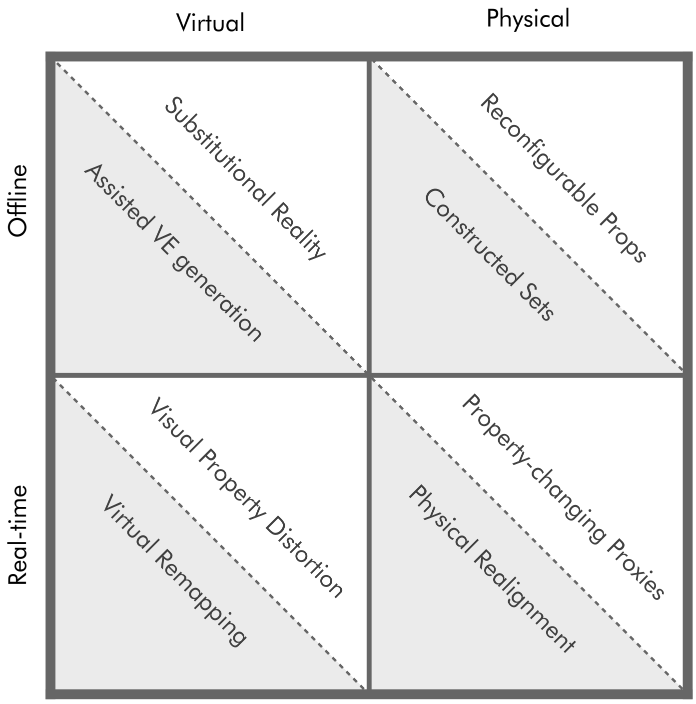

Figure 3.19: Taxonomy of techniques for deploying haptic proxies for VR by Nilsson et al. (2021). Here, the horizontal axis represents the reality being manipulated, the vertical axis considers the time of manipulation, and the diagonal cell division separates the criteria of similarity (white) or co-location (gray). Image adapted from Nilsson et al. (2021)

3.3.3 *Passive Haptic Feedback*

To serve tactile experiences, passive approaches make use of real world physical properties. As outlined in Section 3.3.1, in passive haptic feedback (PHF) physical proxy objects are paired with virtual objects to serve both visual and haptic modalities (Hinckley et al., 1994; Insko, 2001). In the following section, we detail further on the challenges of passive haptic approaches, and outline existing methods for enabling tactile experiences in VR.

3.3.3.1 *Challenges of Haptic Proxies*

Approaches for PHF are able to provide highly detailed tangible representations of virtual objects. However, the use of proxy objects presents challenges designers need to overcome to create consistent experiences. Specifically, PHF is burdened by the challenge of *similarity*, and the challenge of *co-location* (Nilsson et al., 2021).

The challenge of similarity states that haptic proxy objects should provide similar haptic qualities to the virtual objects they aim to represent. While some freedom is granted, users, expecting certain physical sensations during interaction, will experience a break in immersion when those sensations are highly mismatching. The challenge of co-location is concerned with the spatio-temporal matching of the physical and virtual environment. In essence, when a user reaches out to grab a virtual object, they expect physical feedback to arise at a given time in a given location. Upon grabbing thin air, or noticing misaligned props, the illusion breaks. Strandholt et al. (2020) found both challenges to be orthogonal, meaning it is possible to solve both separately.

To understand and categorize different approaches to extend PHF, (Nilsson et al., 2021) propose the taxonomy for deploying haptic proxies in VR, see Figure 3.19. They contrast the dimensions of the reality that is being manipulated, i. e., virtual versus physical, to the time at which the manipulation is taking place, i. e., real-time or offline. Moreover, every dimension is split into the challenge it aims to address, i. e., similarity or co-location. In total, their depiction consists of 8 strategies:

- **Substitutional Reality** is a concept where visual information paired with a passive proxy may vary in terms of aesthetic features, addition or removal of physical details, substitution of functional affordances, or even categorical substitution where the proxy has little or no resemblance to the virtual substitute (Simeone et al., 2015);
- **Assisted VE Generation** allows users to align a virtual environment with a physical space, e. g., through manual user effort (Garcia et al., 2018), or through automatic scanning approaches (Sra et al., 2016);
- **Reconfigurable Props** consist of toolkits that enable users to construct physical props from basic building blocks, e. g., through configuring Rubik's Twists (Zhu et al., 2019), or by constructing custom sets (Feick et al., 2020);
- **Constructed Sets** aim to ensure co-location through building an entire physical environment that aligns with the virtual space, notably illustrated by Insko (2001);
- **Virtual Property Distortion** manipulates aspects of the virtual space and relies on visual dominance to alter a user's perception of certain features, e. g., through *pseudo-haptic* feedback (Lecuyer et al., 2000; Speicher et al., 2019a), redirected touching (Kohli, 2013), or resized grasping (Bergström et al., 2019);
- **Virtual Remapping** refers to the process of aligning virtual objects and haptic proxies in real time by warping the virtual environment or the users' movements, e. g., redirected walking (Kohli et al., 2005), or haptic retargeting (Azmandian et al., 2016; Zhao and Follmer, 2018);
- **Property-Changing Proxies** are interfaces that are capable of altering their configuration to provide different perceptions to the user, e. g., dynamic passive haptic feedback (DPHF) (Zenner and Krüger, 2017, 2019), or human actuated approaches (Cheng et al., 2017).
- **Physical Realignment** builds co-location through altering the physical location of props, e. g., through robotic means (Araujo et al., 2016), or through manual adjustment (Cheng et al., 2015).

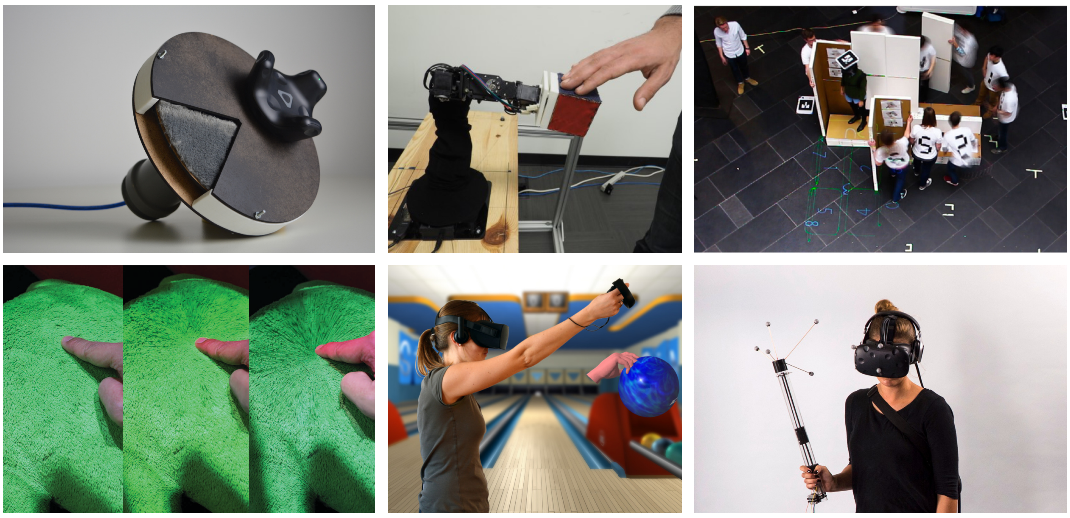

Figure 3.20: Examples of Passive Tactile Experiences, with (left top) the *HapticPalette*, a DPHF controller for exploring textures (Degraen et al., 2020a), (left bottom) visual softness simulation in *SoftAR* (Punpongsanon et al., 2015), (middle top) a robotic arm for spatially aligning texture proxies in *SnakeCharmer* (Araujo et al., 2016), (middle bottom) visual weight simulation by influencing the C/D ratio (Rietzler et al., 2018), (right top) physical realignment of walls using human actuation (Cheng et al., 2015), (right bottom) the *Shifty* device, a DPHF controller for influencing weight and mass perception through inertia (Zenner and Krüger, 2017).

3.3.3.2 *Passive Tactile Experiences*

Tactile experiences are of particular importance to this dissertation. While passive haptic approaches are capable of serving highly detailed perceptions, they are highly susceptible to the challenges mentioned above. Building on the requirements of similarity and co-location, we provide an overview of approaches for extending passive tactile experiences in VR.

MATERIAL AND TEXTURE PROPERTIES Several research contributions investigated approaches to extend passive haptic material and texture perception in both VR and AR.

To accurately represent virtual tactile properties both visually and haptically, often passive proxies with corresponding physical materials and textures are aligned with their virtual counterparts. In order to ensure each object can be perceived upon touch, physical realignment approaches are used. To this aim, Araujo et al. (2016) build upon the notion of *Robotic Graphics* by McNeely (1993), and illustrate a robotic arm which spatially aligns with different virtual representations to provide physical feedback in terms of shape, texture, and temperature.

An alternative approach uses property-changing devices. For example, the *Haptic Revolver* employs a rotating cylinder underneath the user's index finger to align physical materials with virtual surfaces (Whitmire et al., 2018). Their investigation shows that the perceptual range of a surface can be larger than the total physical surface available. In one example of our work, we investigated a texture changing DPHF controller, i. e., the *HapticPalette*, for enabling users to explore different texture and material variations of virtual objects (Degraen et al., 2020a). As user's select different objects inside the scene, an internal disc rotates in order to present the correct surface texture for that object. Moreover, we note that such an approach is able to extend the perceptual range of a limited set of physical materials, as virtual representations and physical textures can be explored in different combinations. Using a set of hairs of a brush, Lee et al. (2021) present a controller which is able to change the compression and angle of the hairs to influence the perception of hardness, roughness and surface height underneath the user's index finger. Their results build upon our investigation into how differently fabricated hair-like structures are able to influence the perception of hardness and roughness, and how influencing different tactile dimensions is able to alter material perception in VR (Degraen et al., 2019b).

As virtual environments lend themselves to separate configurations of the visual and haptic modality, previous work has aimed at utilizing the effect of visual dominance to alter users' perception. For example, by presenting discrepancies between different modalities, the reliability of each modality is weighted. As one modality shows dominance over another, the user's entire perception is influenced. For example, Yamaguchi et al. (2020) determined the permissible range for the discrepancy between tactile and visual perception using a set of surface samples with varying one-dimensional gratings. They found that the range showed an increase for textures having a ridge and groove width larger than 0.6 mm, while for coarser textures, the acceptable range remained relatively small. Similarly, Iesaki et al. (2008) used fabricated surface samples to control physical roughness, and superimposed them with real texture images. Their work shows that tactile perception can be intentionally changed by providing appropriate visual stimulation. However, the illusion only remained valid when the coarseness of the visual and tactile textures were highly similar.

A similar approach, called *pseudo-haptic feedback*, visually simulates haptic sensations, such as stiffness or friction, to influence users' perception (Lécuyer, 2009). Here, methods manipulating the control/display ratio (C/D) alter the gain in visual restitution, i. e., the ratio between the user's displacement of the input interface and the visual displacement of the virtual object. Through reducing the displacement of a virtual object moved horizontally across a virtual environment, the C/D effect was used for manipulating the perception of object friction (Lécuyer, 2009). Specifically, as the user drags a physical object across a surface, the delayed visual representation creates the impression that the object is harder to drag due to a high level of friction.

In terms of hardness perception, previous research on pseudo-haptics investigated different degrees of visual deformations to modify an object's perceived stiffness Lécuyer, 2009. Hirano et al. (2011) superimposed an indentation animation when users pressed down on an object, and note that the visual manipulation affected hardness perception regardless of the physical hardness experienced during touch. Building on this, Punpongsanon et al. (2015) present a computational model based on two visual augmentation approaches to reliably influence softness perception in an AR environment. In our work, we investigated the perception of pseudo-haptic effects on virtual user interface elements, and show that visual manipulation is able to improve performance (Speicher et al., 2019a).

In terms of material perception, Kitahara et al. (2010) observed that by overlaying different visual materials onto physical samples, the physical properties of the haptic sample can control which variant of the visual material is perceived. This effect exploits users' real world experience with known materials, indicating that existing knowledge influences sensory integration in terms of material perception. Our work builds upon these insights by investigating different matching and mismatching visuo-haptic combinations in order to evoke material perceptions in VR (Degraen et al., 2019b).

SHAPE AND SIZE To simulate different shape and size configurations, research has investigated property-changing proxies. For example, McClelland et al. (2017) present a shape changing interface capable of folding together to represent a larger set of two- and three-dimensional shapes. In a similar approach, Teng et al. (2018) utilize an inflatable prop attached to the user's hand palm, and investigate the extent to which the size of a virtual object can differ from the size of its proxy.

On-demand props for size perception have been illustrated using *DPHF* controllers affixed to the user's wrist (Kovacs et al., 2020). Similarly, encountered-type haptic devices (ETHD) utilize robotic interfaces to physically align and configure proxy objects such that they match their virtual counterpart (Bouzbib and Bailly, 2022). One example includes the work by Yoshida et al. (2020), where authors present a handheld pin-based shape display rendering size and shape information. For room-scale environments, objects, such as walls and furniture, realignment has been illustrated using computer controlled robots (Suzuki et al., 2020; Yixian et al., 2020), or by employing bystanders (Cheng et al., 2015), while Teng et al. (2019) use large inflatable interfaces that align with virtual content.

Another approach includes the use of real world objects. To this aim, Hettiarachchi and Wigdor (2016) present a method to track physical objects and match their size and shape information to virtual representations. In a similar approach, our work employs everyday objects for PHF (Daiber et al., 2021, 2020), or the use of smart devices to provide both passive and active feedback (Makhsadov et al., 2022). Alternatively, research has proposed various reconfigurable objects (Feick et al., 2020; Zhao et al., 2017; Zhu et al., 2019).

When dealing with proxies of different sizes and shapes, the degree of mismatching properties has been investigated. Specifically, Tinguy et al. (2019a) focused on pinch interactions to determine to which degree physical and virtual shapes can differ without users noticing. Using their insights, authors present a follow-up work that details on an optimization approach for haptic pinching sensations in virtual settings (Tinguy et al., 2019b). To determine the influence of size and shape on general usability, Kwon et al. (2009) focused on relative differences between virtual objects and tangible props. Authors found that manipulation was more efficient with equally sized and shaped props and virtual objects, while the size factor by itself did not significantly affect interaction.

MASS AND INERTIA Through influencing the perception of an object's mass or its inertial properties, the perception of its material can be altered. To this aim, Rietzler et al. (2018) influenced the C/D ratio during virtual object manipulation. Upon lifting a physical object, its virtual representation would lag behind, creating the perception of an object with a higher weight. As their approach was able to influence user's weight perception, they note that visual attention to the illusion was required.

To investigate the impact of different weight distributions, Zenner and Krüger (2017) present *Shifty*, a DPHF controller capable of shifting an internal weight. Their results underline that weight distribution is a highly influential proxy property that lends itself to generate perceptual illusions. For example, through visual-haptic discrepancies, their approach is able to simulate different length and weight configurations of virtual objects. In a follow-up work, their *Drag:on* controller utilizes a shape changing interface to influence drag perception in VR (Zenner and Krüger, 2019).

3.4 CONCLUSION

Virtual reality (VR) is a computer-generated digital environment that can be experienced and interacted with as if it were real. Throughout the years, technology for VR has evolved greatly to provide convincing experiences that serve the different senses. Gradually, different application areas have found their way to VR to support scenarios that would otherwise be too expensive, too hazardous, or even impossible to achieve in the real world.

The goal of an immersive virtual environment (IVE) is to provide the user with a plausible VR experience wherein they can feel *present*. As we are used to concurrently experiencing the real world through multiple modalities, high expectations are placed upon interacting with such virtual scenes. Therefore, the system has to fulfill these requirements to a certain degree in order to maintain the illusion of the virtual world presented to the user.

In this work, we look towards the haptic modality of IVEs to enhance the user's virtual experience. Through the design of effective tactile feedback, the user's sense of touch is stimulated, which allows virtual objects to gain a sense of tactility. By creating realistic tactile impressions, IVEs provide plausible visuo-haptic experiences for immersed users.

To provide such haptic sensations, a plethora of different approaches have been illustrated in both research and industry. Whereas active haptic feedback (AHF) involves the use of haptic interfaces that mechanically adjust their internal actuators in order to simulate the appropriate haptic feedback to the user, passive haptic feedback (PHF) relies on passive objects, or props, to serve as physical proxy objects, or proxies, for virtual representations. Additionally, mixed approaches, such as dynamic passive haptic feedback (DPHF), or substitutional reality, take advantage of both worlds to stimulate the user's tactile senses.

Using these methods, convincing tactile experiences can be created, such as the perception of different shapes, textures, and materials. However, each approach has their own drawbacks and caveats. As AHF requires a powered connection to drive complex internal circuits and actuators, their form factor can become burdening for the user. On the other hand, PHF is able to serve highly realistic tactile perceptions, however, it lacks in terms of flexibility and scalability, as each user requires access to each object with its respective material represented in the virtual scene. Mixed approaches are heavily streamlined to solve one specific problem, and therefore lack generalizability. With this in mind, our work aims to enhance tactile experiences in IVEs by looking to improve their design approach.

These were subtle, nuanced sensations that could never be re-created or simulated by a pair of haptic gloves.

— Ernest Cline, *Ready Player Two*

4

DESIGNING TACTILE EXPERIENCES

The design of effective haptic feedback for immersive virtual environments (IVEs) is essential for supporting a user's sense of presence in the virtually generated experience. In this chapter, we investigate the field of haptic design. Specifically, we discuss why the design of haptic experiences remains a challenging aspect, elaborate on existing design approaches for both active and passive technologies, and detail on modeling methods that aim to understand the relationship between haptic designs and user perception.

4.1 HAPTIC DESIGN

Haptic technology is maturing. Through miniaturization, tactile actuators are abundantly present in our everyday devices to provide subtle notifications, support interaction mechanisms, and enhance overall user experience. Analogously, in the field of fabrication, technological advances continuously increase the resolution to which designs can be realized, which is enabling designers to look beyond mere functional aspects and consider the tactile experience of physical artifacts they create.

However, designing effective haptic experiences remains a challenging task. Reasons for this are manifold, e. g., the high complexity of the haptic sense in itself (MacLean et al., 2017), a general unfamiliarity with the haptic domain in other fields (Moussette and Banks, 2010), a high diversity of haptic interfaces that remains difficult to navigate (Seifi et al., 2019), and even a lack of understanding of the need for including the user's sense of touch (Schneider et al., 2017; Vezzoli et al., 2022). To address these challenges, haptic design is establishing itself as a field of research, and aims to construct universal and sustainable design practices to ensure designers do not need to “reinvent the [haptic] wheel” with each new project (Schneider et al., 2022; Seifi et al., 2020b).

In this work, we focus on the design of tactile experiences for visuo-haptic exploration in IVEs. To this aim, we investigate different approaches to create effective feedback and examine if they are perceived as intended. This starts from an understanding of the field of haptic design and its ongoing challenges, how current technologies are used to create experiences, and how design parameters can be modeled to influence users’ haptic perception.

4.1.1 *Central Challenges*

The task of the haptic designer, or *haptician*, is to bring the world of touch to digital experiences. Through haptic technology, the haptician aims to translate their intention into an effective haptic experience (HX). To understand how HX constitutes to user experience (UX), Kim and Schneider (2020) define HX as follows.

> *“[HX is] a distinct set of quality criteria combining usability requirements and experiential dimensions that are the most important considerations for people interacting with technology that involves one or more perceived senses of touch, possibly as part of a multisensory experience.”*

While this might seem trivial, the field of haptic design still remains in its infancy, and is lacking universal design practices that allow designers to consistently translate their intention into effective haptic experiences. To understand where the ongoing challenges lie, we investigate the difficulties of designing for the sense of touch.

TOUCH IS COMPLEX As illustrated in Chapter 2, our sense of touch stems from a complex network of diverse receptors distributed throughout the skin and muscles. With varying density, these give rise to sensations and perceptions of temperature, texture, forces, and motion, initiated through physical interactions with the world around us. Designing for the entirety of such a distributed and multiparameter sense requires integrated devices supporting different modalities (MacLean et al., 2017).

Touch sensations can originate from different interactions, i. e., from passive sensory reception where stimuli are applied to a passive receiver, or from active sensorimotor exploration to support bidirectional physical manipulation and interaction. These varying uses of our haptic sense challenge a designer, as they must consider the context of the feedback. Moreover, the manner in which touch is obtained, defines a different connection to attention, providing different affordances and design requirements (MacLean et al., 2017).

Additionally, our sense of touch is closely related to, and influenced by, other senses. As underlined in Chapter 2, different sensations are integrated based on their reliability and the context in which they are perceived. Therefore, designing for the sense of touch is a multi-modal challenge that needs to consider all relevant senses.

TOUCH IS PERSONAL The personal nature of the sense of touch is made apparent due to individual user characteristics in perception and preferences (Schneider et al., 2017). Not only does this involve social norms and etiquette of appropriateness, each one of us experiences touch differently. Tactile acuity varies between bodily position, age, and person, therefore haptic equity is a challenging task. As the work of Seifi (2019) underlines, there is an urgent need for methods to personalize haptics.

The nature of haptic sensations makes them personal and private (MacLean, 2008). As haptic perceptions are perceived on our body, haptic interfaces either require continuous contact with their user, or need to inform them when they need to interact with the interface, which might further complicate the design of the feedback.

While many users can simultaneously observe visual information, haptic sensations are individual. This makes touch a sense that remains difficult to share, and complicates collaborative design practices. Chan et al. (2019) underline that research in the field of haptic feedback has primarily focused on two directions, i. e., simulating realistic experiences, and information transfer, e. g., for communicating symbolic or affective information. This narrow focus has caused a communication gap between haptic designers and users, as it remains unclear if a haptic design is perceived as intended.

HAPTIC MEDIA IS NOVEL The field of haptic design still remains it its infancy, with lots of progress to be made. One major challenge, lies with the fact that there is no universally accepted vocabulary for physical sensations (Obrist et al., 2013). This is impacting users' ability to describe, communicate, and possibly even to perceive distinctions.

Furthermore, users are not accustomed to processing synthetically encoded haptic meaning (MacLean et al., 2017). In other modalities, sensory design language has been developed over years, even to support relatively simple communication. For example, gestural language is able to communicate ideas using iconic representations, e. g., a thumbs-up.

Lastly, haptic design is in need of common design practices to underpin the factors that constitute experience of haptic technology (Kim and Schneider, 2020). Through improved conceptual infrastructure, such as design languages and evaluative tools, haptic designers are better able to understand the experiences they aim to design (Schneider et al., 2017).

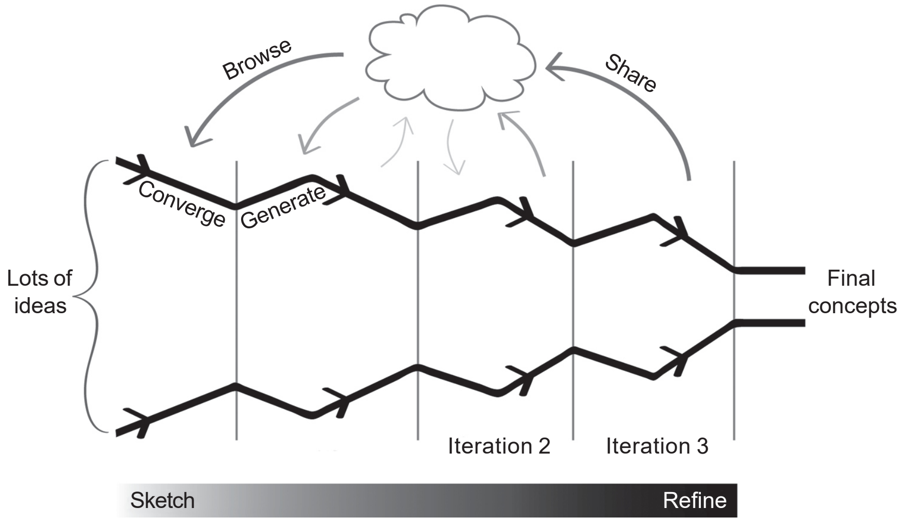

Figure 4.1: Iterative design process incorporating four design activities for haptics, i. e., browsing, sketching, refining, and sharing. Image adapted from MacLean et al. (2017).

4.1.2 *Haptic Experience Design*

To translate knowledge of the physical and semantic haptic design space into compelling, coherent, and learnable haptic experiences, research in the field of haptic design has built upon the notion of design thinking (MacLean et al., 2017; Schneider et al., 2017). At the basis of this notion lies a rapid generation, evaluation and iteration of multiple ideas at once, in order to converge to a representative result (Buxton, 2007). Activities performed in the design thinking framework are generalized as problem preparation, sketching-like iteration, and collaboration.

To this aim, research has established the field of haptic experience design (HaXD) to frame the design of haptic experiences in the context of user experience design. To better understand the haptic design process, Schneider et al. (2017) identified four major design activities and associated obstacles.

BROWSE Often, a first step in any design process is to rely on previous experience and look towards existing solutions that address similar problems. From mood boards to inspirational websites, this 'gathering' step provides a first direction that enables the designer to get a handle on the problem by framing the challenges and match it to their repertoire (Schneider et al., 2017). Therefore, research has proposed collections of a wide range of haptic experiences, e. g., *VibViz* (Seifi et al., 2015), or the *UPenn Texture Toolkit* (Culbertson et al., 2014a), combined with different ways of organizing and exploring haptic elements such that users can conceptualize them (Seifi and MacLean, 2017).

In our work, we look towards information available to us in the real world. To this aim, Chapter 5 proposes to capture information from physical textures to appropriate their perceptual qualities in the design of haptic experiences. We illustrate this through fabricating haptic replicas and investigating their perception, both inside and outside VR.

SKETCHING To better understand the different aspects of a design problem, sketching supports users to form abstracted and partial views (MacLean et al., 2017). Mostly used in the early design phases, sketching supports rapid iteration of potential solutions and is key in collaborative processes. Prototypes can be constructed to explore and express practical design implementations that guide future decisions (Houde and Hill, 1997). In the context of haptic design, prototyping haptic media can be done using physical materials combined with interactive technologies to build effective interactive, physical haptic prototypes (Moussette and Banks, 2010), or through rapid iteration methods for designing vibrotactile actuation (Hong et al., 2013; Schneider and MacLean, 2014).

In our work, we look towards sketching tactile feedback by capturing designers' vocalizations of haptic designs. This creates a rapid prototyping cycle in which the designer is able to iterate over different designs during interaction. From our results, we see that this approach provides an intuitive method for communicating design intent in VR.

REFINING Going from initial sketches and prototypes to an effective solution, requires an iterative refinement process (MacLean et al., 2017). Gradual improvements narrow the path to the final design, and additionally allow final tweaks and modifications valuable to support individual differences. In the process of haptic design, this step is often cumbersome, as each complex set of hardware solutions demand significant effort. Here, customization tools support iterative refinement through software design (Seifi et al., 2014), however, such approaches still remain in their infancy.

In our work, we look towards refinement by allowing the designer to fine-tune their designs. Specifically, in Chapter 9, we use modifiers that are able to influence the process of converting recorded vocalizations into vibrotactile actuation. Combined with user-specific calibration, our approach provides an intuitive method for translating intent into effective haptic designs.

SHARING Lastly, during the design process, sharing designs is essential for receiving feedback, general evaluation, and distribution (MacLean et al., 2017). With haptic experiences, the challenge lies with the fact that the experience must be felt, creating a hardware dependency in terms of available technology and physical materials. While visual and audio design support capturing and sharing of ideas, this remains an open challenge in haptics.

As a central motivation for this dissertation, sharing touch experiences is an end-goal we build towards. Through the use of digital fabrication technologies, haptic experiences can be fabricated on-demand to share with other stakeholders. The added value of VR contributes to the multi-modal aspect of tactile experiences, and allows sharing the context of touch.

4.2 TACTILE SIGNAL DESIGN

From an understanding of the complexity and challenges associated with the design of haptic experiences, we continue with an investigation of practical approaches for creating tactile experiences. Parts of this dissertation address the design of active haptic feedback, specifically in terms of vibrotactile actuation. The following section provides an overview of different approaches that support the design of such feedback mechanisms.

4.2.1 *Haptic Signals*

During surface texture exploration, lateral movements of the fingertip generate collisions between the skin and the variations of the investigated surface. These interactions are translated into vibrations that are received by the skin's mechanoreceptors. With this understanding, research has investigated the close relationship between vibrotactile sensations and physical object properties, and has drawn parallels between the signal features of vibrations elicited by textures and their tactile perception (Bensmaïa and Hollins, 2003).

Simulating tactile properties through vibrations is done through defining a haptic signal. Each signal is encoded in terms of variations in frequency and amplitude over time, where time can relate to a spatio-temporal mapping of a tactile experience. Using vibrotactile actuators, a haptic signal can then be rendered through physical activation of the actuator based on the properties of the stored signal.

However, developing effective and convincing tactile experiences using vibrotactile feedback remains a challenge. While manipulate low-level controllable parameters, such as frequency and amplitude, allows for designing a wide range of experiences, it is unclear how to transfer such abstract parameters into understandable haptic effects (Schneider et al., 2017; Seifi and MacLean, 2017). Implementing convincing experiences is an even greater challenge for those inexperienced in haptics, e. g., video game programmers who seek to design playful experiences with tactile sensations, students learning haptics through prototyping, or interaction designers wanting to provide tactile feedback in UI widgets (Seifi et al., 2020a). As pointed out by recent work (Kim and Schneider, 2020; Seifi et al., 2020a), there is a need for more timely, intuitive and hands-on interfaces and tools to allow designers to better grasp the experiences they aim to design.

4.2.2 *Design Methodologies*

Different methodologies for haptic design have been proposed. With the aim of providing more understandable methods for creating experiences, these methods draw inspiration from different fields and build upon different concepts. To illustrate their variety, we focus on conceptual methods for defining vibrotactile experiences.

TACTONS Haptic icons, tactons, and haptic phonomenes are different terms used to refer to structured abstract messages that encode information (Brewster and Brown, 2004; Enriquez et al., 2006; Maclean and Enriquez, 2003; MacLean et al., 2017). Building upon the notion of visual icons and their auditory equivalent earcons (Blattner et al., 1989; Brewster et al., 1993), tactons are small, compositional, and iconic signals are aimed at providing designers with a set of basic building blocks to share haptic ideas (Brewster and Brown, 2004). Enriquez et al. (2006) introduce the concept of haptic phonomenes to construct haptic icons similar to the construction of language words. The use of tactons can lead to distinct, recognizable haptic messages that relate to perceptual roughness (Brown et al., 2005, 2006a), and can support collaborative turn taking processes (Chan et al., 2008).

METAPHORS In order to construct haptic signals, different metaphors or design schemas have been used. One important analogy connects the design of haptics to musical design, especially for vibrotactile actuation. The use of musical notes and rests to build upon rhythm provides an intuitive method for design (Brown et al., 2005, 2006b; Chan et al., 2008; Ternes and MacLean, 2008), while notes by themselves provide descriptive support for tactile icons (Brewster and Brown, 2004; Brewster et al., 1993), complete with tactile analogues of crescendos and sforzandos (Brown et al., 2006b). Moreover, musical approaches have been illustrated to 'compose' vibrotactile sensations (Gunther and O'Modhrain, 2003).

SCHEMAS AND FACETS Another method of conceptualizing haptic signals, is to employ a conceptual or translational schemas (MacLean et al., 2017). Here, a haptic sensation can be interpreted as an emotion, e. g., exciting, or compared to a different natural occurrence, e. g., a purring cat. Such schemas are influenced by the context of use and the background of the interpreter (Obrist et al., 2013; Schneider and MacLean, 2014; Seifi et al., 2015). Analogously, facets capture the sense-making schemas for haptic sensations and define a set of related properties or labels that describe an aspect of an object (MacLean et al., 2017). For the design of vibrotactile stimuli, five descriptive facets have been proposed (Seifi et al., 2015). Physical properties are defined by low-level signal properties, e. g., duration and energy, whereas sensory properties refer to tactile sensations, e. g., roughness. Emotional connotations relate to a signal's mental interpretation, e. g., its pleasantness, while metaphors create analogies, e. g., a purring cat, and usage examples refer to other contexts, e. g., an incoming message.

LANGUAGE Haptic design research has given great attention to uncovering the basic building blocks of touch sensations. To this aim, defining a language of touch is generally considered a promising way to capture user experience, both more generally and for haptics in particular (Obrist et al., 2013). However, its personal nature makes touch difficult to describe, with evidence that the existence of a general tactile language is highly unlikely (Jansson-Boyd, 2011). Therefore, a unifying haptic language remains an open challenge to this day.

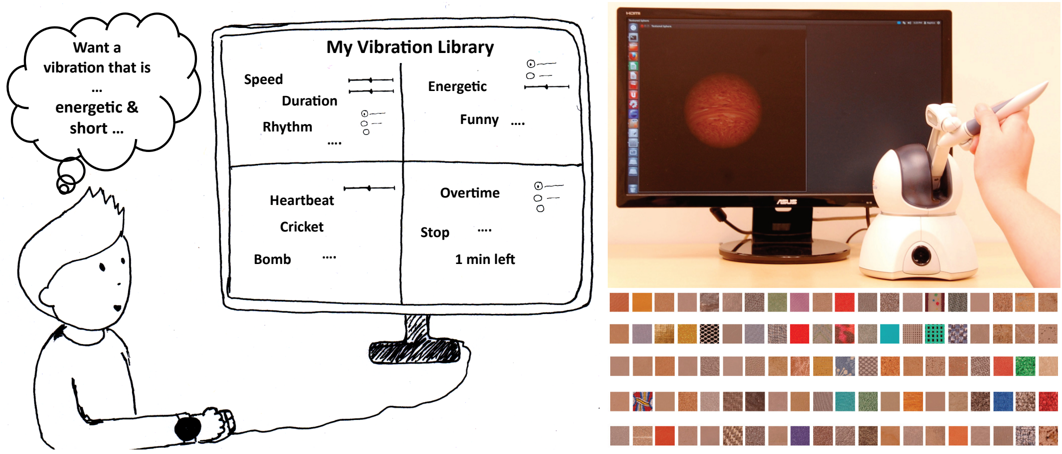

Figure 4.2: Examples of Haptic Signal Library Approaches, with (left) organizing signals using facets in *VibViz* (Seifi et al., 2015) (Image adapted from Seifi et al. (2015)), and (right) real physical texture recordings in the *UPenn Texture Toolkit* (Culbertson et al., 2014a,c) (Image adapted from Culbertson et al. (2014b)).

4.2.3 *Design Tools*

Building upon different design methodologies, research has proposed different design tools. Whereas collections support the activities of browsing and sharing, tools aim to provide intuitive ways for sketching and refining. Here, we detail on several approaches focused at designing and understanding vibrotactile feedback.

COLLECTIONS Libraries and content collections support developers by providing examples to browse, and supporting faster, easier programming and customization for sketching and refining (MacLean et al., 2017). Examples include the *UPenn Texture Toolkit* which consists of recordings of 100 physical textures (Culbertson et al., 2014a,b,c), and the vibration pattern database presented by Toscani and Metzger (2022), which includes signals elicited by free haptic exploration and participants' judgements about its perceptual attributes and material category. Through vibrotactile and impedance-type force feedback devices, these signals can be used to render haptic texture data. Both the *HapticTouch* toolkit (Ledo et al., 2012) and the *Feel Effect* library (Israr et al., 2014) take a practical design approach to support designers in defining tactile effects through controlling semantic parameters, such as softness, or oscillation, and connecting these to digital interaction scenarios. In *VibViz*, Seifi et al. (2015) structure 120 vibrations using a multi-faceted scheme. Their approach allows designers to organize, visualize and navigate vibration libraries through physical properties, sensory properties, emotional connotations, metaphors, and usage examples.

HARDWARE Hardware platforms lower the barrier to designing haptics, and support exploration and knowledge transfer through prototyping (MacLean et al., 2017). Here, tools

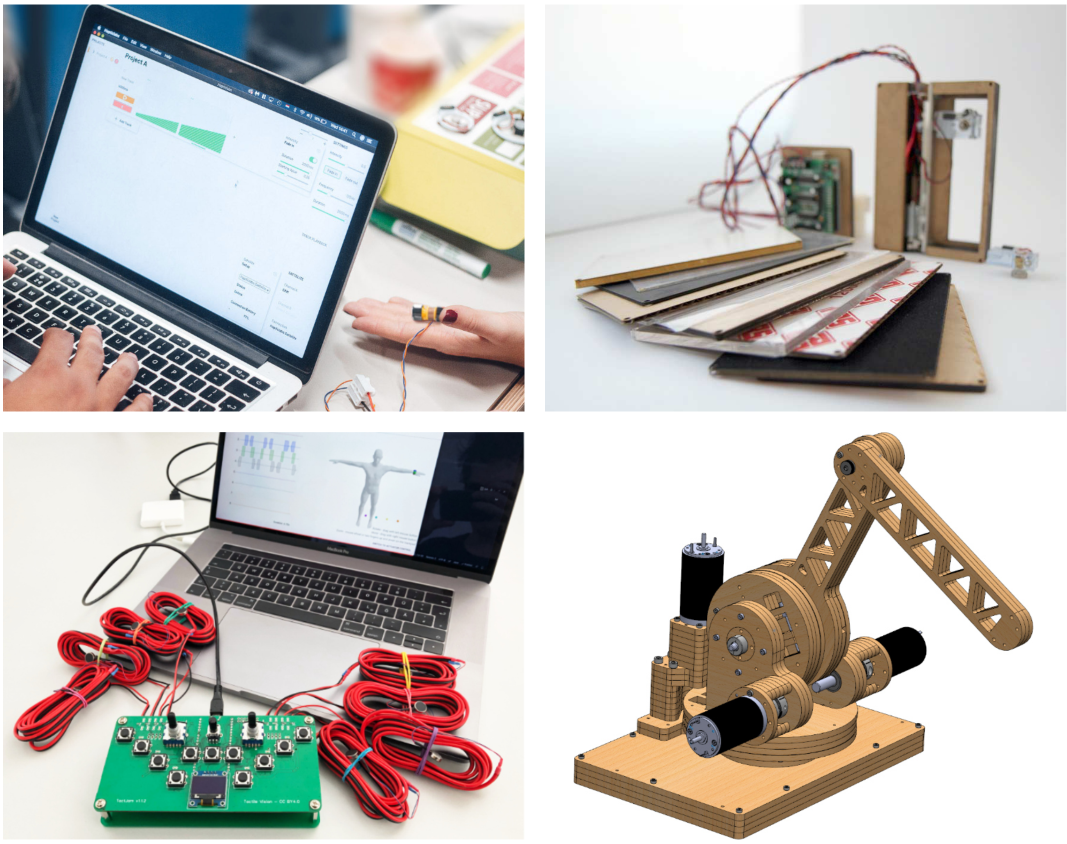

Figure 4.3: Examples of Haptic Hardware Platforms, with (left top) the *HapticLabs* platform, (left bottom) designing vibrotactile actuation with *TactJam* (Wittchen et al., 2022), (right top) a slider prototype from the *Simple Haptics* toolkit (Moussette and Banks, 2010), and (right bottom) a wooden force feedback design from *WoodenHaptics* (Forsslund et al., 2015).

aim to bring physical interaction widgets to a wider audience, e. g., *Phidgets*[1] (Greenberg and Fitchett, 2001), or *Zooids* (Kim and Follmer, 2019; Le Goc et al., 2016). In terms of force feedback, Forsslund et al. (2015) propose *WoodenHaptics*[2] using fast laser cutting techniques, while Moussette and Banks (2010) present a set of physical haptic prototypes called *Simple Haptics* to explore the haptic design space. Similarly, a wide range of expressive actuators is available[3], such as the *Haptuator* (Yao and Hayward, 2010), to allow designers to integrate vibrotactile actuation using microcontroller prototyping platforms, such as *Arduino*[4], by controlling them using signal parameters or audio design approaches. Moreover, no-code frameworks, such as *TactJam* (Wittchen et al., 2022), or *HapticLabs*[5], provide all-in-one approaches to prototype vibrational feedback.

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[1] Phidgets — https://bit.ly/3BFCboZ
[2] WoodenHaptics — https://bit.ly/3LJPoSy
[3] Tactile Labs — https://bit.ly/3C7X6Th
[4] Arduino — https://bit.ly/3SdKHma
[5] HapticLabs — https://bit.ly/3LNwJoL

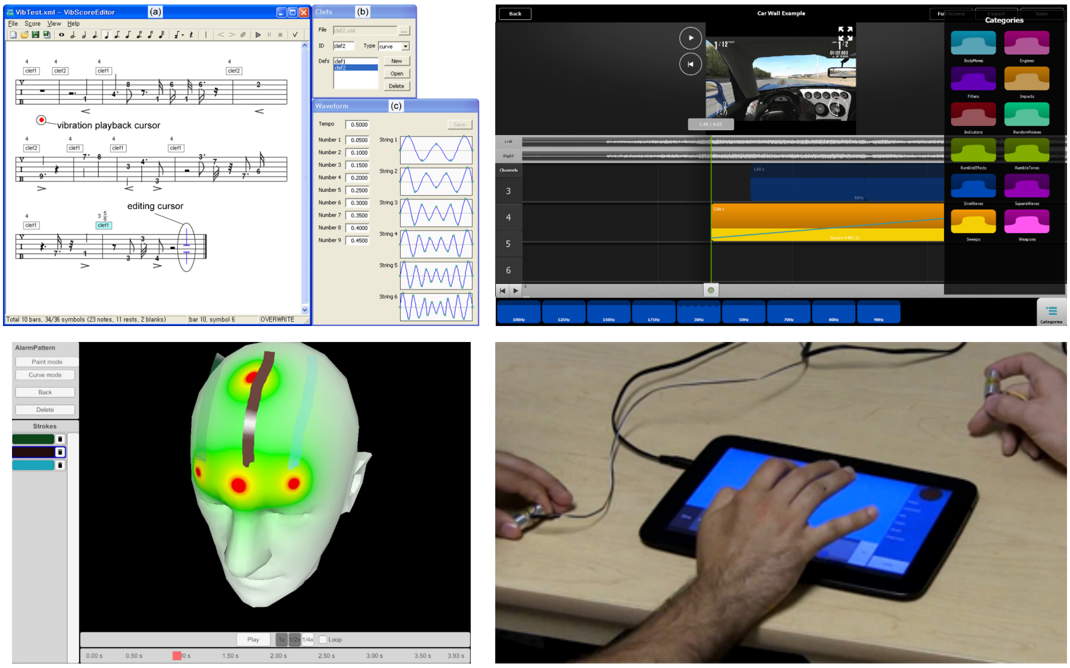

Figure 4.4: Examples of Haptic Software Editors, with (left top) a musical notation analogy from *Vibrotactile Score* (Lee et al., 2009), (left bottom) spatially drawing feedback with *3DTactileDraw* (Kaul et al., 2019), (right top) track-based haptic effect composing with *ViviTouch Studio* (Swindells et al., 2014), and (right bottom) drawing vibrotactile feedback using a musical instrument metaphor with *mHIVE* (Schneider and MacLean, 2014).

SOFTWARE Lastly, different software tools provide designers with the means to compose haptic feedback using different methodologies. For a detailed overview of prototypes presented in literature, we refer to the work of Terenti and Vatavu (2022). Numerous prototyping interfaces revert to the direct representation of the underlying signal, and present the designer with graphical representations to edit either waveforms or profiles of dynamic parameters, often combined with track-based composition using an audio-tool analogy. Examples include the *Haptic Icon Prototyper* (Swindells et al., 2006), the *The Hapticon Editor* (Enriquez and MacLean, 2003), *VITAKI* (Martínez et al., 2014), the *posVibEditor* (Ryu and Choi, 2008), and *Macaron* (Schneider and MacLean, 2016). Swindells et al. (2014) build upon the notion of track-based audio editing and use haptic tracks for rapid prototyping of haptic effects by connecting events to audio and vibrotactile output.

Furthermore, indirect representation tools use metaphor-based approaches to design haptic effects and interactions. Panëels et al. (2013) use a visual metaphor-based approach that combines temporal and spatial feedback mechanisms. Building on visual abstraction, using visual prototyping tools for haptic interactions, designers can easily and quickly create haptic interactions through a visual programming interface with tunable parameters (Panëels et al., 2010). A similar approach for force-based feedback, uses a visual programming environment which combines sketching in terms of position based haptics and time based haptic effects (Oosterhout et al., 2020).

Building on musical representations, the *Vibrotactile Score* presents a graphical editing tool for designing vibration patterns as musical notes (Lee et al., 2009). As musical representations often require expert knowledge of musical theory and notation (Lee and Choi, 2012), research has looked towards more improvisational musical design methods. Here, *mHIVE* provides the designer with a touch interfaces for rapid prototyping and exploration of vibrotactile feedback using a musical instrument methodology (Schneider and MacLean, 2014). Analogously, the *TactJam* prototype allows for recording of improvisational feedback with a spatial component, i. e., to ‘jam’ tactile feedback (Wittchen et al., 2022). Musical analogy has further been explored by creating tactile compositions, or aesthetic compositions for the sense of touch (Gunther and O’Modhrain, 2003). Here, *Beadbox* uses a composition analogy with iconic representation of haptic effects using beads (Nam and Fels, 2016).

Touch-based tools allow designers to use a ‘by-example’ approach, where direct interaction is translated to haptic effects (Hong et al., 2013). For example, painting interfaces allow both spatial and temporal drawing of tactile actuation, e. g., *3DTactileDraw* (Kaul et al., 2019), while direct manipulation has been used in the context of designing feedback for VR (Huang et al., 2016). Moreover, Schneider et al. (2015) present an approach to design tactile animations using spatially defined haptic effects.

4.3 FABRICATING HAPTIC ARTIFACTS

Parts of this dissertation address the design of passive proxy objects for tactile experiences in VR. In our work, we employ fabrication technologies to produce haptically-varying artifacts, which we overlay with virtual information. To this aim, this section introduces the field of personal fabrication, describes different available technologies, and discusses how these have been (and potentially could be) used to create tactile experiences.

4.3.1 *Fabrication Technologies*

Initial fabrication technologies, such as computer-controller laser cutting or 3D printing, were conceived to support the need for fast prototyping in industry settings (Baudisch and Mueller, 2017). With the expiration of the first major patent in 2009, the transfer of technology from industry was able to start. This led to the rapid growth of a new culture of Do-It-Yourself (DIY) technology enthusiasts, and paved the way for the democratization of manufacturing through personal fabrication technologies (Mota, 2011).

CLASSIFICATION Personal fabrication hardware is typically classified based on the manufacturing method used, i. e., additive, subtractive, or formative methods (Baudisch and Mueller, 2017). Subtractive fabrication technologies, such as milling and laser cutting, cut objects from a block or sheet of material. While a key benefit is that the qualities of the used material remain preserved, e. g., the inner structure of a wooden block persists, these methods are generally only able to utilize a single material type and are unable to alter the inner structure of the final object. Formative technologies, such as vacuum forming, reshape materials through stretching or compressing them. Such approaches are generally less time-consuming than other methods. However, similar to subtractive methods, they are even more limited in designing internal structures. Additive fabrication technologies, such as 3D printing, construct artifacts by depositing smaller amounts of material to incrementally reach the intended design goal. Using a voxel-by-voxel or layer-by-layer process, additive methods require materials that can be broken down and reassembled, which might affect the integrity of the final product. However, such methods provide the most amount of freedom to design both the inner structure and outer shape, making them an extensively researched fabrication approach.

DIGITAL-ANALOG CONVERSION Nowadays, a large variety of digital fabrication technologies exists. In essence, their underlying concept remains the same, i. e., converting digital designs into physical objects. To understand this process, Baudisch and Mueller (2017) draw analogy to specialized key copy machines that trace the design of an existing key and simultaneously mill the recorded pattern onto a blank key. The personal fabrication workflow shows a high level of similarity to a key copy machine, with an analog-to-digital conversion process that records physical information into a digital representation, and a digital-to-analog conversion process that turns virtual objects into physical artifacts. This underlying enables users to create, modify and share customized designs of highly specialized parts, and supports remote collaboration through iterative design processes.

While digitization abstracts from the fabrication hardware used, the final output remains dependent on the selected method in terms of supported materials and output resolution. For example, the smoothness of a final product heavily relies on the minimum amount of material that can be deposited at a single location when 3D printing. Low resolutions can cause discretization effects, such as stair-stepping artifacts, and degrades the physical output of the digital design, which in turn affects an object's tactile experience.

Part of this dissertation looks towards fabrication methods for producing physical objects with tactile properties. The goal of producing such objects is to create physical props which can be used as haptic proxies for virtual objects, building upon passive haptic feedback for IVE (Insko, 2001). By visually overlaying such proxies with virtual content, users can both visually and haptically explore objects in the virtual environment and assess their tangible properties. Through fabrication methods, we can utilize the underlying digitization aspect to enable sharing and on-demand production of haptic proxies.

4.3.2 *Fabricating Tactile Artifacts*

The haptic response of a fabricated object is dependent on the used material, its digital design, e. g., outer shape and inner structure, and the utilized fabrication process. This

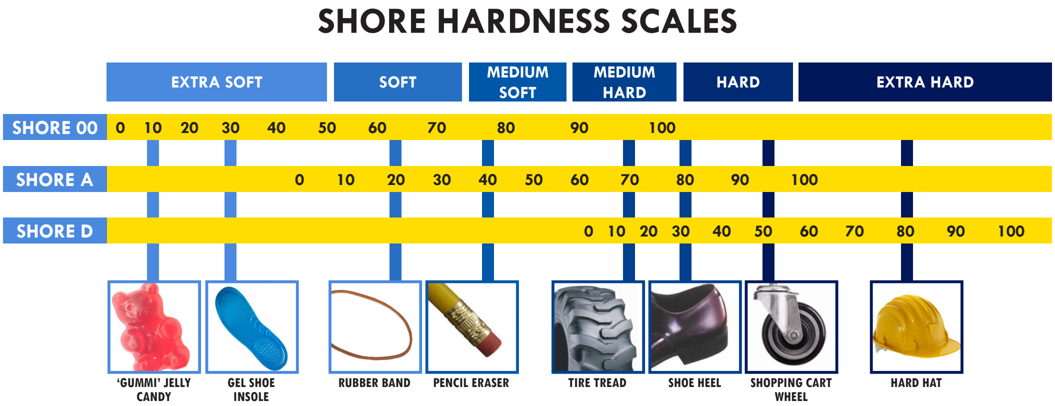

Figure 4.5: Durometer Shore Hardness Scale by Smooth-On. Figure adapted from © Smooth-On[6].

section introduces various personal fabrication methods able to produce haptically-varying structures, with a focus on tactile properties. While not exhaustive, we aim to provide a general overview of vastly different approaches to underline their parametric range.

4.3.2.1 *Material Design Approaches*

Each material has a set of intensive properties, independent of the amount of material used, which provide insights into the material's performance under specific conditions. By harnessing these underlying properties and understanding how they can be combined, the haptic perception of a fabricated object can be influenced reliably.

MATERIAL VARIATION To fabricate objects varying in terms of hardness, a material's hardness property can be harnessed. For materials such as rubbers and plastics, hardness can be determined using a *Shore durometer*, which measures the depth of an indentation in the material created by a given force. The results are expressed in different *Shore Hardness* scales to provide a common point of reference, see Figure 4.5. For common materials, three different scales dependent on the standardized indenter are used. The *Shore 00* scale measures soft rubbers and gels, while *Shore A* is used for flexible mold rubbers ranging from very soft and flexible, to medium and somewhat flexible, to hard with almost no flexibility at all, and *Shore D* measures the hardness of hard rubbers, and semi-rigid and hard plastics.

Materials used in fabrication processes can vary in terms of hardness properties, with the applied method additionally influencing the hardness of the final artifact (Truby and Lewis, 2016). Commonly used thermoplastics used in additive manufacturing range from medium soft to extra hard[7,8] (Vian and Denton, 2018), while light- and ink-based 3D printing technologies range even further in terms of printing soft matter (Truby and Lewis, 2016).

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[6] Durometer Shore Hardness Scale by Smooth-On — https://bit.ly/3SeB5HB
[7] Polylactic Acid (PLA) Biopolymer by MatWeb — https://bit.ly/3f42Fci
[8] Acrylonitrile Butadiene Styrene (ABS), Extruded by MatWeb — https://bit.ly/3dn1B2Q

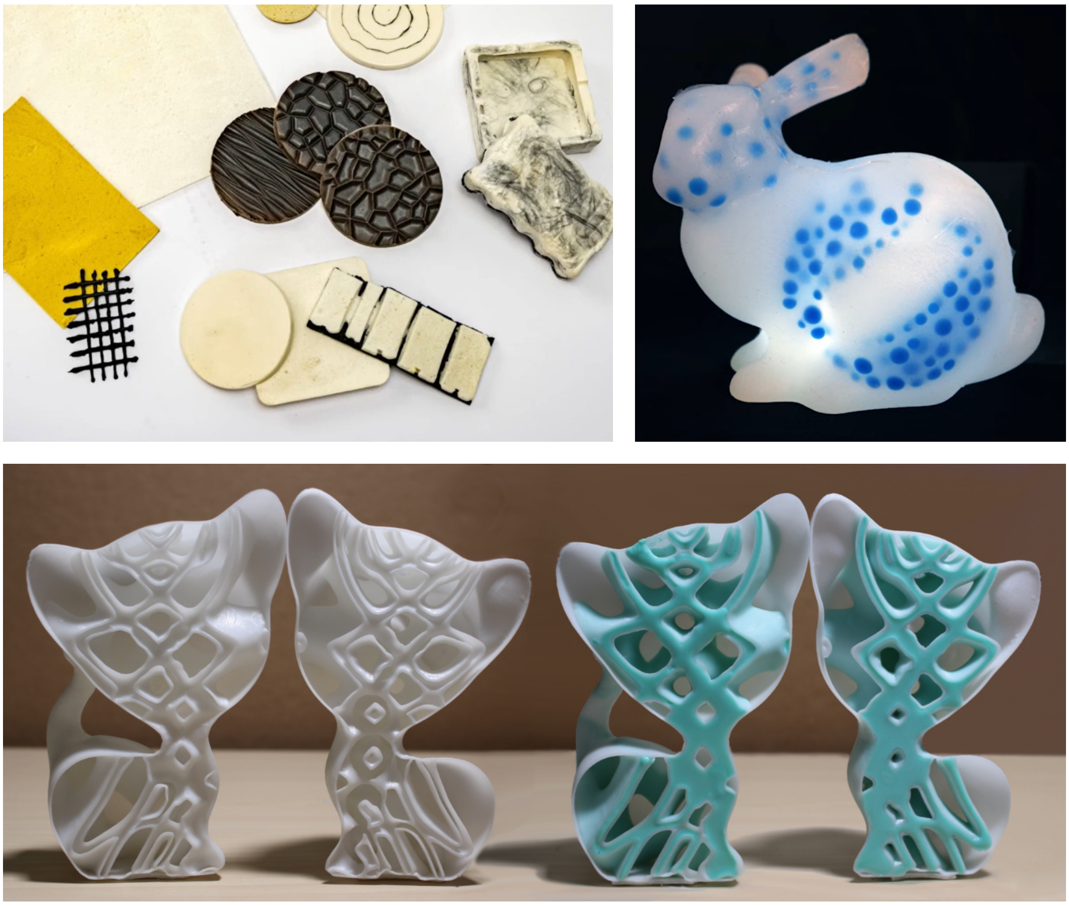

Figure 4.6: Examples of (Multi-)Material Hardness approaches, with (left top) different tactile samples made from biofoam (Lazaro Vasquez et al., 2022), (right top) multi-material method for desired compliance fabrication (Zehnder et al., 2017), and (bottom) inner channels filled during post-processing for creating strong objects (Yan et al., 2020).

However, many soft materials used for fabrication lack durability, causing them to break or rupture upon deformation. Consequently, research has looked towards multi-material printing approaches (Choi et al., 2011; Khalil et al., 2005; Maruo et al., 2001; Sitthi-Amorn et al., 2015). To create objects with low stiffness levels, Greenwood et al. (2021) elaborate on a removable embedded 3D printing process. Here, an ink-based deposition approach is combined with a support silicone that can easily be removed afterwards. Zehnder et al. (2017) pair a similar syringe-based deposition method with conventional molding to fabricate objects with a desired compliance while maintaining detailed surface geometry.

On the other side of the spectrum, Yan et al. (2020) focus on 3D printing strong objects. Their method generates inner structures used as channels into which external materials of any desired property and strength can be injected. A similar approach is taken by Torres et al. (2015) in their design tool called *HapticPrint*. Here, an inner chambering design method allows users to fill a design with other materials during the post-processing stage in order to modify an artifact’s weight or hardness.

In a recent approach, motivated to reduce the use of petroleum-based materials to support more sustainable fabrication processes, Lazaro Vasquez et al. (2022) look towards bio-based materials for tangible interaction. Such materials are defined as materials that are created from biomass, and remain biodegradable (Curran, 2010). Through different fabrication methods, e. g., molding, layering, or extruding, their approach enables the design of artifacts varying in hardness through material composition, and roughness through surface texture design, while additionally supporting conductivity.

MAGNETIC PROPERTIES Magnetic properties, while for some still considered to be miraculous[9], are well understood material properties that can provide convenient building blocks to generate attraction and repulsion forces. In HCI, permanent magnets have been used to enhance various interaction scenarios, e. g., for detecting user actions during smart device interaction (Kadomura and Siio, 2014), or for providing tactile feedback on multitouch screens (Jansen et al., 2010) and tabletops (Weiss et al., 2011).

Yasu and Katsumoto (2015) illustrate the use of magnetic interfaces using permanent magnets for haptic stimulation with tangible artifacts. Through careful arrangement of magnetic arrays, their approach proposes an easy, simple, cheap method for constructing haptic surface systems. Building upon this concept, Zheng and Do (2018) and Zheng et al. (2019) integrate permanent magnets into the 3D printing process for creating tactile mechanisms. The design of their tangible interfaces provide attraction and repulsion forces through tangent and normal alignment of cylindrical neodymium magnets. Their work showcases a set of 6 input mechanisms, i. e., a toggle switch, a push button, an analog stick, a stepped slider, a 2D slider, and a slide toggle, and 3 actuation mechanisms, i. e., a latch, and 2 types of multi-solenoid configurations. Ogata (2018) connect the design of permanent magnet interfaces to perceived tactile properties during interaction. Their work models and simulates the forces provided by arranged magnets during motion on a physical slider. From their user study, they note that users were able to distinguish between 4 distinctly designed magneto-haptic devices, and that their perception in terms of weight, roughness, hardness, and sharpness was influenced. In a follow-up work, authors present a computational design approach, where an optimization solves the arrangement of permanent magnets to provide haptic feedback according to a target input graph (Ogata and Koyama, 2021).

While permanent magnets do not require any augmentation, they provide relatively weak forces in relationship to their size, while their strength and polarity cannot be changed. To enable the design of magnetic interfaces, Yasu (2017) presents an approach that uses magnetically programmable thin magnetic rubber sheets as media to create magnetic fields. Using a desktop-sized plotter, neodymium magnets are used to write and rewrite the active fields on a sheet's surface. By altering the pattern and its sizing, the vibrating frequency of two sheets interacting together is able to simulate a programmed haptic texture through interacting lateral forces. This approach is similar to methods which simulate surface

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[9] Know Your Meme - "Miracles" / [redacted] Magnets, How Do They Work? - https://bit.ly/3ujW2Yf

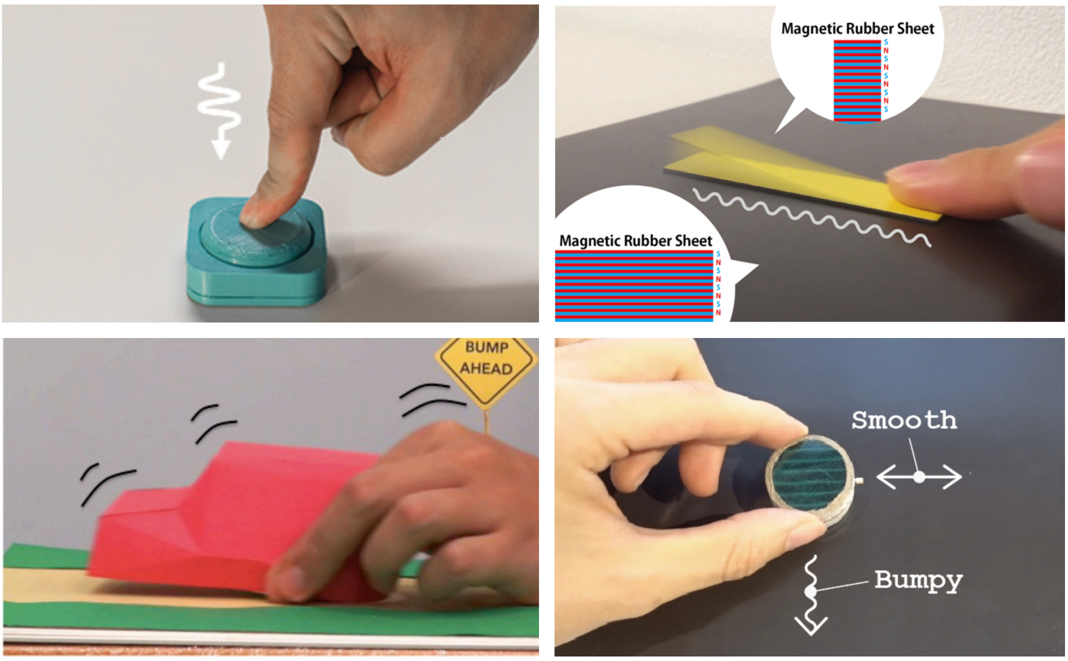

Figure 4.7: Examples of Magnetic Haptic Fabrication, with (left top) a button with embedded magnets for tactile feedback (Zheng and Do, 2018), (left bottom) a toy car with embedded magnets to simulate bumps (Yasu and Katsumoto, 2015), (right top) two magnetic sheets interacting to simulate macrotextures (Yasu, 2017), and (right bottom) a haptic shifter to alter magnetic frequencies without re-magnetization (Yasu, 2020).

textures from surface texture depth maps (Minsky et al., 1990), and has been used in lateral-force-based haptic displays (Saga, 2015). Authors investigate the interacting forces of differently spaced striped and checkered patterns. They conclude that similarly spaced patterns provide the highest attraction force area ratio, while the sizing of the pattern is able to reliably influence the frequency of the macrotexture during interaction. Authors build upon their concept with a set of magnetic interfaces for interacting with touch screens (Yasu, 2019). Their toolkit consists of customizable buttons, switches, cross keys, and sliders, that provide haptic feedback while still supporting touch detection due to the dielectric behavior of the magnetic sheet. A recent contribution called *Mixels* presents an automated approach for designing magnetic pixels to enable the design of new tangible, tactile, and haptic interfaces (Nisser et al., 2022).

Through superimposing multiple magnetic sheets on top of each other, even more complex patterns and haptic magnetic fields can be designed Yasu (2020). Their layering approach allows for a robot to select a different path based on interacting magnetic patterns, and supports varying tactile feedback for different devices interacting with the same base layer. Moreover, shifting layers respectively shifts the haptic response of the combined sheets. Furthermore, the frequency response of interacting tactile sheets has been translated into upward motion to animate kinetic toy animals (Yasu and Ishikawa, 2021).

Figure 4.8: Examples of Conductive Haptic Fabrication, with (left top) tactile feel-trough effects (Withana et al., 2018), (left bottom) combined electro-tactile and electrostatic forces (Kato et al., 2018), (right top) tactile pixels embedded inside a 3D printed remote (Groeger et al., 2019), and (right bottom) an on-skin interface (Muth et al., 2014).

CONDUCTIVE PROPERTIES In recent years, research in the field of fabrication has explored a diverse set of materials. This includes polymers and filaments with electrical and thermal conductive properties through metal, carbon, and polymer composites (Zheng et al., 2021). With a wide range of application areas, such as wearable devices (Muth et al., 2014), or interactive paper (Ramakers et al., 2015), fabrication of conductive materials allows designers to easily prototype interactive devices.

In the context of tactile experiences, Groeger et al. (2019) illustrate a method for the design and rapid fabrication of interactive devices that include electro-tactile feedback. Their design tool allows users to modify digital designs with tactile pixels, or taxels, that can be arranged in order to create an array providing tactile output. Each taxel is realized as two or more printed electrodes, while user input is captured using a resistive touch-sensing.

Conductive fabrication approaches, such as inkjet printing, often lend themselves for creating flexible interfaces with a small spatial footprint. Consequently, research has employed conductive printing to create wearable and on-skin interfaces with integrated sensing and actuation (Nittala et al., 2019; Yu et al., 2019). For prototyping such wearable interfaces, Withana et al. (2018) embed taxels into fabricated on-skin tattoos. Their method is specifically aimed at providing feel-through effects, where the wearer's touch sensation of real objects is modified through electro-tactile actuation during physical exploration. Similarly, Yun et al. (2020) present a soft and transparent wearable with an integrated touch sensitive visual display able to provide vibrational feedback. Their approach combines different fabrication approaches, such as molding and spray coating, to create a flexible layered interface aimed at creating interactive skin when worn. Another method is illustrated by Shi et al. (2021), where they embed actuated ball electrodes in a skin-based interface to provide tactile feedback during virtual experiences.

Furthermore, the use of conductive material has been shown to be able to influence the perception of friction. For example, Mishra et al. (2022) utilize the electroadhesion principle to generate attractive forces between objects. Their investigation includes preliminary insights for visuo-haptic friction perception in a VR scenario. Kato et al. (2018) present a wearable hybrid tactile display able to combining electrostatic forces with electro-tactile feedback. Using a double-sided conductive ink fabrication method, they present a multi-finger prototype designed and fabricated for use in VR. Their results underline that their combined feedback approach presents more realistic and richer tactile feedback compared to a single modality method.

SENSORY AND ACTUATOR INTEGRATION In order to create haptic interfaces through fabrication, integration of sensory and actuation technologies can take place. For example, haptic displays and shape changing surfaces providing detailed tactile experiences can be designed and fabricated using diverse actuation methods (Follmer et al., 2013; Hachisu and Fukumoto, 2014; Hafez and Khoudja, 2004; Iwata et al., 2001; Poupyrev et al., 2004). Consequently, many of the haptic devices used for studying haptic feedback in VR, see Section 3.3.2 and Section 3.3.3, were realized using a combination of fabrication and prototyping methods. As a plethora of approaches exist to create interactive devices, we focus on a short overview of methods that utilize integrated sensors and actuators to build upon material design approaches.

In order to manipulate hardness and roughness perception, research has explored methods to create dynamically soft interfaces. One such approach, called *GelTouch*, utilizes programmable gel interfaces that are able to change their viscoelasticity (Miruchna et al., 2015). Through integrating heating elements into the embedded hydrogel, predefined areas become taxels or tactile edges to render stiffness on top of a digital interface. Yao et al. (2013) utilize pneumatically-actuated composite materials to create soft interfaces. Their shape changing devices are able to provide haptic sensations in the form of dynamic hardness through changing air pressure, or surface texture simulation through the use of different composite layers. Through different form factors, pneumatic interfaces are able to provide localized haptic feedback, e. g., on the user's wrist using a band interface (Young et al., 2019). In terms of vibrotactile feedback, Yoon et al. (2019) present a soft haptic device with

Figure 4.9: Examples of Sensory Integration Approaches, with (left top) a pneumatic interface with surface texture changing properties (Yao et al., 2013), (left bottom) a pneumatic wristband (Young et al., 2019), (middle) an arm-worn SMA-based interface for simulating virtual touch (Muthukumarana et al., 2020), (right top) an on-skin SMA-based soft interface with touch detection in *HapSense* (Yoon et al., 2019), (right bottom) an on-skin SMA-based interface in *Springlets* (Hamdan et al., 2019).

integrated force sensing. In a compact form factor, their approach provides a wearable interface able to build vibrations while simultaneously detecting user input.

Another interesting approach involves the use of shape memory alloy (SMA). Such springs are thin and soft alloys with a higher force-to-weight density than any electromechanical actuator, and are able to generate expressive, non-vibrating, and silent output through actuation. In terms of tactile output, Hamdan et al. (2019) propose the concept of *Springlets*, a class of SMA-based tactile interfaces that consist of worn stickers with integrated actuators. Analogously, Muthukumarana et al. (2020) present an SMA matrix approach intended to be worn as an on-skin interface. Their layered approach integrates actuators with stretchable and adhesive textiles, and simulates skin touch through generating shearing forces. More recently, Messerschmidt et al. (2022) build upon this concept, and propose an end-to-end prototyping approach for SMA-based skin deformation devices.

TEXTILE INTEGRATION To create more flexible artifacts, recent work has looked towards integrating textiles and fabrics into fabrication processes. To this aim, Mikkonen (2013) create flexible, 3D printed objects intended to be integrated with cloth. Their approach uses post-processing methods for attaching hard objects to textiles, such as sewing buttons onto the fabric. Similarly, Sabantina et al. (2015) demonstrate simple 3D printed shapes combined with textile structures and their mechanical and geometric properties. Building upon this, the work by Rivera et al. (2017) presents a first set of design primitives, techniques and examples to support the combination of textiles and 3D printed components.

Figure 4.10: Examples of Textile Integrated Haptic Design, with (left top) providing brushing sensations with *KnitDermis* (Kim et al., 2021b), (left bottom) textile-embedded, string actuated mechanical arms (Rivera et al., 2017), (right top) *WovenProbe's* on-skin woven interactive textiles (Huang et al., 2021), and (right bottom) *Project Jacquard's* interactive jacket with sensing and vibrotactile feedback (Poupyrev et al., 2016).

Fabrics and textiles also lend themselves for integration with interactive technologies. Through weaving and knitting techniques, electrical circuits and components can be integrated on the structural level to create e-textiles or smart fabric capable of sensing and actuation (Devendorf and Di Lauro, 2019; Friske et al., 2019; Ou et al., 2019; Poupyrev et al., 2016; Pouta and Mikkonen, 2022). For example, Huang et al. (2021) elaborate on an approach for creating interactive on-skin fabrics, while Poupyrev et al. (2016) manufacture interactive textiles at scale starting from the yarn itself. Alternatively, fabrics and textiles can be made interactive after manufacturing. For example, Honnet et al. (2020) use polymerization to enhance existing textiles with piezoresistive properties. This process enables pressure and deformation sensing, while preserving the fabric's haptic and mechanical properties.

In terms of tactile experiences, the close relationship between a fabric and the wearer's skin supports an intimate and subtle interface. This is illustrated by the work of Kim et al. (2021b) through machine-knitted on-body textiles. Using SMA micro-springs that contract when activated, their tactile interfaces provide feedback in terms of compression, skin stretch, and brushing. Similarly, Muthukumarana et al. (2021) combine 3D printing with SMAs to create a set of tiles for actuating textiles.

Figure 4.11: Examples of Surface Texture Design, with (left top) cylindrical objects fabricated with different surface variations using *HapticPrint* (Torres et al., 2015), (left bottom) extrusion based surface variation to generate tactile objects and sheets (Takahashi and Miyashita, 2016), (right top) parametric surface variations applied with *Tabby* (Suzuki et al., 2018), and (right bottom) natural texture application onto a digital design (Yan et al., 2021).

4.3.2.2 *Digital Design Approaches*

As the resolution of common fabrication technologies is already high enough to produce rich and fine-grained tactile structures, increasingly more complex and detailed physical objects can be manufactured from digital representations. Through meticulous design of both the inner and outer geometrical properties, artifacts can be designed with customized haptic feedback.

SURFACE TEXTURE DESIGN Through lateral exploration of an object's surface, tactile properties, such as roughness, are extracted. Therefore, the surface texture of a digital design is an essential aspect in varying the fabricated object's tactile impression. Consequently, research has investigated different approaches to prototype varying surface designs.

A first approach includes generated designs that can be applied to existing digital objects. To this aim, Torres et al. (2015) consider the *feel aesthetics* during the design of digital objects (Torres et al., 2015). To extend the haptic gamut (or vocabulary) of 3D-printing tools, authors present *HapticPrint*, a set of design tools to augment the external and internal features of a print. In terms of exploratory procedures as defined by Lederman and Klatzky (1987), their external design tool focuses on lateral motion and contour following (cutaneous touch), while the internal design tool provides methods for augmenting pressure and unsupported holding (kinesthetic touch). Therefore, their external design tool allows applying a diverse set of surface variations onto the surface of existing digital designs, while their internal design tool builds upon different infill and slicing methods. As different regions can be filled differently to provide a local compliance variations, while additional weight can be provided through post-processing a print by filling the infill with a heavier material. Similarly, Suzuki et al. (2018) present *Tabby*, an interactive design tool for creating and exploring 3D printing textures. To design textures, a designer would only need to indicate the first few units of a texture through either drawing on a 2D canvas or importing an SVG file. Users place starting units on top of a 3D object, after which the system automatically infers a complete pattern through an autocompletion process. Once satisfied, the system will convert the 2D indications to a series of triangle meshes to create 3D textures and ensures these meshes are fused with the main object.

Using FDM printing, Takahashi and Miyashita (2016) present a method for fabricating tactile sheets. Specifically, they influence the extrusion rate during the printing process to control the amount of deposited material at any given time. This allows for the creation of thickness controlled patterns on an object's surface. Their method directly generates G-code, therefore does not require any augmentation to the used 3D printer.

However, artificially generated surface information can lead to unrealistically looking objects. In computer graphics, surface modification of digital designs using textures or displacement maps has since long been investigated (Elber, 2005; Fu et al., 2018; Jeschke et al., 2009; Oliveira et al., 2000; Szirmay-Kalos and Umenhoffer, 2008). In terms of fabrication, such approaches have been extended to generate more natural and realistic looking artifacts. For example, Yan et al. (2021) present a method for applying existing 2D textures onto 3D objects for fabrication. Through directly modifying the G-code of an object to be printed, their approach is generalizable across different additive manufacturing technologies. As their method focuses on the aesthetics of fabricated designs, their tactile perception remains unexplored. To this aim, our work in Chapter 5 investigates the haptic elements of applying surface textures onto digital designs.

INTERNAL AND STRUCTURAL DESIGN Through altering the internal material or construction of a digital design, a fabricated object can vary in terms of its tactile perception. As illustrated by Lu et al. (2014), careful design of internal honeycomb structures is able to influence an object's weight through optimizing its strength-to-weight ratio. The *HapticPrint* design tool builds on this concept by allowing the user to alter the internal infill in order to design an object's *feel* aesthetics (Torres et al., 2015). Moreover, through filling a fabricated object with a curable material during the post-processing phase, the final design can be made heavier than a complete infill with the original printing material.

By designing and optimizing microstructures, additive manufacturing has been used to create *elastic textures*, i. e., parametric, tileable, and printable cubic patterns which achieve a broad range of isotropic elastic material properties (Panetta et al., 2015). Through combining and optimizing truss-like elements, topologies built through such cell-based patterning are able to gain material-like properties in terms of elasticity and compliance. Schumacher et al. (2015) propose a similar approach in a framework for fabricating deformable objects. Here,

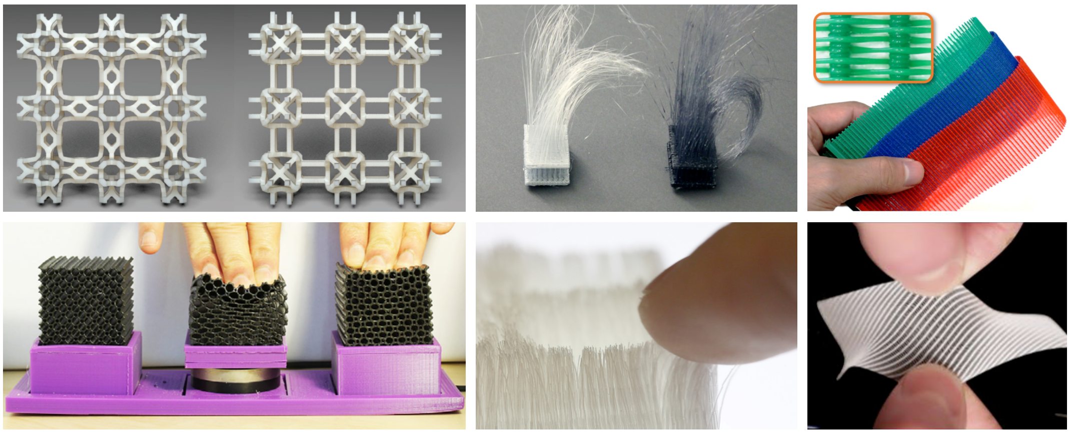

Figure 4.12: Examples of Internal and Structural Design, with (left top) microstructures creating elastic textures (Panetta et al., 2015), (left bottom) perceptually motivated compliance design (Piovarči et al., 2016), (middle top) FDM 3D-printed hair-like structures (Laput et al., 2015), (middle bottom) SLA 3D-printed hair-like structures in *Cilllia* (Ou et al., 2016), (right top) fabricated textiles using *fiber bridging* (Takahashi and Kim, 2019), and (right bottom) fabricated textiles using FDM extrusion variation in *DefeXtiles* (Forman et al., 2020).

the interior of a digital design is tiled with microstructures from a database to construct desired and localized elastic properties while maintaining the outer design. A similar method for additive manufacturing of foams procedurally generates internal Voronoi microstructures to define an object's elasticity (Martínez et al., 2016, 2018). Piovarči et al. (2016) build upon computational approaches, and take the human in the loop. Their method connects tactile perception to procedural fabrication to express the controlled deformation in terms of perceived compliance, and builds a computational model for stiffness.

Through either structural design or extrusion modification, recent advancements in additive manufacturing have made it possible to create thin hair-like structures. Such structures are easily bendable, providing more subtle tactile impressions than solid designs (Gedsun et al., 2022). To this aim, Laput et al. (2015) utilize a concept known as *fiber bridging*, where thin strands are extruded to serve as bridges connecting fixed endpoints in FDM 3D-printing. Originally used for connecting points in a model without support material, this fabrication technique is able to construct soft strands, fibers and bristles. Using Stereolithography (SLA) 3D-printing, Ou et al. (2016) construct similar surface structures using a volumetric staircase approach. In our work, this method's ability to construct dense and flexible hair-like interfaces provided the ideal foundation for visuo-haptic texture simulation in VR.

Other structural design approaches take inspiration from the field of textile and fabric design, i. e., through warp and weft components. In textile design, the lengthwise warp yarns are held stationary while the transverse weft is drawn through and inserted over and under the warp. Inspired by such methods, both Melnikova et al. (2014) and Beecroft (2016) fabricate weft knitted structures to create fabric-like designs, while Yao et al. (2021) create weft yarn-like structures that serve as infill patterns. Furthermore, Takahashi and Kim (2019) present

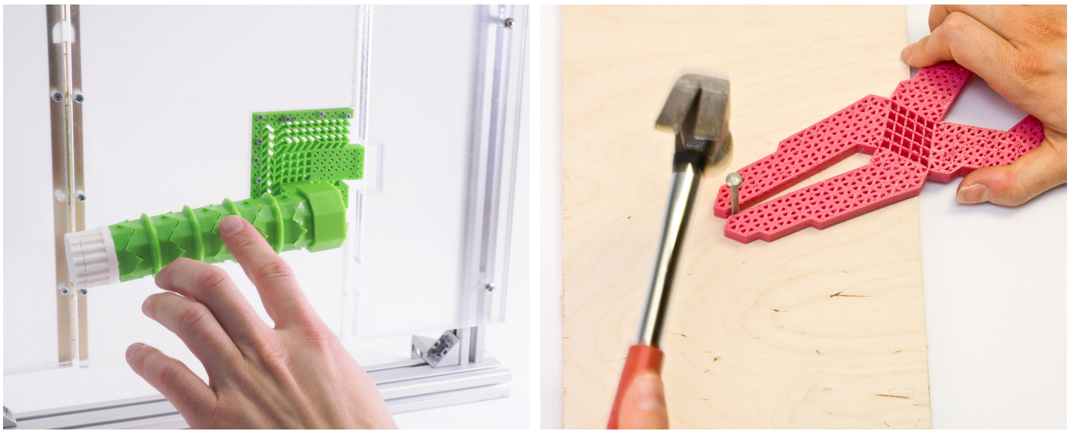

Figure 4.13: Examples of Metamaterial Designs, with (left) a door handle consisting of metamaterial structures that can alter in surface texture (Ion et al., 2018), and (right) fabricated pliers consisting of cell-based metamaterial structures (Ion et al., 2016).

a technique for fabricating soft and flexible textiles using FDM 3D-printing. Their method builds upon *fiber bridging* to achieve a stringing effect, while creating intermediate pillars serving as support structures. In *DefeXtiles*, Forman et al. (2020) increase the geometrical complexity of fabricated textiles through dynamically modifying the extrusion parameters to generate *quasi-warp* and *quasi-weft* microstructures.

METAMATERIALS Akin to approaches that redesign the internal structure of an artifact to influence its behavior, are metamaterial structures. First theoretically conceptualized by Russian physicist Victor Veselago in the context of electrodynamics (Veselago, 2002), metamaterials are understood as any given material engineered to have a property that is not found in naturally occurring materials (Kshetrimayum, 2005). For example, auxetic metamaterials are carefully constructed to exhibit a negative Poisson's ratio. When such a structure is stretched, it will become thicker, rather than thinner, perpendicular to the applied force.

Initial investigations of metamaterial structures focused on manipulating optical, acoustic and thermal properties, which led to new applications such as perfect lenses (Bertoldi et al., 2017). More recently, they have found their way into the field of digital fabrication to design the behavior of fabricated artifacts (Ion et al., 2016). This is commonly done by dividing a digital design into repetitive cells with specific deformation behaviors.

Ion et al. (2016) illustrate the concept of 3D printed metamaterials to create desired mechanical behaviors. Using their toolkit, users interactively design objects that exhibit controlled directional movements using a cell-based approach. Individual cells consist of basic open squares with optional single or double diagonal reinforcements to control and limit shear direction. Each cell's wall thickness is used to influence the level of stiffness. By compounding cells, their method is able to build *reinforced hinge* and *four-bar* mechanisms which have a programmed shearing or rotational behavior. These mechanisms build what authors call fabricated *machines* performing a mechanical function, such as pliers.

In terms of tactile fabrication, metamaterial mechanisms have been used for shape-changing interfaces able to alter their surface texture under compression (Ion et al., 2018). Here, single cell primitives consist of parameterizable walls, hinges, and members that enable an upwards fold to transform the surface composition from straight to textured. The topological deformations of metamaterial textures can be influenced in terms of amplitude and frequency of the resulting texture, with different texture primitives and force dependent actuation behavior. Utilizing this approach, surface texture properties, such as roughness and hardness, can be adjusted through simple actuation, therefore providing a currently unexplored basis for creating haptic proxies. Furthermore, Bilal et al. (2020) propose spiral shaped metamaterials that have a specific resonant frequency in order to create haptic interfaces in compact form. Such interfaces build the gap between passive and active haptics through specialized design.

4.3.2.3 *Specialized Fabrication Methods*

Through varying the used material and the design of fabricated objects, off-the-shelf fabrication technologies are able to support a wide range of tactile experiences. To extend this gamut, research has looked proposed modifying existing technologies, or creating specialized fabrication methods.

EXTRUSION MODIFICATION As we have illustrated in the previous section, changing the amount of deposited material in additive manufacturing, such as FDM 3D-printing, is able to create tactile structures (Takahashi and Miyashita, 2016), or construct thin hair-like strands (Laput et al., 2015). Building further on this concept, Pezutti-Dyer and Buechley (2022) present *ExtruderTurtle*, a library for fabricating delicate, textured, and flexible objects. Their approach combines existing methods to enable designers to create a wide range of tactile objects by only modifying G-code instructions. Extrusion modification approaches have further been investigated in 3D-printing methods that apply spinning procedures during fabrication. For example, Hamanishi et al. (2019) propose a method that extrudes fiber-like structures through heating thermoplastic pellets inside a spinning centrifuge. Based on the concept of a cotton candy machine, the rotary extrusion method is able to create primitive shapes that can post-processed into a final design (Hamanishi et al., 2018). A similar concept is proposed by Rivera and Hudson (2019). However, rather than applying rotational movements to the extruded material, authors modify the standard FDM process by adding a high voltage power connection between the print head and the build plate. In electrospinning mode, the connection applies a high electric potential to a polymer, which propels the material out of the spinneret towards the collector. This procedure results in electrospun fibers dependent on the temperature, voltage, extrusion rate and infill density.

Figure 4.14: Examples of Specialized Fabrication Methods, with (left top) rotary-spun fibers with *Fibritary* (Hamanishi et al., 2019), (left bottom) electro-spun fibers (Rivera and Hudson, 2019), (left middle top) felting a teddy bear (Hudson, 2014), (left middle bottom) the Stanford bunny in layered fabric (Peng et al., 2015), (right middle top) Kirigami inspired paper interfaces (Chang et al., 2020), (right middle bottom) embossed tactile interfaces (Klamka and Dachselt, 2018), and (right) a large spray-painted wall interface (Wessely et al., 2020).

The fiber-like structures these approaches generate, show a potential for tactile experiences, can easily be post-processed, e. g., by applying conductive paint to detect user input.

FABRICS AND TEXTILES As fabrics have a wide range of tactile properties, research has proposed specialized fabric printing technologies. In terms of weaving, a plethora of approaches exist to construct e-textiles (Pouta and Mikkonen, 2022). Through different material combinations and yarn arrangements, both visual and tactile surface characteristics can be influenced, for example in *Project Jaquard* (Poupyrev et al., 2016), or the *Involving the Machines* collection (Perner-Wilson and Satomi, 2012). Building upon felting, Hudson (2014) present a needle felting print head able to feed yarn that is felted onto a build plate consisting of fabric. Their approach is able to generate soft objects, while the addition of nylon or thermoplastic meshes is able to alter the stiffness of the resulting design. Furthermore, Peng et al. (2015) present an approach for creating layered soft objects through cutting and combining layers of fabric sheets. This method is able to print electrically functional objects, while multiple materials can be combined to influence visual and tactile properties.

INTERACTIVE PAPER Layering and folding paper augmented with printed conductive circuits and interactive components enables rapid fabrication of thin, lightweight, and inexpensive interactive prototypes (Ramakers et al., 2015). Interactive paper has been used to create interactive paper user interfaces (Klamka and Dachselt, 2017), while combined with different technologies, hybrid interactive paper (Han et al., 2021) is able to extend paper affordances, e. g., by providing intuitive notifications (Probst et al., 2014). Furthermore, the flexibility of interactive paper has been used to create prototypes for underwater usage (Liu et al., 2021), while conductive ink, the main element for printing circuits, can be printed on the fly on a variety of different surfaces (Pourjafarian et al., 2022).

In terms of tactile experiences, paper lends itself to folding, leading to research investigating interactive paper to create shape changing objects (Olberding et al., 2015). Kirigami and origami inspired methods use cut-and-fold fabrication techniques to add height to interactive paper, enabling different types of haptic feedback (Chang et al., 2020). Moreover, through heated embossing, dome-shaped membrane switches allow for novel interactive paper prototypes that provide push-button haptic feedback (Klamka and Dachselt, 2018).

SPRAY-PAINTING Lastly, research has investigated spray-coating and painting methods to post-process 3D-printed objects, or modify existing surfaces. To this aim, spray-deposition is able to create interactive surface elements (Falco et al., 2016) onto large areas and complex surfaces (Sandström et al., 2014). In the field of HCI, Hanton et al. (2020) propose *ProtoSpray*, a fabrication technique that combines 3D printing with spray coating to create interactive displays of arbitrary shapes, while Wessely et al. (2020) enable makers to create large-scale interactive surfaces on various materials and curved geometries.

In terms of tactile perception, off-the-shelf spray paints commonly create a smooth surface, as their main focus lies with aesthetic modification. Through different compounds, spraying is able to alter the surface composition to create more varied features, e. g., the Montana texture and effect sprays[10]. However, as of now, no formal investigation into the potential of spray-painting for tactile perception exists.

4.4 MODELING TACTILE RESPONSES

The previous sections provided an overview of why designing haptic feedback is difficult, and how active and passive experiences can be built from a technical perspective. With this understanding, we now focus on approaches that bridge the gap between the process of haptic design and the experience of the end-user. To this aim, we detail on computational design approaches that model physical experiences, haptic reproduction methods that aim to reproduce real world impressions, and perceptual modeling techniques that aim to understand a user's sense of touch in terms of physical variations.

4.4.1 *Computational Design*

The idea behind computational design, is to employ algorithms and parameters to solve complex design problems. Often, these design problems target a certain behavior or property that is not straightforward to achieve. For tactile experiences, computational design has been used for simulating texture and material properties in both active and passive approaches.

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[10] Montana Cans — https://bit.ly/3xPa7P4

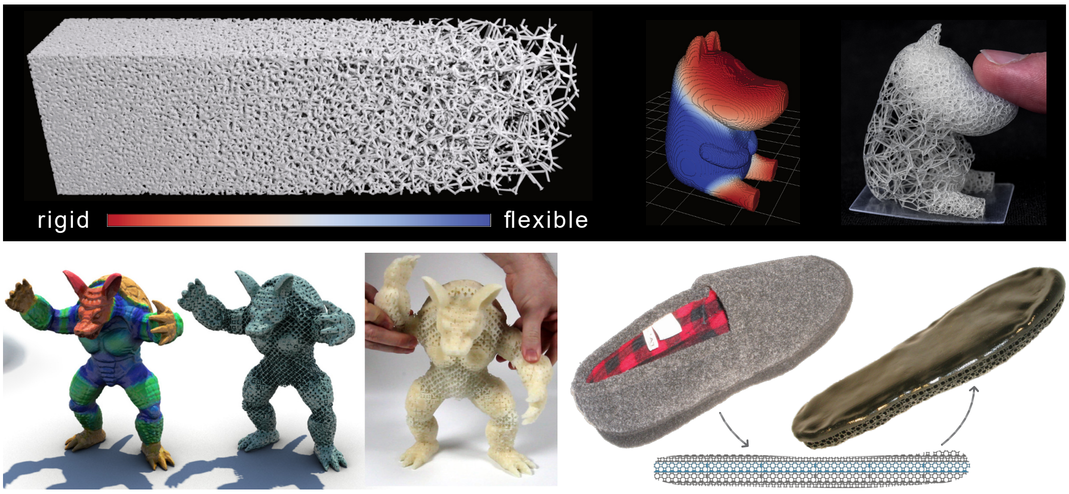

Figure 4.15: Examples of Computational Design approaches, with (top) procedurally generated Voronoi foams for controlling rigidity (Martínez et al., 2016), (left bottom) microstructures to control elasticity (Schumacher et al., 2015), (right bottom) designing desired deformation behavior through varying internal microstructure (Bickel et al., 2010).

In the field of fabrication, computational fabrication aims to produce a wide range of artifacts based on algorithmic design. Here, meta-materials are commonly used to produce objects with varying properties, such as surface textures (Ion et al., 2018), or weight (Torres et al., 2015). In order to generate objects with desired characteristics, optimization-based approaches can be applied to produce physical qualities, such as a desired compliance, or global object properties, such as desired motion. In terms of desired mechanical deformation, Bickel et al. (2010) use a data-driven process that considers a set of example deformations. Using a finite-element method, their approach is able to reproduce desired deformation behavior using a set of predefined material structures and a multi-material printer. Similarly, Schumacher et al. (2015) and Panetta et al. (2015) propose methods to approximate heterogeneous and anisotropic material behavior with high-resolution 3D structures, significantly widening the gamut of existing single-material 3D printing technologies. Martínez et al. (2016) use a stochastic approach to synthesize materials with a desired elastic behavior, and support the generation of metamaterials at the slicing stage. Instead of relying on connected structures, Zehnder et al. (2017) propose a multi-material approach for designing desired mechanical properties in silicone rubbers.

Parts of our work apply computational fabrication. Specifically, in Chapter 5, we utilize the microgeometry of real surface textures to generate and fabricate tactile structures. In Chapter 7, we synthesize physical hair-like structures with varying tactile properties for use in passive haptic in VR. This method, based on an existing approach (Ou et al., 2016), uses a voxel-based staircase construction algorithm to generate thin structures that converge to the top. By altering the height of the produced structures, their tactile perception is varied in terms of roughness and hardness.

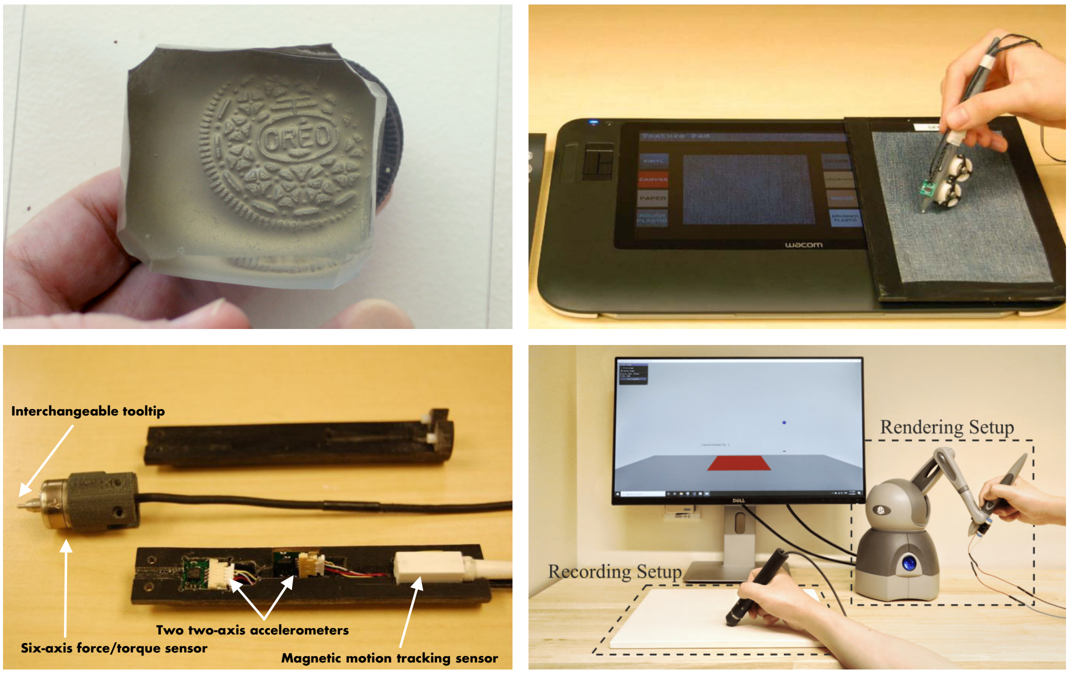

Figure 4.16: Examples of Haptic Reproduction approaches, with (left top) retrographic sensing with *GelSight* (Johnson and Adelson, 2009), (left bottom) a tactile probe to measure force and acceleration (Culbertson et al., 2013), (right top) rendering haptic textures using an augmented tablet and pen interface (Romano and Kuchenbecker, 2012), (right bottom) rendering haptic textures using a wold-grounded robotic interface (Lu et al., 2022).

4.4.2 *Haptic Reproduction*

Haptic reproduction, also referred to as *haptography*, aims to record and reproduce the haptic impression of surfaces and objects (Kuchenbecker, 2008; Kuchenbecker et al., 2011). Building upon the idea of photography, haptography aims to empower users to capture their own experiences and share them with others. With common application areas in teleoperation and virtual environments, haptography aims to recreate the richness and usefulness of natural haptic feedback.

Here, modeling-based approaches aim to reproduce haptic sensations using computational metrics. For example, Basdogan et al. (1997) use grayscale surface images to render surface shapes, while Choi and Tan (2004) proposed a parametric approach using sinusoidal waveforms to generate non-uniform haptic surface shapes. In terms of tactile properties, Minsky et al. (1990) propose to simulate surface roughness using a lateral-force-based haptic illusion. Here, the probe used during interaction receives tangential repelling and attracting forces when moved across a flat surface. A similar rendering approach generates Gaussian-distributed force fields to simulate texture interaction (Fritz and Barner, 1996). More recently, Park and Choi (2017) presented a physics-based rendering method for synthesizing vibrotactile feedback using collision events. Their approach, although computationally expensive, was able to synthesize plausible feedback during interaction.

On the other hand, data-driven modeling methods propose to generate haptic sensations from real-world physical measurements (Lang and Andrews, 2011). Reproducing such haptic impressions from real surface textures requires a challenging three-step approach, i. e., capturing, modeling, and rendering (Romano and Kuchenbecker, 2012). As haptic information arises from detailed surface variations, the capturing process needs to be accurate enough to investigate the small-scale topography and interaction properties of a surface and the used recording device. To this aim, different approaches have been illustrated, e. g., through the use of surface profilometers (Costa and Cutkosky, 2000; Wall and Harwin, 1999), tactile probes (Culbertson et al., 2013; Pai and Rizun, 2003), accelerometer-based measurements (Meyer et al., 2016; Okamura et al., 2001), pressure sensor arrays (Maheshwari and Saraf, 2006), or visual surface reconstructions (Shin and Choi, 2020).

Once such measurements are taken, they need to be represented in a model able to capture the subtleties of micro-surface interaction, while the rendering of the recorded information needs to be able to accurately simulate computationally complex real-time interactions. To this aim, Lu et al. (2022) present a preference-driven rendering approach that uses a friction model and haptic texture model for simulating surface features using a *Phantom* haptic interface. Such robotic interfaces have previously been used to render physical hardness, friction, and texture (Culbertson and Kuchenbecker, 2017; McMahan and Kuchenbecker, 2009a,b; Shin and Choi, 2020). Romano and Kuchenbecker (2012) present a complete solution for simulating realistic virtual textures. Their rendering approach builds a linear predictive model from real-world captured texture information. Using a tablet and pen setup augmented with electromagnetic actuators, their results show their method was able to recreate the tactile feeling of real textured surfaces. Furthermore, optimization based approaches have been used to render tactile information using a haptic display attached to the user's finger (Perez et al., 2017). This method formulates the computation of the device configuration as a contact surface matching optimization problem to simulate surface contact with a virtual object. Alternatively, Ban and Ujitoko (2018) illustrate a generative adversarial network-based approach for haptic rendering of texture images. To simulate haptic textures, Heravi et al. (2020) propose a data-driven model that uses both visual and height map information of real surface textures.

In our work presented in Chapter 5, we use a vision-based approach to capture the microgeometry of real surfaces. Our implementation, based on a retrographic sensing approach called *GelSight* (Johnson and Adelson, 2009; Johnson et al., 2011), employs a transparent elastomeric silicone coated with a layer of reflective paint. Through capturing the microscopic deformations of the reflective layer when an object is pressed against it, the object's surface topography is made visible through the clear side of the sensor. Using a photometric stereo algorithm, the reconstructed surface texture information was reproduced using state-of-the-art 3D-printing. Combined with visual information in VR, we investigate their perception to inform future fabrication approaches for haptic reproduction.

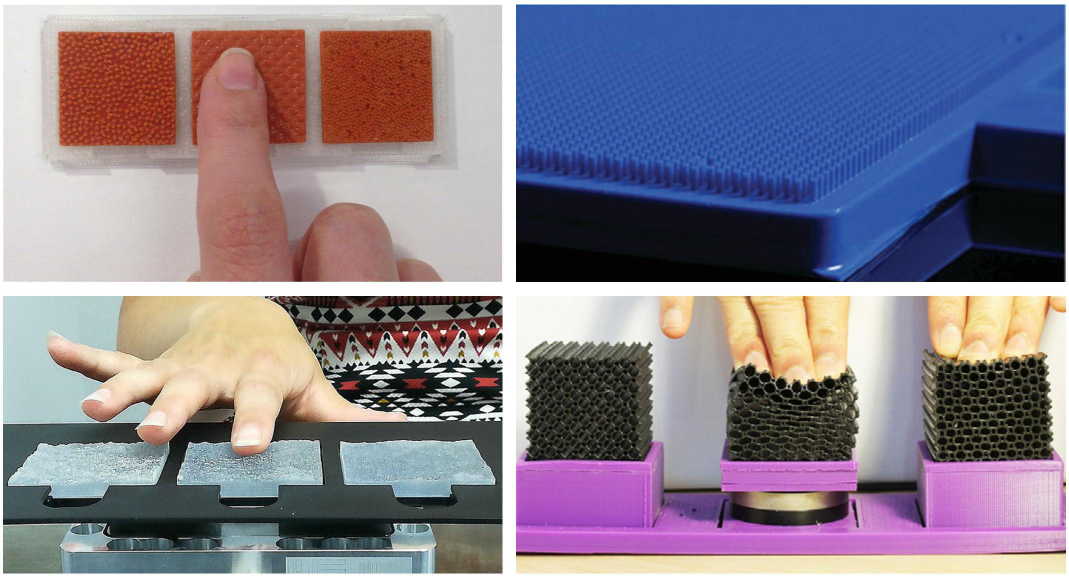

Figure 4.17: Examples of Perceptual Modeling approaches, with (left top) 3D-printed surface structures varying in surface bump density (Tymms et al., 2018), (left bottom) varying surfaces' topographic structure and statistical roughness (Sahli et al., 2020), (right top) fibrillar surfaces for softness perception (Gedsun et al., 2022), (right bottom) internal microstructure variation for softness perception Piovarči et al., 2016.

4.4.3 *Perceptual Modeling*

As detailed in the previous section, optimization-based approaches for computational fabrication are able to extend the gamut of haptic properties of a 3D-printed designs. However, as their implementation commonly uses standard metrics to quantify differences in material mechanical properties, they ignore a major component of haptic interaction, namely the user. Therefore, perceptual modeling approaches use perceptual metrics to find computationally efficient and accurate models that can outperform standard measures for designing fabricated objects with desired haptic properties.

To this aim, Piovarči et al. (2016) introduced a perceptual-aware approach that modifies the softness of 3D-printed objects through quantifying their elastic modulus. Their work found that one tactile dimension is sufficient to describe compliance perception on objects with a non-linear mechanical characteristic. Similarly, Dhong et al. (2019) fabricated elastic slabs with micro-patterned pits to investigate softness perception. Their results indicate an explicit relationship between the perception of softness and the slab parameters, and note that indentation depth and contact area were key factors for softness discrimination. For fibrillar surfaces, i. e., surfaces with bristle-like structures on top, Gedsun et al. (2022) found that their bending during tactile exploration was a key mechanism for tactile discrimination.

In terms of the tactile roughness, Sahli et al. (2020) investigate the perception of randomly rough surface textures. Through independently varying topographic structure and statistical roughness, their results indicate that the tactile perception of similarity between surfaces was dominated by the statistical micro-scale roughness, while their similarity in terms of visual perception was dominated by their topographic resemblance. Analogously, Hartcher-O'Brien et al. (2019) examine the influence of fabrication parameters, such as print speed, in 3D-printed surface structures on perceptual roughness, and found that objective surface roughness parameters were unable to predict users' haptic experience. Furthermore, Tymms et al. (2018) propose a quantifiable roughness perception model for fabricated surface textures. Through psychophysical experiments using a set of 3D-printed surface structures varying in surface bump density, their model is able to predict perceptual roughness with a single scalar value. Their follow-up work integrates the final object's visual aspect in the design process (Tymms et al., 2020). From a target texture, their optimization-based procedure models desired tactile roughness while preserving visual appearance, resulting in visually similar but haptically-varying objects.

In terms of design tools, Kim et al. (2021a) propose to connect perceptual softness to the design of 3D-printed objects using a by-example metaphor. This enables designers to model an object's softness using reference objects with varying softness factors to fabricate desired tactile characteristics. Furthermore, Miyoshi et al. (2021) detail on a concept to allow users to design the desired softness and roughness as an input for 3D printing. Using both surface texture variation and infill modification, their work connects perceptual aspects with physical manufacturing parameters.

In our work, we build upon the notion of perceptual modeling by taking the user's perception in mind. To this aim, in Chapter 5, we use non-Metric Multidimensional Scaling (nMDS) to build a perceptual model of replicated surface textures, and further investigate their visuo-haptic perception in Chapter 6. Furthermore, through user studies, we investigate users' perception of computationally fabricated hair-like structures in Chapter 7, while Chapter 8 investigates users' perception of object interaction by having them vocalize their experience. The latter was used to inform a rapid prototyping process in Chapter 9 that allows designers to create vibrotactile feedback while immersed.

4.5 CONCLUSION

Haptic technology is maturing. However, designing effective haptic experiences remains challenging. Reasons for this can be found with the complexity of the haptic sense itself, the novelty of designing for the sense of touch, and the personal and private nature of touch sensations. Therefore, haptic design is establishing itself as a field of research by investigating universal and sustainable design practices that build upon other design fields, such as user experience design.

In the field of active haptics, a wide range of haptic experiences has been illustrated using different haptic rendering methods. Designing such experiences often relies on manipulating low-level signal parameters, such as frequency and amplitude, making it challenging to transfer such abstract concepts into understandable haptic effects. To better understand the design parameters of effective and convincing tactile experiences, haptic design has proposed different methodologies, including the use of abstract messages, e. g., tactons, conceptualizations of haptic signals, e. g., metaphors, schemas, and facets, or by addressing a generalizable language for communicating haptic sensations. While design tools building upon these concepts have broadened the space of active haptic experiences, there is still no generalizable and scalable method for designing visuo-tactile experiences for VR.

In terms of passive haptics, recent advancements in fabrication technologies have enabled designers to produce rich and fine-grained tactile structures. Through variations of the used material, alterations of the digital design, or modifications to the fabrication process, the haptic response of fabricated objects can be altered. Considering the broad design space of fabricated haptics, we envision these methods to be able to extend passive haptic feedback in VR. The use of fabricated props as haptic proxies for virtual objects enables the design of more scalable and flexible haptic proxies that can be fabricated by the end-user. However, it remains unclear how to transfer these approaches to a wide gamut of experiences through utilizing fabricated proxies in virtual environments.

As a large amount of research has investigated the design of active and passive haptic experiences from a technical perspective, there remains a need to bridge the gap between the process of haptic design and the experience of the end-user. To this aim, computational design approaches model physical experiences, while haptic reproduction methods aim at reproducing real world impressions. Moreover, perceptual modeling techniques build an understanding of a user's sense of touch in relation to physical design variations. These insights lay the foundation to enhance the design of tactile experiences for IVEs.

Part III

CONTRIBUTIONS

> *"Taking pictures is savoring life intensely, every hundredth of a second."*
>
> — Marc Riboud

5

CAPTURING TACTILE PROPERTIES FOR HAPTIC REPRODUCTION

To extend the design of tactile experiences, we firstly investigate the case of haptic reproduction. By capturing and replicating real-world information, we aim to create effective tactile experiences from known properties of the physical environment. This chapter addresses RQ1, and was previously published under the following publication.

Donald Degraen, Michal Piovarči, Bernd Bickel, and Antonio Krüger (2021c). "Capturing Tactile Properties of Real Surfaces for Haptic Reproduction." In: *The 34th Annual ACM Symposium on User Interface Software and Technology*. UIST '21. Virtual Event, USA. DOI: 10.1145/3472749.3474798

5.1 INTRODUCTION

In this chapter, we investigate the replication of real-world information for the purpose of fabricating tactile variations. Rather than aiming for direct reproduction of tactile perception, we investigate the change in haptic properties upon replication. To this aim, we follow an end-to-end process. We start by capturing the haptic properties of materials, which we propose to do by reproducing their stable surface geometry. The geometry is captured using a photometric sensing technique called *GelSight* (Johnson and Adelson, 2009) as height fields of surface samples. This approach works by pressing a soft polymer onto the material, similar to the investigation by direct touch. As a set of materials, we opted for a set of 15 cloth samples from a fabric samples book, depicted in the leftmost image in Figure 5.1. We opted for these challenging materials due to their large coverage of compliance, roughness,

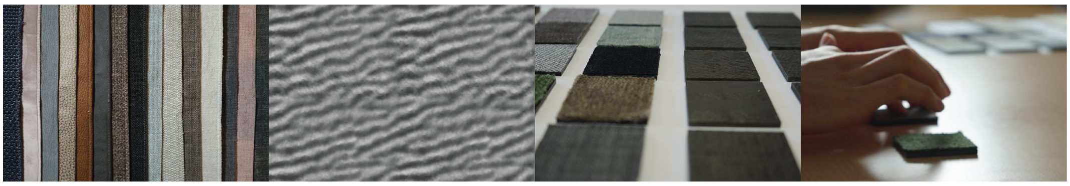

Figure 5.1: Overview of our approach. By reconstructing surface textures from a sample book using a photometric reconstruction method, we created fabricated replicas. The set of original and replica surface samples were used in a 2-part user study to investigate the transfer of tactile properties for additive manufacturing.

and friction properties, as well as their varying surface structures. To fabricate the materials, we treat the captured height maps as displacement maps and use an Objet Connex 260 multi-jet printer[1] with VeroBlack[2] material.

In a psychophysical experiment, we assess the perception of the reproductions based on individually perceived attributes. From these results, we conclude that our fabrication process supports a wide gamut of *feel* aesthetics. While direct reproduction of surface geometry is not sufficient to consistently replicate the haptics of real-life materials, certain stable properties can still be reproduced to an extent. By further analyzing the results, we discover that our reproductions manifest a consistent shift in perceived attributes. This suggests that the alteration of haptic feedback due to the selected fabrication technique is systematic and could be reversed by adjusting the printing parameters for our surfaces. Therefore, we propose a method to appropriate, i. e., adapt, the haptic feedback of materials for digital fabrication. As a core of our approach, we construct a so-called perceptual space of our stimuli in which the perceived difference corresponds with measurable physical attributes. We leverage the perceptual space to propose several strategies for adapting material properties to more closely mimic their haptic properties after fabrication. Our results provide insights for the field of haptic design by supporting hapticians in creating versatile haptic experiences through capturing real-world information for fabrication processes.

5.2 HAPTIC SURFACE REPLICATION

When exploring an object's surface, the high spatial acuity of our fingertips enables us to distinguish between the minuscule details in its texture. During this process, different aspects of the material are taken into account, most notably roughness, compliance, coldness, and slipperiness (Bergmann Tiest, 2010). Of these features, related work has established roughness to be the most important for discrimination of haptically explored surface textures (Bergmann Tiest and Kappers, 2006; Hollins et al., 2000, 1993). The perception of roughness is evoked by an uneven pressure distribution on the skin when touched statically,

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[1] Statasys Objet260 Connex — https://bit.ly/3SPobx6
[2] Stratasys Vero — https://bit.ly/3C2uLwc

and vibrations when stroked. Physically, roughness is related to height differences on a material's surface.

We follow the idea that the geometric roughness of a surface can explain its tactile behavior. To reproduce the haptic feedback of real-life materials, we leverage the capabilities of modern manufacturing to reproduce the surface details at micron resolution. Recovering the surface information for fabrication requires a capture method that estimates the geometric features appreciated by an observer. During exploration, our fingers actively contact the underlying substrate, which causes deformations of surface geometry. As a result, estimating the true stable contact requires a scanning method capable of inducing and measuring finger-like deformation of the original material.

5.2.1 *Approach*

Our implementation is based on retrographic sensing (Johnson and Adelson, 2009; Johnson et al., 2011). This approach also referred to as *GelSight*, employs a transparent elastomeric silicone coated with a layer of reflective paint of which the bidirectional reflectance distribution function (BDRF) is known. When pressing the silicone onto an object, the microscopic deformations of the reflective layer caused by the object's surface topography are made visible through the clear side of the sensor. By capturing the deformation under calibrated lighting conditions from different angles, the desired 3D shape and texture can be accurately reconstructed using a photometric stereo algorithm. This approach is highly flexible as the overall shape, thickness, and hardness of the sensor do not significantly affect the precision due to individual calibration (Johnson et al., 2011; Shimonomura, 2019). Additionally, surface reconstruction with a calibrated sensor is possible using a single image capture while abstracting physical surface information from the visual appearance. The only practical constraint is that the sensor needs to be sufficiently large enough to scan the area of interest.

This technique is closely related to the haptic exploration of surface textures with our fingers. While pressing down onto an object, stable surface features, such as surface variations, are perceived by the receptors in our fingers, while unstable features, such as hairs, are compressed. We envisioned this approach to serve as a realistic means for haptic reproduction.

5.2.2 *Surface Reconstruction*

Building on the *GelSight* technique, we constructed a sensor, see Figure 5.2a, consisting of a hexagonal silicone slab measuring 1.5 cm in height and 8 cm in diameter. The clear silicone used has a Shore A hardness rating of 15[3] and was spray-painted with a layer of aluminum powder with a purity of 99.7% and a size of −325 mesh using a silicone paint base[4]. The

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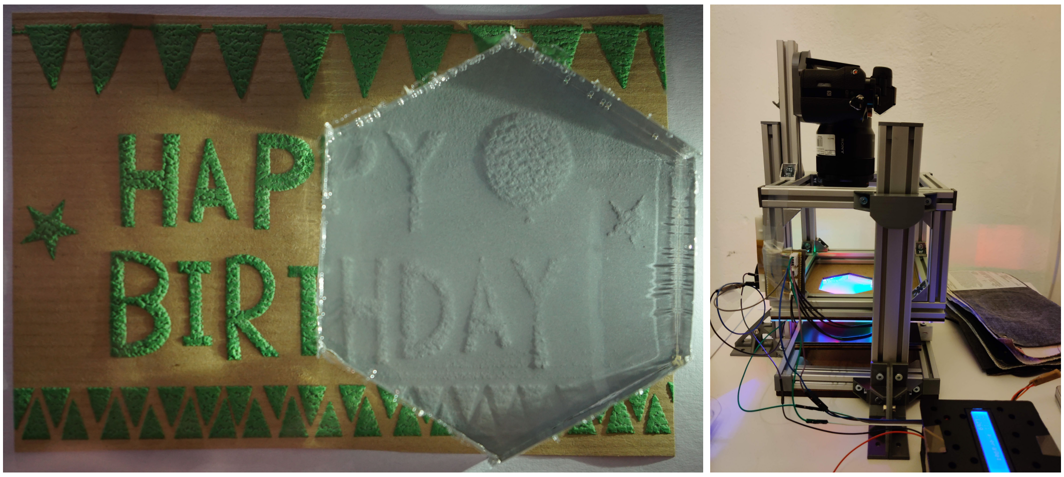
[3] KauPo Solaris®— https://bit.ly/3CDWHIz

[4] Smooth-On PsychoPaint — https://bit.ly/3UVEPzE



(a) Silicone Sensor (b) Bench Setup

Figure 5.2: Our reconstruction setup. (a) A silicone slab with a reflective layer deforms and visualizes the surface texture of an object pressed underneath. (b) Using a bench setup, consistent captures are taken with a high resolution camera and a macro lens.

reflective layer was powdered with corn starch to reduce stickiness. To capture consistent images, we built a bench setup, see Figure 5.2b. Attached to the top of the setup is a Sony Alpha 7s full-frame DSLR camera with a Sony SEL FE 50 mm f2.8 macro lens. The camera is pointed towards the silicone sensor attached to a 2 mm transparent acrylic support. Driven by an Arduino Uno, 3 LEDs illuminate the sensor from different angles, each corresponding to a different base color, i. e., green, red and blue. The base of the setup contains a load cell measuring the applied pressure to the surface. The reconstruction process follows a photometric stereo algorithm to generate a height field from the object visible under the sensor. To calibrate our setup, we capture the sensor's deformation of a 4 mm spherical object in 36 locations across the image. For each surface texture to be reconstructed, 4 pictures of the sensor's deformation were taken with the texture in different locations and orientations. For more details on the reconstruction algorithm, please refer to the work by Johnson and Adelson (2009) and Johnson et al. (2011).

For each recorded texture sample, the resulting height field corresponded to a surface area of 2.8 cm^2 of the original texture. As we considered this surface area too small to be sufficiently explored by participants, we upscaled the surface area to a size of 5 cm^2 using a blended texture tiling approach. Here, each height field was tiled in a 4×4 grid with a 10% gradually blended overlap. The vertices of a 5×5 plane were transformed along the Z-axis by using the associated height field as a displacement map in Blender[5]. The edges of the plane were extruded downwards along the Z-axis by a factor of 0.4 and a bottom face was generated to create a closed cuboid with the replicated texture on top. Our models were fabricated using an Objet Connex 260 printer with VeroBlack material and a layer resolution of 30 µm. VeroBlack is a rigid, durable and high resolution photo-polymer with a

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[5] Blender, a free and open-source 3D creation suite – https://bit.ly/3CcBVOK

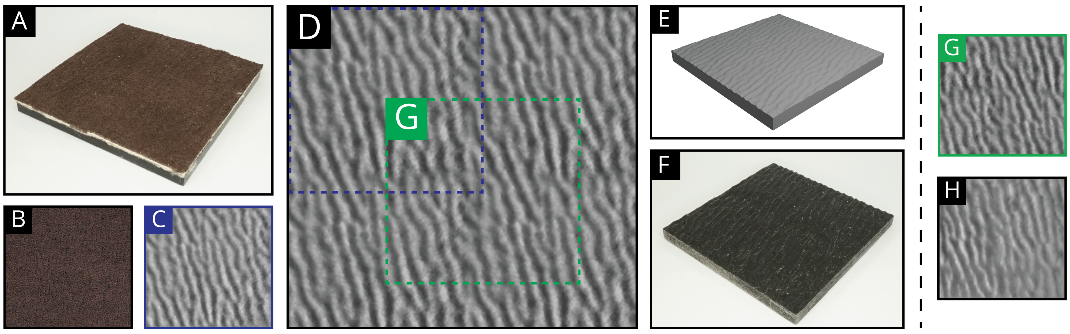


Figure 5.3: Reconstruction example. Visually capturing the texture surface (A) yields (B). The *GelSight* approach captures the stable subsurface geometry in a heightfield (C). From this information, we create a 5 cm² height field (D) using a combination of tiling and blending. The full height field is used as a displacement map to generate a textured surface (E), which is fabricated in (F). This process replicates the stable subsurface geometry of (A) in (F). For accuracy estimation, the fabricated sample (F) was re-reconstructed, i.e., here (G) is re-reconstructed in (H).

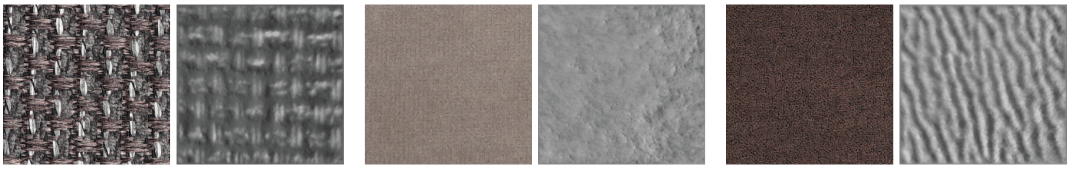
Shore Hardness of 83–86 (Scale D). A step-by-step overview of the reconstruction process is presented in Figure 5.3.

5.2.3 *Textures*

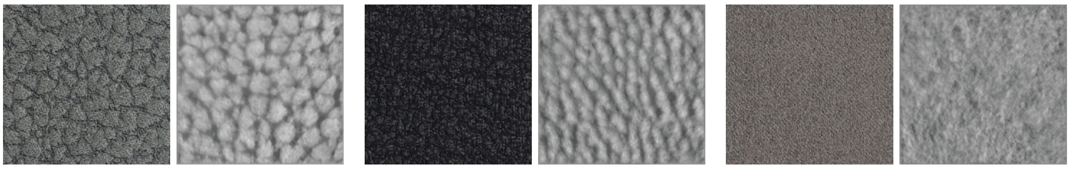
To study the human perception of materials, we seek to construct a dataset that covers a wide variety of haptic properties. As we were interested in how physical features affect the perception after reconstruction, we explored a large assortment of materials with a high variety of characteristics. For our final set of reconstructed materials, we decided on 15 samples from a sample book for a commercially available sofa. These materials were found to have a wide range of tactile properties, and maintained a stable surface suitable for reconstruction.

After reconstruction, physical measurements of the samples were taken to record their tactile properties of roughness, hardness, and slipperiness, see Table 5.1. The assessment of roughness was determined by calculating the root-mean-square of the reconstructed height field (Black, 2019). Hardness was measured by recording the indicated weight on a load cell when multiple stacked layers of the surface with a uniform height were compressed with a fixed displacement (Panetta et al., 2015). Lastly, we recorded the angle of inclination of which a fixed object on top of the surface would start a movement to assess slipperiness (Kurtus, 2005). These data, depicted in Table 5.1, show the range of tactile properties present in the selected set of samples.

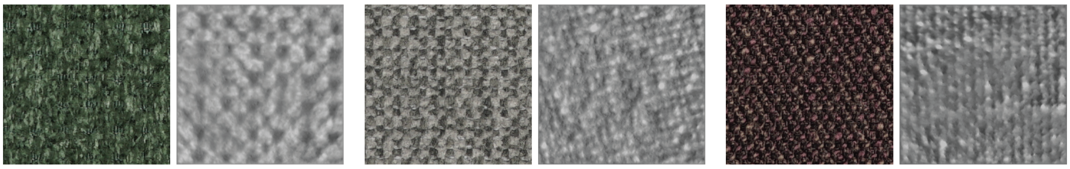
To prepare the cloth samples for our study, we cut 5 cm² rectangles from the bulk material and attached them to 2 mm acrylic plates of the same dimensions. The final set of samples and their height field reconstructions are depicted in Figure 5.4.



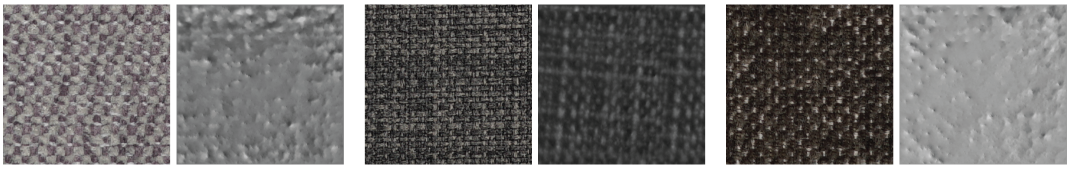
1 – Casino 2 – Velvet 3 – Crown



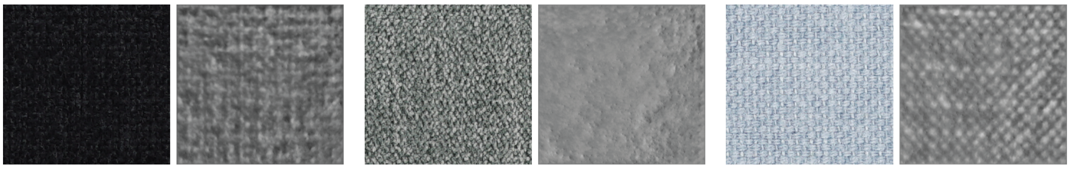
4 – Havanna 5 – Deluxe 6 – Clash



7 – Cosy 8 – Florida 9 – Yelda



10 – Trend 11 – Onyx 12 – Cosmopolitan



13 – Easy Care 14 – Matrix 15 – Vintage

Figure 5.4: Our final set of surface textures and their reconstructed height fields.

5.3 STUDY

To evaluate the haptic feedback of our original and reproduced textures, we rely on psychophysical experiments grounded in literature (Vardar et al., 2019). More specifically, we conducted our user study in two phases: (A) a self-assessment test in which the participants compare the samples based on a set of perceptual attributes, and (B) a magnitude estimation study that recovers the differences between our stimuli in an unsupervised manner.

Ethical approval for this study was obtained from the Ethical Review Board of the Department of Computer Sciences at Saarland University (No. 20-07-2).

Sample	Name	Roughness (RMS)	Compliance (kg)	Stickiness (angle)
1	Casino	0.16259	2.82	16.5
2	Velvet	0.01412	1.03	28.0
3	Crown	0.07589	2.40	26.0
4	Havanna	0.06618	1.75	27.0
5	Deluxe	0.07799	2.00	22.0
6	Clash	0.03667	1.20	20.5
7	Cosy	0.09089	0.52	20.5
8	Florida	0.09807	1.38	14.5
9	Yelda	0.05816	2.03	19.0
10	Trend	0.06598	1.36	19.0
11	Onyx	0.15941	1.14	14.5
12	Cosmopolitan	0.04553	0.99	24.5
13	Easy Care	0.10260	3.75	19.5
14	Matrix	0.01632	3.15	22.0
15	Vintage	0.08882	0.72	15.5
	Mean	0.07728	1.75	20.6
	SD	0.04342	0.94	4.37

Table 5.1: The physical measurements of our texture samples, taken from the set of original texture samples before reproduction to provide insights into their physical variations in terms of roughness, compliance and stickiness.

5.3.1 *Apparatus*

To limit visual cues, participants were seated in front of a screen separating them from the experimenter and the surface samples, see Figure 5.5. A gap in the screen with a piece of cloth in front allowed the participants to reach their hand through to access the presented samples. On the other side, the experimenter prepared the samples for exploration by the participant. Samples were fixed in place using a laser cut MDF frame. The order of presentation of the samples was listed in a spreadsheet on a laptop next to the screen. Here, the experimenter would also record participants' answers.

5.3.2 *Participants*

A total of 20 participants (9 female, 11 male, 24–33 years, avg. 26.6 years) with backgrounds in Computer Science, Microbiology, Linguistics, and Law, were recruited for our study. When asked about their hand dominance, 19 participants indicated to be right-handed,

(a) The experimenter side

(b) The participant side

Figure 5.5: The experimental setup. (a) The experimenter prepared the samples for exploration by the participant. (b) The participant rated the tactile perception of the samples hidden behind the screen.

while 1 participant stated to be ambidextrous. All participants performed the study with the index finger of their right hand, and were informed they could only use this finger.

All participants confirmed that, to the best of their knowledge, they did not suffer from any impairment of their haptic perception, such as arthritis or hypoesthesia (numbness). Participants rated on a scale from 1 (= never) to 5 (= regularly) how often they performed precise handwork ($M = 2.50$, $SD = 1.00$) and how frequently they worked with textiles ($M = 1.55$, $SD = 0.76$). The study lasted between 2 and 2.5 hours, depending on the speed of the participant. Compensation in the equivalent of € 20 was given to all participants not employed in our lab.

5.3.3 *Procedure*

Before starting the experiment, participants provided written consent and completed a COVID-19 form for contact tracing purposes. To comply with data protection regulations, the responses of the latter were removed 14 days after participation. The experimenter briefed participants on the upcoming events and asked them to seat themselves behind a separation screen.

After introducing the participants to the experimental conditions, we conducted a short training session. This training aimed to ensure understanding of the perceptual descriptors investigated in the study. Participants were presented with exemplar structures for each descriptor and asked to explore them under the experimental conditions. Once we were confident participants could identify the individual descriptors, we proceeded with the study itself.

Our study consisted of two phases, i. e., individual surface texture assessments (A), and surface texture similarity assessments (B). During phase A, the experimenter placed one of the surface samples on a fixed location behind the screen. The participant was then asked to explore the sample and rate various tactile properties of the sample one by one. During this phase, the participant was allowed to touch the sample continuously with the index finger of their dominant hand. The experimenter noted the responses for each trial and placed the next sample upon completion of the 9 questions. The following questions were depicted on a sheet of paper in front of the participant:

- **Q1**: How **hard** does this surface feel?
  (1 meaning extremely soft, 9 meaning extremely hard)

- **Q2**: How **rough** does this surface feel?
  (1 meaning extremely smooth, 9 meaning extremely rough)

- **Q3**: How **bumpy** does this surface feel?
  (1 meaning extremely flat, 9 meaning extremely bumpy)

- **Q4**: How **sticky** does this surface feel?
  (1 meaning extremely slippery, 9 meaning extremely sticky)

- **Q5**: How **scratchy** does this surface feel?
  (1 meaning extremely dull, 9 meaning extremely scratchy)

- **Q6**: How **hairy** does this surface feel?
  (1 meaning extremely clean, 9 meaning extremely hairy)

- **Q7**: How **uniform** does this surface feel?
  (1 meaning extremely irregular, 9 meaning extremely uniform)

- **Q8**: How **isotropic** does this surface feel?
  (1 meaning extremely anisotropic, 9 meaning extremely isotropic)

- **Q9**: What kind of **material** is this?
  (Open question)

During phase B, the experimenter placed two surface samples behind the screen on fixed locations next to each other. The participant was then asked to explore both samples and rate the similarity of the tactile sensations on a 9-point scale, where 1 meant both samples were extremely dissimilar, i. e., opposites, and 9 meant both samples were extremely similar, i. e., identical. To improve consistency, participants were only allowed to use the tip of their index finger on their dominant hand to interact with the samples. The interaction window was limited to 5 seconds per sample to ensure participants' first impressions were communicated to the experimenter, and to limit the study duration. Within this time, there were no limitations on the interaction mode. Participants were allowed to stroke the samples in arbitrary patterns and lightly press or tap the samples to assess their hardness. The experimenter noted the response for each trial and placed the next samples upon completion of the similarity question.

Breaks were issued between phases, every 100 assessments, or when the participant noted a feeling of numbness in their finger. In terms of COVID-19, windows were opened to air the room at regular intervals, both the experimenter and the participant wore masks, and the setup and all samples were disinfected between participants. After the experiment, participants completed a post-study questionnaire inquiring about their demographics.

5.3.4 *Design*

We used a within-subjects experimental design with a total set of 30 samples, consisting of 15 real surface textures and their 15 replicated counterparts. In order to counterbalance both study phases for carry-over effects, participants were assigned sequence numbers. Each evenly numbered participant started with phase A, while each unevenly numbered participant first performed phase B.

For phase A, we considered the presented sample as the independent variable and distinguish 9 dependent variables, i. e., participants' tactile impressions of a sample in terms of hardness, roughness, bumpiness, stickiness, scratchiness, hairiness, uniformity, and to which degree the surface geometry of the sample felt isotropic, each on a 1-to-9 Likert scale, 1 indicating a low assessment and 9 indicating a high assessment of the respective variable. We chose compliance, roughness, and stickiness since they are considered the base of tactile exploration models (Hollins et al., 2000, 1993; Okamoto et al., 2013; Vardar et al., 2019; Yoshioka et al., 2007). The inclusion of bumpiness and scratchiness is motivated by (Okamoto et al., 2013) where the authors show that roughness can be divided into two dimensions for macro and micro roughness. The inclusion of hairiness, uniformity, and isotropy was motivated by the fact that our original set of textures were fabric samples. As hairs are inherent to them, their lack in the set of replicated structures would show correlations to other perceptions, specifically uniformity and isotropy, as the directionality given by the sensing of hairs could influence these factors. The last dependent measure was the open answer, in which participants stated which material they thought to experience. For this open question, participants were not provided a list of materials to choose from, but were free to provide any answer they saw fit. For counterbalancing measures, we constructed experimental design tables using a 30×30 Latin square. Here, counter-balancing was incomplete as the Latin square was performed for 20 rows, i. e., one row per participant.

For phase B, we distinguish the independent variable as the combination of samples presented to the user. Each participant was presented with all 435 possible combinations of our 30 samples. The order of sample presentation was randomized, while the relative location of the presented sample for a given combination was alternated between participants. This meant that for a given combination, a sample was presented on the left side for an evenly numbered participant and on the right side for an unevenly numbered participant.

5.4 RESULTS

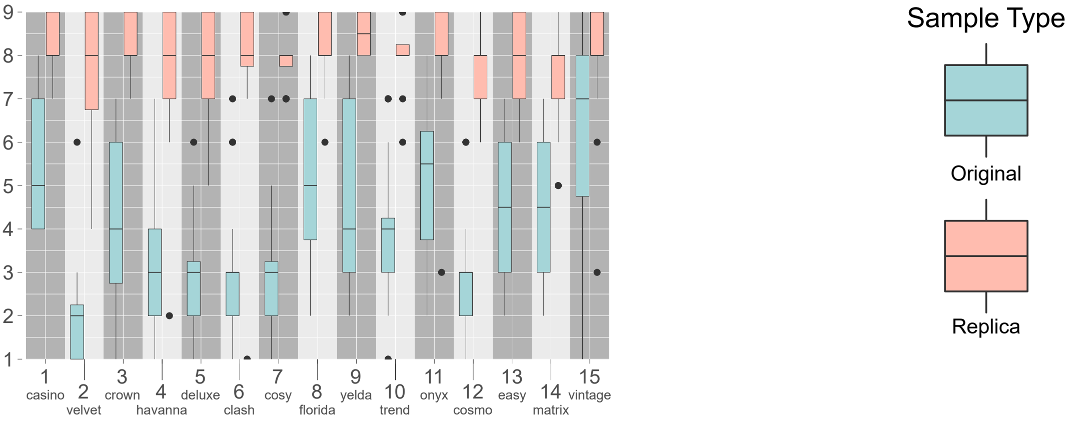
In the following section, we describe the analysis and the obtained results from our texture perception study.

5.4.1 *Individual Tactile Ratings*

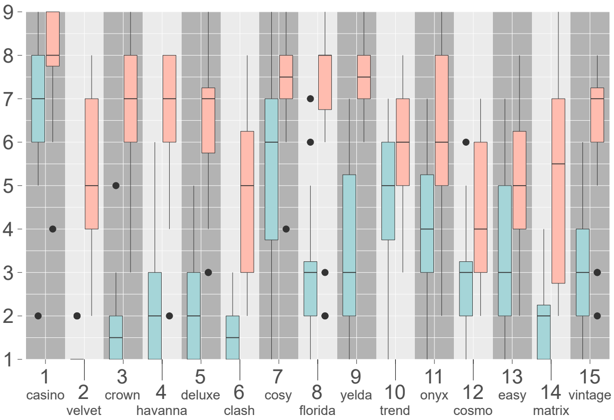
To analyze the individual tactile assessments, we conducted Friedman tests with post-hoc analysis using Wilcoxon signed ranks tests and Bonferroni-Holm correction for all comparisons. For completeness, all results are depicted in Section a.1. The ratings per sample for each case are depicted in Figure 5.6 and Figure 5.7. Here, we focus our results on the patterns that arise in the analysis, specifically for the results within the set of original texture samples (T), within the set of replicated surface samples (R), and their cross-comparison for the same surface texture (T-R).

HARDNESS The ratings of hardness were found to significantly differ depending on the sample ($\chi^2(29) = 445.83$, $p < .001$). Overall, the average ratings for the T samples ($M = 4.10$) were found to be lower than the average ratings for the R samples ($M = 7.95$). From our results, we could verify that the original set of samples consisted of surfaces with differing degrees of hardness. In contrast, the replicated samples were rated consistently high in terms of hardness. While this caused most original samples to differ from their replicas significantly, some similarities remained. The hardness of rough samples did not significantly differ between the original samples and their replicas. This effect was most notable for $T_{15\text{-vintage}}$. From these observations, we can conclude that the surface replication process affected the tactile perception of hardness.

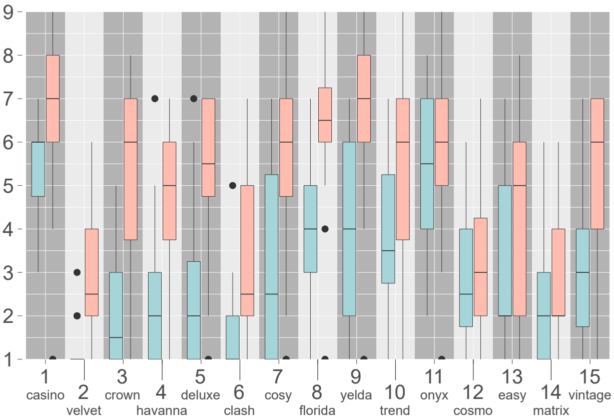
ROUGHNESS The ratings of roughness were found to significantly differ depending on the sample ($\chi^2(29) = 382.29$, $p < .001$). In terms of roughness, the T samples' average ratings ($M = 4.26$) were found to be lower than the R samples ($M = 6.82$). Differences in perceived roughness were significant in both original and replicated samples. While the general trend indicates an increase in tactile roughness after replication, the replication process created a varying set of replicas by partly translating the roughness gamut. Cross-comparisons between all T and R samples indicated that 9 of our surface samples showed roughness to significantly increase from their original counterpart, while 6 samples preserved their level of roughness.



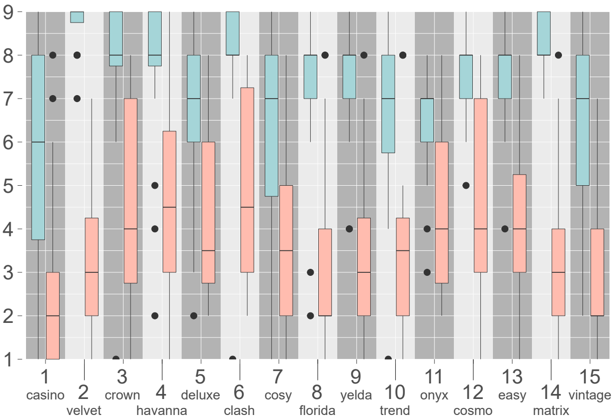
(a) Hardness.



(b) Bumpiness.

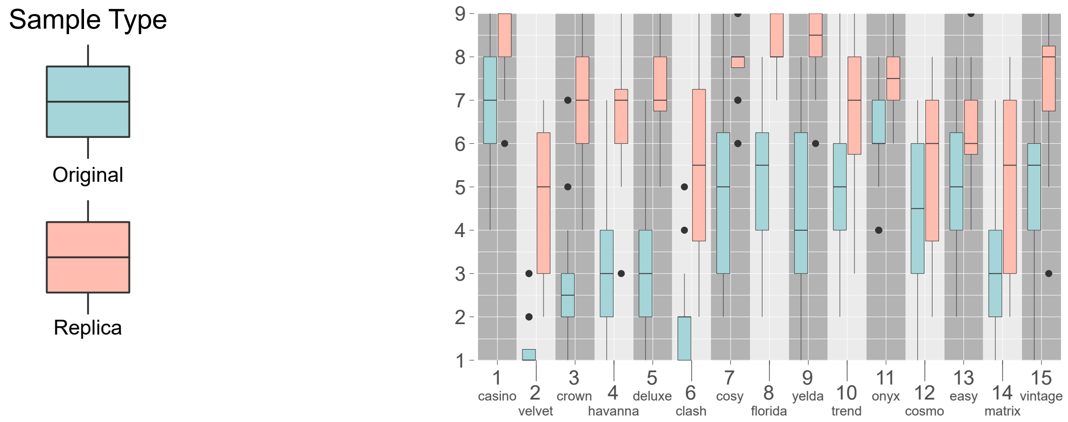


(c) Scratchiness.

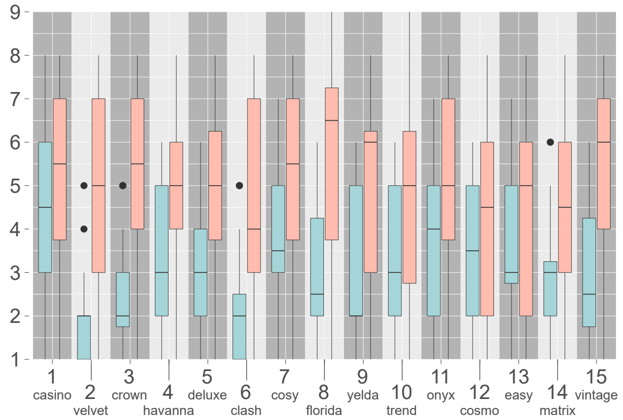


(d) Uniformity.

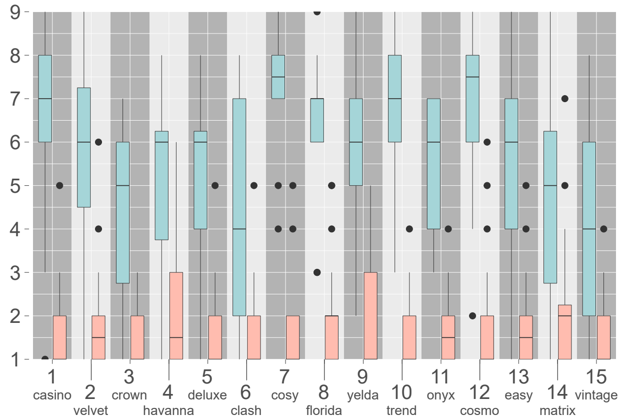
Figure 5.6: Boxplots indicating the individual assessments for each sample (Part 1).



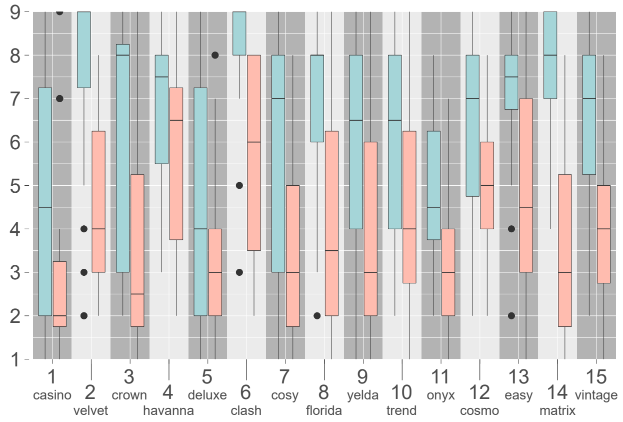
(a) Roughness.



(b) Stickiness.



(c) Hairiness.



(d) Isotropy.

Figure 5.7: Boxplots indicating the individual assessments for each sample (Part 2).

BUMPINESS The ratings of bumpiness were found to significantly differ depending on the sample ($\chi^2(29) = 393.01$, $p < .001$). The average ratings for the T samples ($M = 3.19$) were found to be lower than those of the R samples ($M = 6.14$). Similar to the results of perceived roughness, the ratings of bumpiness indicate differences within the original samples' set and within the set of replicated samples. The general trend indicates an increase in tactile bumpiness, while some variance was preserved after replication. Cross-comparisons between all T and R samples indicated 6 samples preserved their level of bumpiness.

STICKINESS The ratings of stickiness were found to significantly differ depending on the sample ($\chi^2(29) = 172.08$, $p < .001$). The average rating of the T samples ($M = 3.18$) was lower than the R samples ($M = 4.92$). Pair-wise analysis within the set of T samples and within the set of R samples indicated no significant differences. Cross-comparison between T and R samples revealed that only $T_{2\text{-velvet}}$ significantly differed from its replica. Here, we note that both our original and replicated samples were found to be mostly neutral in terms of stickiness, and the replication process did not alter its perception.

SCRATCHINESS The ratings of scratchiness were found to significantly differ depending on the sample ($\chi^2(29) = 315.01$, $p < .001$). In terms of scratchiness, the T samples' average rating ($M = 3.11$) was lower than the R samples ($M = 4.91$). Both within the set of original samples and the set of replicated samples, differences in perceived scratchiness were significant. While the general trend indicates an increase in tactile scratchiness after replication, the replication process created a varying set of replicas by partly translating the gamut of scratchiness. Cross-comparisons between all T and R samples indicated that only 5 of our surface samples showed scratchiness to differ from their original counterpart significantly; meanwhile, 10 samples preserved their level of scratchiness.

HAIRINESS The ratings of hairiness were found to significantly differ depending on the sample ($\chi^2(29) = 394.38$, $p < .001$). The average rating of hairs on the replicated samples was lower than those of the T samples (T, $M = 5.63$; R, $M = 1.78$). For some T samples, the presence of hairs was significantly apparent compared to other T samples. As expected, in between all replicated samples, no significant differences were found for all combinations. For the cross-comparison between T and R samples, we note that the R samples were significantly different from most T samples, excluding those with a low hair presence. These results show that participants noticed the lack of hairs on the replicated samples.

UNIFORMITY The ratings of uniformity were found to significantly differ depending on the sample ($\chi^2(29) = 329.88$, $p < .001$). On average, the T samples' ratings ($M = 7.15$) were higher than the set of R samples ($M = 3.91$). While some significant differences were found within the original sample set, no differences were found within the set of replicas.

Cross-comparison for the same texture showed 6 samples preserved their uniformity while 9 did not. From this, we see that the replication process lowered some indications of uniformity.

ISOTROPY The ratings of isotropy were found to significantly differ depending on the sample ($\chi^2(29) = 189.08$, $p < .001$). When rating the uniformity in all orientations, participants noted higher isotropy for the original samples (T, $M = 6.33$; R, $M = 4.20$). Only three comparisons showed significant differences for all T samples, while for all R samples, no significant differences occurred. When comparing T samples to their partnered R samples, only $T_{6\text{-clash}}$ and $T_{14\text{-matrix}}$ did not preserve their level of isotropy. These results indicate that the replication process did not significantly alter the perceived isotropy for 13 samples.

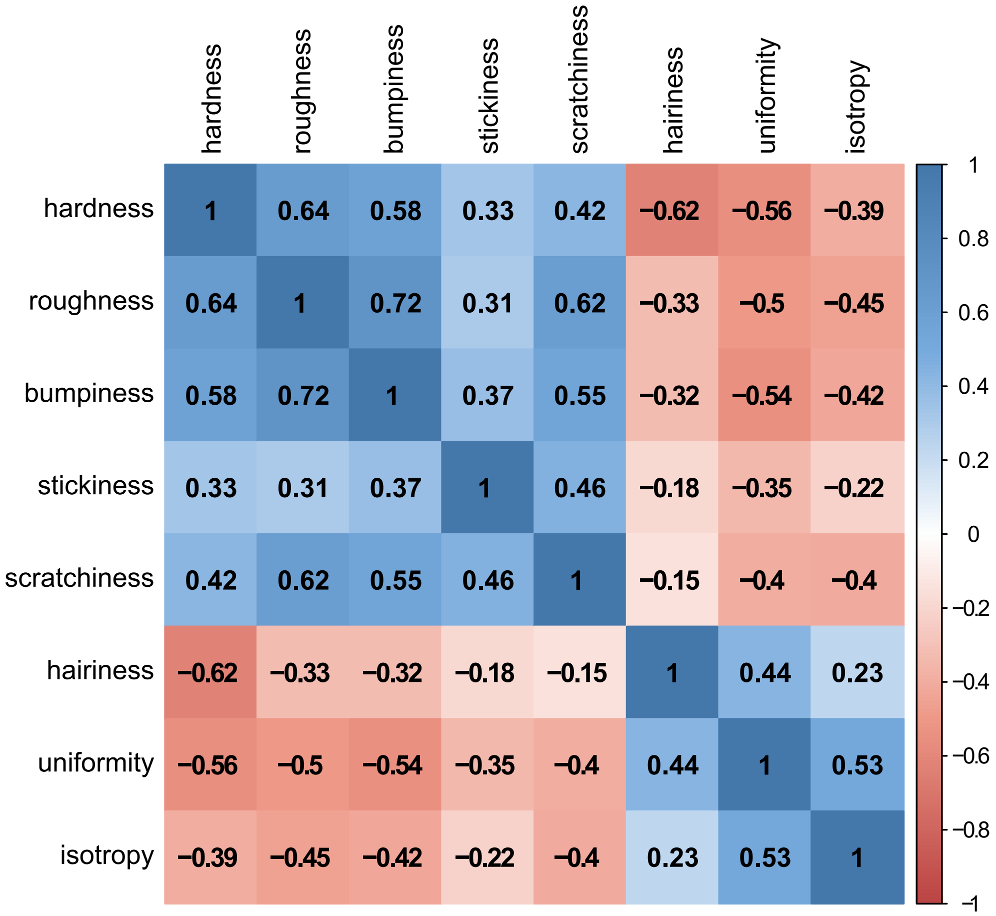
5.4.2 *Tactile Correlations*

Using a Spearman's rank-order correlation, we found significant correlations between the different tactile assessments provided by participants. All correlations with their Spearman's rank order coefficients (R_s) are depicted in Figure 5.8. Here, all correlations were found to be significant ($p < .01$).

Strong positive correlations were found between the tactile ratings of roughness, bumpiness, and scratchiness. These observations were confirmed by the fact that participants noted it was sometimes difficult to distinguish between the individual features. The hardness of our samples is with varying effects positively correlated with the roughness, bumpiness, and scratchiness assessments. Interestingly, while hairiness is negatively correlated with hardness it has almost no effect on roughness, bumpiness, or stickiness. Two groups of tactile properties are appearing with opposite correlations with each other. While hairiness, uniformity, and isotropy are positively correlated with varying effect sizes, they are negatively correlated to the other tactile ratings.

5.4.3 *Material Perceptions*

The anecdotal data of the perceived materials were further analyzed by manually extracting the materials and objects identified by the participants. For the R samples, we characterized a set of 12 distinct perceived categories, namely *plastic-like* (28%), *stone-like* (27%), *wood-like* (27%), *fabric-like* (3%), *paper-like* (2%), *rubber-like* (2%), and *other* (4%, e. g.soap, dry glue, rough human skin, a surface with Braille, plastic made to feel like wood). For the T samples, we characterized a set of 9 distinct perceived categories, namely *fabric-like* (77%), *hair-like* (6%), *sponge-like* (6%), *leather-like* (6%), *rubber-like* (6%), *plastic-like* (6%), *paper-like* (6%), *stone-like* (6%), and *other* (6%, e. g.skin, mouse pad, feather, car ceiling). Within the category of *fabric-like* of the latter, we noted 10 recurring indications across participants, i. e.carpet,



	hardness	roughness	bumpiness	stickiness	scratchiness	hairiness	uniformity	isotropy
hardness	1	0.64	0.58	0.33	0.42	−0.62	−0.56	−0.39
roughness	0.64	1	0.72	0.31	0.62	−0.33	−0.5	−0.45
bumpiness	0.58	0.72	1	0.37	0.55	−0.32	−0.54	−0.42
stickiness	0.33	0.31	0.37	1	0.46	−0.18	−0.35	−0.22
scratchiness	0.42	0.62	0.55	0.46	1	−0.15	−0.4	−0.4
hairiness	−0.62	−0.33	−0.32	−0.18	−0.15	1	0.44	0.23
uniformity	−0.56	−0.5	−0.54	−0.35	−0.4	0.44	1	0.53
isotropy	−0.39	−0.45	−0.42	−0.22	−0.4	0.23	0.53	1

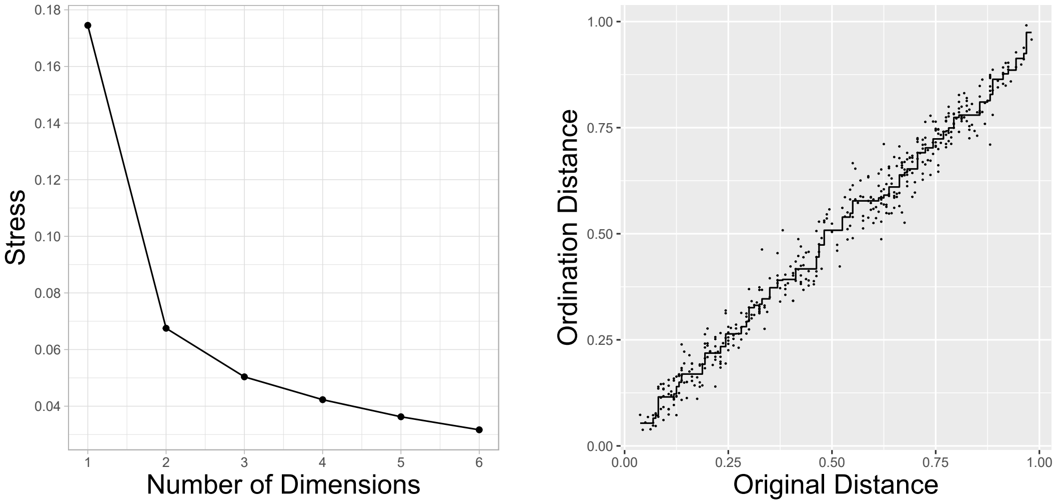
Figure 5.8: Correlation plot for the individual assessments. The numbers depict the Spearman's rank order coefficient (R_S). All correlations were found to be significant ($p < .01$).

cloth, clothing, velvet, cotton, wool, felt, fleece, generic fabric, and others (fibers, linen, couch, curtain, and pillow).

5.4.4 *Analysis of Similarities*

To determine consistency across participants, we used Spearman's rank correlation tests on the similarity assessments. Here, we found the similarity ratings for each participant to be highly correlated with those of every other participant ($M_r = 0.69$, $p < .01$). Given this result, we note that participants rated the similarity assessments consistently.

For further analysis, the similarity assessments (1–9) were converted to normalized dissimilarity ratings (0–1). With these ratings, we created a symmetric dissimilarity matrix containing the perceptual distances between all original and replicated samples. Using an analysis of similarities, we compared different groupings within our distance matrix. We found a significant difference when comparing groups of the different sample types, i. e.original textures and replicated samples ($R = 0.9528$, $p < 0.001$). However, we did not



(a) Stress plot.

(b) Shepard diagram.

Figure 5.9: NMDS analysis. Here, (a) depicts the stress values for solutions using 1 to 6 dimensions, while (b) visualizes the relationship between the original and the ordination distances for a 3-dimensional solution.

find a significant difference when comparing groups of different sample numbers, i. e.all different sets of textures ($R = -0.3456$, $p = 0.99$).

5.4.5 *Perceptual Space*

For rating perceived similarity between two samples, participants were asked to consider all aspects of the tactile perception as they saw fit. This instruction was given in order to not bias the judgments and acquire the true similarity assessments between our samples.

Analogous to literature (Vardar et al., 2019), we used the obtained symmetric dissimilarity matrix to perform a non-Metric Multidimensional Scaling (nMDS) analysis, which is an indirect gradient analysis approach producing an ordination based on a distance or dissimilarity matrix. When dealing with human similarity data, such an approach is common for calculating and visualizing perceptual spaces of the distances (Cooke et al., 2006; Culbertson et al., 2013; Vardar et al., 2019). To understand how many axes are sufficient to visualize the perceptual space, we calculated the stress values for the first 6 dimensions, see Figure 5.9a. Here, the stress value of 0.05 for 3 dimensions approaches a faithful representation with no prospect of misinterpretation (Clarke, 1993). The low-stress level is underlined by the relationship between the original and ordination distances in Figure 5.9b.

Using Kruskal's non-metric multidimensional scaling approach, we then generated the perceptual space for our recorded assessments. In the resulting representation, the axes are unknown combinations, as they do not represent apparent tactile assessments. To better understand the relationship between samples, we first build a physical space for the original texture samples. To this end, we build upon the previous work and use the 3

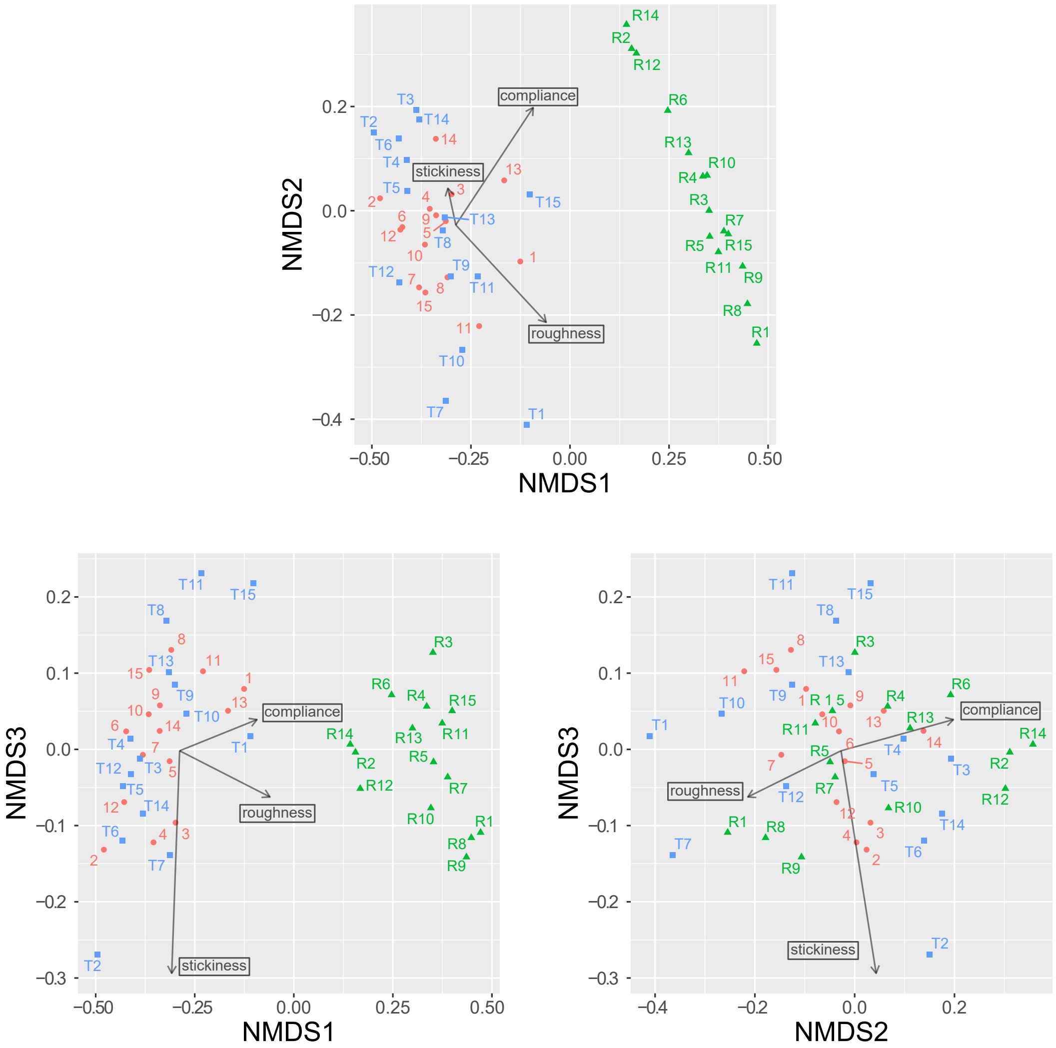


Figure 5.10: NMDS Perceptual space. Here, the distances between the original set of samples (blue), their physical measurements (red) and the replicated set (green) are visualized. The vectors represent the transformed axes of the physical measurement space taken from the original set of samples.

dominant dimensions of the tactile perception of surfaces, i. e., hardness, roughness, and stickiness (Culbertson and Kuchenbecker, 2017; Yoshioka et al., 2007). For each dimension, we use the z-scores of the respective recorded physical values for roughness, hardness and slipperiness, see Section 5.2.2.

Using a Procrustean randomization test, we calculated the goodness of fit and its significance between the dissimilarity space of the original samples and the physical space ($m^2 = 0.65$, $p < 0.01$), between the dissimilarity space of the replicated samples and the physical space ($m^2 = 0.64$, $p < 0.01$), and between the dissimilarity space of the replicated samples and the original samples ($m^2 = 0.57$, $p < 0.01$). These results indicate that all data sets exhibit greater concordance than expected at random, indicating an agreement between the measurements obtained. Next, we performed a Procrustes analysis to calculate the transformation function from the physical space to the original sample's dissimilarity space such that they are in a state of maximal superimposition ($ss = 0.64$). The resulting rotation, translation, and scaling matrices were used to transform the physical space onto the perceptual space. Here, we included the physical's space axis as vectors in the transformation and label them according to their metrics. We depict the final perceptual space using 3 individual plots per dimension combination, see Figure 5.10.

5.5 DISCUSSION

Motivated by the recent advancements in the field of fabrication, we replicated a set of 15 texture samples by capturing and reconstructing their height fields. Rather than aiming for direct reproduction of tactile perception, we investigate how the fabrication process affects the perceived haptic properties. We frame our discussion in two parts by first elaborating on the obtained results and their interpretations, and providing insights for the fabrication of haptic properties.

5.5.1 *Surface Haptics Appropriation*

We aimed to determine how our approach influenced tactile surface properties' perception and gain insights into the relationship between the replication method and material perceptions. As we expected to see interactions between the original samples' tactile features and the perception of their replicated counterparts, we performed a psychophysical user study to understand these relationships. Here, we discuss our results that indicate our approach is an initial step for appropriating surface haptics and propose strategies for fabricating tactile properties.

5.5.1.1 *Does surface geometry replication reproduce aspects of its feeling?*

The individual assessment results reveal that our set of original textures manifests significant variations in all observed tactile properties across samples. While many of the tactile variations of the set of replicated surfaces were compressed into smaller ranges, the replicas still indicated a degree of diversity. Therefore, appropriating tactile features from a diverse set of natural surfaces can provide an attractive solution for creating diverse haptic impressions on fabricated objects.

When comparing the original textures to their replicas, we observe that the printed materials do not maintain all the original materials' tactile properties. As is inherent to our replication approach, in terms of hardness and hairiness, participants' assessments showed significant differences to occur. However, in terms of stickiness and isotropy, most replicas maintained their tactile properties, as no significant differences could be found for respectively 14 and 13 pairs. For scratchiness, 10 samples were close to the original, while in terms of roughness, bumpiness, and uniformity, only 6 pairs did not show any significant deviations. In terms of tactile properties, the pairs of T-R$_{1\text{-casino}}$, T-R$_{10\text{-trend}}$, T-R$_{11\text{-onyx}}$ were not significantly different for a total of 6 metrics, while T-R$_{7\text{-cosy}}$, T-R$_{12\text{-cosmopolitan}}$, T-R$_{13\text{-easycare}}$, and T-R$_{15\text{-vintage}}$ for 5; T-R$_{5\text{-deluxe}}$ for 4, T-R$_{4\text{-havanna}}$ and T-R$_{14\text{-matrix}}$ for 3, T-R$_{3\text{-crown}}$, T-R$_{6\text{-clash}}$, and T-R$_{8\text{-florida}}$ and T-R$_{9\text{-yelda}}$ for only 2. The composition of T$_{2\text{-velvet}}$ proved it to be the most challenging surface sample to reproduce. Here, participants indicated to be able to quickly identify T$_{2\text{-velvet}}$ as the tactile perception of velvet was a unique sensation compared to all other samples.

Additionally, we found tactile perceptions to show high correlations with each other. Most importantly, the effect of increasing hardness was positively coupled to other properties, such as roughness, or bumpiness. From this, we see that the loss of hardness in our replication method influenced other tactile properties, as our manufacturing process only reproduced a surface's stable geometry. Intuitively seen, a hard surface makes the specific geometrical surface features more pronounced as they comply less to touch. This interaction may lead to increased subjective ratings of other perceptions. While hairiness did negatively correlate to hardness, its effect on other tactile assessments seemed to be limited. Here, we note that the influence of highly deformable structures, i. e., hairs, is minimized upon direct touch.

5.5.1.2 *Does surface geometry replication convey the feeling of the original material?*

The high degree with which participants reported the original samples' material as *fabric-like* indicates that they correctly identified their material properties. Interestingly, in contrast to the original materials, our replicas manifest a wide variation in identified materials. Our set of reconstructed samples was printed using the same plastic material. We see that by changing the surface structure, participants indicated to perceive different materials. This underlines the influence of surface microgeometry on the perception of materials and its benefit to fabrication processes. Here, an opportunity exists to explore different methods to guide the participant's perception towards a specific material, e. g., through visual priming in a Virtual Reality context.

5.5.1.3 *Does surface geometry replication support a wide gamut of feel aesthetics?*

Our perceptual space allows us to inspect how the replication process influences the distance between the original and fabricated samples, see Figure 5.10. We can observe a clear separation between original materials and our replicas based on the perceived hardness, which is an effect of the manufacturing process that does not use elastic materials. However, the space occupied by the set of replicas shows the great variety with which microgeometry replication influenced the tactile impressions.

The similarity analysis results indicate that the replication process significantly affected the original and replicated samples' perceived distance. However, the distance created by the fabrication process did not seem to vary between different textures. From this, we can conclude that the replication process uniformly distorted perception between original and replicated samples, meaning no randomness was introduced in the process. Therefore, optimizing the replication process would optimize the haptic perception distance between the original and replicated sample.

Further visual analysis of the perceptual space in terms of roughness and stickiness vectors allows us to comprehend the surface replication distortion. Here, we observe that the shift between original and reproduction potentially leads to perceptually good matches for certain other sample combinations, e.g, $\text{T-R}_{3\text{-crown}}$ with $\text{T}_{1\text{-casino}}$, $\text{T-R}_{2\text{-velvet}}$ with $\text{T}_{7\text{-cosy}}$, $\text{T-R}_{6\text{-clash}}$ with $\text{T}_{10\text{-trend}}$, and $\text{T-R}_{14\text{-matrix}}$ with $\text{T}_{12\text{-cosmopolitan}}$. These results indicate that a potential transformation function of haptic surface appropriation could guide the understanding of tactile properties before fabrication. Such a function can be integrated into existing literature, such as in Torres et al., 2015, where authors present a tool for designing the *feel* aesthetics of objects to be fabricated.

5.5.2 *Applications for Fabricating Haptics*

Designing haptic experiences remains a challenging task. Our work is motivated by the lack of prototyping methods for haptic design (Schneider et al., 2017), and the importance of supporting personalization by end-users (Seifi et al., 2020a). Rather than relying on computational tools, surface capturing methods support both end-users and professionals to design their own *feel* aesthetics (Torres et al., 2015) guided by real-life tactile experiences. With our approach, designers could use portable capturing devices, as illustrated in (Li et al., 2014), to record information in the world around them and build custom tactile libraries. Using these, digital objects fabrication can be enriched with tactile properties using common modeling tools.

The results of our study show that stable surface replication supports the fabrication of materials with similar haptic properties to the originals. Our approach to capturing only the stable features corresponds well with how our participants perceived the presented materials. We found that the deformable hair-like features of the materials affect the perceived compliance but do not have an influence on the perceived geometrical attributes like roughness, bumpiness, and scratchiness. As a result, deformable hair-like structures can be integrated into compliance and do not need to be present on the surface of the object. Focusing reproduction effort on stable features not only significantly facilitates the reproduction process but also increases the durability of reproduced surfaces, as thin deformable features are most likely to be affected by mechanical wear.

Another exciting result of our study is the discovered coupling between the perceived properties. Prior works generally considered the perceived compliance, roughness, and stickiness as independent orthogonal directions (Bergmann Tiest and Kappers, 2006; Hollins et al., 2000). However, our results suggest that the increase in hardness caused the shift in perceived roughness of the 3D printed stimuli. We can distill this observation into a simple design rule. To successfully reproduce the perceived roughness, the designer should decrease the roughness of the object proportionally with the increase in hardness.

The printing process used in our work had a significant effect on the perceived haptic properties of our samples. Upon closer investigation, we observe that the pairwise dissimilarity captured by the original materials is still present in our digital replicas. This suggests that our manufacturing process applies a systematic transformation that effects the haptics of our digital replicas. This is further supported by the anecdotal assessment where participants were able to correctly identify the material of the original cloth samples but perceived a far wider gamut of materials in the digital replicas, ranging from plastics, through stone, to wood. These results underline an uncertainty present in the material perception of the replicas, which could be guided through the addition of multisensory perception. As visual and haptic perception are statistically integrated Ernst and Banks, 2002, our approach could serve material perception using passive haptics in immersive virtual environments.

5.6 CONCLUSION

In this chapter, we presented an approach for adapting haptic experiences from real-life for manufacturing purposes. To this end, we implemented an existing pressure-based geometry acquisition process for recovering the stable microgeometry investigated during active touch. We use this method on a challenging set of 15 cloth samples that manifest a wide range of haptic properties. We evaluate the reproduction quality by conducting individual assessments of the perceived qualities. From our results, we see that that direct reproduction of a material's surface can approximate the perceived geometry of some materials, but it is not sufficient to consistently mimic their haptics. However, both in terms of perceptual features, such as roughness, and material perceptions, our digital reproductions show a great variation only through alterations of their surface construction. Therefore, our fabrication process supports a wide gamut of *feel* aesthetics. Furthermore, we investigate the shift that occurs after replication and discover that the change in perception of the reproduced samples was not stochastic, but rather followed a uniform transformation. To find this transformation, we conduct a magnitude estimation study and recover a perceptual-space of our samples, which we correlate with measurable physical attributes. We leverage our perceptual space to formulate direct strategies that can be applied to the digital designs to better resemble the haptic sensations of the original materials. We believe that the techniques proposed here will have direct benefits for fabrication methods of haptic features, and that our findings can serve as a basis for the future development of the field. Our results provide insights for the field of haptic design by supporting hapticians in creating versatile haptic experiences through capturing real-world information for fabrication processes.

"In life you need colors."

— Bob Ross, *Happy Little Accidents*

6

VISUO-HAPTIC PERCEPTION OF REPLICATED TEXTURE SURFACES

Building upon the results of the haptic reproduction process in the previous chapter, we further extend our investigation of this approach to VR. In this chapter, we use the generated haptic replicas as passive haptic structures while overlaying them with visual texture information. This chapter continues to build upon RQ1, and was not previously published.

6.1 INTRODUCTION

In this chapter, we build upon the insights of the previous chapter, and consider the visuo-haptic perception of replicated surface textures in VR. To this aim, we look towards passive haptic feedback (PHF), a method where physical props are registered to virtual objects as haptic proxies, typically in a 1-to-1 fashion (Insko, 2001). A naïve implementation of passive haptics requires virtual objects with varying materials to be represented by the same number of physical objects with corresponding materials. While this approach can provide highly realistic haptic details, it remains bound by several limitations. As continuous synchronization of physical and virtual objects is required for every change in the virtual environment, it is inherently inflexible. Additionally, when IVEs consist of large numbers of objects, each with their own different surface material, scaling issues arise as the required collection of physical materials with increases rapidly.

Our aim is to counter issues related to the material availability of proxy objects. To serve consistent visuo-haptic experiences in VR, each user requires access to the same materials. As transporting physical materials is costly and does not scale well, we consider the case of replication using fabrication technologies an ideal solution. The idea behind this, is that the user locally fabricates proxy objects on demand, which enables sharing and physical duplication of tactile impressions. To this intent, we explore the use of replicated surface structures to serve as versatile proxy surfaces for influencing texture perception.

Specifically, we present a user study in which we used a subset of the replicated surface textures presented in Chapter 5. In combination with their corresponding original samples, we investigate users' visuo-haptic perception of virtual materials in VR. Our results describe how participants experienced both virtual and haptic textures separately, and how tactile perceptions of replicated surface textures are influenced through mixed visual-haptic combinations. We discuss practical findings for the future of using fabricating passive haptic feedback in virtual settings.

6.2 VISUO-HAPTIC TEXTURE REPLICAS

The following section describes the selection of samples used in the study, and the generation of the virtual texture modals.

6.2.1 *Sample Selection*

In order to investigate the visuo-haptic perception of our replicated surface textures, we selected a set of representative samples from our previous investigation. Here, we considered 5 samples that varied across the dimensions of hardness, roughness, and stickiness. Our final set of samples was $T_{1\text{-casino}}$, $T_{3\text{-crown}}$, $T_{7\text{-cosy}}$, $T_{8\text{-florida}}$, and $T_{15\text{-vintage}}$.

To ensure consistent sample quality for this study, we re-fabricated the reconstructed digital models. To this aim, we used a Stratasys PolyJet J826 3D printer[1] with VeroVivid material[2], a rigid, durable and high resolution photo-polymer with a Shore Hardness of 83–86 (Scale D). The change in used fabrication method was caused by printer availability. Both the used material and printer were comparable in terms of quality to the previously used setup, therefore, the resolution of the final samples and their tactile characteristics remained indistinguishable. As this study considered visual characteristics of the fabricated samples, we intentionally changed the color of the material from black to blue to ensure surface features were easily recognizable.

In case of the cloth samples, we cut 5 cm^2 rectangles from the bulk material and attached them to 2 mm acrylic plates of the same dimensions. Some of the source material was not available anymore in the same color, therefore, some of the real textures differed in color from those that were used for reconstruction. This was not considered an issue, as all material stemmed from the same fabric sample book and therefore remained identical in terms of surface features, regardless of color.

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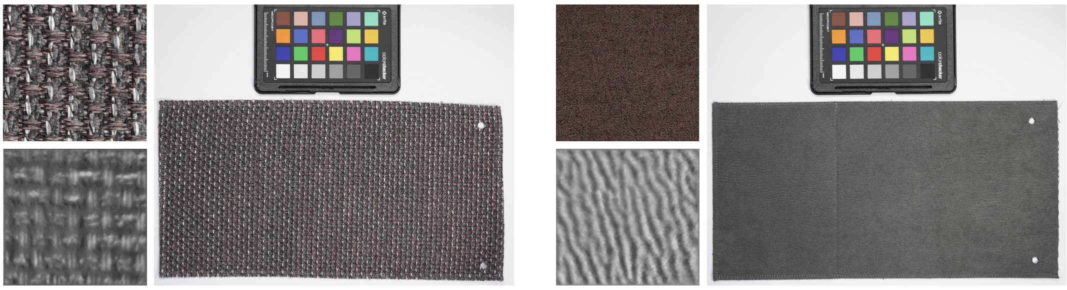
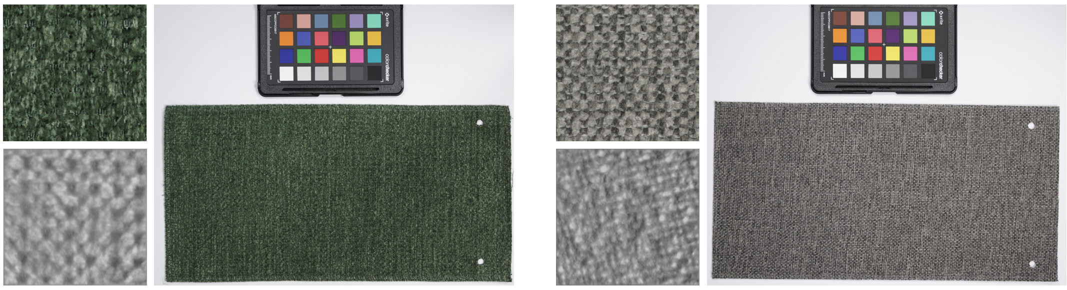
[1] Stratasys J826 Prime — https://bit.ly/3eqNond

[2] Stratasys VeroVivid Color Family — https://bit.ly/3TejUWW



1 – Casino 3 – Crown



7 – Cosy 8 – Florida

15 – Vintage

Figure 6.1: Our set of used surface textures, together with their reconstructed height fields, and the visual image used to generate the virtual representation.

6.2.2 *Virtual Texture Models*

In order to accurately represent the visual appearance of our samples in VR, we captured high resolution images of the bulk material using a Sony Alpha 7s full-frame DSLR camera with a Sony SEL2870 35 mm (FE 28–70 mm F 3.5—5.6 OSS) lens. The set of original textures together with their captured height maps and visually captured bulk material are shown in Figure 6.1. The color discrepancies between $T_{3\text{-crown}}$ and $T_{15\text{-vintage}}$ originate from the availability of materials. As all materials stem from the same fabric sample book, no distinguishable differences in tactile properties were present between materials with color differences.

An X-Rite ColorChecker Passport[3] embedded in the image allowed us to ensure color consistency across captured textures, and additionally provided a ruler that easily allowed to convert pixels to real world measurements. For each material, the captured images were cropped to a $5\,\text{cm}^2$ rectangle. Both the cropped textures and the digital reconstruction

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[3] X-Rite ColorChecker Passport Photo 2 — https://bit.ly/3RSjCUK

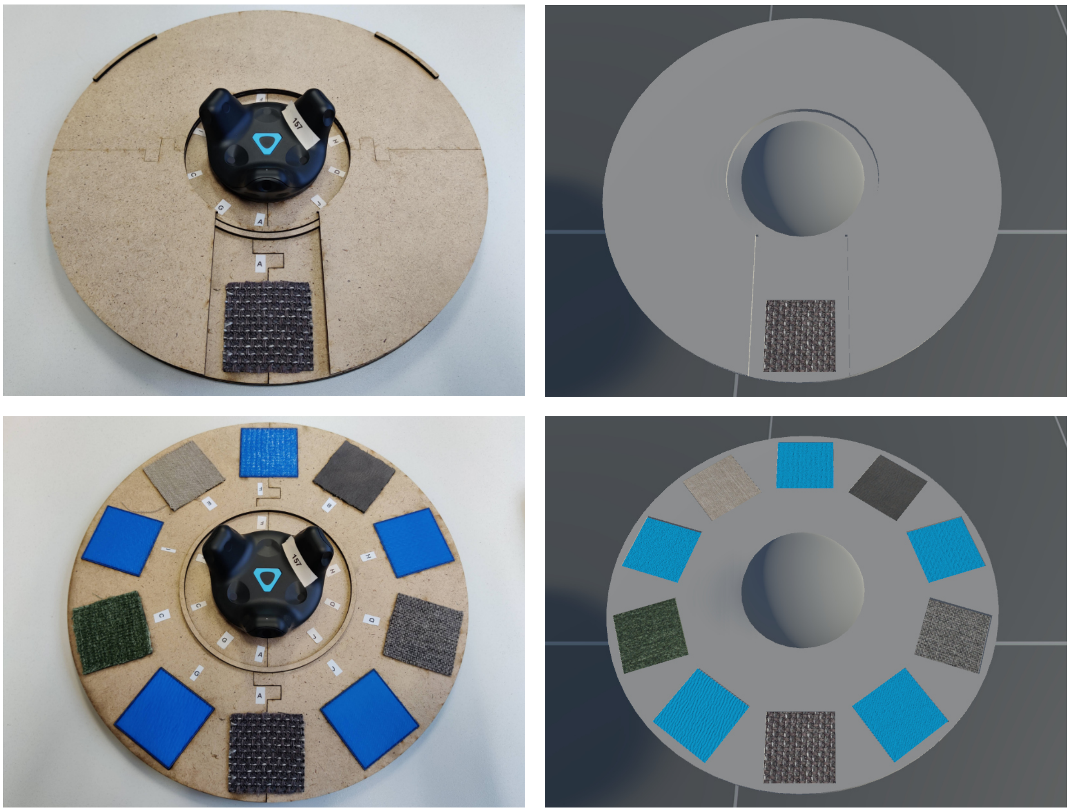


Figure 6.2: The setup used during the study, with (left top) the physical plate showing one real texture, (left bottom) the plate with the cover removed, (right top) the virtual plate showing one virtual texture, (right bottom) the virtual plate with the cover removed.

models used for 3D-printing were imported into a virtual environment in the Unity game engine. This setup allowed us to virtually represent the real surface textures through texture mapping, and the replicated surface samples through the capture models. The latter models were colored using a blue color shader to ensure the virtual models were consistent with the physical replicated samples.

6.3 STUDY

To evaluate the haptic feedback of the selected subset of original and reproduced textures, we conducted a user study where participants rated visual and haptic properties of the samples, both inside and outside VR. By overlaying physical samples with virtual textures, we further investigated different combinations of visuo-haptic sensations.

Ethical approval for this study was obtained from the Ethical Review Board of the Department of Computer Sciences at Saarland University (No. 21-10-6).

6.3.1 *Apparatus*

We performed the user study in our lab. Using a laser cut wooden board, we placed the selected original and reproduced surface textures in an interleaved circular manner. A removable and rotatable cover enabled the experimenter to hide all but one texture during real-world conditions. This physical cover was removed during virtual conditions. In the center of the board, a Vive tracker was placed to register and track the setup in the virtual scene. This plate, shown in Figure 6.2, allowed participants to precisely hit a required structure without touching a different surface. A Leap Motion controller, used for hand tracking, was statically positioned above the table facing downwards.

The virtual context consisted of a neutral environment where the user was seated in front of a virtual desk. The construction carrying the sample structures was represented by a 1-to-1 scale virtual model, including the cover element. To prevent participants from colliding with the physical Vive tracker, we placed the upper half of a virtual sphere over its physical location. The sphere and the plate were rendered in a neutral gray texture in order not to distract the participant.

Rendering was done in Unity 2019.4.30f1 using a HTC Vive Pro headset connected to a laptop computer with an Intel i7 CPU, 32 GB RAM and an Nvidia GeForce RTX 3070 Max-Q graphics card. A second laptop was used to record participants' answers in a spreadsheet.

6.3.2 *Participants*

A total of 18 participants (13 male, 5 female, 19 – 35 years, avg. 26 years) with backgrounds in Computer Science, Haptic Design, Engineering, Medical Science, and Sports Science, were recruited for our study. Regarding vision, 2 participants indicated they wore corrective glasses or contact lenses. In terms of hand dominance, 16 participants indicated to be right-handed, while 2 participants were left-handed. All participants confirmed that, to the best of their knowledge, they did not suffer from any impairment of their haptic perception, such as arthritis or hypoesthesia (numbness). Participants performed the study with the index finger of their dominant hand, and were informed they could only use this finger.

Participants rated on a scale from 1 (= never) to 5 (= regularly) how frequently they used VR technology ($M = 2.67$, $SD = 1.15$), how often they performed precise handwork ($M = 2.81$, $SD = 1.24$), and how frequently they worked with textiles ($M = 1.72$, $SD = 0.80$). Sickness ratings on a scale from 1 (= I never felt ill) to 5 (= I felt ill all the time) after completion of the experiment verified low levels of cyber-sickness ($M = 1.56$, $SD = 0.90$), while post-experiment presence scores ($M = 1.28$, $SD = 2.14$) suggested low but sufficient immersion of the virtual experience (Slater et al., 1994).

Each study lasted between 45 and 60 minutes. Compensation in the equivalent of € 20 was given to all participants not employed in our lab.

6.3.3 *Procedure*

Before starting the experiment, participants provided written consent and completed a COVID-19 form for contact tracing purposes. To comply with data protection regulations, the responses of the latter were removed 14 days after participation. Afterwards, the lead experimenter briefed participants on the upcoming events.

Our study consisted of two phases, i. e., (A) baseline perception assessments, and (B) mixed perception assessments. During phase A, participants were asked to rate the characteristics of each sample presented to them. Here, participants were only able to either see or touch a sample, and were motivated to only rate the respective available modality, i. e., either visual or haptic. Depending on the condition, participants rated either (A1) the *haptic properties of a physical sample* without the presence of visual information, (A2) the *visual properties of a real structure* without the presence of haptic information, or (A3) the *visual properties of a virtual texture* without the presence of haptic information.

During phase B, participants were again asked to rate the characteristics of each sample presented to them. Here, participants were allowed to both see and touch the sample, and were asked to rate the entire perception by considering both visual and haptic impressions. Depending on the condition, participants rated each sample's characteristics, while (B1) touching the sample and seeing a *matching visual texture* in VR, (B2) touching the sample and seeing a *mismatching visual texture* in VR, and (B3) touching and seeing the sample in the *real world*.

The study consisted of mixed real and virtual conditions. In the case of real world conditions, a second experimenter prepared the correct sample on the plate by rotating the physical setup such that the sample in question was as close to the participant as possible, and the only one visible at that time. For virtual conditions, the second experimenter performed the same task in the real world. However, an automated script would rotate and present the virtual information required at the moment. The lead experimenter noted the responses for each trial, and guided the experimental procedure. For each rating, participants were asked the following questions, either presented to them in VR or on a sheet of paper.

- **Q1**: On a scale from 1 to 9, how **hard** is this surface?
  (1 meaning extremely soft, 5 meaning neutral, 9 meaning extremely hard)

- **Q2**: On a scale from 1 to 9, how **rough** is this surface?
  (1 meaning extremely smooth, 5 meaning neutral, 9 meaning extremely rough)

- **Q3**: On a scale from 1 to 9, how **sticky** is this surface?
  (1 meaning extremely slippery, 5 meaning neutral, 9 meaning extremely sticky)

- **Q4**: What kind of **material** is this?
  (Open question)

During the study, participants were asked to remain seated in front of the desk with the setup. To improve consistency in evaluations that included haptic exploration, participants were only allowed to use the tip of their index finger on their dominant hand to interact with the samples. There were no limitations on the interaction mode, meaning participants were allowed to stroke the samples in arbitrary patterns and lightly press or tap the samples to assess their hardness. For visual ratings, participants were allowed to reposition their head to visually inspect each texture. The general evaluation window for each trial was limited to 10 seconds per sample to ensure participants' first impressions were communicated to the experimenter, and to limit the study duration.

After the experiment, participants completed two post-study questionnaires. One inquired about their demographics, and the Slater-Usoh-Steed presence questionnaire (Slater et al., 1994) recorded the experienced presence in the virtual environment.

6.3.4 *Design*

We used a within-subjects experimental design consisting of two phases, i. e., (A) baseline perception assessments, and (B) mixed perception assessments. In order to counterbalance both study phases for carry-over effects, participants were assigned sequence numbers. Each unevenly numbered participant started with phase A and ended with phase B, while each evenly numbered participant first performed phase B, and continued with phase A.

Each phase consisted of 3 sub-phases. During phase A, participants rated either (A1) the haptic properties of the structure without the presence of visual information, (A2) the visual properties of the real structure without the presence of haptic information, or (A3) the visual properties of the virtual structure without the presence of haptic information. Here, we consider 2 independent variables, i. e., the presented sample, and the active modality (haptic in VR, visual in VR, visual in real world). During phase B, participants rated each sample's characteristics either (B1) while touching the sample and seeing a *matching visual texture* in VR, (B2) while touching the sample and seeing a *mismatching visual texture* in VR, and (B3) while touching and seeing the sample in the *real world*. Here, we distinguish 2 independent variables, i. e., the type of haptic structure (original versus replicated), and the type of visual texture shown on top (matching virtual texture, mismatching virtual texture, and real texture). Within each phase, we counterbalanced the sub-phases and each condition using experimental design tables according to the Williams design using Latin squares (Williams, 1949). For counterbalancing the sub-phases, we used a 9×3 design, while each condition within used one row of a 10×10 design.

We further distinguish 4 dependent variables. For each presented sample, we consider the rating of its roughness, its hardness, and its stickiness, each on a 1-to-9 Likert scale. The last dependent measure was the open answer, in which participants stated which material they thought to experience. For this open question, participants were not provided a list of materials to choose from, but were free to provide any answer they saw fit.

6.4 RESULTS

In the following section, we describe the analysis and the obtained results from our study. We focus the current contribution on the flexibility of the replicated surfaces to serve as material proxies in VR. Therefore, we only consider data points concerning the perception of the haptic replicas, and their visual perception while overlaid as virtual proxy objects.

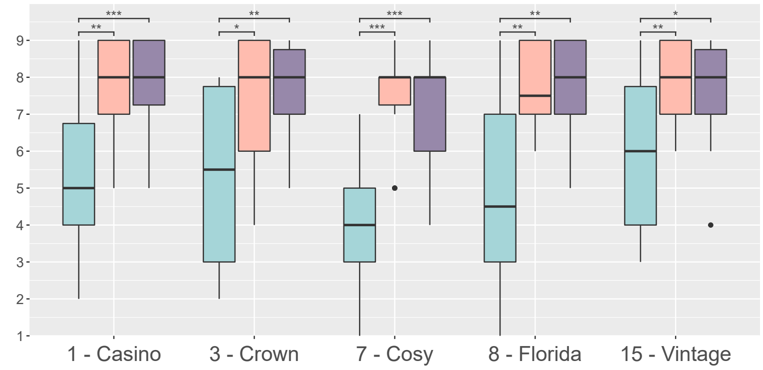
6.4.1 *Modality Variation*

The first part of our analysis investigates the haptic perception of the replicated surface textures, the visual perception of the virtual textures, and the visuo-haptic perception of the haptic replicas overlaid with virtual textures in VR. Specifically, we investigate how each modality is rated separately and how mismatching visuo-haptic information is rated in terms of the tactile dimensions of roughness, hardness, and stickiness. For each replicated texture, we conducted a Friedman test with post-hoc analysis using Wilcoxon signed-ranks tests and Bonferroni-Holm correction. The ratings combined with significant differences are visualized in Figure 6.3.

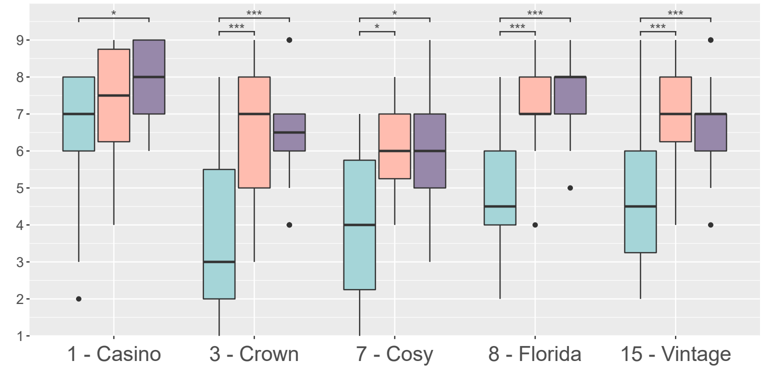
CASINO The ratings for $T_{1\text{-casino}}$ were found to significantly differ depending on the modality presented to the user, i. e., in terms of hardness ($\chi^2(2) = 17.018$, $p < .001$), and roughness ($\chi^2(2) = 8.170$, $p < .05$). In terms of stickiness, no significant statistical difference was found ($\chi^2(2) = 5.547$, $p = .062$). Pair-wise analysis of hardness showed that the visual perception of the virtual texture was significantly lower than the haptic perception of the replica ($p < .001$), and the visuo-haptic perception of the combined perception ($p < .01$). In terms of roughness, the visual perception of the virtual texture was significantly lower than the haptic perception of the replica ($p < .05$).

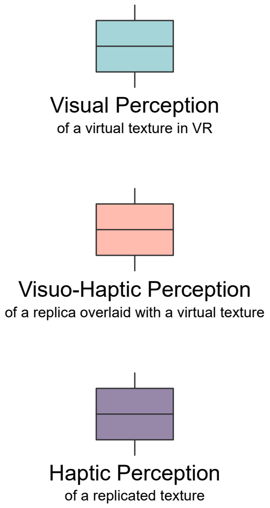
CROWN The ratings for $T_{3\text{-crown}}$ were found to significantly differ depending on the modality presented to the user, i. e., in terms of hardness ($\chi^2(2) = 11.207$, $p < .01$), roughness ($\chi^2(2) = 17.746$, $p < .001$), and stickiness ($\chi^2(2) = 8.585$, $p < .05$). Pair-wise analysis of hardness showed that the visual perception of the virtual texture was significantly lower than the haptic perception of the replica ($p < .01$), and the visuo-haptic perception of the combined perception ($p < .05$). In terms of roughness, the visual perception of the virtual texture was significantly lower than the haptic perception of the replica ($p < .001$), and the visuo-haptic perception of the combined perception ($p < .001$). For stickiness, the visual perception of the virtual texture was significantly lower than the haptic perception of the replica ($p < .01$), and the visuo-haptic perception of the combined perception ($p < .05$).

COSY The ratings for $T_{7\text{-cosy}}$ were found to significantly differ depending on the modality presented to the user, i. e., in terms of hardness ($\chi^2(2) = 21.046$, $p < .001$), roughness

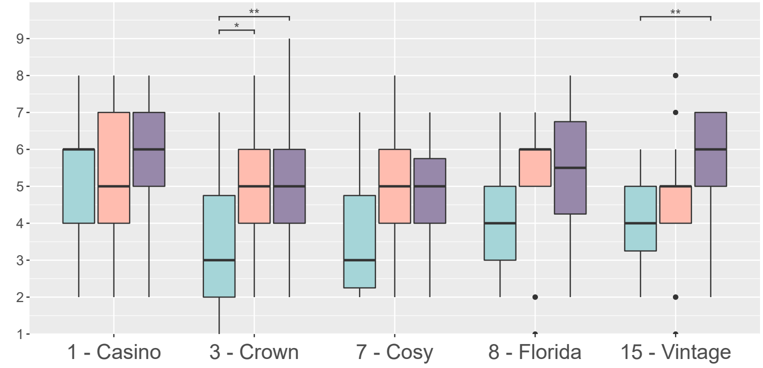


(a) Hardness Ratings





(b) Roughness Ratings



(c) Stickiness Ratings

Figure 6.3: Boxplots depicting the assessments for different modalities. Brackets connect groups with statistically significant differences (*, $p < .05$; **, $p < .01$; ***, $p < .001$).

($\chi^2(2) = 11.246$, $p < .01$), and stickiness ($\chi^2(2) = 7.746$, $p < .05$). Pair-wise analysis of hardness showed that the visual perception of the virtual texture was significantly lower than the haptic perception of the replica ($p < .001$), and the visuo-haptic perception of the combined perception ($p < .001$). In terms of roughness, the visual perception of the virtual texture was significantly lower than the haptic perception of the replica ($p < .01$), and the visuo-haptic perception of the combined perception ($p < .01$). For stickiness, no pair-wise significant differences appeared after correction.

FLORIDA The ratings for $T_{8\text{-florida}}$ were found to significantly differ depending on the modality presented to the user, i. e., in terms of hardness ($\chi^2(2) = 23.560$, $p < .001$), roughness ($\chi^2(2) = 28.459$, $p < .001$), and stickiness ($\chi^2(2) = 9.480$, $p < .01$) Pair-wise analysis of hardness showed that the visual perception of the virtual texture was significantly lower than the haptic perception of the replica ($p < .01$), and the visuo-haptic perception of the combined perception ($p < .01$). In terms of roughness, the visual perception of the virtual texture was significantly lower than the haptic perception of the replica ($p < .001$), and the visuo-haptic perception of the combined perception ($p < .001$). For stickiness, no pair-wise significant differences appeared after correction.

VINTAGE The ratings for $T_{15\text{-vintage}}$ were found to significantly differ depending on the modality presented to the user, i. e., in terms of hardness ($\chi^2(2) = 13.672$, $p < .01$), roughness ($\chi^2(2) = 19.964$, $p < .001$), and stickiness ($\chi^2(2) = 14.140$, $p < .001$) Pair-wise analysis of hardness showed that the visual perception of the virtual texture was significantly lower than the haptic perception of the replica ($p < .05$), and the visuo-haptic perception of the combined perception ($p < .01$). In terms of roughness, the visual perception of the virtual texture was significantly lower than the haptic perception of the replica ($p < .001$), and the visuo-haptic perception of the combined perception ($p < .001$). For stickiness, the visual perception of the virtual texture was significantly lower than the haptic perception of the replica ($p < .01$).

6.4.2 *Subjective Material Perception*

The anecdotal data of the perceived materials was further analyzed by manually extracting the materials and objects identified by the participants. In total, we characterized a set of 50 distinct perceived materials, both abstract and concrete depictions. These were grouped into 7 categories, namely *fabric-like* (backside of carpet, blanket, burlap, carpet, cloth, cover, curtain, doormat, fabric, felt, jeans, polyester, Santa's bag, sofa, textile, velvet), *stone-like* (asphalt, brick, concrete, granite, gravel, grout, marble, plaster, plate, rendering, rock, sandstone, stone, tile), *metal-like* (grid, grindstone, iron plate, metal), *paper-like* (cardboard, paper, sandpaper, wallpaper), *plastic-like* (fake leather, plastic, Plexiglas, rubber), *wood-like*

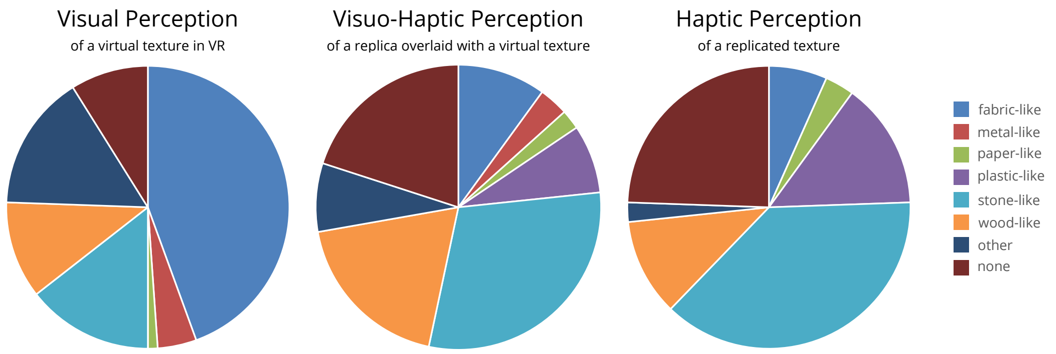


Figure 6.4: Distribution of material perceptions per presented modality.

(bark, fiber, floor, particle board, table, tree, turf, wood), and *other* (algae, broom, elephant skin, flax, foam, leather, moss, Nori, soap).

The distribution per modality is plotted in Figure 6.4. From these results, we see that for the visual rating of the virtual texture, when a material was recognized (91.11%), the majority of the indications point to *fabric-like* impressions (44.44%), followed by *other* (15.65%), *stone-like* (14.44%), *wood-like* (11.11%), *metal-like* (4.44%), and *paper-like* (1.11%), with no reference to *plastic-like* materials. For the haptic rating of the replicated surface textures, when materials were indicated (75.56%), the indications pointed to *stone-like* (37.78%), *plastic-like* (14.44%), *wood-like* (11.11%), *fabric-like* (6.67%), *paper-like* (3.33%), and *other* materials (2.22%), with no reference to *metal-like* materials. In the case of visuo-haptic perception of the combination, materials were perceived 80.00% of the time, with material categories referring to *stone-like* (30.00%), *wood-like* (18.89%), *fabric-like* (10.00%), *paper-like* and *other* (both 7.78%), *metal-like* (3.33%), and *paper-like* (2.22%).

6.5 DISCUSSION

Building upon the results obtained from Chapter 5, we investigated the use of replicated surface textures as passive haptic proxy objects in VR.

When comparing the ratings for the haptic perception of replicated surface textures to the ratings of the visual perception of virtual textures, and the visuo-haptic perception of haptic replicas overlaid with virtual textures, a common trend arises. For all indications of hardness, the visual perception of the virtual texture was clearly found to be lower than both other modalities. In terms of roughness, results indicate the same tendency, excluding the case of $T_{\text{1-casino}}$, while for stickiness only $T_{\text{3-crown}}$ adhere to the same principle. This reinforces the results from Chapter 5, by underlining that the loss of compliance and surface variety of the original samples to the replicated surfaces was noticed by participants. Additionally, the perception of stickiness of the replicas was influenced more by the used material, while the visual perception of stickiness of the virtual textures was in most cases not significantly different.

In terms of visuo-haptic integration, our results show that for most cases, the haptic modality dominated the perception in terms of roughness and hardness. Following the notion of multisensory integration, this indicates that the haptic modality was found to be more reliable than the visual one. This could have been caused by different reasons. One explanation is that in the absence of haptic information, the impression of the virtual texture left more room for interpretation, while the addition of haptic input provided certainty of its characteristics. This implies that a visual texture experienced in VR can be perceived as a texture material, while the addition of mismatching haptic information causes the visual texture to be interpreted as a visual overlay without haptic properties. Alternatively, the questions asked during the study referred to tactile dimensions, which can be interpreted differently. When asked about the roughness of an object, visual assessments are made based on different qualities, such as glossiness, compared to haptic assessments. Faced with mismatching visuo-haptic information, users might tend to interpret questions inquiring about tactile dimensions through haptic characteristics, meanwhile ignoring visual qualities.

Considering material perception, both the separate haptic and visual scenarios provided room for interpretation. This underlines that mere surface variations on the same physical material, i. e., plastic, or mere visual texture variations in VR can provide a wide range of interpretations. In the case of mixed perception, the material perception of the visuo-haptic scenarios shows that users are able to combine material interpretations, even if tactile dimensions are significantly varying. We see this by the absence of *metal-like* indications of the haptic modality and the absence of *plastic-like* indications in the visual modality, which were both present in the visuo-haptic case. This points towards the potential of creating a broader gamut of material perceptions in virtual settings through combining a limited set of haptic samples and visual textures.

As an initial exploration of combining replicated surface sample with visual textures as passive haptic proxy objects in VR, our results underline the potential of fabrication processes to support passive haptics. However, our current investigation has limitations that need to be taken into account. Firstly, the full study compared a wider range of modalities and samples, which were not all taken into account for this initial analysis. Therefore, it remains to be seen how the results transfer to other cases, such as the visual perception of the replicated textures, the haptic perception of the original textures, and the visuo-haptic perception of different combinations.

While all cases were counterbalanced, there still might have been an influence on other perceptions. For example, participants that first rated the samples in the real world, could have considered this information in virtual scenarios, as visual correspondences could easily be made. However, in practical application scenarios where users would fabricate their own structures at home, they will firstly see what they have made, before experiencing the visuo-haptic scenario during immersion. Considering this, the results underlining that participants tried to make sense of different combinations, supports the use of fabricated proxies for material perception in VR.

6.6 CONCLUSION

Based on multi-modal perception, this chapter investigated how replicated surface textures can serve as passive haptic structures in VR. In a user study, we investigated the perception of a subset of original and reproduced textures from Chapter 5. Through baseline and mixed perception investigations, we examined the haptic perception of the replicated surface textures, the visual perception of the virtual textures, and the visuo-haptic perception of the haptic replicas overlaid with virtual textures in VR. Our focus in this work was on the tactile dimensions of hardness, roughness, and stickiness, and the general material perception.

From our results, we see that in terms of hardness and roughness, most visual textures communicated lower haptic values, while the visuo-haptic perception aligned more with the haptic perception of our samples. In terms of stickiness, ratings were found to be closer in most assessments, indicating that its perception for our set of samples was more aligned regardless of the modality available to the user. Considering material perception, we note that the material perception of haptic and visual impressions are combined when both modalities are present. This indicates that our visuo-haptic approach has the potential to increase the gamut of material perception in VR.

As haptic impressions highly influenced the visuo-haptic case, their sensations overwhelmingly push perception in a certain direction. Therefore, the use of more abstract structures with varying degrees of hardness and roughness would be able to extend our method. To this aim, the next chapter details on an investigation using fabricated hair-like structures with more versatile tactile characteristics.

"Going to the Feelies this evening, Henry?" enquired the Assistant Predestinator. "I hear the new one at the Alhambra is first-rate. There's a love scene on a bearskin rug; they say it's marvelous. Every hair of the bear reproduced. The most amazing tactual effects."

— Aldous Huxley, *Brave New World*

7

PROCEDURAL TEXTURE PERCEPTION IN VIRTUAL REALITY

As we conclude from the previous chapters, fabrication of haptically-varying surface structures is able to support passive haptic feedback in VR. In this chapter, rather than aiming for haptic reproduction, we investigate the case of procedurally generated surfaces to enhance tactile experiences. This chapter addresses RQ2, and was previously published under the following publication.

Donald Degraen, André Zenner, and Antonio Krüger (2019b). "Enhancing Texture Perception in Virtual Reality Using 3D-Printed Hair Structures." In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems.* CHI '19. Glasgow, Scotland UK. DOI: 10.1145/3290605.3300479

7.1 INTRODUCTION

In order to support haptic feedback beyond standard hand-held controllers, literature has investigated passive haptic feedback, a technique which enables users to touch and feel their virtual surroundings through passive haptic proxy objects (Insko, 2001). Here, props are physical representations of virtual objects, typically registered in a 1-to-1 fashion. A naïve implementation of passive haptics requires virtual objects with varying materials to be represented by the same number of physical objects with corresponding materials. While this approach can provide highly realistic haptic details, it remains bound by several

Figure 7.1: A sample book to explore different fabrics.

limitations. As continuous synchronization of physical and virtual objects is required for every change in the virtual environment, it is inherently inflexible. Additionally, when IVEs consist of large numbers of objects, each with their own different surface material, scaling issues arise as the required collection of physical materials with increases rapidly.

Our aim is to counter the limitations of passive haptics by looking towards novel fabrication techniques for constructing more flexible proxy objects. Similar to the evolution of the paper printer, 3D printers will take their place into the everyday lives of consumers. As the resolution of these printers is already high enough to produce rich and fine-grained tactile structures, they have the potential to extend IVEs with customized haptic feedback. To this intent, we explore the design of 3D-printed hair structures to serve as versatile proxy surfaces for influencing texture perception.

In this chapter, we present a user study in which we used hair samples of different lengths overlaid with visual textures to investigate the users' perception of virtual materials in VR. Our results describe how participants experienced both virtual and haptic textures separately, and how both modalities are influenced through mixed visual-haptic combinations. We discuss practical findings for the future of fabricating passive haptic feedback.

7.2 HAIR-LIKE STRUCTURES FOR TEXTURE PERCEPTION

The following section introduces our approach to enhance texture perception in VR using 3D-printed hair structures.

7.2.1 *Use Cases*

Our aim was to investigate the perception in terms of roughness and hardness of combined visual and haptic sensations using fabricated structures. To test the appropriateness of potential fabrication designs, we motivated two use cases in which our approach could fit.

A customer looking to buy a couch uses a furniture store's mobile application to browse through their collection. The novel augmented reality (AR) functionality makes it easier to decide on size and color by visualizing the couch in the customer's living room. As sitting in a couch stimulates the tactile senses, its *feeling* in terms of fabric and material is extremely important. Similar to a fabric sample books, see Figure 7.1, the customer is able to explore different types of upholstery using a limited set of 3D-printed samples. Combined with visual information, each sample is able to convey a larger set of materials.

An interior designer working on cars goes through an elaborate process to configure every small aspect according to the needs and requirements of the company. Physical prototypes give detailed visual and tactile impressions, but can become extremely expensive. Using VR, the designer is able to experience both visual aspects of 3D designs and tactile elements using passive haptic feedback. Supported by fabricated tactile structures, this approach reduces the cost of the proxy objects while ensuring reusability. Additionally, a varying set of material impressions is offered to potential customers at local car dealers.

7.2.2 *3D-Printed Hair*

During our initial exploration, we aimed to find a uniform structure which allowed a maximum of haptic variance in roughness and hardness, yet minimized the degrees of freedom in the print. After exploring a multitude of fabrication techniques and designs using different printers and materials, 3D-printed hair-like structures promised to be the most favorable haptic structures. While relatively easy to fabricate, we noticed changes in design directly influenced perceived tactile properties. After printing a large set of samples varying hair length, density and thickness, We found that decreasing the density or the thickness severely harmed the structural integrity of the design. An increase rapidly affected the flexibility of the hairs, causing hardness to reach a plateau. The length of hair was found to be a crucial parameter strongly affecting tactile impressions. While short 3D-printed hair conveyed a very rough and hard feeling, with increasing hair length samples grew

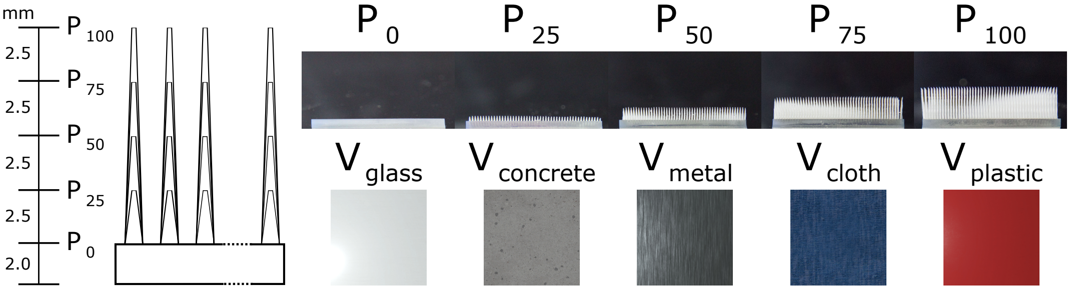


Figure 7.2: Overview of the five physical surfaces and five virtual textures used in our study. Note that the material used for glass is highly transparent and would reflect the environment.

smoother and at the same time softer. Thus, we designed and printed a set of hair structures to experimentally investigate during VR interaction.

Our set of hair-like structures, shown in Figure 7.2, was printed using an Autodesk Ember[1] with an X-Y resolution of 50 µm and a layer thickness of 25 µm. Our printing technique was based on the staircase approach described in (Ou et al., 2016). The maximum length we could print reliably was 1 cm as longer designs would not produce uniform structures. To keep the experiment feasible with regard to time and user fatigue, we limited our final set of prints to 5 different samples with enough haptic variance. As an interesting extreme case, the first sample was a flat surface without attached hairs, i. e., a sample with hair length of 0 cm. Each subsequent structure increased the hair length by 2.5 mm. The structures were printed on a 800 px × 800 px (40 mm × 40 mm) base with a height of 2.0 mm. Each individual hair consisted of a 8 px × 8 px base, converging to a 2 px × 2 px top. Depending on its length, each hair print resulted in a growing cone-like shape. All hairs were spaced apart by 8 px, yielding a 50 × 50 grid.

7.2.3 *Augmented Virtual Textures*

Based on the expected tactile feeling of the five tested hair samples, we chose five materials to be haptically augmented by them in VR. For every sample, we chose a representative texture that matched the anticipated feeling of the hair sample with regard to hardness and roughness. For the flat, hard and smooth sample without hairs (P_0), we chose *glass* as a representative texture. For the short-haired samples (P_{25}, 2.5 mm & P_{50}, 5 mm), we chose *concrete* and brushed *metal*, respectively. The decrease in hardness and roughness of the last two samples (P_{75}, 7.5 mm & P_{100}, 10 mm), we associated with a medium rough *fabric*, i. e., jeans, and the soft and smooth *plastic* of a balloon, i. e., latex. To improve recognizability, every texture's color hinted at its intended material. The virtual textures, seen in Figure 7.2, were purchased from various sources and imported into the Unity environment.

---

[1] Autodesk Ember - https://bit.ly/3RIi3bZ

7.3 STUDY

In this section, we describe the design of the user study, where we presented participants with different physical samples overlaid with different virtual textures in VR and recorded the perception of roughness and hardness.

7.3.1 *Apparatus*

We performed the user study in our lab. The hair structures, fabricated as described above, were attached in a clockwise manner on a circular wooden board. This board was raised in order to allow the placement of a Vive controller used for registration and tracking. A Leap Motion controller, used for hand tracking, was statically positioned above the table facing downwards. This setup, shown in Figure 7.3, allowed participants to precisely hit a required hair structure without touching a different surface.

The virtual environment consisted of a virtual apartment model where the user was positioned in a small room in front of a virtual work desk. The construction carrying the hair structures was represented by a 1-to-1 scale model of a wooden cylinder. The location of each sample was indicated by a cuboid with a neutral gray texture. To prevent participants from colliding with the physical Vive controller, we placed the upper half of a virtual sphere over its physical location. By applying the active texture to the sphere, the reflected environmental lighting allowed participants to better inspect the material's surface properties. Additionally, participants could reposition their head to receive better impressions of the visual details.

Rendering was done in Unity 5.6 using a HTC Vive headset connected to a desktop computer with an Intel i7 CPU, 16 GB RAM and an Nvidia GeForce GTX 980Ti graphics card. The experimenter recorded participants' answers on a second computer.

7.3.2 *Participants*

A total of 10 participants (7 male, 22 – 29 years, avg. 26 years) volunteered for our study. All participants were right-handed and 2 wore glasses or contact lenses. Participants rated on a scale from 1 (= never) to 5 (= regularly) how often they played 3D video games ($M = 3.00$, $SD = 1.49$) and how frequently they used VR technology ($M = 2.00$, $SD = 1.25$). We asked how regularly the participants performed precise handcrafts on the same scale and received responses between 1 and 4 ($M = 2.90$, $SD = 1.20$). Sickness ratings on a scale from 1 (= I never felt ill) to 5 (= I felt ill all the time) after completion of the experiment verified the absence of cyber-sickness, as all participants responded with 1. The post-experiment SUS presence scores ($M = 1.20$, $SD = 1.62$) suggested low but sufficient immersion of the virtual experience (Slater et al., 1994).

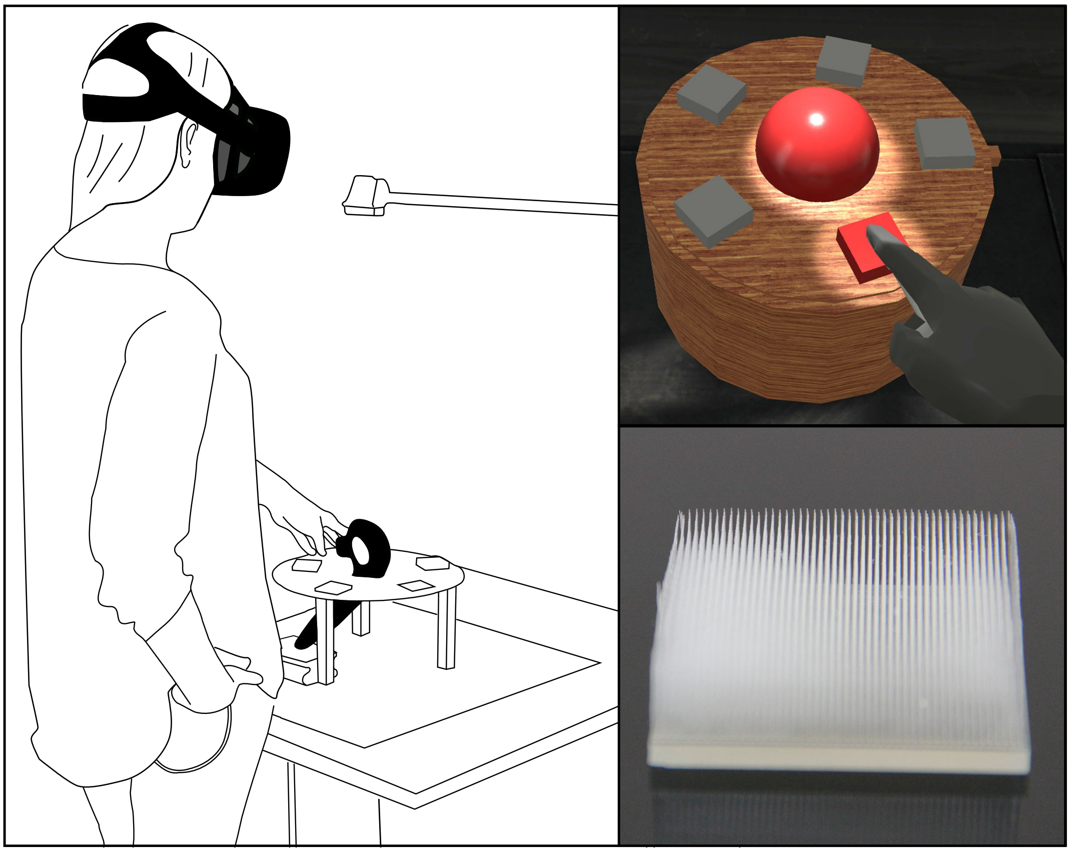


Figure 7.3: Experiment Setup. (left) A user touching a physical sample on the proxy plate with a Vive controller in the center and a Leap Motion positioned above the user's hand. (right top) First person view of a user touching a virtual plastic material. (right bottom) A patch of 3D-printed hair.

7.3.3 *Procedure*

Before starting the experiment, each participant signed a consent form and was briefed regarding the course of events. During the initial phase, each participant performed two separate baseline assessments. Here, we collected visual and haptic baseline ratings of both roughness and hardness for each virtual texture and each physical sample.

During the haptic baseline assessment, the view of the virtual environment in the HMD was blacked out. This was to ensure no visual input would influence the participant's haptic sensation. The operator guided the participant's dominant hand to each of the physical samples and asked them to rate on a scale from 1 to 10 how rough the sample felt (1 = very smooth, 10 = very rough) and how hard the sample felt (1 = very soft, 10 = very hard). These questions were simultaneously visible in the blacked out HMD.

During the visual baseline assessment, the participant was shown the virtual environment where each visual texture appeared one by one. For each visual texture, the participant was asked to rate on a scale from 1 to 10 how rough the texture looked (1 = very smooth, 10 = very rough) and how hard the texture looked (1 = very soft, 10 = very hard). Touching any object in the real world was not allowed to ensure no haptic input would influence the visual assessments.

Upon completion of both baseline phases, each combination of physical sample and virtual texture was shown 5 times per participant, resulting in 125 individual trials per participant. For each trial, the virtual cuboid corresponding to the location of the active physical sample was assigned the active visual texture. Participants were instructed to both look at and touch the sample, see Figure 7.3, while answering 6 questions, i. e., 2 regarding haptic sensations, 2 regarding visual sensations, and 2 regarding the combined haptic and visual sensations. The questions, depicted in the virtual environment on the wall in front of the participant, were:

1. On a scale from 1 to 10, how **rough** does this object **feel**?
   (1 meaning very smooth, 10 meaning very rough)
2. On a scale from 1 to 10, how **hard** does this object **feel**?
   (1 meaning very soft, 10 meaning very hard)
3. On a scale from 1 to 10, how **rough** does this object **look**?
   (1 meaning very smooth, 10 meaning very rough)
4. On a scale from 1 to 10, how **hard** does this object **look**?
   (1 meaning very soft, 10 meaning very hard)
5. On a scale from 1 to 10, how well do you think the visual perception of the object **matches** the tactile perception?
   (1 meaning no match, 10 meaning perfect match)
6. What do you think the **material** of the object is?
   (Open question)

The observer noted the responses for each trial and activated the next sample upon completion of the 6 questions. The table containing the physical samples was rotated after each set of 25 combinations to counterbalance any learning effect associating positional knowledge to haptic properties. During this, the rendering of the virtual object was disabled to ensure participants were not able to see the manipulations.

After the experiment, participants completed two post-study questionnaires. One inquired about their demographics, and the SUS presence questionnaire (Slater et al., 1994) recorded the experienced presence in the virtual environment.

7.3.4 *Design*

We used a within-subjects experimental design consisting of two baseline phases, i.e., the tactile perception of the printed structures and the visual perception of the visual textures, and a main phase in which we assessed all visual-haptic combinations. We distinguish 2 independent variables (the hair length on the physical sample and the type of visual texture shown on top), each with 5 different instances.

In order to balance for first-order carry-over effects, we constructed experimental design tables according to the Williams design using Latin squares (Williams, 1949). For an uneven number of conditions such as our 25 visual-haptic combinations, each table consists of two Latin squares, i. e., a 50 × 25 experimental design table. Here, the Latin square was completed exactly once as each of the 10 participants achieved 125 trials by assessing each of the 25 combinations 5 times. During the analysis, the results were averaged for each participant. The visual and haptic baseline stages were counterbalanced amongst the participants using a Latin square of $n = 2$ and in both stages, the texture exposures were counterbalanced using a Latin square design of $n = 5$.

We further distinguish 6 dependent variables: the ratings of how rough a combination feels, how hard it feels, how rough it looks, how hard it looks and how well tactile and visual perception match, each on a 1-to-10 Likert scale. The sixth dependent measure was the open answer, in which participants stated which material they thought to experience. For this open question, participants were not provided a list of materials to choose from, but were free to provide any answer they saw fit.

7.4 RESULTS

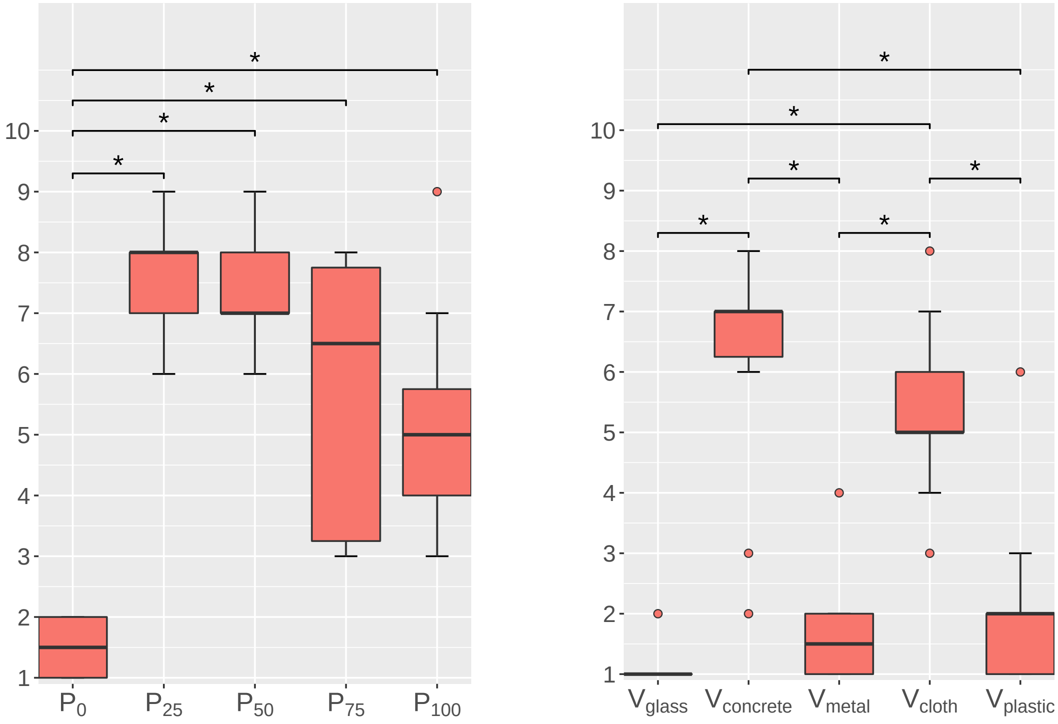
In the following section, we describe the analysis and the obtained results from our texture perception study.

7.4.1 *Baseline Results*

Participants' assessments of both baselines allowed us to test our initial assumptions about the perception of each physical sample and each virtual texture. We distinguish between roughness and hardness for *the haptic ratings of physical samples* without visual information, see Figure 7.4a and 7.4c, and *the visual ratings of virtual textures* without haptic information, see Figure 7.4b and 7.4d. For each case, we conducted a Friedman test with post-hoc analysis using Wilcoxon signed-ranks tests and Bonferroni-Holm correction.

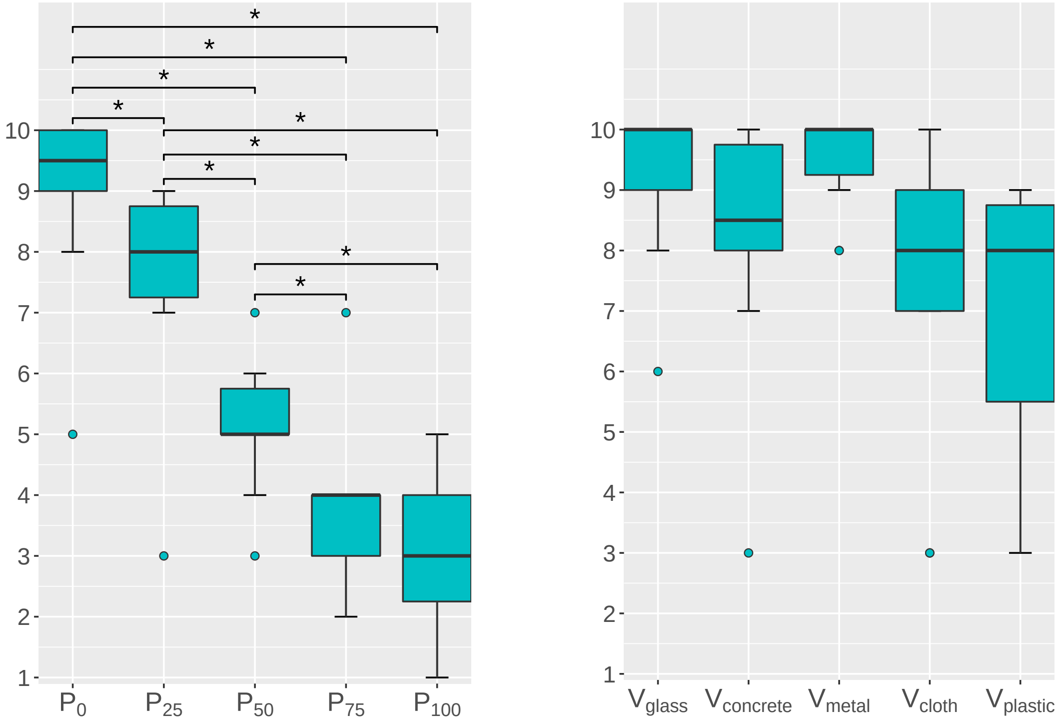
7.4.1.1 *Haptic Baseline*

The haptic ratings were found to significantly differ depending on the type of physical sample presented to the user, i. e., in terms of roughness ($\chi^2(4) = 28.908$, $p < .001$), and hardness ($\chi^2(4) = 38.184$, $p < .001$). Pair-wise analysis of roughness showed a significant increase from the P_0 sample to all others ($p < .05$), however, no differences were found between P_{25}, P_{50}, P_{75}, and P_{100}. Hardness significantly decreased for each step of hair length



(a) Haptic roughness

(b) Visual roughness



(c) Haptic hardness

(d) Visual hardness

Figure 7.4: Boxplots depicting the baseline assessments. Haptic ratings of the physical samples without visual information for roughness (a) and hardness (c). Visual ratings of the virtual textures without haptic information for roughness (b) and hardness (d). Brackets connect groups with statistically significant differences ($p < .05$).

for all physical sample combinations ($p < .05$), excluding the increase from P_{75} to P_{100}. The brackets in Figure 7.4a and 7.4c indicate significant differences.

These results reveal that the addition of hair to the surface of a sample was clearly noticeable by users. While most increases in hair length were above the just-noticeable difference (JND) threshold for the perception of hardness, there was no significant change in the feeling of roughness.

7.4.1.2 *Visual Baseline*

Depending on the virtual texture presented to the user, visual roughness ($\chi^2(4) = 32.978$, $p < .001$) and hardness ($\chi^2(4) = 14.262$, $p < .001$) were found to change significantly. For roughness, we found V_{cloth} and V_{concrete} to be substantially rougher than V_{glass}, V_{plastic}, and V_{metal}. The virtual textures did not significantly vary in terms of visual hardness.

When asked what material was recognized for each visual texture, V_{glass} was identified the best, as all participants indicated *glass*. For V_{metal} 9 participants correctly appointed *metal* and one participant specified the material *onyx*, a banded variety of quartz mineral. While 7 participants assigned *plastic* for V_{plastic}, 2 indicated it could be *wood*, leaving one participant with *rubber*. Stone-like materials in V_{concrete} were viewed by 8 participants, with 4 participants indicating *stone*, 3 indicating *concrete* and one indicating *marble*. V_{concrete} was also designated once as *polystyrene foam (Styrofoam)* and once as *sponge*. V_{cloth} demonstrated the widest range of possible materials, including *stone* (3), *denim* (2), *wood* (2), *soil* (1), *marble* (1) and a *shell* (1).

These results show that our set of virtual textures were divided into 2 groups when considering how rough they appeared. Where V_{cloth} and V_{concrete} were regarded medium-high in roughness, V_{glass}, V_{plastic}, and V_{metal} were considered to be very smooth. The resolution and quality of the image projected in the HMD seemingly had an effect on the details and visual artifacts that hinted towards more a more diverse roughness. All virtual textures were believed to be generally high in hardness. While V_{glass} and V_{metal} were clearly identifiable, other textures left some confusion as to what they represented. Here, the static visual representation of our textures might have caused a lack in visual hints.

7.4.1.3 *Baseline Matching*

Our set of virtual textures was compiled based on the expected tactile feeling of the 3D-printed hair samples. Even though we did not expect the visual ratings to perfectly match the haptic ratings, it is worthwhile to reflect on the appropriate matching of the visual and haptic choices.

As expected, V_{glass} paired almost exactly as the physical sample P_0, i.e., very smooth and hard. Even though absolute average ratings clearly deviated, the textures V_{concrete}, V_{cloth}, and V_{plastic} showed a similar downwards trend in roughness and hardness compared to their physical pairs P_{25}, P_{75} and P_{100} respectively. In contrast to our intended brushed metal

	V_{glass}			V_{cloth}			$V_{concrete}$			$V_{plastic}$			V_{metal}		
	P (%)	M	A (%)	P (%)	M	A (%)	P (%)	M	A (%)	P (%)	M	A (%)	P (%)	M	A (%)
P_0	94%	8.70	30%	64%	4.86	60%	56%	5.74	64%	98%	9.10	16%	88%	8.46	36%
P_{25}	28%	4.02	100%	84%	7.02	48%	84%	8.06	36%	66%	5.34	61%	62%	5.60	68%
P_{50}	24%	3.16	92%	78%	7.08	41%	72%	6.70	28%	48%	4.82	42%	44%	4.64	55%
P_{75}	24%	2.70	67%	68%	6.40	24%	54%	4.90	19%	34%	4.04	53%	18%	2.80	22%
P_{100}	18%	2.60	56%	64%	5.78	34%	50%	4.24	32%	44%	4.28	32%	18%	2.50	45%

Table 7.1: Perception and Matching Rate Summary. *P:* Percentage each combination was identified as *some* material. *M:* Average visual-haptic match on a scale from 1 to 10. *A:* Percentage of used adjectives for positive perceptions.

texture, V_{metal} was visually assessed as very smooth and very hard. We believe that the visual quality of the HMD is in part responsible for this, as fine reflections and bumps that indicate the roughness were hard to identify.

7.4.2 *Roughness and Hardness Augmentation*

For all visual-haptic combinations, we recorded users' visual and haptic assessments of roughness and hardness. Similar to the baseline, Friedman tests were used to detect overall significant differences with post-hoc analysis using Wilcoxon signed-ranks tests and Bonferroni-Holm correction applied. In the analysis, we considered 2 statistical variants, i. e., *the cross-modal influence* and *the multi-modal influence.*

7.4.2.1 *Cross-modal Influence*

For the analysis of the cross-modal influence, we assessed how consistently a modality is rated while the other modality is changed. For each visual texture, we compared how users visually rated them while experiencing different physical samples underneath. For each physical sample, we compared how users rated haptic properties while varying visual textures are visualized on top. In these 2 cases, the baseline assessments are considered an extra group, i. e., visual ratings without haptic information and haptic ratings without visual information respectively. For both analyses, we did not find any statistically significant differences between groups.

While rating one modality, users consistently assess perceptual properties belonging to that modality. There was no apparent guidance of one modality onto the other.

7.4.2.2 *Multi-modal Influence*

In the analysis of the multi-modal influence, we investigated how a changing modality is rated in the presence of another fixed modality. Here, we firstly compared how the haptic perception between physical samples changes while a fixed visual texture is shown. We found that regardless of the visual texture present, the haptic ratings between physical samples significantly change ($p < .001$). More specifically, the feeling of roughness significantly decreases with increasing hair length for all cases ($p < .05$) excluding the increase in hair from P_{75} to P_{100} when V_{glass} or $V_{plastic}$ were visible. For all samples with hairs attached, the rating for hardness significantly decreases with increasing hair length, regardless of the visual texture shown ($p < .05$). The addition of hair from P_0 to P_{25} did not cause a significant decrease in the perception of hardness.

Secondly, we compared how the visual assessments differ across visual textures while a fixed physical sample is present. Similar to the trend in the visual baseline, the rating of visual roughness for V_{cloth} and $V_{concrete}$ was significantly higher than V_{glass}, $V_{plastic}$, and V_{metal}, regardless of the physical sample active (P_0 & P_{50}, $p < .05$; P_{25} & P_{75} & P_{100}, $p = .05$). In the case of visual hardness, users rated V_{cloth} to be significantly softer than V_{metal} (P_0 & P_{25}, $p < .05$; P_{50}, $p < .01$; P_{100}, $p = 0.05$) and V_{glass} (P_{50}, $p < .05$; P_{100}, $p = 0.05$).

These results show that the perception of haptic roughness for varying hair lengths became clearly pronounced for most cases in the visual-haptic augmentation. While the difference in haptic hardness between P_{75} and P_{100} also became more apparent, the change from P_0 to P_{25} fell below the JND threshold. This indicates that haptic perception benefits from the presence of visual information. Considering visual roughness, the same trend of 2 groups of virtual textures appears compared to the visual baseline, however many of the significances were borderline. While visually the textures did not seem to differ in hardness during the visual baseline, the presence of most physical samples caused a difference to occur between V_{cloth} and V_{metal}, and to a lesser degree between V_{cloth} and V_{glass} during the visual-haptic augmentation. Visual perception of haptic properties can thus be enhanced by haptic presence, however to a much lesser degree than the inverse, due to the effect of visual dominance.

7.4.3 *Perception and Matching Rate*

For each visual-haptic combination, we recorded the matching rate by asking participants how well the experienced haptic and visual perceptions agreed. Additionally, material perceptions for all combinations were recorded by asking participants what they thought the material they experienced, was. If the participant was able to provide a meaningful material or object assignment, the trial was indicated as a positive perception.

The perception rate combined with each combination's matching rate provided insights into how specific combinations were identified. As expected, certain combinations showed high perception percentages, and were perceived as a better match, which can be seen in Table 7.1. The combinations of V_{glass}, V_{metal} and $V_{plastic}$ with P_0 clearly had very high recognition rates. Here, the haptic feedback of a smooth and hard surface matched the expected feeling implied through the visuals. Both $V_{concrete}$ and V_{cloth} were recognized most in combination with P_{25}. As they showed overall perception ratings $\geqslant 50\%$ across all physical samples, these textures showed the highest perceptual flexibility. The look of $V_{plastic}$ left room for interpretation regarding the expected roughness and hardness. There-

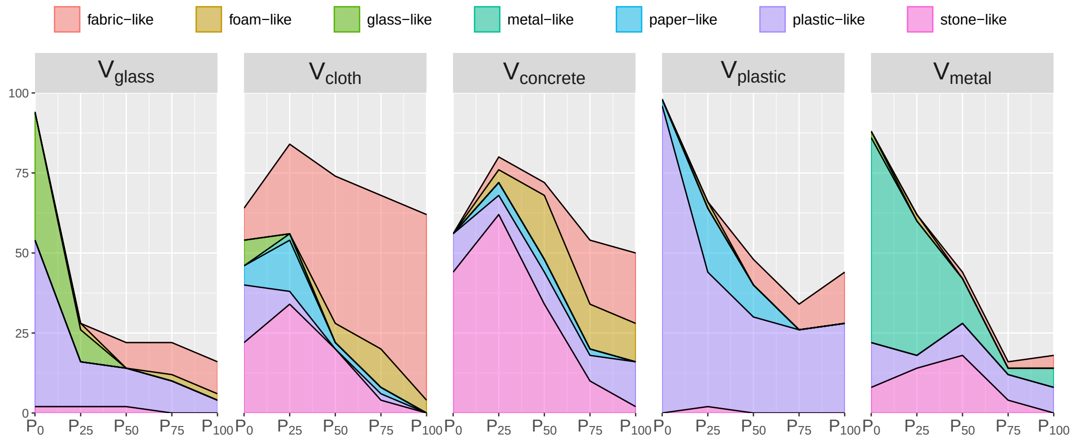


Figure 7.5: Stacked perception graphs per virtual texture indicating for each physical sample the percentage of samples identified per material category. Unassigned space depicts the percentage of times no meaningful material or object was assigned.

fore, $V_{plastic}$ showed moderate to high recognition rates $\geqslant 34\%$ across all haptic samples. However, as V_{glass} and V_{metal} seemed to unarguably convey a distinct feeling of smoothness and hardness, perception rates decreased rapidly with increasing roughness and softness. These results imply that, when facing textures that visually provide strong indications of their tactile properties, modifying users' perception with discrepant tactile cues is harder. Contrarily, more ambiguous visual surfaces can show shifts in haptic perception.

Performing a Kendall's rank correlation coefficient test, we found the matching and the perception rates to significantly correlate across the entire dataset ($p < .001$, $N = 1250$). This positive correlation indicates that when users have a concrete idea of the material they engage with, they typically perceive the visual texture and the haptic surface as matching. Vice-versa, if users are unable to create a mental model of the mixed texture impression, they tend to regard both stimuli as a weak match. This suggests that in borderline cases, providing additional information about the mixed texture could push users towards perceiving a better match through priming their expectations.

7.4.4 *Subjective Material Perception*

The anecdotal data of the perceived materials was further analyzed by manually extracting the materials and objects identified by the participants. In total, we characterized a set of 35 distinct perceived materials, both abstract and concrete depictions. These were grouped into 7 categories, namely *fabric-like* (brush, carpet, denim, fabric, fiber, flanel, fur, silk, wool), *foam-like* (polystyrene, sponge), *glass-like* (crystal, glass), *metal-like* (aluminum, metal, steel), *paper-like* (drywall, paper, sandpaper, wood), *plastic-like* (crayon, linoleum, plastic, rubber, silicone), and *stone-like* (coal, concrete, coral, chalk, clay, granite, marble, mineral, stone, tarmac).

The percentages per group for each visual-haptic combination are plotted in Figure 7.5. Colored areas represent the percentage and distribution of identified materials, while unassigned space in the graphs reflects the users' inability to provide meaningful perceptions. This is clearly illustrated by V_{glass} where increasing the length of hair quickly restricted meaningful impressions. Both within and in between groups, we observed switches in material perception for the same visual texture presented with different physical samples. For example, V_{cloth} with shorter hair length samples led to variations of *fabric-like* and *stone-like* while an increase in length more consistently indicated *fabric-like* perceptions. Interestingly, increasing the hair length for V_{concrete} caused users to note more *fabric-like* or *foam-like* materials, e. g., *polystyrene*.

During the study, participants used adjectives to clarify their impression, as they felt a simple material or object would not suffice. Three distinct groups of adjectives were noted, i.e., visual, haptic and other. Visual adjectives indicated properties referring to cues such as coloring, reflectance or observable visual artifacts. Haptic adjectives described tactile impressions, e.g., details in roughness or hardness. Lastly, other adjectives elaborated on features such as age, quality or temperature. For each combination, the percentage of adjectives for all positive perceptions is shown in Table 7.1. Kendall's rank correlation coefficient tests indicated inverse correlations for the adjective usage to the rate of perception and to the average matching rate (both $p < .05$, $N = 25$).

7.5 DISCUSSION

Motivated by related work (Kitahara et al., 2010), we used fabricated passive proxy objects with varying tactile properties overlaid with different virtual textures. We aimed to determine the effectiveness of 3D-printed hair samples as more flexible and universal structures for the perception of roughness and hardness. As we expected to see interactions between the visual and haptic modalities, we assessed how our approach influenced the users' material impressions. Here, we discuss our results which support using 3D-printed hair to enhance texture perception in VR and open questions for future work.

7.5.1 *Haptic Perception of Hair Length*

From the baseline assessment of our physical samples, we find that the addition of hairs was clearly perceived in terms of roughness and hardness. Without visual information, an incremental increase of hair length did not cause the expected decrease in the perception of roughness. For hardness, the expected decrease for each increasing step in hair length was noticed by the users, excluding the step from P_{75} to P_{100}. In a multi-modal setting with virtual textures overlaid on physical samples, the sensation of roughness rises above the JND. A shift in hardness perception caused the difference between P_{75} and P_{100} to appear, while the difference between P_0 and P_{25} faded.

These results support the use of hair-like structures for roughness and hardness perception in the presence of visual information. By combining our approach with state-of-the-art redirection techniques, users are able to experience different variations of physical proxies with varying tactile properties. While we only focused on hair-like structures, other fabrication designs could extend our results with more detailed tactile variants or might include alternative perceptual properties, such as stickiness.

7.5.2 *Haptic Perception of Visual Textures*

In terms of roughness, our set of virtual textures was divided into two groups, with V_{cloth} and V_{concrete} visually appearing medium rough while V_{glass}, V_{metal} and V_{concrete} seemed smooth. In the presence of haptic information, the results indicated the same trend to occur. When considering hardness, users consistently rated all virtual textures to be hard in the baseline assessment. The limited differences that arose in the presence of haptic input were not consistent across physical samples.

From this, we can see that influencing the perception of visual information is much harder. Although visual dominance remains highly present, our results suggest that the potential for the tactile to guide the visual does occur. As our set of visual textures was limited, a much broader range could uncover visual aspects important in the interplay between visual and haptic modalities.

7.5.3 *Cross-Modal Consistency*

In our study, neither the visual nor the haptic modality was able to overwhelm, as indicated by the lack of significant differences in the analysis of the cross-modal influence. This shows users were consistently rating perceptual properties belonging to each modality. A user asked to rate visual properties focused on the visual information presented and, vice-versa, focus on haptic input when asked to rate haptic properties. Making one modality convincing enough to guide the other, remains future work.

7.5.4 *Visuo-Haptic Material Perception*

A total of 35 materials were perceived from our set of 5 visual textures and 5 different physical samples. As perception and matching rates correlated, most of these materials were perceived when users found both haptic and visual information to be corresponding. In cases where matching rates were low, the use of adjectives for explaining materials increased. In certain instances, the variation in haptic perception for a given virtual texture led to perceptional switches where perception of a material changes.

These results show users actively try to make sense of sensory input, whether matching or not. By providing additional information related to the texture in borderline combinations, the user's perception could be primed. This might lead to more precise and consistent material perceptions and would open up our approach for practical applications.

7.6 CONCLUSION

Based on multi-modal perception, this chapter investigated how 3D-printed hair structures can serve as versatile passive haptic structures for VR. In a user study, we found that visual-haptic augmentations enhance the user's haptic perception by making small variations in hair length distinguishable. We show that higher rates of matching perceptions correlate to material recognitions. As users actively make sense of mixed modalities, mismatches are clarified with adjectives and varying augmentations cause perceptual switches.

In this work, the single parameter of hair length allowed users to perceive a larger set of material impressions. While other designs could more controllably guide perception, active approaches might build upon our results by manipulating hair length in real-time. Future experiments improving consistency and accuracy would require a larger amount of participants. By combining our approach with techniques for redirection in VR, the perception of a large set of materials can be supported by a limited set of fabricated proxies.

Did it sound anything like this?
Squawk!

— Kelly, *Modern Girls (1986)*

8

CROSSMODAL EXPRESSION OF TACTILE FEEDBACK

The previous chapters addressed the design of tactile experiences from either real-world physical information through haptic reproduction, or through procedural generation of haptically-varying structures. In this chapter, we investigate the relationship between tactile impressions and vocal expressions, with the aim of supporting rapid design processes of haptic feedback. This chapter addresses RQ3, and was previously published under the following publication.

Donald Degraen, Bruno Fruchard, Frederik Smolders, Emmanouil Potetsianakis, Seref Güngör, Antonio Krüger, and Jürgen Steimle (2021a). “Weirding Haptics: In-Situ Prototyping of Vibrotactile Feedback in Virtual Reality through Vocalization.” In: *The 34th Annual ACM Symposium on User Interface Software and Technology.* UIST ’21. Virtual Event, USA. DOI: 10.1145/3472749.3474797

8.1 INTRODUCTION

Developing effective and convincing tactile experiences using vibrotactile feedback remains a challenge. State-of-the-art design tools, e. g., as illustrated by Interhaptics (2021), Lofelt (2021), Schneider and MacLean (2014), and Strohmeier et al. (2020), propose to manipulate low-level controllable parameters such as frequency and amplitude, but it remains challenging to transfer such abstract parameters into understandable haptic effects (Schneider et al., 2017; Seifi and MacLean, 2017). Moreover, these design tools rarely support fast-prototyping methods nor do they support direct and easy mapping of vibrotactile feedback to users’ (spatio-temporal) interactions in VR (Kim and Schneider, 2020). Implementing convincing experiences is an even greater challenge for those inexperienced in haptics, e. g., video game programmers who seek to design playful experiences with tactile sensations, students learning haptics through prototyping, or interaction designers wanting to provide tactile feedback in UI widgets (Seifi et al., 2020a). As pointed out by recent work (Kim and Schneider, 2020; Seifi et al., 2020a), novice hapticians need more *timely*, *hands-on* interfaces leveraging *direct manipulation* to better grasp the experiences they want to design.

In this chapter, we investigate the use of the voice to serve as a means for designing tactile experiences. To this aim, we performed an elicitation study where participants were asked to vocally express the tactile impression received during interaction with a wide range of objects. Through a thematic analysis approach, we identify what kind of spatio-temporal mappings are needed to create convincing haptic experiences that are directly linked to object interactions. Additionally, as we want to assist untrained voices and support a rapid design cycle while immersed in IVEs, we identify modifiers that enable designers to rapidly fine-tune the output generated by their vocalizations in real-time.

8.2 STUDY

To investigate the use of the voice to serve as a means for designing tactile experiences, we conducted a study where we elicited vocalizations of tactile impressions. While interacting with common physical objects, we asked participants to vocally express their tactile impressions in as many ways as they saw fit. The goal of this study was to provide insights into (1) spatial and temporal relationships between vocalizations and the user's actions, and (2) how a computational tool can support novice hapticians to vocalize tactile experiences.

Ethical approval for this study was obtained from the Ethical Review Board of the Department of Computer Sciences at Saarland University (No. 21-01-3).

8.2.1 *Design and Apparatus*

Using an iterative process, we aimed to identify parameters that would influence users' vocalizations. To this aim, rather than selecting a wide range of shapes, we focused on the manner in which objects would be interacted with and included variations in size and texture, as these parameters highly influence the type of feedback produced during manipulation.

We identified three primary features important to our context, i. e., the *type of action* performed, whether the object is *directly manipulated* or is used as a *tool*, and the *size* of the manipulated object. We consider the two former as independent variables (*Action* and *Tool*) and the latter as a control variable (*Size*). The list of actions, inspired from the haptic exploration procedures by Lederman and Klatzky (1987), is as follows: *slide*, *pull*, *push*, *press*, *rotate*, *passive feel*. By crossing the two independent variables, we obtain a set of 10

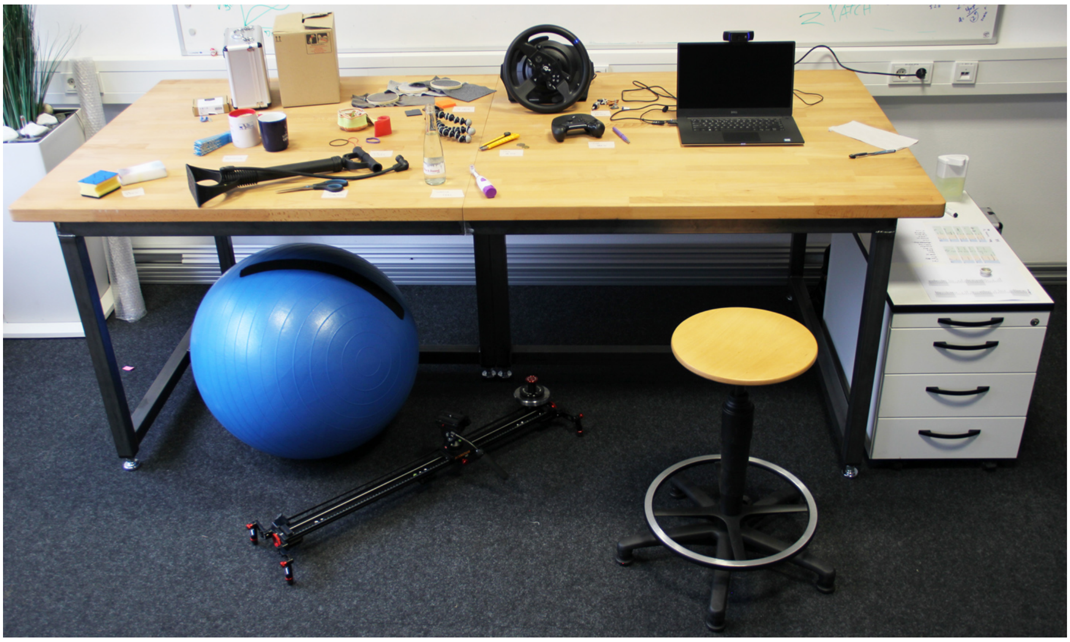


Figure 8.1: Experimental Setup. Here, (left) the objects used for interaction are depicted, each having a label detailing the action to be applied, while (right) the laptop and camera for recording the study are shown. For a full list of objects and their actions, please refer to Section b.1.

categories; most tools could be *pushed* and *pulled* so we merge these actions, and the action *passive feel* includes a tool by definition. Each category included a set of 3 to 6 object-action pairs. In total, we evaluated a set of 44 objects that present various characteristics (size, texture, weight), e. g., fabric samples, knobs and buttons offering various levels of resistance, sponges and elastic bands, or an electrical toothbrush, see Figure 8.1. While we tried to cover a broad range of object-action tasks to include tactile experiences produced by object deformation (e. g., stretching an elastic band or squeezing a sponge), object actuation (e. g., sliding a camera trolley), or the object's texture (e. g., rubbing fabric samples with various roughness), this list is not exhaustive.

We counterbalanced the categories to avoid any order effect. To allow simple comparisons between similar objects like fabric samples with various roughness or elastic bands with various stiffness, we always use the same order of object-action tasks for a given category.

8.2.2 *Participants*

We recruited nine novice hapticians (2 identified as female, 7 identified as male) aged between 23 and 35 (median 29) with backgrounds in Computer Science, Media Informatics and Linguistics. Participants had diverse cultural backgrounds and various native tongues such as English, Ukrainian, Russian, Chinese, Hindi, Farsi, and French. Seven of nine (78%) participants indicated to have a background in musical training, while three (33%) had prior experience in voice acting or singing.

8.2.3 *Procedure*

Before starting the experiment, participants completed a short warm-up task to stimulate their creative skills, which consisted in producing as many animal noises as possible in under one minute. Afterwards, each participant proceeded with the vocalization tasks. For each task, we asked participants to perform a single action with the object as many times as they wanted. When ready, they were asked to vocalize the tactile experience. In pre-pilots, we noticed participants reproduced the sound that objects would make during manipulation. To avoid confusion and ensure participants would focus on tactile sensations, we instructed them to focus primarily on the tactile sensation while producing vocalizations. However, we did not forbid them to reproduce those noises if they felt the sensation matched the noises produced by the objects. We motivated participants to provide as many vocalizations as they could come up with. Should a participant not be able to provide any vocalization, the experimenter would move on to the next task. However, if a participant could not produce the vocalizations they intended due to physical constraints (e.g., frequency too high to produce), we asked them to explain as clearly as possible what they were missing.

8.2.4 *Analysis*

We video recorded each session and analyzed them using a thematic analysis approach, following an inductive process (Braun and Clarke, 2006). Our focus was to observe in detail how participants mapped these vocalizations to their interactions with the objects, and where they would need features their voice could not produce. Data consisted of short video clips of participants vocalizing tactile feedback while manipulating an object and occasional remarks. In a first round, the two first authors watched the video recordings and coded the temporal and spatial features of the vocalizations (instantaneous, repetitive, continuous, interaction bound, random) as well as the kind of sounds produced (pitch-based, amplitude-based, onomatopoeia, etc.). In a second round, they refined the set of codes used to reach agreement, and used it to generate a set of themes.

8.3 RESULTS

From our analysis, we identified four themes of spatio-temporal mappings between the vocalization and the action performed. We complement these themes with a set of challenges participants faced during vocalization.

8.3.1 *Spatio-Temporal Mappings*

Participants mapped their vocalizations to specific events during object manipulation, relating to either time or space, from which we abstracted the following mappings.

INSTANTANEOUS. An instantaneous vocalization described short events in the tactile experiences such as flicking a marble, pressing a button, or closing scissors. This was sometimes combined with *continuous* vocalizations as a way to express a stronger signal, like a bump when reaching the end of a rotatory knob. All participants produced such a mapping at least once during the experiment.

REPETITIVE. A repetitive mapping consists of a sequence of similar instantaneous vocalizations. A repetitive vocalization strongly relates to the speed of the user's action as its frequency increases or decreases accordingly. All participants used repetitive mappings during the experiment to describe bursts in the tactile experience, such as a knob producing distinct positional clicks during rotation.

CONTINUOUS. A continuous mapping represents a smooth, invariable experience while performing an action with an object. Participants unanimously used such a mapping when passively feeling the vibrations of an active electric toothbrush. A majority of participants also used such mappings while sliding a coin over a table or sliding their finger on smooth or rough, uniform pieces of fabric.

ACTION-RELATED. While all mappings relate to the actions performed, some mappings are tightly connected to the movement or the force exerted on the object. By varying their pitch or volume based on the change in tactile sensations, participants used these mappings when squeezing or pulling deformable objects (e.g., sponge or elastic band), or when sliding actuated parts of a tool (e.g., sliding a bike pump or a drawer).

8.3.2 *Challenges in Producing Vocalizations*

Participants sometimes faced difficulties producing vocalizations. For instance, a participant remarked "*the pitch [for the hard sponge] should be higher than [the pitch for] the soft sponge*" (P6) and "*I would like a more grainy voice*" when pressing a finger on a rough sponge. Another participant produced a vocalization and specified it should be "*with a higher pitch, very high*" (P3). In general, participants acknowledged the complexity of the tactile experience and the various layers they comprehend. In this regard, one participant (P6) made interesting remarks while vocalizing the rotation of a stepper motor. They wanted to superimpose two different "*tracks*": a repetitive pattern and "*some random stuff*". While this is challenging in terms of vocalizations, a design tool could provide support here.

8.4 DISCUSSION

The themes extracted from this study alongside participants' comments enable us to infer design implications for design tools implementing vocalization design processes.

8.4.1 *Spatio-temporal Mapping Inferrence*

We observed four distinct spatio-temporal mappings adopted by the participants to vocalize tactile experiences. A design tool should infer such mappings and let users decide upon them in a fine-tuning stage of the design process. For example, a system might infer an *instantaneous* mapping based on the user's actions, while they actually intended to use a *repetitive* mapping with the same vocalization, e. g., pouring water out of a bottle.

8.4.2 *Interaction Speed Adaption*

To not bias participants' natural ways to manipulate an object, we intentionally did not constrain the speed of their actions. This speed, however, has a great impact on the vocalization process for repetitive and action-based mappings; stretching an elastic band rapidly or slowly results in the elastic band wiggling or not. Features of a vocalization should adapt based on the speed of the action performed.

8.4.3 *Supporting Untrained Voices*

Vocal skills of users are limited, particularly when their voice is not trained. Our observations showed the necessity to provide such virtual augmentations in various scenarios. For instance, participants needed to produce random patterns to generate noise that would better match the tactile experiences, or to increase their frequency range at multiple occasion. A design tool should provide fine-tuning functionalities that one can use to compensate for imprecise vocalizations and provide computer-supported functionalities.

8.4.4 *Layered-based Approach*

Our analysis showed users sometimes needed to decouple their voice in several layers to reach a desired result. Combining different layered tracks, and adding various effects and setting unique properties, is a common concept in audio production software, and other vibrotactile design tools. Therefore, users should be able to iterate over a design, and stack various layers together to generate a complete experience.

8.5 CONCLUSION

In this chapter, we presented an investigation of the crossmodal relationship between tactile experiences and users' vocalizations. With the aim of understanding how novice hapticians express tactile sensations, and how this could support the haptic design process, we conducted an elicitation study. While interacting with a varying set of objects, we asked participants to vocalize their tactile sensations. From a thematic analysis of the recorded interviews, we derive different spatio-temporal mappings that were used by participants, and uncover challenges that need to be overcome to reach a successful expression. We further detail on four design implications that guide tools aiming to implement a vocalization design process for creating tactile experiences. These guidelines relate to the use of spatio-temporal mappings, the relationship between the interaction speed and users' vocalizations, the need for supporting users' untrained voices, and the requirement to provide a layered and incremental design process.

> *This is part of the weirding way that we will teach you.*
>
> — Paul Atreides, *Dune (1984)*

9

PROTOTYPING VIBROTACTILE FEEDBACK IN VIRTUAL REALITY

Building upon the results of the investigation of tactile vocalizations in the previous chapter, we further extend our investigation of this approach to VR. In this chapter, we use the insights gained, and present a design tool that allows designers to create tactile experiences in a rapid-prototyping method while immersed. This chapter addresses RQ3, and was previously published under the following publication.

Donald Degraen, Bruno Fruchard, Frederik Smolders, Emmanouil Potetsianakis, Seref Güngör, Antonio Krüger, and Jürgen Steimle (2021a). "Weirding Haptics: In-Situ Prototyping of Vibrotactile Feedback in Virtual Reality through Vocalization." In: *The 34th Annual ACM Symposium on User Interface Software and Technology.* UIST '21. Virtual Event, USA. DOI: 10.1145/3472749.3474797

9.1 INTRODUCTION

In this chapter, we contribute Weirding Haptics[1], a novel concept for in-situ rapid prototyping of vibrotactile feedback in VR environments. It combines fast and expressive vocalizations with the ease and directness of interaction with virtual objects, to offer a streamlined process for prototyping tactile experiences of virtual objects. Compared to existing approaches, using the voice enables designers to vocalize vibrotactile feedback

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[1] Inspired by the weirding module, an object controlled by vocalizing an intention, from the 1984 Dune movie — https://bit.ly/3T4tfAS

Figure 9.1: With the Weirding Haptics design tool, one can design vibrotactile feedback in a virtual environment using their voice. (a) A designer waves a lightsaber in the air while vocalizing the intended feedback. (b) A *vocalization layer* depicts properties of the tactile experience and allows for switching mappings as well as fine-tuning using modifiers (sliders) directly in VR. (c) While waving the lightsaber, the feedback can be felt with the controller.

while interacting with virtual objects inside VR (Figure 9.2). Moreover, designing with the voice does not require expert knowledge in haptic design.

Informed by the insights of Chapter 8, we contribute a VR design tool that enables in-situ fast-prototyping of vibrotactile experiences using vocalizations. Using this tool, one can synchronously vocalize the intended vibrotactile experience of a virtual object during in-situ interaction with objects in VR, see Figure 9.1a. After sampling frequency and amplitude, the design tool infers how to map these vocalizations to vibrations in space and time based on the designer's interactions. Moreover, the designer can control properties of the tactile experience through a *vocalization layer* inside the VR environment, see Figure 9.1b. With this layer, the designer can switch between different spatio-temporal mappings and fine-tune the experience in real-time using modifiers. Changes are immediate, meaning the designer can quickly experience the vibrotactile feedback and assess whether it matches their original intention, see Figure 9.1c. Several vocalization layers can be combined to stack different effects, e. g., background sensation with bursts overlaid, or enable quick comparison. To the best of our knowledge, this design tool is the first to support direct object interaction synchronized with vocalizations to design vibrotactile feedback in-situ.

Through a validation study involving a set of virtual objects, we demonstrate how Weirding Haptics, with only a short training period (~15 minutes), supports novice hapticians in designing experiences that match their intentions. Participants designed effective illusions of sand flowing or a rock tumbling inside wooden boxes, a slider providing resistance, surface textures with different roughness sensations, waving a lightsaber in the air, or the realistic sensation of opening and closing metallic and wooden drawers. The results of our study uncovered design implications concerning the in-situ design of vibrotactile feedback with the voice. Future tools must balance the level of fidelity designers require while supporting a fast-prototyping approach, and need to support high spatio-temporal resolutions for synchronizing vocalizations with the user's interactions. We discuss these challenges and conclude that using the voice to design tactile experiences in VR enables novice hapticians to create vibrotactile feedback for virtual objects aligned with their intentions.

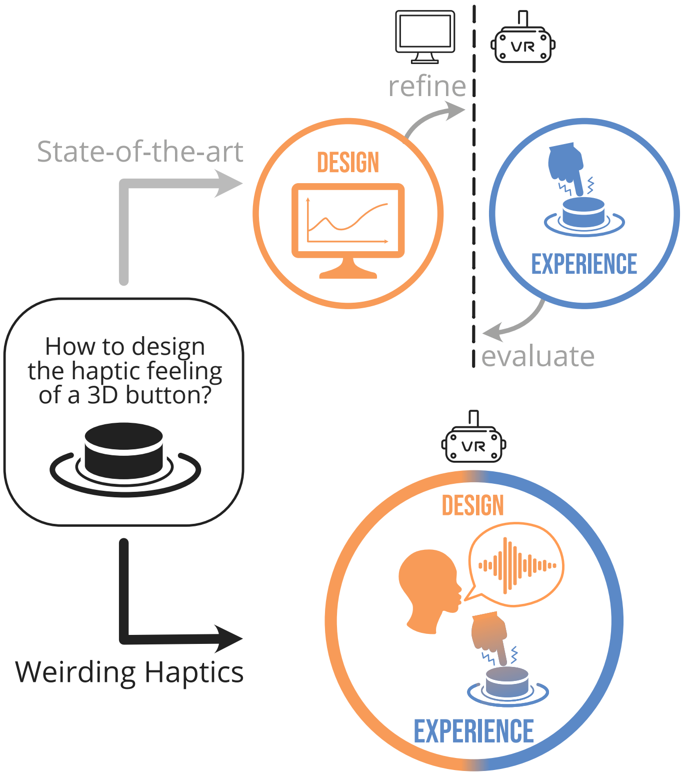

Figure 9.2: To design the tactile experience of a virtual 3D button, state-of-the-art design tools require designers to go back and forth between designing low-level parameters on a desktop computer and experiencing tactile feedback in VR. In contrast, Weirding Haptics enables designing *inside* the VR environment through vocalizations and supports fast-prototyping through a rapid iterative process.

9.2 DESIGNING VIBROTACTILE FEEDBACK IN VR

Based on the design implications presented in Chapter 8, we created the Weirding Haptics design tool, which transforms users' vocalizations into vibrotactile feedback inside a virtual environment. Designers can rapidly record vocalization while interacting with virtual objects inside VR and iterate over different designs quickly. To design effective vibrotactile feedback, the design tool takes an *in-situ design* approach based on direct manipulation methods, infers *spatio-temporal mappings* based on object interactions, and enables *fine-tuning* output from vocalizations through real-time *modifiers*, see Figure 9.3. The Weirding Haptics design tool is built on top of the Unity[2] game engine and is available online (Degraen and Fruchard, 2021). While we used the Oculus Quest 2 during development, we made our tool adaptable to various VR setups by building upon the SteamVR Unity plugin (Valve Corporation, 2022).

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[2] Unity Real-Time Development Platform — https://bit.ly/2uxjqBS

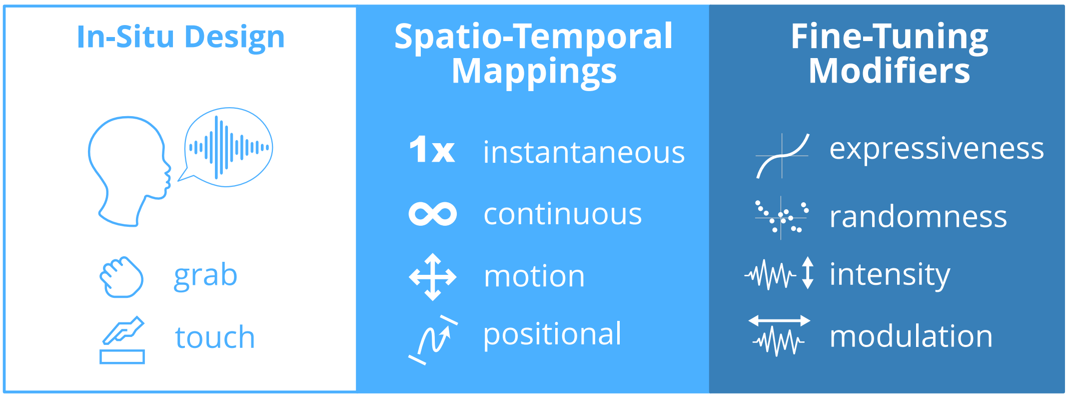

Figure 9.3: Core principles of the Weirding Haptics design tool. Through an in-situ design approach, designers can vocalize vibrotactile feedback while interacting with virtual objects in VR. The spatio-temporal mapping is inferred based on the movement magnitude and recording duration. To support rapid iterative design, vibrotactile feedback can be fine-tuned using modifiers.

9.2.1 *In-Situ Design Process*

Our aim is to enable the designer to easily and rapidly prototype expressive vibrotactile feedback for virtual object interactions. The design tool builds on vocalizations, i. e., audio signals produced by the user's voice, recorded while directly manipulating objects inside the virtual environment. From these recordings, we extract audio features, i. e., frequency and amplitude, map them to vibrotactile feedback, and enable the designer to control their processing during the playback pipeline.

To normalize the range of vibrotactile feedback everyone can produce, the design tool allows designers to calibrate their voice with two simple tasks to set the bounds of their vocal range in terms of amplitude and frequency. The tool only considers normalized features in the playback pipeline.

In the current version, we focus on the design of haptic feedback for interaction with single objects. To avoid conflicts between recording and experiencing vibrotactile feedback, we leverage a bi-manual interaction design, with the non-dominant hand controlling the context and the dominant hand interacting with objects (Guiard, 1987). The non-dominant hand is used to arm and possibly stop the recording process, while the dominant hand is used to perform interactions with objects inside the scene.

The recording process starts once the user has armed the recording and starts directly when manipulating an object. It ends as soon as the user stops interacting with the object, or releases the trigger used to arm the recording. The vocalization is automatically mapped to the respective object and interaction, and immediately visually depicted in the VR scene as a *vocalization layer*, see Figure 9.4. The designer can directly experience the vibrotactile output by again performing the interaction with the object. To support fast prototyping of vibrotactile designs, vocalizations can easily be added, removed and fine-tuned.

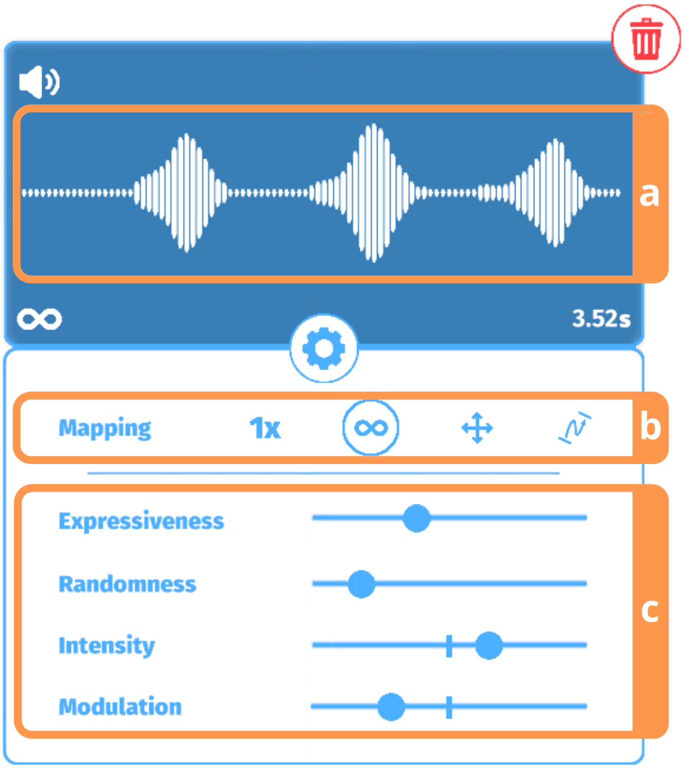

Figure 9.4: Graphical representation of a vocalization layer. (a) The *vocalization* is represented as a stylized waveform. (b) The designer can switch between different *spatio-temporal mappings* to try out different experiences, (c) or fine-tune the experience by manipulating the *modifiers* using sliders.

Multiple vocalization layers can be superimposed on an object, to create more complex vibrotactile feedback of multiple discrete vocalizations. For instance, a designer could design the continuous humming vibrations of a lightsaber as one layer, and more intense bursts when waving it as another. Superimposed layers are experienced synchronously during interaction by compounding them and playing the maximums of their amplitudes and frequencies. While recording new vocalizations, all vibrotactile feedback from already existing layers for the same object interactions can be felt to ensure alignment.

9.2.1.1 *Implementation*

Once a vocalization is recorded, the system will optionally timescale the vocalization, and pre-process the signal by sampling frequency and amplitude.

TIME-SCALING. In order to support vocalizations that are directly linked to positions in space, it is important to produce the correct vibrations at defined landmarks. As the speed of interaction when experiencing the feedback is unknown at the time of recording, we normalize the audio recording based on the recording speed. Therefore, for positional recordings, we record the user's hand position through time on a one-dimensional line

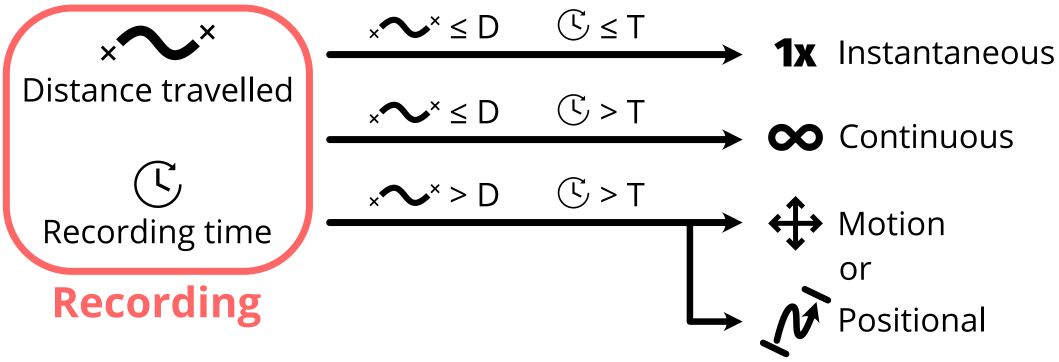

Figure 9.5: The design tool infers the spatio-temporal mapping of a vocalization directly after recording by considering the user's movement magnitude and the recording duration. D (0.5 m) and T (2.5 s) are empirically determined constants.

segment. Using this information, we apply a non-linear time-scaling algorithm using the python Rubber Band Library (Breakfast Quay, 2021). The time-scaling ensures signal features remain correctly aligned to the position at which they were recorded. This phase is only applied once for objects able to receive a positional mapping.

SAMPLING. As processing delays negatively influence the timeliness of the provided feedback, the system pre-processes recorded vocalizations to extract frequency and amplitude. For amplitude extraction, we first calculate the envelope of the signal[3] and sample the result in 50 ms intervals. Frequency extraction is done directly on the signal using a Yin pitch recognizer (Cheveigné and Kawahara, 2002) with 100 ms intervals. The interval for frequency sampling is longer than the interval of the amplitude sampling, as frequency sampling on shorter signals provides incorrect or no results.

9.2.2 *Spatio-Temporal Mappings*

Each vocalization layer is assigned a spatio-temporal mapping which defines how the signal is sequenced and repeated in relation to the interaction. Based on the insights gained from the pilot study, we distinguish between four different types of mappings, i.e., instantaneous, continuous, motion, and positional.

With an *instantaneous* mapping, the vocalization is experienced exactly once. This mapping supports, for example, designing the tactile experience of tapping on a surface or pressing a button. Using the *continuous* mapping, the layer is played repetitively as long as the user interacts with the object. This mapping supports, for example, constant humming vibrations produced by an active object like an electrical toothbrush. Similar to the continuous mapping, the *motion* mapping will keep iterating over the vocalization as long as the

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[3] We implemented the Shockley diode algorithm used in the audio_dspy python library: https://bit.ly/3SArR9i

user is interacting with the object, such as moving while grabbing or touching the object. In this case, however, we multiply the vocalization amplitude and frequency by the designer's movement velocity. As a consequence, the designer will not feel the vocalization when idling, while the intensity will increase with speed. This mapping supports, for example, exploring surface textures or particles moving inside a container. The *positional* mapping is used to map parts of the vocalization at given spatial positions. This mapping supports, for example, interacting with a drawer that provides various resistance throughout its path or when opening a door that creaks at given landmarks.

9.2.2.1 *Implementation*

After recording a vocalization, the spatio-temporal mapping is inferred based on the user's movement magnitude while manipulating the object as well as the recording duration. We assess the movement magnitude based on the SteamVR Unity plugin's controller velocity for free movement and angular velocity for rotational interaction. Our current implementation infers the mapping based on two thresholds established during informal testing of the system: $D = 0.5\,\mathrm{m}$ for the magnitude, and $T = 2.5\,\mathrm{s}$ for the duration, see Figure 9.5. Of note, our concept is not limited to this approach and compatible with future, more advanced algorithms for automatically inferring the mapping.

When interacting with the object, the features of the recorded signal are extracted during the sampling phase. Based on the spatio-temporal mapping assigned to the vocalization layer, the sampling location within the signal is determined. For all the mappings excluding the positional one, the system samples the signal based on time. For the positional mapping, the system samples the signal based on the current position of the user's hand on a line segment. This limitation was chosen to lower the complexity of the mapping between the recorded signal and the generated output. Our framework easily allows us to extend the positional mapping to any segment in 3D space. Once the sampling interval within the signal is determined, we get the amplitude (A_{raw}) and frequency (F_{raw}) for the current interval. We then normalize the vocalization features in real-time based on the designer's calibration. Once the features are normalized, we obtain A_{norm} and F_{norm}.

9.2.3 *Rapid Iterations with Fine-Tuning Modifiers*

Enabling fine-tuning of vocalization layers is crucial in our approach: it allows tweaking subtle parameters of the vibrotactile feedback that would be hard to control with the voice, supports designers with computer-generated modifications, and supports untrained designers' voices. We propose modifiers for simple and direct fine-tuning of a vibrotactile experience, by adjusting sliders on the vocalization layer, see Figure 9.4c and Figure 9.6. When modifying the vibrotactile feedback with one of the modifiers, it is updated in real-time such that the designer can directly feel the changes.

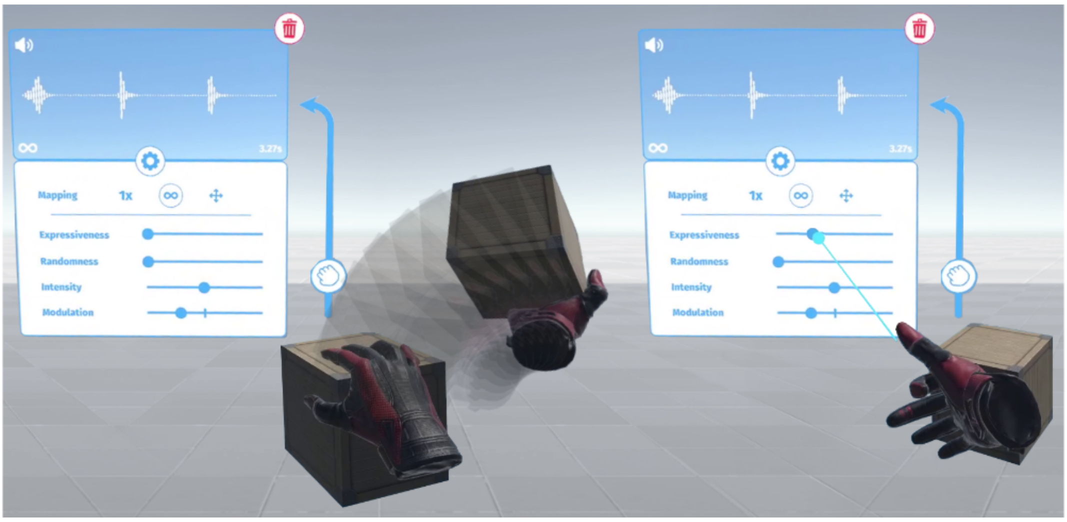

Figure 9.6: The designer can interact with the object to evaluate a vibrotactile feedback (left), and leverage the rapid prototyping cycle provided by the system to fine-tune it (right).

The design tool proposes an *intensity* and *modulation* modifier, respectively modifying the amplitude and frequency of the vocalization. The former is particularly useful to amplify or dampen a vocalization when it does not match the initial intention of the designer, or to balance several vocalization layers. The latter is useful to change how the vibrotactile feedback can be perceived, as shown by previous work (Obrist et al., 2013).

In the pilot study, some participants remarked they would like to create random patterns for certain tactile experiences they could not produce directly with their voice. Previous work showed the interest of such patterns when generating virtual material to "evoke natural experiences" (Strohmeier et al., 2020), as well as when designing robotic movements to create more natural behaviors (Marino et al., 2017). Therefore, the design tool proposes a *randomness* modifier to introduce noise in the feedback.

Lastly, the system provides an *expressiveness* modifier that enables contrasting peaks in the signal. Based on the pilot study, we noted participants repeating certain onomatopoeia, e.g., saying “tick”, to describe singular bursts in the tactile sensation. Such bursts can be smoothed out based on the vocalization rhythm and the tool frame rate, thus the expressiveness modifier enables designers to control their attack and intensity directly, whereas boosting up the intensity would uniformly change the vocalization.

9.2.3.1 *Implementation*

Each modifier controls a given variable (E for expressiveness, R for randomness, I for intensity, and M for modulation) that has a unique impact on the output signal. We detail how we take into account these variables in the following, along with explanations about how the vocalization-to-vibration algorithm iterates for each update cycle (50ms update rate), see Figure 9.7.

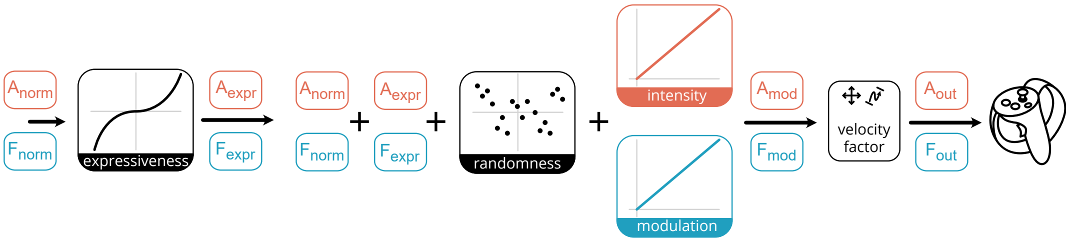

Figure 9.7: The playback pipeline. Based on the normalized samples produced by the mapping used, we first compute the *expressiveness*, then add the *randomness*, and later apply the *intensity* and *modulation* respectively. The resulting features are multiplied by the relative velocity of the user's movement for motion or positional mappings.

MODIFIERS. We first apply the *expressiveness* modifier. It builds on a sigmoid function using the normalized features to contrast peaks in the vocalizations:

$$A_{\text{expr}} = A_{\text{norm}} \times \left(\frac{2}{1 + e^{-E(A_{\text{norm}} - A_{\text{median}})}} - 1 \right) \times e,$$

for

$$E \in]0, 10],$$

where

e	is an empirically informed constant;
A	the amplitude of the current vocalization;
A_{norm}	the normalized amplitude;
A_{median}	the median between the minimum and maximum amplitude.

We apply the same procedure for the frequency. Both the amplitude and frequency results are added to the normalized features. We then add the *randomness* modifier, i.e., we add a random value $R \times r$ with $R \in [0, 1]$ and $r \in [-0.5, 0.5]$. As a last step, we add the intensity value $I \in [0; 1]$ to the amplitude, and the modulation value $M \in [0; 1]$ to the frequency.

VELOCITY FACTOR. For motion and positional mappings, once all modifiers have been applied to the amplitude and frequency values, we multiply the ratio between the velocity of the user's action and the average recording velocity with A_{mod} and F_{mod}.

After all the processing stages, the amplitude (A_{out}) and frequency (F_{out}) values are ready to be sent to the controller for actuation.

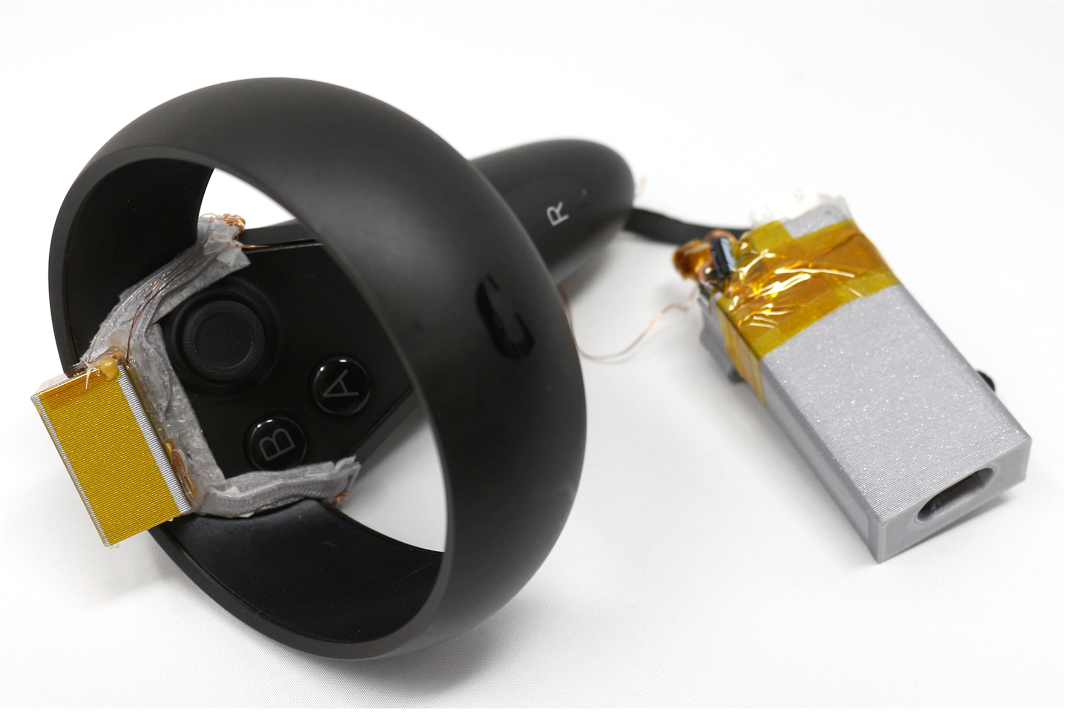

Figure 9.8: The custom actuator attached to the standard Oculus controller to enable direct parameterization of a vibrotactile signal's amplitude and frequency.

9.2.4 *Haptic Output*

Varying both frequency and amplitude is essential to build a large gamut of tactile experiences (Obrist et al., 2013; Strohmeier et al., 2018, 2020). While the SteamVR plugin proposes to input both frequency and amplitude to control VR controller vibrations, it seems to not correctly control these two variables for all commodity controllers. To verify this, we performed hardware tests by placing an IMU on the Oculus controller and swiping through frequencies using the same amplitude, which confirmed changing frequencies to have no effect. To tackle this issue, we devised two possible solutions. Firstly, for commodity controllers with frequency limitations, we compound the F_{out} result as a factor to the A_{out},

$$A_{out} = A_{out} + (F_{out} \times 2 - 1) \times f,$$

where

$f = 0.25$ is an empirically informed constant.

This method compensates for the limitations by varying vibrations based on frequency modulation.

Secondly, to avoid restraining our vocalization approach with a low-resolution output, we built an alternative hardware setup for more advanced vibrotactile rendering that can be attached to the VR controller. We use a similar actuator (AFT14A903A) as the one found in

Oculus Touch controllers[4]. To compensate for natural resonant frequencies inherent to such a device, we normalize the amplitude response of frequencies between 150 Hz to 300 Hz to produce a 1G output approximation. We chose this frequency range as Pacinian cells are most sensitive to ranges around 220 Hz (Obrist et al., 2013; Strohmeier et al., 2020; Strohmeier and Hornbæk, 2017; Verrillo, 1966), but the design tool can adapt to any kind of frequency range as it solely deals with relative values. The final device is controlled by an ESP32-DevKitC V4 microcontroller board, connected via USB. The input frequency, amplitude and duration values sent by the host are used to create fitting sine waves to avoid artifacts created by switching frequencies too abruptly. A digital potentiometer (AD5280BRUZ50) applies the amplitude to the signal, and a Class D amplifier (PAM8403) amplifies the result for playback by the actuator. We attach this *custom* actuator on the Oculus controller and directly use the A_{out} and F_{out} values for vibrotactile actuation, see Figure 9.8.

9.3 STUDY

We conducted a user study with novice hapticians in which they designed vibrotactile sensations inside VR using their voice. The focus of this study was to assess the usability of the Weirding Haptics concept and design tool, and better understand the research challenges related to in-situ design of haptic feedback. We used a think-aloud process with open-ended tasks. Ethical approval for this study was obtained from the Ethical Review Board of the Department of Computer Sciences at Saarland University (No. 21-03-9).

9.3.1 *Apparatus*

To provide participants with a varying and attractive virtual environment, we created a scene with 6 different types of objects, see Figure 9.9. These objects were partly inspired from the pilot study, leveraged various types of interactions, and provided different appearances, thus could convey various properties such as roughness, weight, or uniformity. Three surface textures and two walls were stationary and allowed the user to design vibrotactile feedback to touch events. Two sliders with different designs and two drawers of varying materials invited participants to design positional mappings. Lastly, three boxes of different sizes and two types of swords supported vibrotactile feedback for touch interaction or for moving them. Vibrotactile feedback was first provided with the native actuators of the Oculus Quest 2 controllers, followed by the custom actuator. This comparison aimed to understand the effect of high-resolution frequencies on the vocalization design process.

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[4] iFixit Nintendo Switch Teardown — https://bit.ly/3E8Flo4

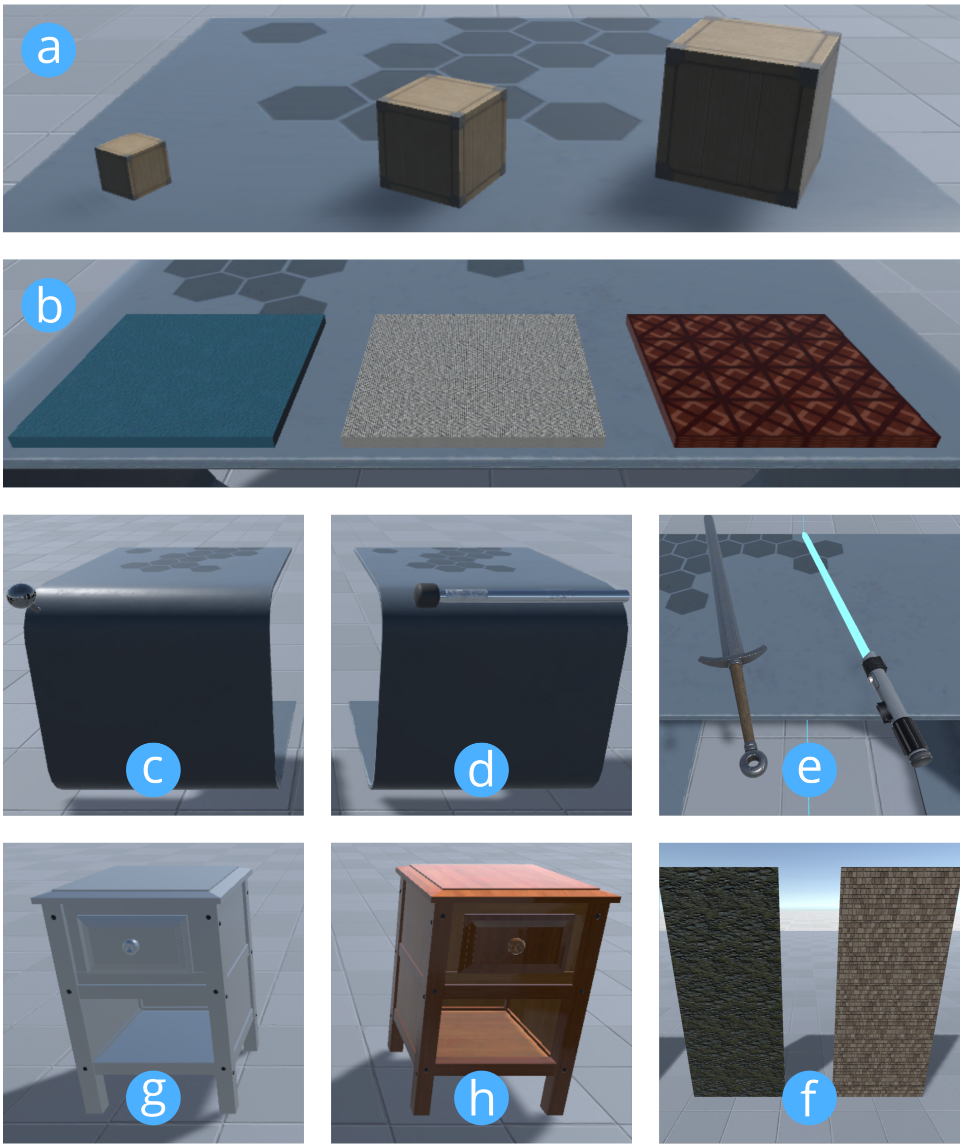

Figure 9.9: Virtual objects used in the study to inspire participants to design vibrotactile feedback: (a) boxes of different sizes, (b) surface textures, (c) slider, (d) slider with textures on sliding rod, (e) medieval sword and lightsaber, (f) textured walls, and (g) metallic and (h) wooden drawers.

9.3.2 *Participants*

We recruited a total of 8 novice hapticians (4 identified as male, 4 identified as female) aged between 23 and 33 (avg. 27) with backgrounds in Computer Science, Media, Microbiology and Linguistics. Three of these participants had participated in the pilot study, while 5 where newly recruited[5]. One participant indicated to regularly use VR for work purposes, 4 participants indicated to have experienced VR a few times, 1 participant indicated to have experienced VR only once, while 2 participants did not have any VR experience at all. All participants indicated to be novices in the field of haptic design. All participants provided consent to record both video and audio during their session.

9.3.3 *Procedure*

Before starting the experiment, participants were explained the concept of designing haptics through vocalizations. Using an example of a vocalization layer, see Figure 9.4, we explained the procedure of creating, experiencing, fine-tuning and deleting layers. After this introduction, participants were asked to attach a clip-on microphone and enter the virtual environment by putting on the Oculus Quest 2 HMD.

Once inside the virtual environment, a training scene was loaded. Here, participants calibrated the framework to their vocal range. We then introduced participants to the controls and guided them in creating a vibrotactile design for touching a surface and for grabbing a box. As soon as participants felt they could control the system efficiently, the next scene was loaded. On average, this training task lasted around 14 minutes ($\sigma = 2\,\text{min}$).

The study scene consisted of all the objects depicted in Figure 9.9. We asked participants to vocalize haptic experiences for these objects in a given sequence. To help them to get inspired, we started the tasks with the three boxes and gave specific instructions for each of them: we tasked participants to create the illusion of sand flowing, pebbles moving, or a rock tumbling inside the small, medium, and large box respectively. For the other objects, they were free to interact with each object as they saw fit and were allowed to create, fine-tune and delete as many experiences as they wanted. Their initial designs were first experienced with the native controller actuators for each object. Once they were satisfied with the result, participants were asked to rate their creations based on their *initial vocalization intention* on a 7-point scale, where 1 meant "not as intended", and 7 meant a "perfect fit". If something was not aligned with how they wanted it to be, participants were asked to elaborate on which aspects of the resulting experience felt close or near to their intentions. After each rating, the haptic output was provided using the custom actuator. Here, participants were able to experience their designs again and were free to fine-tune or

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[5] This partial overlap was caused by the difficulties of recruiting participants during the COVID-19 pandemic. Due to the time in-between both studies (2 months) and their difference in nature, we did not find a reason for this to bias participants' performance.

even re-design the experience if necessary. Again, they were asked to rate and elaborate on the experience based on their intention. After completing the experiment, participants filled out a demographics form, and were asked about their experience of designing vibrotactile feedback using vocalizations.

On average, the study lasted 84 min (σ=14) and breaks were issued at the halfway point, or upon request by the participant.

9.4 RESULTS

After the experiment, the video recordings and remarks provided by participants were analyzed. Based on our observations, we assess the usability of our approach, reflect on the impact of the Weirding Haptics core principles on the tactile experiences created, and discuss the limitations of our current approach for designing vibrotactile feedback in VR.

9.4.1 *In-Situ Design of Vibrotactile Feedback*

After a relatively short training session, all participants were able to design and fine-tune vibrotactile experiences regardless of their previous experience with VR. On average, the designed feedback was indicated to be close to their intention ($\bar{x} = 5.49$), see Figure 9.10. The highest average rating was given for feedback designed for the lightsaber ($\bar{x} = 6.25$), followed closely by the textured slider ($\bar{x} = 6.13$), the illusion of a rock inside the large box ($\bar{x} = 6.13$), and opening or closing the wooden drawer ($\bar{x} = 6.06$). The lowest ratings were given to the designed feedback of touching the right wall ($\bar{x} = 4.63$), and the right texture ($\bar{x} = 4.21$). Participants commented that the initial experience felt "*surprisingly good*" (P3) and rated their overall experience positively (P4: "*it was fun*"; P8: "*it's really cool, it's fun*"). Interestingly, we observed participants being sometimes satisfied by the result of a vocalization on the very first iteration, i.e., recording one vocalization that would instantly match their intention, see Figure 9.11b. This indicates novice hapticians can produce vocalizations that are accurate enough to match their intention using an in-situ design approach.

On average, participants used 1.11 layers ($\sigma = 0.37$) for each tactile experience. Most of the designed tactile experiences consisted of a single vocalization layer (81.21%), while the use of 2 (6.84%) or even 3 layers (1.71%) was infrequent. While some participants intuitively used this feature to enhance experiences, others needed to be reminded of its availability, or we had to explain to them how a certain effect they described could be implemented using this feature. Designs using multiple layers were mostly aimed at adding more detail to a signal. Additionally, by using layers, participants were able to separately design individual features of the tactile experience. For example, while looking at the lightsaber, P3 said "*OK, I'm going to do two layers*" and proceeded to create two layers with two different mappings, one for the background humming and another for the waving interactions, see Figure 9.11a.

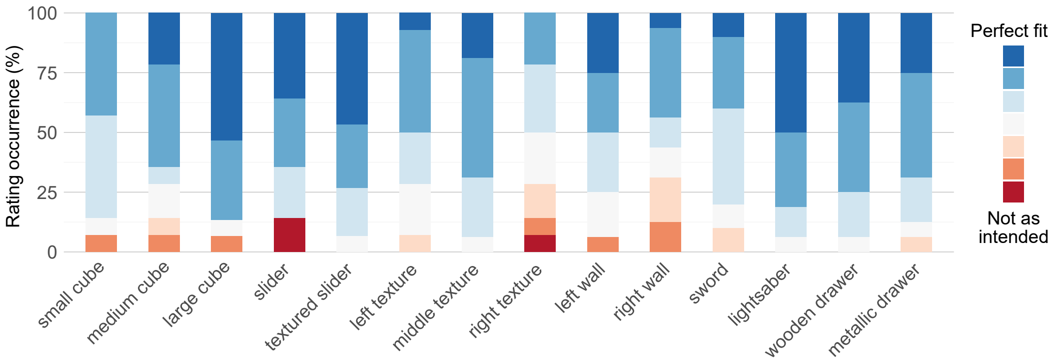


Figure 9.10: Occurrences of the participants' ratings for each object used in the validation study.

9.4.2 *Spatio-Temporal Mappings Usage*

From the created designs, we saw that both the *motion* and *positional* mappings were most commonly used, respectively 63 (50%) and 34 times (27%), while the *instantaneous* and *continuous* mapping were less common, respectively 17 (13%) and 13 times (10%). This underlines the relevance of mapping vibrotactile feedback to spatial and temporal interactions in the VR environment. Figure 9.11a shows an interesting example of a participant leveraging two layers to produce an experience combining *continuous* and *motion* mappings. Figure 9.11c depicts an example where a participant designed vibrotactile actuation for opening a metallic drawer. As noted by the participant, it was important to have a smooth experience that would provide an intense "boom" when the drawer reached the end. While the mappings available in the design tool enabled participants to create various experiences, participants were sometimes missing added temporal or spatial resolution. For instance, in our design tool vocalizations start as soon as the user starts interacting, however, this was not always matching the user's intention (P1: "*the sword, for instance, I had some vibrations when I was taking it, but not when I was putting [it] back on the table*"). Also, some participants wanted to have more degrees of freedom on the action performed. For instance, one participant wanted to trigger different vocalizations based on the direction of the movement while stroking a texture (P4: "*one [vocalization] I'd like to have when I move to the right, and one [vocalization] when I move to the left*") and another wanted to feel sand moving inside the box only when rotating it, but not when translating it (P8: "*I would have found it cooler to use the rotation as the playback [...] now it does not really matter how you move it, since I am moving it will produce this [output]*").

9.4.3 *Relevance of the Fine-tuning Modifiers*

Generally, participants felt more inclined to alter the experience with modifiers than to re-record their vocalization, as explained by P2: "*for me, it's better to adjust the first recording than to record over and over again*". We observed participants manipulating modifiers

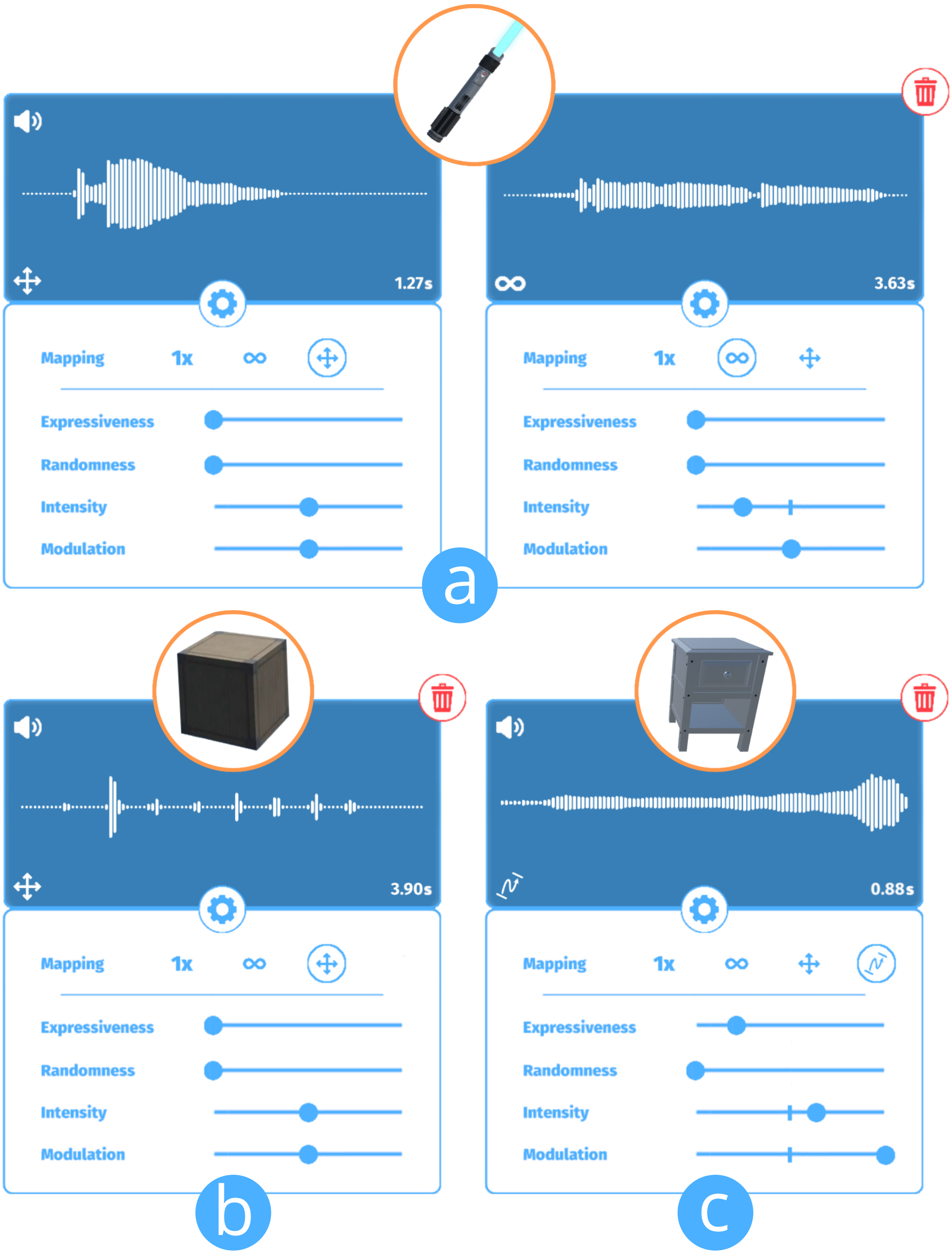


Figure 9.11: Examples of vibrotactile experiences designed by the participants during the study: (a) two layers with different mappings for isolating tactile experiences of a lightsaber, (b) the illusion of pebbles inside a box when shaking, (c) emphasis on end of movement with positional mapping when interacting with a drawer. More examples can be found in Section c.1.

extensively to refine a vocalization layer for better matching their intentions. Out of 117 effective vocalization layers, only 19 (16%) were left with modifiers untouched, which indicates the importance of the fine-tuning phase. *Expressiveness* was used 58 times (50%) and helped, for example, to make the rock illusion more convincing (P1: "*[expressiveness] makes the rock feel bigger*"). *Randomness* was used 28 times (24%) and helped, for example, to create more sand grains in the small box (P7: "*[randomness] helps to make [the objects inside] feel less dense.*", or make a surface rougher (P6: "*Randomness [...] makes [the slider] rougher.*"). *Intensity* was used often (66 times, 56%) to amplify a vocalization, and sometimes to balance various layers. However, *modulation* was used less (25 times, 21%) as its effect only slightly impacted the experience using the commodity controller. When using the custom actuator, *modulation* was used more often to fine-tune experiences, as here the effect was clearly noticeable. Overall, these results indicate fine-tuning modifiers are essentials to design vibrotactile feedback in-situ through vocalizations. However, several participants wished a more pronounced visual feedback on the effect of modifiers, as part of the waveform representing the vocalization.

While Weirding Haptics promotes direct manipulation and rapid prototyping through a quick vocalization process rather than through extensive post-processing functionalities, participants pointed out an important trade-off in the design process: they were missing audio processing functionalities. For example, they wanted to *trim* or *dampen* part of the vocalization to better control the timing of the vocalization or to fine-tune it (P2: "*can I somehow delete one part of the audio, because [then the experience] would be perfect*', P5: "*It would be very good if I can directly edit this [waveform]. [...] I would like to remove this part*"). Several participants wanted to apply the *modifiers* to certain parts rather than the entire vocalization (P2: "*I would like to [apply] intensity only on this part of the audio, but if I adjust the intensity, everything will change*"). Some participants wondered whether they could speed up or down the vocalization they recorded to better match the movements performed in the playback phase (P8: "*can I speed it up? That would be great*").

9.4.4 *Output Modalities*

To understand the effect of high-resolution frequencies on the vocalization design process, participants were asked to rate all experiences using both *native* and *custom* actuators. On average, the former was rated lower than the latter (native actuator: $\bar{x} = 5.25$; custom actuator: $\bar{x} = 5.75$; Mann-Whitney test: $p < 0.01, r = 0.361$ - moderate effect). Participants found the custom actuator could "*bring out the details*" (P1) of the experience and made objects feel lighter or heavier (P6: "*it feels heavier, and it makes it more realistic kind of*"; P8: "*feels much more heavy, much more deep, and way too strong*"). Outputting frequencies could also produce better precision (P7: "*it feels like a smoother experience, like I am pulling the drawer more easily*"; P8: "*it's more refined, there is more difference in the signal*"), or increase the randomness or sharpness of the experience (P3: "*feels more random*"). Additionally, frequencies produced rougher (P7: "*it feels better, it feels rougher*") and stickier sensations (P8: "*it feels like it's slightly sticky [...] that's actually not what I wanted, but feels pretty cool*").

However, sometimes the *custom* actuator produced worse experiences. Some participants remarked it could introduce a sense of delay (P3: "*weird, it feels delayed*"; P6: "*it feels more off, it does not really react to my movements*") or dampen vibrations to the extent of canceling out important bits of a vocalization (P3: "*it feels like there is a dip [...] like you're not doing anything*"). While producing sharper experiences made some of the experiences more convincing, it could also feel off in certain cases (P5: "*I think you made it even more random and also sharper, but in this case, it should not be sharper*"; P7: "*it does not feel as smooth*"). Similarly, while frequencies induced weight, it sometimes did not align with the intention of the participant (P4: "*it feels a bit softer, that's not how I imagine it would feel*"; P8: "*too deep kind of*").

9.5 DISCUSSION

Here, we discuss lessons learned through the implementation of our design tool and observations from our studies. We reflect on Weirding Haptics' efficiency to rapidly design vibrotactile feedback using the voice, as well as limitations highlighted during design. Furthermore, we formulate important design implications uncovered by the results of our initial validation study for in-situ fast-prototyping of vibrotactile feedback.

IN-SITU DESIGN OF VIBROTACTILE FEEDBACK Our validation study results show that novice hapticians can use their voice to design a variety of tactile experiences that match their intention, after only a short training period (~15min). They quickly grasped how to control vibrotactile feedback through vocalizations, and how to interact with virtual objects to map these vocalizations to actions in the VR environment using spatio-temporal mappings. While users have created interesting tactile experiences only with their voice, they fine-tuned most (84%) of the vocalizations with the set of modifiers proposed by our design tool. This highlights the importance of the refinement phase in the design process. Furthermore, while we offered a multi-layered vocalization approach, in most cases (81.20%) a single vocalization layer was sufficient to reach the user's goals.

HIGH-RESOLUTION SPATIO-TEMPORAL MAPPINGS While the number and type of virtual objects used in our study might have constrained the mappings used, all available spatio-temporal mappings were used during the study. The limitation placed on the positional mapping to be constrained to a line segment was not mentioned as an issue by participants. As the visual mapping corresponded to the vibrational mapping, the interaction was similar to how real-world interactions are constrained, e.g., when opening a door using its handle the same path is traversed each time. Future versions of our framework could extend the positional mapping's functionality to consider any segment in 3D space.

Some participants were observed using multiple mappings for a single interaction by leveraging multiple vocalization layers. While participants created convincing tactile experiences with these mappings, they sometimes remarked missing some degree-of-freedom to map their vocalizations to visuo-spatial features or specific actions. For example, some participants wanted to map vibrotactile feedback to visuo-spatial features of a texture (e.g., holes between bricks in a wall), or trigger vibrotactile feedback based on the direction or type of their movements (rotational vs. translational). While such features can be supported by analyzing users' movements in more depth, high resolution spatial alignments remain a challenge. To tackle this, one could identify the correct part of the vocalization, and interpolate the feedback between landmarks of the same object. Our framework is compatible with more advanced mapping schemes, as extensions can easily be incorporated.

TRADE-OFF IN THE FIDELITY LEVEL WHILE FINE-TUNING Our studies highlighted the importance of the fine-tuning process while designing vibrotactile feedback, as also indicated in previous work (Seifi et al., 2014). With fine-tuning modifiers, our design tool supports rapid iterations for low- and medium-fidelity prototyping. Nevertheless, participants required a finer control of the vocalization audio processing. A recurring request was to provide tools to *trim* the audio signal to compensate for delays and support better timing of the vocalizations, as well as *edit* (with the modifiers or other functionalities) parts of the audio to preserve satisfactory ones. This underlines a limitation in the timeliness aspect of our design tool, as well as a trade-off between the fast-prototyping approach supported by our tool and the relatively high-fidelity control participants aimed to have. While we expected users to re-record mistimed vocalizations, they seemed to be willing to spend more time fine-tuning features of their recordings. Future work will need to investigate the inclusion of higher-fidelity editing features with the ease and directness of in-situ design.

GENERALIZABILITY OF WEIRDING HAPTICS With Weirding Haptics, a vocalization is strongly bound to the object interactions performed while recording. A drawback of this principle is that in order to experience exactly the same experience, one might need to execute exactly the same action (e.g., waving an object using the same timing). Generalizing object interactions to match several interactive scenarios remains a major challenge. To achieve this, a designer's object interactions and vocalizations need to be considered in depth.

Furthermore, the Weirding Haptics design tool only considers single-object manipulation. Yet, many haptic experiences felt in the physical world involve several objects interacting together (e.g., sliding a cup of coffee on a table). Enabling free design of multi-object interactions is not obvious to design tools centered on non-expert users. Open challenges relate to how vocalization layers are assigned in this case, and how to manipulate them.

ACTUATOR'S OUTPUT RESOLUTION. We compared two levels of resolution with two actuators. While we observed higher resolution output to produce more accurate experiences with respect to users' expectations, we constrained users to design with the low resolution actuator. Future work should investigate differences in design strategies depending on the degrees-of-freedom.

9.6 CONCLUSION

We presented Weirding Haptics, a novel concept for in-situ rapid prototyping of vibrotactile feedback in VR environments. Designing such feedback in-situ enables designers to synchronize vocalizations and object interactions using automatically inferred spatio-temporal mappings. Moreover, to provide a rapid design cycle inside VR, we identified fine-tuning modifiers to refine vibrotactile feedback and compensate for vocal limitations. Based on these insights, we presented a VR design tool implementing Weirding Haptics. Through a validation study, we tasked novice hapticians to freely design a set of haptic experiences for several virtual objects. The study results show that Weirding Haptics enables designing vibrotactile feedback that matches the designer's expectations, after only a short training time. Our observations uncovered important research challenges for the design of haptic experiences in-situ.

Part IV

CONCLUSION

Everything you need to know you have learned through your journey.

— Paulo Coelho, *The Alchemist*

10

GENERAL CONCLUSION

In the final chapter, we conclude this dissertation. Firstly, we provide a summary of our work aimed at understanding and improving the design of tactile experiences for virtual environments. Next, we frame and outline the major contributions made in terms of the research questions posed in Chapter 1. With an eye towards the future, we underline the limitations of our approach and describe potential future work.

10.1 SUMMARY AND CONTRIBUTIONS

In this work, we investigated the design of tactile experiences for immersive virtual environments (IVEs). Our main question, guiding this work, inquired how our understanding of real-world touch experiences could enhance the design of effective tactile feedback. To contribute to this, we looked towards the research fields of human-computer interaction (HCI), haptic design, fabrication, haptics, and virtual reality (VR). Our methods considered a wide range of approaches, including prototyping, and procedural and computational design, and relied on investigation and validation through user studies, such as semi-structured interviews, and laboratory studies. To derive answers and insights, we used statistical methods for hypothesis testing, statistical analysis for dataset visualization and investigation, and qualitative research approaches, such as thematic analysis (Braun and Clarke, 2006).

Our work is motivated by the importance of haptic feedback for virtual experiences. As VR technology is finding itself into our everyday lives, the user's experience of the virtually generated world highly depends on convincing and plausible stimulation of different senses.

Without appropriate haptic feedback, the illusion of virtual objects breaks as users grasp for thin air. In turn, this negatively affects the user's sense of presence, which has detrimental effects on the effectiveness of the virtual experience. While the necessity of haptic feedback is well understood, designing for the sense of touch remains challenging. As haptic experiences are inherently personal and private, they are difficult to capture and share. Additionally, haptic media is poorly understood and highly novel to most designers, while lacking a set of basic building blocks to design from. From these insights, we formulated the main question guiding our work, and considered different perspectives which we used to pose our research questions. The main research question is as follows.

> **How can we utilize our understanding of real-world touch experiences to enhance the design of tactile feedback for immersive virtual environments?**

To provide the necessary foundation, we build our work upon a broad range of background and related work. Our investigation started out by framing the human aspects of perception in Chapter 2. With a focus on haptic perception, we noted that touch sensations arise from mechanoreceptors innervated in our skin, muscles, and tendons. We particularly saw that tactile perception consists of different dimensions, i. e., (macro and micro) roughness, hardness, warmness, and friction, which are investigated using different exploratory procedures. However, the sense of touch presents a multi-modal challenge, as perceptual processes integrate different sensory modalities to create robust internal representations. To understand how these sensations can be investigated, we outlined the field of psychophysical investigation. These elements underlined the complexity of designing and evaluating haptic experiences, specifically in terms of texture and material perception.

In Chapter 3, we investigated the history of VR and provided an overview of ongoing research. Our investigation uncovered the importance of the user's sense of presence to provide convincing and plausible experiences, and underlined that effective and appropriate haptic feedback is an essential aspect. Furthermore, we provided an overview of previous work which has explored a plethora of approaches for simulating different haptic experiences. Whereas active haptic feedback (AHF) involves the use of haptic interfaces that mechanically adjust their internal actuators in order to simulate the appropriate haptic feedback to the user, passive haptic feedback (PHF) relies on passive objects, or props, to serve as physical proxy objects, or proxies, for virtual representations. Additionally, mixed approaches, such as dynamic passive haptic feedback (DPHF), or substitutional reality, take advantage of both worlds to stimulate the user's tactile senses. While these methods allow users to engage in convincing tactile experiences, such as the perception of different shapes, textures, and materials, each approach has their own drawbacks and caveats. Moreover, there is still no generalizable and scalable method for simulating detailed and realistic surface texture perceptions, such as the perception of roughness or hardness, for tactile exploration in VR.

Lastly, we considered the field of haptic design to understand how haptic experiences are built, and why this remains challenging. We noted that this field is establishing itself by investigating universal and sustainable design practices that build upon other areas, such as user experience design. From a technological perspective, we noted that different haptic technologies afford highly different approaches. In the field of active haptic experiences, design approaches have evolved from relying on low-level signal parameters, such as frequency and amplitude, to providing different conceptualizations of haptic sensations for creating more understandable haptic effects. Meanwhile, in the field of passive haptic experiences, recent advancements in fabrication technologies have been used to produce rich and fine-grained tactile structures. However, both technologies are burdened by the difficulty of transferring design parameters to generalizable and scalable haptic effects, specifically in the context of VRs. To bridge the gap between the process of haptic design and the experience of the end-user, computational design approaches model physical experiences, while haptic reproduction methods aim at reproducing real world impressions, and perceptual modeling techniques have been used to build an understanding of a user's sense of touch in relation to physical design variations.

In our work, we aimed to enhance the design of tactile experiences for visuo-haptic exploration. We proposed different methods to support the haptic design process in creating feedback that provides users with realistic impressions aligned to the designer's intention. Specifically, we investigated haptic reproduction through capturing and fabricating surface microgeometry, procedural haptic design by generating and fabricating haptically-varying surface structures, and crossmodal correspondence by translating designers' vocalizations into vibrotactile actuation.

10.1.1 *Major Contributions to RQ1*

With RQ1, we looked towards the reproduction of real-world haptics to enhance the design of tactile experiences. The idea behind this follows the notion that designers are already, or could easily get, intimately familiar with their physical surroundings. By taking inspiration from the real world, and reproducing such experiences, the process of haptic design can be guided by designers' personal haptic impressions.

> **RQ1:** How can reproduction of real-world haptics enhance the design of tactile experiences for IVEs?
>
> - Haptic reproduction of physical surface information supports the design of a wide gamut of *feel* aesthetics.
> - Visuo-haptic combinations of virtual textures and physical replicas are able to build material perception in VR.
> - Using vocalizations, designers are able to reproduce tactile impressions to design vibrotactile feedback during object interaction in VR.

We firstly looked towards haptic reproduction, i. e., the direct replication of physical information to serve tactile experiences. To this aim, we built upon an existing method for capturing a surface's microgeometry, and reconstructed the stable surface information of a set of 15 textures from a texture sample book. Fabric sample books often contain different texture samples consisting of identical material and texture properties, but with varying visual appearances. With our digitization process, we abstract the visual information of our set of textures from their haptic characteristics.

In Chapter 5, we investigated this approach by studying which tactile information is reproduced through additive manufacturing. From the evaluation of the replicas compared to the original surfaces, we saw that that direct reproduction of a material's surface can approximate the perceived geometry of some materials, but it was not sufficient to consistently mimic their haptic impression. However, both in terms of perceptual features, such as roughness, and material perceptions, our digital reproductions show a great variation only through alterations of their surface construction. Therefore, our approach supports a wide gamut of *feel* aesthetics. We further investigated the shift that occurred after replication, and discovered that the change in perception of the reproduced samples was not stochastic, but rather followed a uniform transformation. To find this transformation, we conducted a magnitude estimation study, and recovered a perceptual space of our samples, which we correlated with measurable physical attributes. We leveraged our perceptual space to formulate direct strategies that can be applied to the digital designs to better resemble the haptic sensations of the original materials. The technique we proposed directly benefits fabrication methods of haptic features, and provides insights for the field of haptic design by supporting hapticians in creating versatile haptic experiences through capturing real-world information for fabrication processes.

In Chapter 6, we further examined our set of replicas and investigated how the captured physical information can be combined with visual information using VR. From the results of a user study where we presented participants with physical replicas overlaid with different visual variations, we saw that perceptual discrepancies showed haptic dominance in most cases. Interestingly, in terms of material perception, the visuo-haptic combinations were interpreted in a wide gamut. This underlined that reproduced physical structures using a uniform material, i. e., plastic, can be combined with visual information to build material and texture perception in virtual settings.

Furthermore, we contributed to RQ1 by investigating reproduction of tactile experiences using vocalizations. Here, the idea is to enable designers to express the tactile experiences they aim to design, such that the replication process of haptic experiences is done by the designers themselves. Specifically, we contributed a design tool called Weirding Haptics in Chapter 9 which allows designers to record their voices during interaction with virtual objects. These vocalizations are then converted to vibrotactile actuation, and can be iteratively refined to build effective tactile experiences.

10.1.2 *Major Contributions to RQ2*

With RQ2, we considered procedural fabrication methods to enhance the design of tactile experiences for IVEs. Here, rather than replicating real world information, we utilize digital design processes to create more flexible and universal structures that directly influence tactile dimensions, i. e., roughness and hardness. By utilizing such structures in visuo-haptic settings, we aimed to build more flexible tactile experiences, and extend the wide gamut of material perception we noted in the previous approach.

> **RQ2:** How can procedural fabrication methods enhance the design of tactile experiences for IVEs?
>
> - Procedural generation of haptically-varying structures is able to reliably influence tactile perception in terms of hardness and roughness.
> - Visuo-haptic combinations of virtual textures and procedurally generated structures are able to extend the gamut of material perception in VR.
> - Procedural fabrication is able to extend the scalability and generalizability of PHF through on-demand production of haptic proxies.

In Chapter 7, we utilized the high resolution of available digital fabrication technology to generate fine-grained surface variations. Specifically, we constructed 3D-printed hair-like structures that varied with a single parameter, i. e., hair length. From the results of a user study, we confirmed that the construction of these structures was able to reliably influence tactile perception in different dimensions. Combined with visual textures, we found that visual-haptic augmentations enhance the user's haptic perception by making small variations in hair length distinguishable.

As visual and haptic information was manipulated individually, we were able to investigate a wide range of visuo-haptic combinations. While matching perceptions correlated to a higher rate of material recognitions, mismatches presented an interesting case to understand multisensory integration. As users actively made sense of mixed modalities, mismatches were clarified with adjectives. Moreover, in certain instances, the variation in haptic perception for a given virtual texture led to perceptional switches where perception of a material changed.

Our results underline that digital fabrication technology lends itself to share and produce physical objects on demand. Specifically for VR, our approach is able to support passive haptic feedback, where physical props are used as haptic proxies for virtual objects. By overlaying proxies with visual textures, we showed that the visuo-haptic perception of tactile textures can be simulated, and that fabrication of proxy objects is able to extend the scalability and generalizability of PHF.

10.1.3 *Major Contributions to RQ3*

With RQ3, we investigated correspondences between different sensory modalities to enhance the design of tactile experiences. As perceptual processes actively build our understanding of the world, perceptual representations stemming from different modalities are shared between the senses. This leads to non-arbitrary associations between features of different stimuli, e. g., the agreement between the color red and a warm temperature, or the correlation of the visual speed of an object and a higher pitch level of an associated sound. In our work, we look towards correspondences between tactile, visual, and auditory modalities.

> **RQ3:** How can correspondences between different sensory modalities enhance the design of tactile experiences for IVEs?
>
> - Crossmodal correspondences between visual and haptic sensations are able to support material and texture perception in IVEs.
> - Crossmodal expression through vocalization is able to transfer design intent into effective haptic experiences.

In Chapter 7, we investigated the relationship between visual textures and haptic impressions. In a virtual setting, we asked participants to rate tactile properties of visual textures using only visual exploration, and of physical structures using only haptic exploration. By combining visual and haptic information using PHF in VR, we saw that the matching rate of the visual and haptic perception positively correlated to material perception. This underlines that the single material of the physical structure, i. e., plastic, was interpreted as a broader range of materials due to the combination of visual textures and physical structures. Building upon correspondences between visual and haptic sensations is therefore able to support material and texture perception in IVEs.

In Chapter 8, we investigated the relationship between the haptic and auditory modalities. Specifically, we performed an elicitation study where participants were asked to vocally express the tactile impression received during interaction with a wide range of objects. Following this method, we saw that the spatio-temporal relationship of interacting with objects is essential to communicate such experiences, while a layered and incremental design process is required to support untrained voices. In Chapter 9, we built upon these insights with the design tool called Weirding Haptics, and saw that novice designers were able to rapidly create vibrotactile experiences aligned with their intention. Utilizing crossmodal expression was therefore able to transfer design intent into effective haptic experiences.

10.2 LIMITATIONS AND FUTURE WORK

The work presented in this dissertation is subject to certain limitations, which can be improved in future work.

DATASETS Several chapters in this work utilized specific sets of objects, materials and textures, some virtual, others physical. The set of textures used in Chapter 5 and Chapter 6 stemmed from a single fabric sample book, while the virtual textures used in Chapter 7 and Chapter 9 were purchased online, and the objects interacted with in Chapter 8 were chosen based on availability in the lab. The selection of these artifacts presents a dependency that might have influenced certain results.

For example, in Chapter 5, for analyzing the effects of the manufacturing process on the printed replicas, we needed a representative dataset of samples that vary in compliance, geometrical features, and used materials. We opted for a set of 15 cloth samples that we show achieve good coverage in both measured and perceived assessments, with the hopes that the results we achieve in our work would generalize to other material categories. An interesting direction of future work is to investigate new materials, e. g., leathers, metals, or woods, and observe if the results from this work generalize beyond our cloth samples.

Similarly, the objects used in Chapter 8 were selected to cover a broad range of object-action tasks to include tactile experiences produced by object deformation, object actuation, or object texture. The final set of 44 objects came about gradually, and was iterated over several times by the main collaborators. However, our list is not exhaustive, meaning that future work is needed to ensure generalizability, and to explore other types of interaction that produce tactile impressions, e. g., object-to-object interactions.

PRINTING TECHNOLOGY Several chapters in this work rely on digital fabrication technologies to produce haptically-varying structures. Here, the choice of both hardware and software used, depended on availability. While the results of different studies agreed on several insights, further work is needed to ensure generalizability.

In Chapter 5, Chapter 6, and Chapter 7, our results are dependent on the availability of a sufficient printing resolution respectively to reproduce surface microgeometry, and to produce hair-like structures. Unfortunately, common consumer 3D-printing technologies utilize FDM approaches, which rely on filaments at scales that dominate the haptic feedback of many everyday materials. However, higher resolution printing techniques are slowly becoming more accessible. Resin printers with comparable resolution to multi-jet printers are becoming available at competitive prices to FDMs. We believe that now is the correct time to study the haptics achievable with higher resolution processes, as the results discovered today will help makers design haptic experiences soon.

The respective studies focused on the most commonly available material for printing, namely hard plastic polymers. We believe our results are robust to specific plastic selection, as the main difference will be in the coefficient of friction between the material and the finger. This is supported by the results of Chapter 5, where we found only a weak correlation between friction and the remaining perceptual attributes. This indicates that changing the plastic material will likely not have a significant effect on other perceptual attributes. An exciting avenue for future work is to investigate the use of soft materials, as the demonstrated coupling between hardness and roughness leads to an interesting optimization problem.

The proposed observations and strategies for appropriating the haptics of real-life materials are valid only for the used fabrication process. Utilizing drastically different processes and/or materials would lead to perceivable differences in haptic response. While in principle, our study design can be replicated for each new fabrication setup, it might be inefficient in the number of samples and participants required. To this end, an interesting future work lies in identifying a minimal dataset that should be fabricated with a new process to calibrate the haptic reproduction capabilities.

TACTILE DIMENSIONS In order to understand users' tactile experiences, we inquired them about their perception in terms of different tactile dimensions. To this aim, most of our work focused on the dominant dimensions of roughness and hardness. However, as the results in Chapter 5 show, different tactile dimensions are correlated, indicating that further work is needed to assess each dimension's respective contribution to material perception.

The latter is emphasized by the individual assessment analysis in Chapter 5. Here, we found a surprising result, that reproducing the surface geometry is not always sufficient to match the perceived roughness. We explained this by an effect on the compliance of the sample on the perception of roughness. It is possible that such coupled effects also affect the perception of other physical attributes like hardness and friction. An interesting avenue for future work would be to investigate materials that match in a physical property but manifest extreme variation in others. This would allow us to investigate how we can leverage the perceptual coupling between individual physical parameters to design better haptic experiences.

Furthermore, our digital replicas manifest similar perceived friction to the original materials. While we did not specifically optimize for the perceived friction, our reproduction process relies on mimicking the surface geometry, which is one of the governing factors for friction (Skedung et al., 2020). The second important factor is the used materials. An interesting direction of future work would be to investigate how much influence on perceived friction do common manufacturing materials have, and how much we can affect the perceived friction by adjusting the surface geometry.

EXTENDING THE HAPTIC GAMUT In our work, several investigations into individual material perception revealed that different approaches can produce materials with a wide range of perceived qualities, ranging from plastic-like to wood-like. Considering that our fabricated structures consisted of a uniform material, the one-to-many relationship from a single physical material to multiple visuo-haptic material perceptions uncovers potential for future work. An interesting approach lies in further exploring the classes of materials that can be manufactured and quantifying the haptic gamut of a particular manufacturing method.

Furthermore, most of our studies utilized a static approach to PHF, as the focus was on investigating users' visuo-haptic perception, rather than providing them with an interactive virtual experience. Therefore, it remains to be seen how our approach to tactile experience design holds up in more engaging contexts, e. g., VR gaming or training scenarios. An engaging path for future work would be to combine fabricated proxies with other techniques for redirection in VR, e. g., haptic redirection, or through the use of a controller interface, such as the *Haptic Revolver* (Whitmire et al., 2018).

BIBLIOGRAPHY

Victoria E. Abraira and David D. Ginty (2013). “The Sensory Neurons of Touch.” In: *Neuron* 79.4, pp. 618–639. ISSN: 08966273. DOI: 10.1016/j.neuron.2013.07.051.

Richard J. Adams and Blake Hannaford (1999). “Stable haptic interaction with virtual environments.” In: *IEEE Transactions on Robotics and Automation* 15.3, pp. 465–474. ISSN: 1042296X. DOI: 10.1109/70.768179.

Kimi Akita and Mark Dingemanse (2019). “Ideophones (Mimetics, Expressives).” In: *Oxford Research Encyclopedia of Linguistics*. Oxford University Press. ISBN: 978-0-19-938465-5. DOI: 10.1093/acrefore/9780199384655.013.477.

Maximilian Altmeyer, Donald Degraen, Tobias Sander, Felix Kosmalla, and Antonio Krüger (2021). “Does Physicality Enhance the Meaningfulness of Gamification? Transforming Gamification Elements to Their Physical Counterparts.” In: *Proceedings of the 33rd Australian Conference on Human-Computer Interaction*. OzCHI ’21. Melbourne, VIC, Australia: Association for Computing Machinery, pp. 280–292. ISBN: 9781450395984. DOI: 10.1145/3520495.3520500.

Judith Amores and Pattie Maes (2017). “Essence: Olfactory Interfaces for Unconscious Influence of Mood and Cognitive Performance.” In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. Denver Colorado USA: ACM, pp. 28–34. ISBN: 978-1-4503-4655-9. DOI: 10.1145/3025453.3026004.

Christoph Anthes, Ruben Jesus Garcia-Hernandez, Markus Wiedemann, and Dieter Kranzlmuller (2016). “State of the art of Virtual Reality Technology.” In: *2016 IEEE Aerospace Conference*. Big Sky, MT, USA: IEEE, pp. 1–19. ISBN: 978-1-4673-7676-1. DOI: 10.1109/AERO.2016.7500674.

Farah Arab, Sabrina Panëels, Margarita Anastassova, Stéphanie Coeugnet, Fanny Le Morellec, Aurélie Dommes, and Aline Chevalier (2015). “Haptic patterns and older adults: To repeat or not to repeat?” In: *2015 IEEE World Haptics Conference (WHC)*. Evanston, IL, USA: IEEE, pp. 248–253. DOI: 10.1109/WHC.2015.7177721.

Bruno Araujo, Ricardo Jota, Varun Perumal, Jia Xian Yao, Karan Singh, and Daniel Wigdor (2016). “Snake Charmer: Physically Enabling Virtual Objects.” In: *Proceedings of the TEI ’16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI ’16. Eindhoven, Netherlands: Association for Computing Machinery, pp. 218–226. ISBN: 9781450335829. DOI: 10.1145/2839462.2839484.

Oscar Javier Ariza Nuñez (2020). “Wearable Haptic Technology for 3D Selection and Guidance.” PhD thesis. Hamburg, Germany: Universität Hamburg.

Oscar Javier Ariza Núñez, Paul Lubos, Frank Steinicke, and Gerd Bruder (2015). “Ring-shaped Haptic Device with Vibrotactile Feedback Patterns to Support Natural Spatial Interaction.” In: *ICAT-EGVE 2015 - International Conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments*, 7 pages. ISSN: 1727-530X. DOI: 10.2312/EGVE.20151326.

Mahdi Azmandian, Mark Hancock, Hrvoje Benko, Eyal Ofek, and Andrew D. Wilson (2016). “Haptic Retargeting: Dynamic Repurposing of Passive Haptics for Enhanced Virtual Reality Experiences.” In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI ’16. San Jose, California, USA: Association for Computing Machinery, pp. 1968–1979. ISBN: 9781450333627. DOI: 10.1145/2858036.2858226.

Yuki Ban and Yusuke Ujitoko (2018). “TactGAN: Vibrotactile Designing Driven by GAN-Based Automatic Generation.” In: *SIGGRAPH Asia 2018 Emerging Technologies*. SA ’18. Tokyo, Japan: Association for Computing Machinery. ISBN: 9781450360272. DOI: 10.1145/3275476.3275484.

Rosa M. Baños, Cristina Botella, Concepción Perpiñá, Mariano Alcañiz, Jose Antonio Lozano, Jorge Osma, and Myriam Gallardo (2002). “Virtual reality treatment of flying phobia.” In: *IEEE Transactions on Information Technology in Biomedicine* 6.3, pp. 206–212. ISSN: 1089-7771. DOI: 10.1109/TITB.2002.802380.

Joy van Baren and Wijnand IJsselsteijn (2004). *Measuring Presence: A Guide to Current Measurement Approaches.* Tech. rep. OmniPres project IST-2001-39237 Deliverable 5.

Woodrow Barfield and Claudia Hendrix (1995). “The effect of update rate on the sense of presence within virtual environments.” In: *Virtual Reality* 1.1, pp. 3–15. ISSN: 1359-4338, 1434-9957. DOI: 10.1007/BF02009709.

Cagatay Basdogan, Chih-Hao Ho, and Mandayam A. Srinivasan (1997). “A Ray-Based Haptic Rendering Technique for Displaying Shape and Texture of 3D Objects in Virtual Environments.” In: vol. Dynamic Systems and Control. ASME International Mechanical Engineering Congress and Exposition, pp. 77–84. DOI: 10.1115/IMECE1997-0380.

Olivier Bau, Ivan Poupyrev, Ali Israr, and Chris Harrison (2010). “TeslaTouch: Electrovibration for Touch Surfaces.” In: *Proceedings of the 23nd Annual ACM Symposium on User Interface Software and Technology.* UIST ’10. New York, New York, USA: Association for Computing Machinery, pp. 283–292. ISBN: 9781450302715. DOI: 10.1145/1866029.1866074.

Patrick Baudisch and Stefanie Mueller (2017). “Personal Fabrication.” In: *Foundations and Trends® in Human–Computer Interaction* 10.3–4, pp. 165–293. ISSN: 1551-3955, 1551-3963. DOI: 10.1561/1100000055.

David Beattie, William Frier, Orestis Georgiou, Benjamin Long, and Damien Ablart (2020). “Incorporating the Perception of Visual Roughness into the Design of Mid-Air Haptic Textures.” In: *ACM Symposium on Applied Perception 2020.* SAP ’20. Virtual Event, USA: Association for Computing Machinery. ISBN: 9781450376181. DOI: 10.1145/3385955.3407927.

M Beecroft (2016). “3D printing of weft knitted textile based structures by selective laser sintering of nylon powder.” In: *IOP Conference Series: Materials Science and Engineering* 137, p. 012017. DOI: 10.1088/1757-899x/137/1/012017.

Robert J. van Beers, Daniel M. Wolpert, and Patrick Haggard (2002). “When Feeling Is More Important Than Seeing in Sensorimotor Adaptation.” In: *Current Biology* 12.10, pp. 834–837. ISSN: 09609822. DOI: 10.1016/S0960-9822(02)00836-9.

Mafkereseb Kassahun Bekele and Erik Champion (2019). “A Comparison of Immersive Realities and Interaction Methods: Cultural Learning in Virtual Heritage.” In: *Frontiers in Robotics and AI* 6. DOI: 10.3389/frobt.2019.00091.

Pinhas Ben-Tzvi and Zhou Ma (2015). “Sensing and Force-Feedback Exoskeleton (SAFE) Robotic Glove.” In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 23.6, pp. 992–1002. ISSN: 1534-4320, 1558-0210. DOI: 10.1109/TNSRE.2014.2378171.

Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek (2016). “NormalTouch and TextureTouch: High-Fidelity 3D Haptic Shape Rendering on Handheld Virtual Reality Controllers.” In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology.* UIST ’16. Tokyo, Japan: Association for Computing Machinery, pp. 717–728. ISBN: 9781450341899. DOI: 10.1145/2984511.2984526.

Sliman J. Bensmaïa and Mark Hollins (2003). “The vibrations of texture.” In: *Somatosensory & Motor Research* 20.1, pp. 33–43. ISSN: 0899-0220, 1369-1651. DOI: 10.1080/0899022031000083825.

Wouter M. Bergmann Tiest (2010). “Tactual perception of material properties.” In: *Vision Research* 50.24. Perception and Action: Part I, pp. 2775–2782. ISSN: 0042-6989. DOI: https://doi.org/10.1016/j.visres.2010.10.005.

Wouter M. Bergmann Tiest and Astrid M. L. Kappers (2006). “Analysis of haptic perception of materials by multidimensional scaling and physical measurements of roughness and compressibility.” In: *Acta Psychologica* 121.1, pp. 1–20. ISSN: 00016918. DOI: 10.1016/j.actpsy.2005.04.005.

Wouter M. Bergmann Tiest and Astrid M. L. Kappers (2007). “Haptic and visual perception of roughness.” In: *Acta Psychologica* 124.2, pp. 177–189. ISSN: 0001-6918. DOI: https://doi.org/10.1016/j.actpsy.2006.03.002.

Wouter M. Bergmann Tiest and Astrid M. L. Kappers (2008). “Thermosensory Reversal Effect Quantified.” In: *Acta Psychologica* 127.1, pp. 46–50. ISSN: 00016918. DOI: 10.1016/j.actpsy.2006.12.006.

Joanna Bergström, Aske Mottelson, and Jarrod Knibbe (2019). “Resized Grasping in VR: Estimating Thresholds for Object Discrimination.” In: *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology.* UIST ’19. New Orleans, LA, USA: Association for Computing Machinery, pp. 1175–1183. ISBN: 9781450368162. DOI: 10.1145/3332165.3347939.

Katia Bertoldi, Vincenzo Vitelli, Johan Christensen, and Martin van Hecke (2017). "Flexible mechanical metamaterials." In: *Nature Reviews Materials* 2.11, p. 17066. ISSN: 2058-8437. DOI: 10.1038/natrevmats.2017.66.

Matteo Bianchi, Edoardo Battaglia, Mattia Poggiani, Simone Ciotti, and Antonio Bicchi (2016). "A Wearable Fabric-based display for haptic multi-cue delivery." In: *2016 IEEE Haptics Symposium (HAPTICS)*. Philadelphia, PA: IEEE, pp. 277–283. ISBN: 978-1-5090-0903-9. DOI: 10.1109/HAPTICS.2016.7463190.

Bernd Bickel, Moritz Bächer, Miguel A. Otaduy, Hyunho Richard Lee, Hanspeter Pfister, Markus Gross, and Wojciech Matusik (2010). "Design and Fabrication of Materials with Desired Deformation Behavior." In: *ACM Trans. Graph.* 29.4. ISSN: 0730-0301. DOI: 10.1145/1778765.1778800.

Osama R. Bilal, Vincenzo Costanza, Ali Israr, Antonio Palermo, Paolo Celli, Frances Lau, and Chiara Daraio (2020). "A Flexible Spiraling-Metasurface as a Versatile Haptic Interface." In: *Advanced Materials Technologies* 5.8, p. 2000181. ISSN: 2365-709X, 2365-709X. DOI: 10.1002/admt.202000181.

J. Black (2019). *DeGarmo's materials and processes in manufacturing*. Hoboken: Wiley. ISBN: 978-1-119-49282-5.

Jonathan Blake and Hakan B. Gurocak (2009). "Haptic Glove With MR Brakes for Virtual Reality." In: *IEEE/ASME Transactions on Mechatronics* 14.5, pp. 606–615. ISSN: 1083-4435, 1941-014X. DOI: 10.1109/TMECH.2008.2010934.

Meera M. Blattner, Denise A. Sumikawa, and Robert M. Greenberg (1989). "Earcons and Icons: Their Structure and Common Design Principles." In: *Human–Computer Interaction* 4.1, pp. 11–44. DOI: 10.1207/s15327051hci0401_1.

Stanley J. Bolanowski, George A. Gescheider, Ronald T. Verrillo, and Christine M. Checkosky (1988). "Four channels mediate the mechanical aspects of touch." In: *The Journal of the Acoustical Society of America* 84.5, pp. 1680–1694. DOI: 10.1121/1.397184.

Roger Boldu, Sambhav Jain, Juan Pablo Forero Cortes, Haimo Zhang, and Suranga Nanayakkara (2019). "M-Hair: Creating Novel Tactile Feedback by Augmenting the Body Hair to Respond to Magnetic Field." In: *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. New Orleans LA USA: ACM, pp. 323–328. ISBN: 978-1-4503-6816-2. DOI: 10.1145/3332165.3347955.

Roger Boldu, Mevan Wijewardena, Haimo Zhang, and Suranga Nanayakkara (2020). "MAGHair: A Wearable System to Create Unique Tactile Feedback by Stimulating Only the Body Hair." In: *22nd International Conference on Human-Computer Interaction with Mobile Devices and Services*. MobileHCI '20. Oldenburg, Germany: Association for Computing Machinery. ISBN: 9781450375160. DOI: 10.1145/3379503.3403545.

C. Botella, A. García-Palacios, H. Villa, R. M. Baños, S. Quero, M. Alcañiz, and G. Riva (2007). "Virtual reality exposure in the treatment of panic disorder and agoraphobia: A controlled study." In: *Clinical Psychology & Psychotherapy* 14.3, pp. 164–175. ISSN: 10633995, 10990879. DOI: 10.1002/cpp.524.

Matthew Botvinick and Jonathan Cohen (1998). "Rubber hands 'feel' touch that eyes see." In: *Nature* 391.6669, pp. 756–756. ISSN: 0028-0836, 1476-4687. DOI: 10.1038/35784.

Elodie Bouzbib and Gilles Bailly (2022). ""Let's Meet and Work it Out": Understanding and Mitigating Encountered-Type of Haptic Devices Failure Modes in VR." In: *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. Christchurch, New Zealand: IEEE, pp. 360–369. ISBN: 978-1-66549-617-9. DOI: 10.1109/VR51125.2022.00055.

Mourad Bouzit, Grigore Burdea, George V. Popescu, and Rareş Boian (2002). "The Rutgers Master II-new design force-feedback glove." In: *IEEE/ASME Transactions on Mechatronics* 7.2, pp. 256–263. ISSN: 1083-4435. DOI: 10.1109/TMECH.2002.1011262.

Doug A. Bowman and Ryan P. McMahan (2007). "Virtual Reality: How Much Immersion Is Enough?" In: *Computer* 40.7, pp. 36–43. ISSN: 0018-9162. DOI: 10.1109/MC.2007.257.

Virginia Braun and Victoria Clarke (2006). "Using thematic analysis in psychology." In: *Qualitative Research in Psychology* 3.2, pp. 77–101. DOI: 10.1191/1478088706qp063oa.

Breakfast Quay (2021). *Rubber Band Library*. URL: http://breakfastquay.com/rubberband/ (visited on 2021-03-24).

Stephen Brewster and Lorna M. Brown (2004). "Tactons: Structured Tactile Messages for Non-Visual Information Display." In: *Proceedings of the Fifth Conference on Australasian User Interface - Volume 28*. AUIC '04. Dunedin, New Zealand: Australian Computer Society, Inc., pp. 15–23.

Stephen A. Brewster, Peter C. Wright, and Alistair D. N. Edwards (1993). “An Evaluation of Earcons for Use in Auditory Human-Computer Interfaces.” In: *Proceedings of the INTERACT ’93 and CHI ’93 Conference on Human Factors in Computing Systems*. CHI ’93. Amsterdam, The Netherlands: Association for Computing Machinery, pp. 222–227. ISBN: 0897915755. DOI: 10.1145/169059.169179.

Frederick P. Brooks, Ming Ouh-Young, James J. Batter, and P. Jerome Kilpatrick (1990). “Project GROPE - Haptic Displays for Scientific Visualization.” In: *SIGGRAPH Comput. Graph.* 24.4, pp. 177–185. ISSN: 0097-8930. DOI: 10.1145/97880.97899.

Jas Brooks, Steven Nagels, and Pedro Lopes (2020). “Trigeminal-based Temperature Illusions.” In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. Honolulu HI USA: ACM, pp. 1–12. ISBN: 978-1-4503-6708-0. DOI: 10.1145/3313831.3376806.

Joshua P. Brown and Ildar Farkhatdinov (2020). “Soft Haptic Interface based on Vibration and Particle Jamming.” In: *2020 IEEE Haptics Symposium (HAPTICS)*. Crystal City, VA, USA: IEEE, pp. 1–6. ISBN: 978-1-72810-234-4. DOI: 10.1109/HAPTICS45997.2020.ras.HAP20.8.0698f2bb.

Lorna M. Brown, Stephen A. Brewster, and Helen C. Purchase (2005). “A first investigation into the effectiveness of Tactons.” In: *First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics Conference*, pp. 167–176. DOI: 10.1109/WHC.2005.6.

Lorna M. Brown, Stephen A. Brewster, and Helen C. Purchase (2006a). “Multidimensional Tactons for Non-Visual Information Presentation in Mobile Devices.” In: *Proceedings of the 8th Conference on Human-Computer Interaction with Mobile Devices and Services*. MobileHCI ’06. Helsinki, Finland: Association for Computing Machinery, pp. 231–238. ISBN: 1595933905. DOI: 10.1145/1152215.1152265.

Lorna M. Brown, Stephen A. Brewster, and Helen C. Purchase (2006b). “Tactile Crescendos and Sforzandos: Applying Musical Techniques to Tactile Icon Design.” In: *CHI ’06 Extended Abstracts on Human Factors in Computing Systems*. CHI EA ’06. Montréal, Québec, Canada: Association for Computing Machinery, pp. 610–615. ISBN: 1595932984. DOI: 10.1145/1125451.1125578.

Lucie Brunet, Christine Megard, Sabrina Paneels, Gwenael Changeon, Jose Lozada, Marie P. Daniel, and Françoise Darses (2013). ““Invitation to the voyage”: The design of tactile metaphors to fulfill occasional travelers’ needs in transportation networks.” In: *2013 World Haptics Conference (WHC)*, pp. 259–264. DOI: 10.1109/WHC.2013.6548418.

Steve Bryson (1992). “Virtual Reality Takes on Real Physics Applications.” In: *Computers in Physics* 6.4, p. 346. ISSN: 08941866. DOI: 10.1063/1.4823086.

Grigore Burdea, Jiachen Zhuang, Edward Roskos, Deborah Silver, and Noshir Langrana (1992). “A Portable Dextrous Master with Force Feedback.” In: *Presence: Teleoperators and Virtual Environments* 1.1, pp. 18–28. DOI: 10.1162/pres.1992.1.1.18.

Bill Buxton (2007). *Sketching user experiences: Getting the design right and the right design*. Interactive Technologies. Oxford, England: Morgan Kaufmann. ISBN: 978-0-12-374037-3.

Darwin Caldwell, Nikos Tsagarakis, and C. Giesler (1999). “An integrated tactile/shear feedback array for stimulation of finger mechanoreceptor.” In: vol. 1, 287–292 vol.1. ISBN: 0-7803-5180-0. DOI: 10.1109/ROBOT.1999.769991.

Tom Carter, Sue Ann Seah, Benjamin Long, Bruce Drinkwater, and Sriram Subramanian (2013). “UltraHaptics: Multi-Point Mid-Air Haptic Feedback for Touch Surfaces.” In: *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology*. UIST ’13. St. Andrews, Scotland, United Kingdom: Association for Computing Machinery, pp. 505–514. ISBN: 9781450322683. DOI: 10.1145/2501988.2502018.

Müge Cavdan, Knut Drewing, and Katja Doerschner (2021). “The look and feel of soft are similar across different softness dimensions.” In: *Journal of Vision* 21.10, pp. 20–20. ISSN: 1534-7362. DOI: 10.1167/jov.21.10.20.

Andrew Chan, Karon MacLean, and Joanna McGrenere (2008). “Designing haptic icons to support collaborative turn-taking.” In: *International Journal of Human-Computer Studies* 66.5, pp. 333–355. ISSN: 1071-5819. DOI: https://doi.org/10.1016/j.ijhcs.2007.11.002.

Liwei Chan, Mu-Hsuan Chen, Wen-Chi Ho, Roshan Lalintha Peiris, and Bing-Yu Chen (2019). “SeeingHaptics: Visualizations for Communicating Haptic Designs.” In: *Proceedings of the 21st International Conference on*

Human-Computer Interaction with Mobile Devices and Services. MobileHCI '19. Taipei, Taiwan: Association for Computing Machinery. ISBN: 9781450368254. DOI: 10.1145/3338286.3340112.

Zekun Chang, Tung D. Ta, Koya Narumi, Heeju Kim, Fuminori Okuya, Dongchi Li, Kunihiro Kato, Jie Qi, Yoshinobu Miyamoto, Kazuya Saito, and Yoshihiro Kawahara (2020). "Kirigami Haptic Swatches: Design Methods for Cut-and-Fold Haptic Feedback Mechanisms." In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI '20. Honolulu, HI, USA: Association for Computing Machinery, pp. 1–12. ISBN: 9781450367080. DOI: 10.1145/3313831.3376655.

Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch (2017). "Mutual Human Actuation." In: *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*. UIST '17. Québec City, QC, Canada: Association for Computing Machinery, pp. 797–805. ISBN: 9781450349819. DOI: 10.1145/3126594.3126667.

Lung-Pan Cheng, Thijs Roumen, Hannes Rantzsch, Sven Köhler, Patrick Schmidt, Robert Kovacs, Johannes Jasper, Jonas Kemper, and Patrick Baudisch (2015). "TurkDeck: Physical Virtual Reality Based on People." In: *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. UIST '15. Charlotte, NC, USA: Association for Computing Machinery, pp. 417–426. ISBN: 9781450337793. DOI: 10.1145/2807442.2807463.

Alain de Cheveigné and Hideki Kawahara (2002). "YIN, a fundamental frequency estimator for speech and music." In: *The Journal of the Acoustical Society of America* 111.4, pp. 1917–1930. DOI: 10.1121/1.1458024.

Inrak Choi, Heather Culbertson, Mark R. Miller, Alex Olwal, and Sean Follmer (2017). "Grabity: A Wearable Haptic Interface for Simulating Weight and Grasping in Virtual Reality." In: *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*. Québec City QC Canada: ACM, pp. 119–130. ISBN: 978-1-4503-4981-9. DOI: 10.1145/3126594.3126599.

Inrak Choi, Elliot W. Hawkes, David L. Christensen, Christopher J. Ploch, and Sean Follmer (2016). "Wolverine: A wearable haptic interface for grasping in virtual reality." In: *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. Daejeon, South Korea: IEEE, pp. 986–993. ISBN: 978-1-5090-3762-9. DOI: 10.1109/IROS.2016.7759169.

Inrak Choi, Eyal Ofek, Hrvoje Benko, Mike Sinclair, and Christian Holz (2018). "CLAW: A Multifunctional Handheld Haptic Controller for Grasping, Touching, and Triggering in Virtual Reality." In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: Association for Computing Machinery, pp. 1–13. ISBN: 9781450356206. DOI: 10.1145/3173574.3174228.

Inrak Choi, Yiwei Zhao, Eric J. Gonzalez, and Sean Follmer (2021). "Augmenting Perceived Softness of Haptic Proxy Objects Through Transient Vibration and Visuo-Haptic Illusion in Virtual Reality." In: *IEEE Transactions on Visualization and Computer Graphics* 27.12, pp. 4387–4400. ISSN: 1077-2626, 1941-0506, 2160-9306. DOI: 10.1109/TVCG.2020.3002245.

Jae-Won Choi, Ho-Chan Kim, and Ryan Wicker (2011). "Multi-material stereolithography." In: *Journal of Materials Processing Technology* 211.3, pp. 318–328. ISSN: 09240136. DOI: 10.1016/j.jmatprotec.2010.10.003.

Seungmoon Choi and Hong Z. Tan (2004). "Toward realistic haptic rendering of surface textures." In: *IEEE Computer Graphics and Applications* 24.2, pp. 40–47. DOI: 10.1109/MCG.2004.1274060.

K. R. Clarke (1993). "Non-parametric multivariate analyses of changes in community structure." In: *Australian Journal of Ecology* 18.1, pp. 117–143. DOI: 10.1111/j.1442-9993.1993.tb00438.x.

R. H. Cook (1965). "An automatic stall prevention control for supersonic fighter aircraft." In: *Journal of Aircraft* 2.3, pp. 171–175. ISSN: 0021-8669, 1533-3868. DOI: 10.2514/3.43636.

Theresa Cooke, Sebastian Kannengiesser, Christian Wallraven, and Heinrich H. Bülthoff (2006). "Object feature validation using visual and haptic similarity ratings." In: *ACM Transactions on Applied Perception* 3.3, pp. 239–261. ISSN: 1544-3558, 1544-3965. DOI: 10.1145/1166087.1166093.

Michael A. Costa and Mark R. Cutkosky (2000). "Roughness Perception of Haptically Displayed Fractal Surfaces." In: vol. Dynamic Systems and Control: Volume 2. ASME International Mechanical Engineering Congress and Exposition, pp. 1073–1079. DOI: 10.1115/IMECE2000-2414.

National Research Council (1995). *Virtual reality: Scientific and technological challenges.* Ed. by Nathaniel I. Durlach and Anne S. Mavor. Washington, DC: The National Academies Press. ISBN: 978-0-309-05135-4. DOI: 10.17226/4761.

James A. Covington, Samuel O. Agbroko, and Akira Tiele (2018). "Development of a Portable, Multichannel Olfactory Display Transducer." In: *IEEE Sensors Journal* 18.12, pp. 4969–4974. ISSN: 1530-437X, 1558-1748, 2379-9153. DOI: 10.1109/JSEN.2018.2832284.

Carolina Cruz-Neira, Daniel J. Sandin, and Thomas A. DeFanti (1993). "Surround-Screen Projection-Based Virtual Reality: The Design and Implementation of the CAVE." In: *Proceedings of the 20th Annual Conference on Computer Graphics and Interactive Techniques.* SIGGRAPH '93. Anaheim, CA: Association for Computing Machinery, pp. 135–142. ISBN: 0897916018. DOI: 10.1145/166117.166134.

Heather Culbertson, Juan Jose Lopez Delgado, and Katherine J. Kuchenbecker (2014a). "The Penn Haptic Texture Toolkit for Modeling, Rendering, and Evaluating Haptic Virtual Textures." In: *Department of Mechanical Engineering & Applied Mechanics*, p. 11. URL: https://repository.upenn.edu/meam_papers/299.

Heather Culbertson and Katherine J. Kuchenbecker (2017). "Importance of Matching Physical Friction, Hardness, and Texture in Creating Realistic Haptic Virtual Surfaces." In: *IEEE Transactions on Haptics* 10.1, pp. 63–74. ISSN: 1939-1412. DOI: 10.1109/TOH.2016.2598751.

Heather Culbertson, Juan Jose Lopez Delgado, and Katherine J Kuchenbecker (2014b). "[D11] The Penn Haptic Texture Toolkit." In: *2014 IEEE Haptics Symposium (HAPTICS).* Houston, TX, USA: IEEE.

Heather Culbertson, Juan Jose Lopez Delgado, and Katherine J. Kuchenbecker (2014c). "One hundred data-driven haptic texture models and open-source methods for rendering on 3D objects." In: *2014 IEEE Haptics Symposium (HAPTICS).* Houston, TX, USA: IEEE, pp. 319–325. ISBN: 978-1-4799-3131-6. DOI: 10.1109/HAPTICS.2014.6775475.

Heather Culbertson, Samuel B. Schorr, and Allison M. Okamura (2018). "Haptics: The Present and Future of Artificial Touch Sensation." In: *Annual Review of Control, Robotics, and Autonomous Systems* 1.1, pp. 385–409. ISSN: 2573-5144, 2573-5144. DOI: 10.1146/annurev-control-060117-105043.

Heather Culbertson, Juliette Unwin, Benjamin E. Goodman, and Katherine J. Kuchenbecker (2013). "Generating haptic texture models from unconstrained tool-surface interactions." In: *2013 World Haptics Conference (WHC).* Daejeon: IEEE, pp. 295–300. ISBN: 978-1-4799-0088-6. DOI: 10.1109/WHC.2013.6548424.

Heather Culbertson, Julie M. Walker, and Allison M. Okamura (2016). "Modeling and design of asymmetric vibrations to induce ungrounded pulling sensation through asymmetric skin displacement." In: *2016 IEEE Haptics Symposium (HAPTICS)*, pp. 27–33. DOI: 10.1109/HAPTICS.2016.7463151.

James J. Cummings and Jeremy N. Bailenson (2016). "How Immersive Is Enough? A Meta-Analysis of the Effect of Immersive Technology on User Presence." In: *Media Psychology* 19.2, pp. 272–309. ISSN: 1521-3269, 1532-785X. DOI: 10.1080/15213269.2015.1015740.

Mary Ann Curran (2010). "Biobased Materials." In: *Kirk-Othmer Encyclopedia of Chemical Technology.* John Wiley & Sons, Ltd, pp. 1–19. ISBN: 9780471238966. DOI: https://doi.org/10.1002/0471238961.biobcurr.a01.

Aleksandra Ćwiek, Susanne Fuchs, Christoph Draxler, Eva Liina Asu, Dan Dediu, Katri Hiovain, Shigeto Kawahara, Sofia Koutalidis, Manfred Krifka, Pärtel Lippus, Gary Lupyan, Grace E. Oh, Jing Paul, Caterina Petrone, Rachid Ridouane, Sabine Reiter, Nathalie Schümchen, Ádám Szalontai, Özlem Ünal-Logacev, Jochen Zeller, Marcus Perlman, and Bodo Winter (2022). "The bouba/kiki effect is robust across cultures and writing systems." In: *Philosophical Transactions of the Royal Society B: Biological Sciences* 377.1841, p. 20200390. ISSN: 0962-8436, 1471-2970. DOI: 10.1098/rstb.2020.0390.

Florian Daiber, Donald Degraen, André Zenner, Tanja Döring, Frank Steinicke, Oscar Javier Ariza Nunez, and Adalberto L. Simeone (2021). "Everyday Proxy Objects for Virtual Reality." In: *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems.* CHI EA '20. Honolulu, HI, USA: Association for Computing Machinery, pp. 1–8. ISBN: 9781450380959. DOI: 10.1145/3411763.3441343.

Florian Daiber, Donald Degraen, André Zenner, Frank Steinicke, Oscar Javier Ariza Núñez, and Adalberto L. Simeone (2020). "Everyday Proxy Objects for Virtual Reality." In: *Extended Abstracts of the 2020 CHI*

Conference on Human Factors in Computing Systems. CHI EA '20. Honolulu, HI, USA: Association for Computing Machinery, pp. 1–8. ISBN: 9781450368193. DOI: 10.1145/3334480.3375165.

Donald Degraen (2019). "Exploring Interaction Design for the Social Internet of Things." In: *Social Internet of Things.* Ed. by Alessandro Soro, Margot Brereton, and Paul Roe. Cham: Springer International Publishing, pp. 85–106. ISBN: 978-3-319-94659-7. DOI: 10.1007/978-3-319-94659-7_5.

Donald Degraen (2021). *Github Repository for the Weirding Haptics Framework.* URL: https://github.com/darty/wh (visited on 2022-07-31).

Donald Degraen and Bruno Fruchard (2021). *Weirding Haptics Code Repository.* URL: https://github.com/darty/wh (visited on 2022-10-01).

Donald Degraen, Bruno Fruchard, Frederik Smolders, Emmanouil Potetsianakis, Seref Güngör, Antonio Krüger, and Jürgen Steimle (2021a). "Weirding Haptics: In-Situ Prototyping of Vibrotactile Feedback in Virtual Reality through Vocalization." In: *The 34th Annual ACM Symposium on User Interface Software and Technology.* UIST '21. Virtual Event, USA: Association for Computing Machinery, pp. 936–953. ISBN: 9781450386357. DOI: 10.1145/3472749.3474797.

Donald Degraen, Hannah Hock, Marc Schubhan, Maximilian Altmeyer, Felix Kosmalla, and Antonio Krüger (2021b). "FamilyFlower: An Artifical Flower to Foster Distant Family Connections." In: *20th International Conference on Mobile and Ubiquitous Multimedia.* MUM 2021. Leuven, Belgium: Association for Computing Machinery, pp. 204–207. ISBN: 9781450386432. DOI: 10.1145/3490632.3497833.

Donald Degraen, Felix Kosmalla, and Antonio Krüger (2019a). "Overgrown: Supporting Plant Growth with an Endoskeleton for Ambient Notifications." In: *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems.* CHI EA '19. Glasgow, Scotland Uk: Association for Computing Machinery, pp. 1–6. ISBN: 9781450359719. DOI: 10.1145/3290607.3312833.

Donald Degraen, Michal Piovarči, Bernd Bickel, and Antonio Krüger (2021c). "Capturing Tactile Properties of Real Surfaces for Haptic Reproduction." In: *The 34th Annual ACM Symposium on User Interface Software and Technology.* UIST '21. Virtual Event, USA: Association for Computing Machinery, pp. 954–971. ISBN: 9781450386357. DOI: 10.1145/3472749.3474798.

Donald Degraen, Anna Reindl, Akhmajon Makhsadov, André Zenner, and Antonio Krüger (2020a). "Envisioning Haptic Design for Immersive Virtual Environments." In: *Companion Publication of the 2020 ACM Designing Interactive Systems Conference.* DIS' 20 Companion. Eindhoven, Netherlands: Association for Computing Machinery, pp. 287–291. ISBN: 9781450379878. DOI: 10.1145/3393914.3395870.

Donald Degraen, Marc Schubhan, Maximilian Altmeyer, and Antonio Krüger (2021d). "Hakoniwa: Enhancing Physical Gamification Using Miniature Garden Elements." In: *Academic Mindtrek 2021.* Mindtrek 2021. Tampere/Virtual, Finland: Association for Computing Machinery, pp. 117–127. ISBN: 9781450385145. DOI: 10.1145/3464327.3464362.

Donald Degraen, Marc Schubhan, Kamila Mushkina, Akhmajon Makhsadov, Felix Kosmalla, André Zenner, and Antonio Krüger (2020b). "AmbiPlant - Ambient Feedback for Digital Media through Actuated Plants." In: *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems.* CHI EA '20. Honolulu, HI, USA: Association for Computing Machinery, pp. 1–9. ISBN: 9781450368193. DOI: 10.1145/3334480.3382860.

Donald Degraen, André Zenner, and Antonio Krüger (2019b). "Enhancing Texture Perception in Virtual Reality Using 3D-Printed Hair Structures." In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems.* CHI '19. Glasgow, Scotland UK: Association for Computing Machinery, pp. 1–12. ISBN: 9781450359702. DOI: 10.1145/3290605.3300479.

Laura Devendorf and Chad Di Lauro (2019). "Adapting Double Weaving and Yarn Plying Techniques for Smart Textiles Applications." In: *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction.* TEI '19. Tempe, Arizona, USA: Association for Computing Machinery, pp. 77–85. ISBN: 9781450361965. DOI: 10.1145/3294109.3295625.

Charles Dhong, Rachel Miller, Nicholas B. Root, Sumit Gupta, Laure V. Kayser, Cody W. Carpenter, Kenneth J. Loh, Vilayanur S. Ramachandran, and Darren J. Lipomi (2019). "Role of indentation depth and contact area on human perception of softness for haptic interfaces." In: *Science Advances* 5.8, eaaw8845. ISSN: 2375-2548. DOI: 10.1126/sciadv.aaw8845.

JoAnn Difede and Judith Cukor (2007). "Virtual Reality Exposure Therapy for the Treatment of Posttraumatic Stress Disorder Following September 11, 2001." In: *The Journal of Clinical Psychiatry* 68.11, pp. 1682–1689. ISSN: 0160-6689. DOI: 10.4088/JCP.v68n1102.

Lisa Dopjans, Christian Wallraven, and Heinrich H. Bulthoff (2009). "Cross-Modal Transfer in Visual and Haptic Face Recognition." In: *IEEE Transactions on Haptics* 2.4, pp. 236–240. ISSN: 1939-1412. DOI: 10.1109/TOH.2009.18.

Gershon Elber (2005). "Geometric Texture Modeling." In: *IEEE Computer Graphics and Applications* 25.4, pp. 66–76. ISSN: 0272-1716. DOI: 10.1109/MCG.2005.79.

Takahiro Endo, Haruhisa Kawasaki, Tetsuya Mouri, Yasutoshi Doi, Tetsunori Yoshida, Yasuhiko Ishigure, Hisayuki Shimomura, Masato Matsumura, and Kazumi Koketsu (2009). "Five-fingered haptic interface robot: HIRO III." In: *World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp. 458–463. DOI: 10.1109/WHC.2009.4810812.

Mario Enriquez, Karon MacLean, and Christian Chita (2006). "Haptic Phonemes: Basic Building Blocks of Haptic Communication." In: *Proceedings of the 8th International Conference on Multimodal Interfaces*. ICMI '06. Banff, Alberta, Canada: Association for Computing Machinery, pp. 302–309. ISBN: 159593541X. DOI: 10.1145/1180995.1181053.

Mario J. Enriquez and Karon E. MacLean (2003). "The hapticon editor: a tool in support of haptic communication research." In: *11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2003. HAPTICS 2003. Proceedings.* Los Angeles, CA, USA: IEEE Comput. Soc, pp. 356–362. ISBN: 978-0-7695-1890-9. DOI: 10.1109/HAPTIC.2003.1191310.

Marc O. Ernst and Martin S. Banks (2002). "Humans integrate visual and haptic information in a statistically optimal fashion." In: *Nature* 415.6870, pp. 429–433. DOI: 10.1038/415429a.

Marc O. Ernst, Martin S. Banks, and Heinrich H. Bülthoff (2000). "Touch can change visual slant perception." In: *Nature Neuroscience* 3.1, pp. 69–73. ISSN: 1097-6256, 1546-1726. DOI: 10.1038/71140.

Marc O. Ernst and Heinrich H. Bülthoff (2004). "Merging the senses into a robust percept." In: *Trends in Cognitive Sciences* 8.4, pp. 162–169. ISSN: 13646613. DOI: 10.1016/j.tics.2004.02.002.

Aniello Falco, Mattia Petrelli, Emanuele Bezzeccheri, Ahmed Abdelhalim, and Paolo Lugli (2016). "Towards 3D-printed organic electronics: Planarization and spray-deposition of functional layers onto 3D-printed objects." In: *Organic Electronics* 39, pp. 340–347. ISSN: 15661199. DOI: 10.1016/j.orgel.2016.10.027.

Cathy Fang, Yang Zhang, Matthew Dworman, and Chris Harrison (2020). "Wireality: Enabling Complex Tangible Geometries in Virtual Reality with Worn Multi-String Haptics." In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI '20. Honolulu, HI, USA: Association for Computing Machinery, pp. 1–10. ISBN: 9781450367080. DOI: 10.1145/3313831.3376470.

Gustav Theodor Fechner (1860). *Elemente der Psychophysik*. Vol. Volume 1. Germany: Breitkopf und Härtel.

Martin Feick, Scott Bateman, Anthony Tang, Andre Miede, and Nicolai Marquardt (2020). "Tangi: Tangible Proxies For Embodied Object Exploration And Manipulation In Virtual Reality." In: *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. Porto de Galinhas, Brazil: IEEE, pp. 195–206. ISBN: 978-1-72818-508-8. DOI: 10.1109/ISMAR50242.2020.00042.

Davide Filingeri (2015). "Humidity sensation, cockroaches, worms, and humans: are common sensory mechanisms for hygrosensation shared across species?" In: *Journal of neurophysiology* 114.2, pp. 763–767. ISSN: 1522-1598 0022-3077. DOI: 10.1152/jn.00730.2014.

Roland W. Fleming (2017). "Material Perception." In: *Annual Review of Vision Science* 3.1, pp. 365–388. DOI: 10.1146/annurev-vision-102016-061429.

Roland W. Fleming, Shin'ya Nishida, and Karl R. Gegenfurtner (2015). "Perception of material properties." In: *Vision Research* 115, pp. 157–162. ISSN: 00426989. DOI: 10.1016/j.visres.2015.08.006.

Roland W. Fleming, Christiane Wiebel, and Karl R. Gegenfurtner (2013). "Perceptual qualities and material classes." In: *Journal of Vision* 13.8, pp. 9–9. ISSN: 1534-7362. DOI: 10.1167/13.8.9.

Sean Follmer, Daniel Leithinger, Alex Olwal, Nadia Cheng, and Hiroshi Ishii (2012). "Jamming User Interfaces: Programmable Particle Stiffness and Sensing for Malleable and Shape-Changing Devices." In: *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology*. UIST '12. Cambridge, Massachusetts, USA: Association for Computing Machinery, pp. 519–528. ISBN: 9781450315807. DOI: 10.1145/2380116.2380181.

Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii (2013). "inFORM: dynamic physical affordances and constraints through shape and object actuation." In: *Proceedings of the 26th annual ACM symposium on User interface software and technology*. St. Andrews Scotland, United Kingdom: ACM, pp. 417–426. ISBN: 978-1-4503-2268-3. DOI: 10.1145/2501988.2502032.

Jack Forman, Mustafa Doga Dogan, Hamilton Forsythe, and Hiroshi Ishii (2020). "DefeXtiles: 3D Printing Quasi-Woven Fabric via Under-Extrusion." In: *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. UIST '20. Virtual Event, USA: Association for Computing Machinery, pp. 1222–1233. ISBN: 9781450375146. DOI: 10.1145/3379337.3415876.

Jonas Forsslund, Michael Yip, and Eva-Lotta Sallnäs (2015). "WoodenHaptics: A Starting Kit for Crafting Force-Reflecting Spatial Haptic Devices." In: *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '15. Stanford, California, USA: Association for Computing Machinery, pp. 133–140. ISBN: 9781450333054. DOI: 10.1145/2677199.2680595.

Gabriele Frediani, Daniele Mazzei, Danilo Emilio De Rossi, and Federico Carpi (2014). "Wearable Wireless Tactile Display for Virtual Interactions with Soft Bodies." In: *Frontiers in Bioengineering and Biotechnology* 2. ISSN: 2296-4185. DOI: 10.3389/fbioe.2014.00031.

Euan Freeman, Ross Anderson, Julie Williamson, Graham Wilson, and Stephen A. Brewster (2017). "Textured Surfaces for Ultrasound Haptic Displays." In: *Proceedings of the 19th ACM International Conference on Multimodal Interaction*. ICMI '17. Glasgow, UK: Association for Computing Machinery, pp. 491–492. ISBN: 9781450355438. DOI: 10.1145/3136755.3143020.

Erica Fretwell (2020). *Sensory experiments: psychophysics, race, and the aesthetics of feeling*. Durham: Duke University Press. ISBN: 9781478012450.

Emma Frid, Jonas Moll, Roberto Bresin, and Eva-Lotta Sallnäs Pysander (2019). "Haptic feedback combined with movement sonification using a friction sound improves task performance in a virtual throwing task." In: *Journal on Multimodal User Interfaces* 13.4, pp. 279–290. ISSN: 1783-7677, 1783-8738. DOI: 10.1007/s12193-018-0264-4.

Mikhaila Friske, Shanel Wu, and Laura Devendorf (2019). "AdaCAD: Crafting Software For Smart Textiles Design." In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Glasgow, Scotland Uk: Association for Computing Machinery, pp. 1–13. ISBN: 9781450359702. DOI: 10.1145/3290605.3300575.

Jason P. Fritz and Kenneth E. Barner (1996). "Stochastic models for haptic texture." In: ed. by Matthew R. Stein. Boston, MA, pp. 34–44. DOI: 10.1117/12.263011.

Bruno Fruchard and Donald Degraen (2022). "Demonstration of Weirding Haptics: Prototyping Vibrotactile Feedback through Vocalization in Virtual Reality." In: *IEEE 7th VR Workshop on Sonic Interactions for Virtual Environments*. SIVE '22. Virtual, Online: Springer International Publishing. ISBN: 978-3-031-04020-7. URL: https://sive.create.aau.dk.

Qian Fu, Fei Hou, Qian Sun, Shi-Qing Xin, Yong-Jin Liu, Wencheng Wang, Hong Qin, and Ying He (2018). "Decorating 3D models with Poisson vector graphics." In: *Computer-Aided Design* 102, pp. 1–11. ISSN: 00104485. DOI: 10.1016/j.cad.2018.04.019.

Waka Fujisaki, Midori Tokita, and Kenji Kariya (2015). "Perception of the material properties of wood based on vision, audition, and touch." In: *Vision Research* 109, pp. 185–200. ISSN: 00426989. DOI: 10.1016/j.visres.2014.11.020.

Massimiliano Gabardi, Massimiliano Solazzi, Daniele Leonardis, and Antonio Frisoli (2016). "A new wearable fingertip haptic interface for the rendering of virtual shapes and surface features." In: *2016 IEEE Haptics*

Symposium (HAPTICS). Philadelphia, PA, USA: IEEE, pp. 140–146. ISBN: 978-1-5090-0903-9. DOI: 10.1109/HAPTICS.2016.7463168.

Jose F. Garcia, Adalberto L. Simeone, Matthew Higgins, Wendy Powell, and Vaughan Powell (2018). “Inside Looking out or Outside Looking in? An Evaluation of Visualisation Modalities to Support the Creation of a Substitutional Virtual Environment.” In: *Proceedings of the 2018 International Conference on Advanced Visual Interfaces*. AVI ’18. Castiglione della Pescaia, Grosseto, Italy: Association for Computing Machinery. ISBN: 9781450356169. DOI: 10.1145/3206505.3206529.

Azucena Garcia-Palacios, Hunter G. Hoffman, Albert S. Carlin, Thomas A. Furness, and Cristina Botella (2002). “Virtual reality in the treatment of spider phobia: a controlled study.” In: *Behaviour Research and Therapy* 40.9, pp. 983–993. ISSN: 00057967. DOI: 10.1016/S0005-7967(01)00068-7.

Chiara Gaudeni, Leonardo Meli, Lynette A. Jones, and Domenico Prattichizzo (2019). “Presenting Surface Features Using a Haptic Ring: A Psychophysical Study on Relocating Vibrotactile Feedback.” In: *IEEE Transactions on Haptics* 12.4, pp. 428–437. ISSN: 1939-1412, 2329-4051, 2334-0134. DOI: 10.1109/TOH.2019.2938945.

Robert H. Gault (1927). ““Hearing” through the sense organs of touch and vibration.” In: *Journal of the Franklin Institute* 204.3, pp. 329–358. ISSN: 00160032. DOI: 10.1016/S0016-0032(27)92101-2.

Angelika Gedsun, Riad Sahli, Xing Meng, René Hensel, and Roland Bennewitz (2022). “Bending as Key Mechanism in the Tactile Perception of Fibrillar Surfaces.” In: *Advanced Materials Interfaces* 9.4, p. 2101380. DOI: https://doi.org/10.1002/admi.202101380.

George A. Gescheider (1997). *Psychophysics: the fundamentals*. 3rd ed. Mahwah, N.J: L. Erlbaum Associates. ISBN: 978-0-8058-2281-6.

Elias Giannopoulos, Ausiàs Pomés, and Mel Slater (2015). “Touching the Void: Exploring Virtual Objects through a Vibrotactile Glove.” In: *International Journal of Virtual Reality* 11. DOI: 10.20870/IJVR.2012.11.3.2847.

James J. Gibson (1983). *The Senses Considered as Perceptual Systems*. Westport, CT: Praeger.

Daniele Giunchi, Stuart James, Donald Degraen, and Anthony Steed (2019). “Mixing Realities for Sketch Retrieval in Virtual Reality.” In: *The 17th International Conference on Virtual-Reality Continuum and Its Applications in Industry*. VRCAI ’19. Brisbane, QLD, Australia: Association for Computing Machinery. ISBN: 9781450370028. DOI: 10.1145/3359997.3365751.

Guilherme Goncalves, Miguel Melo, Jose Vasconcelos-Raposo, and Maximino Bessa (2020). “Impact of Different Sensory Stimuli on Presence in Credible Virtual Environments.” In: *IEEE Transactions on Visualization and Computer Graphics* 26.11, pp. 3231–3240. ISSN: 1077-2626, 1941-0506, 2160-9306. DOI: 10.1109/TVCG.2019.2926978.

Saul Greenberg and Chester Fitchett (2001). “Phidgets: Easy Development of Physical Interfaces through Physical Widgets.” In: *Proceedings of the 14th Annual ACM Symposium on User Interface Software and Technology*. UIST ’01. Orlando, Florida: Association for Computing Machinery, pp. 209–218. ISBN: 158113438X. DOI: 10.1145/502348.502388.

Taylor E. Greenwood, Serah E. Hatch, Mark B. Colton, and Scott L. Thomson (2021). “3D printing low-stiffness silicone within a curable support matrix.” In: *Additive Manufacturing* 37, p. 101681. ISSN: 22148604. DOI: 10.1016/j.addma.2020.101681.

Daniel Groeger, Martin Feick, Anusha Withana, and Jürgen Steimle (2019). “Tactlets: Adding Tactile Feedback to 3D Objects Using Custom Printed Controls.” In: *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. New Orleans LA USA: ACM, pp. 923–936. ISBN: 978-1-4503-6816-2. DOI: 10.1145/3332165.3347937.

Martin Grunwald, ed. (2008). *Human haptic perception: basics and applications*. Basel, Switzerland: Birkhäuser Verlag AG. ISBN: 978-3-7643-7611-6.

Xiaochi Gu, Yifei Zhang, Weize Sun, Yuanzhe Bian, Dao Zhou, and Per Ola Kristensson (2016). “Dexmo: An Inexpensive and Lightweight Mechanical Exoskeleton for Motion Capture and Force Feedback in VR.” In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI ’16. San

Jose, California, USA: Association for Computing Machinery, pp. 1991–1995. ISBN: 9781450333627. DOI: 10.1145/2858036.2858487.

Yves Guiard (1987). "Asymmetric Division of Labor in Human Skilled Bimanual Action." In: *Journal of Motor Behavior* 19.4, pp. 486–517. DOI: 10.1080/00222895.1987.10735426.

Eric Gunther and Sile O'Modhrain (2003). "Cutaneous Grooves: Composing for the Sense of Touch." In: *Journal of New Music Research* 32.4, pp. 369–381. DOI: 10.1076/jnmr.32.4.369.18856.

Sean A Guynes (2014). "Four-Color Sound: A Peircean Semiotics of Comic Book Onomatopoeia." In: *Public Journal of Semiotics* 6.1, pp. 58–72. ISSN: 1918-9907. DOI: 10.37693/pjos.2014.6.11916.

Antal Haans and Wijnand IJsselsteijn (2006). "Mediated Social Touch: a Review of Current Research and Future Directions." In: *Virtual Reality* 9.2–3, pp. 149–159. ISSN: 1359-4338, 1434-9957. DOI: 10.1007/s10055-005-0014-2.

Taku Hachisu and Masaaki Fukumoto (2014). "VacuumTouch: attractive force feedback interface for haptic interactive surface using air suction." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. Toronto Ontario Canada: ACM, pp. 411–420. ISBN: 978-1-4503-2473-1. DOI: 10.1145/2556288.2557252.

Taku Hachisu, Michi Sato, Shogo Fukushima, and Hiroyuki Kajimoto (2012). "Augmentation of Material Property by Modulating Vibration Resulting from Tapping." In: *Haptics: Perception, Devices, Mobility, and Communication*. Ed. by Poika Isokoski and Jukka Springare. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 173–180. ISBN: 978-3-642-31401-8.

M. Hafez and M.B. Khoudja (2004). "3D tactile rendering based on Bi (multi) stable SMA monolithic systems." In: *Micro-Nanomechatronics and Human Science, 2004 and The Fourth Symposium Micro-Nanomechatronics for Information-Based Society, 2004*. Nagoya, Japan: IEEE, pp. 1–6. ISBN: 978-0-7803-8607-5. DOI: 10.1109/MHS.2004.1421283.

Natsuki Hamanishi, Michinari Kono, Shunichi Suwa, Takashi Miyaki, and Jun Rekimoto (2018). "Flufy: Recyclable and Edible Rapid Prototyping Using Fluffed Sugar." In: *Proceedings of the 23rd International Conference on Intelligent User Interfaces Companion*. IUI '18 Companion. Tokyo, Japan: Association for Computing Machinery. ISBN: 9781450355711. DOI: 10.1145/3180308.3180335.

Natsuki Hamanishi, Michinari Kono, Shunichi Suwa, Takashi Miyaki, and Jun Rekimoto (2019). "Fibritary: Rotary Jet-Spinning for Personal Fiber Fabrication." In: *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI EA '19. Glasgow, Scotland Uk: Association for Computing Machinery, pp. 1–6. ISBN: 9781450359719. DOI: 10.1145/3290607.3312934.

Nur Al-huda Hamdan, Adrian Wagner, Simon Voelker, Jürgen Steimle, and Jan Borchers (2019). "Springlets: Expressive, Flexible and Silent On-Skin Tactile Interfaces." In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Glasgow, Scotland Uk: Association for Computing Machinery, pp. 1–14. ISBN: 9781450359702. DOI: 10.1145/3290605.3300718.

Feng Han, Yifei Cheng, Megan Strachan, and Xiaojuan Ma (2021). "Hybrid Paper-Digital Interfaces: A Systematic Literature Review." In: *Designing Interactive Systems Conference 2021*. DIS '21. Virtual Event, USA: Association for Computing Machinery, pp. 1087–1100. ISBN: 9781450384766. DOI: 10.1145/3461778.3462059.

Teng Han, Shubhi Bansal, Xiaochen Shi, Yanjun Chen, Baogang Quan, Feng Tian, Hongan Wang, and Sriram Subramanian (2020). "HapBead: On-Skin Microfluidic Haptic Interface using Tunable Bead." In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. Honolulu HI USA: ACM, pp. 1–10. ISBN: 978-1-4503-6708-0. DOI: 10.1145/3313831.3376190.

Ollie Hanton, Michael Wessely, Stefanie Mueller, Mike Fraser, and Anne Roudaut (2020). "ProtoSpray: Combining 3D Printing and Spraying to Create Interactive Displays with Arbitrary Shapes." In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI '20. Honolulu, HI, USA: Association for Computing Machinery, pp. 1–13. ISBN: 9781450367080. DOI: 10.1145/3313831.3376543.

Chris Harrison and Scott E. Hudson (2009). "Providing Dynamically Changeable Physical Buttons on a Visual Display." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '09. Boston, MA, USA: Association for Computing Machinery, pp. 299–308. ISBN: 9781605582467. DOI: 10.1145/1518701.1518749.

Jess Hartcher-O'Brien, Jeremy Evers, and Erik Tempelman (2019). "Surface roughness of 3D printed materials: Comparing physical measurements and human perception." In: *Materials Today Communications* 19, pp. 300–305. ISSN: 23524928. DOI: 10.1016/j.mtcomm.2019.01.008.

Keisuke Hasegawa, Liwei Qiu, and Hiroyuki Shinoda (2018). "Midair Ultrasound Fragrance Rendering." In: *IEEE Transactions on Visualization and Computer Graphics* 24.4, pp. 1477–1485. ISSN: 1077-2626. DOI: 10.1109/TVCG.2018.2794118.

Mahmoud Hassan, Florian Daiber, Frederik Wiehr, Felix Kosmalla, and Antonio Krüger (2017). "FootStriker: An EMS-based Foot Strike Assistant for Running." In: *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 1.1, pp. 1–18. ISSN: 2474-9567. DOI: 10.1145/3053332.

Vincent Hayward, Oliver R. Astley, Manuel Cruz-Hernandez, Danny Grant, and Gabriel Robles-De-La-Torre (2004). "Haptic interfaces and devices." In: *Sensor Review* 24.1, pp. 16–29. ISSN: 0260-2288. DOI: 10.1108/02602280410515770.

Morton Leonard Heilig (1992). "El Cine Del Futuro: The Cinema of the Future." In: *Presence: Teleoper. Virtual Environ.* 1.3, pp. 279–294. ISSN: 1054-7460.

Morton A. Heller (1982). "Visual and tactual texture perception: Intersensory cooperation." In: *Perception & Psychophysics* 31.4, pp. 339–344. ISSN: 0031-5117, 1532-5962. DOI: 10.3758/BF03202657.

Seongkook Heo, Jaeyeon Lee, and Daniel Wigdor (2019). "PseudoBend: Producing Haptic Illusions of Stretching, Bending, and Twisting Using Grain Vibrations." In: *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. UIST '19. New Orleans, LA, USA: Association for Computing Machinery, pp. 803–813. ISBN: 9781450368162. DOI: 10.1145/3332165.3347941.

Negin Heravi, Wenzhen Yuan, Allison M. Okamura, and Jeannette Bohg (2020). "Learning an Action-Conditional Model for Haptic Texture Generation." In: *2020 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 11088–11095. DOI: 10.1109/ICRA40945.2020.9197447.

Anuruddha Hettiarachchi and Daniel Wigdor (2016). "Annexing Reality: Enabling Opportunistic Use of Everyday Objects as Tangible Proxies in Augmented Reality." In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI '16. San Jose, California, USA: Association for Computing Machinery, pp. 1957–1967. ISBN: 9781450333627. DOI: 10.1145/2858036.2858134.

James M. Hillis, Marc O. Ernst, Martin S. Banks, and Michael S. Landy (2002). "Combining Sensory Information: Mandatory Fusion Within, but Not Between, Senses." In: *Science* 298.5598, pp. 1627–1630. DOI: 10.1126/science.1075396.

Ronan Hinchet, Velko Vechev, Herbert Shea, and Otmar Hilliges (2018). "DextrES: Wearable Haptic Feedback for Grasping in VR via a Thin Form-Factor Electrostatic Brake." In: *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*. UIST '18. Berlin, Germany: Association for Computing Machinery, pp. 901–912. ISBN: 9781450359481. DOI: 10.1145/3242587.3242657.

Ken Hinckley, Randy Pausch, John C. Goble, and Neal F. Kassell (1994). "Passive Real-World Interface Props for Neurosurgical Visualization." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '94. Boston, Massachusetts, USA: Association for Computing Machinery, pp. 452–458. ISBN: 0897916506. DOI: 10.1145/191666.191821.

Leanne Hinton, Johanna Nichols, and John J. Ohala, eds. (1995). *Sound Symbolism*. Cambridge University Press. DOI: 10.1017/cbo9780511751806.

Yuichi Hirano, Asako Kimura, Fumihisa Shibata, and Hideyuki Tamura (2011). "Psychophysical influence of mixed-reality visual stimulation on sense of hardness." In: *2011 IEEE Virtual Reality Conference*. Singapore, Singapore: IEEE, pp. 51–54. ISBN: 978-1-4577-0039-2. DOI: 10.1109/VR.2011.5759436.

Hunter G. Hoffman, Jerrold Prothero, Maxwell J. Wells, and Joris Groen (1998). "Virtual Chess: Meaning Enhances Users' Sense of Presence in Virtual Environments." In: *International Journal of Human-Computer Interaction* 10.3, pp. 251–263. ISSN: 1044-7318, 1532-7590. DOI: 10.1207/s15327590ijhc1003_3.

Hiroki Hojo, Nozomi Nomachi, Yutaro Tomoto, Tsuyoshi Nakamura, Masayoshi Kanoh, and Koji Yamada (2014). "Fundamental Study for Verbalization of Embodied Expertise based on Pattern Recognition." In: *2014 IIAI 3rd International Conference on Advanced Applied Informatics*, pp. 925–929. DOI: 10.1109/IIAI-AAI.2014.182.

Mark Hollins, Sliman Bensmaïa, Kristie Karlof, and Forrest Young (2000). “Individual differences in perceptual space for tactile textures: Evidence from multidimensional scaling.” In: *Perception & Psychophysics* 62.8, pp. 1534–1544. ISSN: 1532-5962. DOI: 10.3758/BF03212154.

Mark Hollins, Richard Faldowski, Suman Rao, and Forrest Young (1993). “Perceptual dimensions of tactile surface texture: A multidimensional scaling analysis.” In: *Perception & Psychophysics* 54.6, pp. 697–705. ISSN: 1532-5962. DOI: 10.3758/BF03211795.

Mark Hollins and S. Ryan Risner (2000). “Evidence for the duplex theory of tactile texture perception.” In: *Perception & Psychophysics* 62.4, pp. 695–705. ISSN: 0031-5117, 1532-5962. DOI: 10.3758/BF03206916.

Kyungpyo Hong, Jaebong Lee, and Seungmoon Choi (2013). “Demonstration-Based Vibrotactile Pattern Authoring.” In: *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*. TEI ’13. Barcelona, Spain: Association for Computing Machinery, pp. 219–222. ISBN: 9781450318983. DOI: 10.1145/2460625.2460660.

Cedric Honnet, Hannah Perner-Wilson, Marc Teyssier, Bruno Fruchard, Jürgen Steimle, Ana C. Baptista, and Paul Strohmeier (2020). “PolySense: Augmenting Textiles with Electrical Functionality Using In-Situ Polymerization.” In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI ’20. Honolulu, HI, USA: Association for Computing Machinery, pp. 1–13. ISBN: 9781450367080. DOI: 10.1145/3313831.3376841.

Stephanie Houde and Charles Hill (1997). “What do Prototypes Prototype?” In: *Handbook of Human-Computer Interaction (Second Edition)*. Ed. by Marting G. Helander, Thomas K. Landauer, and Prasad V. Prabhu. Second Edition. Amsterdam: North-Holland, pp. 367–381. ISBN: 978-0-444-81862-1. DOI: 10.1016/B978-044481862-1.50082-0.

Kunpeng Huang, Ruojia Sun, Ximeng Zhang, Md. Tahmidul Islam Molla, Margaret Dunne, Francois Guimbretiere, and Cindy Hsin-Liu Kao (2021). “WovenProbe: Probing Possibilities for Weaving Fully-Integrated On-Skin Systems Deployable in the Field.” In: *Designing Interactive Systems Conference 2021*. DIS ’21. Virtual Event, USA: Association for Computing Machinery, pp. 1143–1158. ISBN: 9781450384766. DOI: 10.1145/3461778.3462105.

Da-Yuan Huang, Liwei Chan, Xiao-Feng Jian, Chiun-Yao Chang, Mu-Hsuan Chen, De-Nian Yang, Yi-Ping Hung, and Bing-Yu Chen (2016). “Vibroplay: authoring three-dimensional spatial-temporal tactile effects with direct manipulation.” In: *SIGGRAPH ASIA 2016 Emerging Technologies*. Macau: ACM, pp. 1–2. ISBN: 978-1-4503-4539-2. DOI: 10.1145/2988240.2988250.

Scott E. Hudson (2014). “Printing Teddy Bears: A Technique for 3D Printing of Soft Interactive Objects.” In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’14. Toronto, Ontario, Canada: Association for Computing Machinery, pp. 459–468. ISBN: 9781450324731. DOI: 10.1145/2556288.2557338.

Johannes Hummel, Janki Dodiya, German Aerospace Center, Laura Eckardt, Robin Wolff, Andreas Gerndt, and Torsten W. Kuhlen (2016). “A lightweight electrotactile feedback device for grasp improvement in immersive virtual environments.” In: *2016 IEEE Virtual Reality (VR)*. Greenville, SC: IEEE, pp. 39–48. ISBN: 978-1-5090-0836-0. DOI: 10.1109/VR.2016.7504686.

Robert W. G. Hunt (2004). *The Reproduction of Colour*. 6th ed. The Wiley-IS&T Series in Imaging Science and Technology. Hoboken, NJ: Wiley-Blackwell.

Fabian Hutmacher (2019). “Why Is There So Much More Research on Vision Than on Any Other Sensory Modality?” In: *Frontiers in Psychology* 10, p. 2246. ISSN: 1664-1078. DOI: 10.3389/fpsyg.2019.02246.

Wijnand A. IJsselsteijn, Huib de Ridder, Jonathan Freeman, and Steve E. Avons (2000). “Presence: concept, determinants, and measurement.” In: ed. by Bernice E. Rogowitz and Thrasyvoulos N. Pappas. San Jose, CA, pp. 520–529. DOI: 10.1117/12.387188.

Brent Edward Insko (2001). “Passive Haptics Significantly Enhances Virtual Environments.” PhD thesis. USA: University of North Carolina at Chapel Hill. ISBN: 0-493-17286-6. URL: http://www.cs.unc.edu/techreports/01-017.pdf.

Interhaptics (2021). *Haptic Composer*. URL: https://www.interhaptics.com/haptic-composer.

Alexandra Ion, Johannes Frohnhofen, Ludwig Wall, Robert Kovacs, Mirela Alistar, Jack Lindsay, Pedro Lopes, Hsiang-Ting Chen, and Patrick Baudisch (2016). "Metamaterial Mechanisms." In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology.* Tokyo Japan: ACM, pp. 529–539. ISBN: 978-1-4503-4189-9. DOI: 10.1145/2984511.2984540.

Alexandra Ion, Robert Kovacs, Oliver S. Schneider, Pedro Lopes, and Patrick Baudisch (2018). "Metamaterial Textures." In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems.* Montreal QC Canada: ACM, pp. 1–12. ISBN: 978-1-4503-5620-6. DOI: 10.1145/3173574.3173910.

Ali Israr, Hong Z. Tan, and Charlotte M. Reed (2006). "Frequency and amplitude discrimination along the kinesthetic-cutaneous continuum in the presence of masking stimuli." In: *The Journal of the Acoustical Society of America* 120.5, pp. 2789–2800. DOI: 10.1121/1.2354022.

Ali Israr, Siyan Zhao, Kaitlyn Schwalje, Roberta Klatzky, and Jill Lehman (2014). "Feel Effects: Enriching Storytelling with Haptic Feedback." In: *ACM Transactions on Applied Perception* 11.3, pp. 1–17. ISSN: 1544-3558, 1544-3965. DOI: 10.1145/2641570.

Takayuki Iwamoto, Mari Tatezono, and Hiroyuki Shinoda (2008). "Non-contact Method for Producing Tactile Sensation Using Airborne Ultrasound." In: *Haptics: Perception, Devices and Scenarios.* Ed. by Manuel Ferre. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 504–513. ISBN: 978-3-540-69057-3.

Hiroo Iwata (1993). "Pen-Based Haptic Virtual Environment." In: *Proceedings of the 1993 IEEE Virtual Reality Annual International Symposium.* VRAIS '93. USA: IEEE Computer Society, pp. 287–292. ISBN: 0780313631. DOI: 10.1109/VRAIS.1993.380767.

Hiroo Iwata, Hiroaki Yano, Fumitaka Nakaizumi, and Ryo Kawamura (2001). "Project FEELEX: adding haptic surface to graphics." In: *Proceedings of the 28th annual conference on Computer graphics and interactive techniques - SIGGRAPH '01.* Not Known: ACM Press, pp. 469–476. ISBN: 978-1-58113-374-5. DOI: 10.1145/383259.383314.

Yvonne Jansen, Thorsten Karrer, and Jan Borchers (2010). "MudPad: tactile feedback and haptic texture overlay for touch surfaces." In: *ACM International Conference on Interactive Tabletops and Surfaces - ITS '10.* Saarbrücken, Germany: ACM Press, p. 11. ISBN: 978-1-4503-0399-6. DOI: 10.1145/1936652.1936655.

Cathrine V. Jansson-Boyd (2011). "Touch matters: exploring the relationship between consumption and tactile interaction." In: *Social Semiotics* 21.4, pp. 531–546. DOI: 10.1080/10350330.2011.591996.

Seokhee Jeon and Seungmoon Choi (2009). "Haptic Augmented Reality: Taxonomy and an Example of Stiffness Modulation." In: *Presence: Teleoperators and Virtual Environments* 18.5, pp. 387–408. ISSN: 1054-7460. DOI: 10.1162/pres.18.5.387.

Jason Jerald (2016). *The VR book: human-centered design for virtual reality.* ACM books. New York] [San Rafael, California: Association for computing machinery Morgan & Claypool publishers. ISBN: 978-1-970001-12-9.

Stefan Jeschke, David Cline, and Peter Wonka (2009). "Rendering Surface Details with Diffusion Curves." In: *ACM Trans. Graph.* 28.5, pp. 1–8. ISSN: 0730-0301. DOI: 10.1145/1618452.1618463.

Kenneth O. Johnson (2001). "The roles and functions of cutaneous mechanoreceptors." In: *Current Opinion in Neurobiology* 11.4, pp. 455–461. ISSN: 09594388. DOI: 10.1016/S0959-4388(00)00234-8.

Micah K. Johnson and Edward H. Adelson (2009). "Retrographic sensing for the measurement of surface texture and shape." In: *2009 IEEE Conference on Computer Vision and Pattern Recognition.* Miami, FL: IEEE, pp. 1070–1077. ISBN: 978-1-4244-3992-8. DOI: 10.1109/CVPR.2009.5206534.

Micah K. Johnson, Forrester Cole, Alvin Raj, and Edward H. Adelson (2011). "Microgeometry Capture Using an Elastomeric Sensor." In: *ACM Transactions on Graphics* 30.4. ISSN: 0730-0301. DOI: 10.1145/2010324.1964941.

Lynette A. Jones (2000). "Kinesthetic Sensing." In: *in human and machine haptics.* MIT Press.

Azusa Kadomura and Itiro Siio (2014). "MagNail: augmenting nails with a magnet to detect user actions using a smart device." In: *Proceedings of the 2014 ACM International Symposium on Wearable Computers.* Seattle Washington: ACM, pp. 135–136. ISBN: 978-1-4503-2969-9. DOI: 10.1145/2634317.2634333.

K. Kaeppler and F. Mueller (2013). "Odor Classification: A Review of Factors Influencing Perception-Based Odor Arrangements." In: *Chemical Senses* 38.3, pp. 189–209. ISSN: 0379-864X, 1464-3553. DOI: 10.1093/chemse/bjs141.

Mirela Kahrimanovic, Wouter M. Bergmann Tiest, and Astrid M. L. Kappers (2009). “Context effects in haptic perception of roughness.” In: *Experimental Brain Research* 194.2, pp. 287–297. ISSN: 0014-4819, 1432-1106. DOI: 10.1007/s00221-008-1697-x.

Hiroyuki Kajimoto (2011). “Enlarged electro-tactile display with repeated structure.” In: *2011 IEEE World Haptics Conference*. Istanbul: IEEE, pp. 575–579. ISBN: 978-1-4577-0299-0. DOI: 10.1109/WHC.2011.5945549.

Hiroyuki Kajimoto (2016). “Electro-tactile Display: Principle and Hardware.” In: *Pervasive Haptics*. Ed. by Hiroyuki Kajimoto, Satoshi Saga, and Masashi Konyo. Tokyo: Springer Japan, pp. 79–96. ISBN: 978-4-431-55771-5. DOI: 10.1007/978-4-431-55772-2_5.

Kasun Karunanayaka, Nurafiqah Johari, Surina Hariri, Hanis Camelia, Kevin Stanley Bielawski, and Adrian David Cheok (2018). “New Thermal Taste Actuation Technology for Future Multisensory Virtual Reality and Internet.” In: *IEEE Transactions on Visualization and Computer Graphics* 24.4, pp. 1496–1505. ISSN: 1077-2626. DOI: 10.1109/TVCG.2018.2794073.

Kunihiro Kato, Hiroki Ishizuka, Hiroyuki Kajimoto, and Homei Miyashita (2018). “Double-Sided Printed Tactile Display with Electro Stimuli and Electrostatic Forces and Its Assessment.” In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI ’18. Montreal QC, Canada: Association for Computing Machinery, pp. 1–12. ISBN: 9781450356206. DOI: 10.1145/3173574.3174024.

David Katz and Lester E. Krueger (1989). *The World of Touch*. Hillsdale, NJ, USA: Lawrence Erlbaum Associates. ISBN: 978-0-8058-0529-1.

Oliver Beren Kaul, Leonard Hansing, and Michael Rohs (2019). “3DTactileDraw: A Tactile Pattern Design Interface for Complex Arrangements of Actuators.” In: *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI EA ’19. Glasgow, Scotland Uk: Association for Computing Machinery, pp. 1–6. ISBN: 9781450359719. DOI: 10.1145/3290607.3313030.

S. Khalil, J. Nam, and W. Sun (2005). “Multi-nozzle deposition for construction of 3D biopolymer tissue scaffolds.” In: *Rapid Prototyping Journal* 11.1, pp. 9–17. ISSN: 1355-2546. DOI: 10.1108/13552540510573347.

Mohamed Khamis, Nora Schuster, Ceenu George, and Max Pfeiffer (2019). “ElectroCutscenes: Realistic Haptic Feedback in Cutscenes of Virtual Reality Games Using Electric Muscle Stimulation.” In: *25th ACM Symposium on Virtual Reality Software and Technology*. VRST ’19. Parramatta, NSW, Australia: Association for Computing Machinery. ISBN: 9781450370011. DOI: 10.1145/3359996.3364250.

Rebecca P. Khurshid, Naomi T. Fitter, Elizabeth A. Fedalei, and Katherine J. Kuchenbecker (2017). “Effects of Grip-Force, Contact, and Acceleration Feedback on a Teleoperated Pick-and-Place Task.” In: *IEEE Transactions on Haptics* 10.1, pp. 40–53. ISSN: 1939-1412. DOI: 10.1109/TOH.2016.2573301.

Erin Kim and Oliver Schneider (2020). “Defining Haptic Experience: Foundations for Understanding, Communicating, and Evaluating HX.” In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. Honolulu HI USA: ACM, pp. 1–13. ISBN: 978-1-4503-6708-0. DOI: 10.1145/3313831.3376280.

Jeeeun Kim, Qingnan Zhou, Amanda Ghassaei, and Xiang ’Anthony’ Chen (2021a). “OmniSoft: A Design Tool for Soft Objects by Example.” In: *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI ’21. Salzburg, Austria: Association for Computing Machinery. ISBN: 9781450382137. DOI: 10.1145/3430524.3440634.

Jin Hee (Heather) Kim, Kunpeng Huang, Simone White, Melissa Conroy, and Cindy Hsin-Liu Kao (2021b). “KnitDermis: Fabricating Tactile On-Body Interfaces Through Machine Knitting.” In: *Designing Interactive Systems Conference 2021*. DIS ’21. Virtual Event, USA: Association for Computing Machinery, pp. 1183–1200. ISBN: 9781450384766. DOI: 10.1145/3461778.3462007.

Lawrence H. Kim and Sean Follmer (2019). “SwarmHaptics: Haptic Display with Swarm Robots.” In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI ’19. Glasgow, Scotland Uk: Association for Computing Machinery, pp. 1–13. ISBN: 9781450359702. DOI: 10.1145/3290605.3300918.

Frederick A. A. Kingdom and Nicolaas Prins (2016). *Psychophysics: a practical introduction*. Second edition. Amsterdam: Elsevier/Academic Press. ISBN: 978-0-12-407156-8.

Robert Kirkman and Tony Moore (2004). *The Walking Dead #5*. The Walking Dead. California, USA: Image Comics.

Itaru Kitahara, Morio Nakahara, and Yuichi Oht (2010). “Sensory Properties in Fusion of Visual/Haptic Stimuli Using Mixed Reality.” In: *Advances in Haptics*. Ed. by Mehrdad Hosseini. InTech. ISBN: 978-953-307-093-3. DOI: 10.5772/8712.

Konstantin Klamka and Raimund Dachselt (2017). “IllumiPaper: Illuminated Interactive Paper.” In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI ’17. Denver, Colorado, USA: Association for Computing Machinery, pp. 5605–5618. ISBN: 9781450346559. DOI: 10.1145/3025453.3025525.

Konstantin Klamka and Raimund Dachselt (2018). “Pushables: A DIY Approach for Fabricating Customizable and Self-Contained Tactile Membrane Dome Switches.” In: *The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings*. UIST ’18 Adjunct. Berlin, Germany: Association for Computing Machinery, pp. 1–4. ISBN: 9781450359498. DOI: 10.1145/3266037.3266082.

Roberta L. Klatzky, Susan J. Lederman, and Dana E. Matula (1993). “Haptic exploration in the presence of vision.” In: *Journal of Experimental Psychology: Human Perception and Performance* 19.4, pp. 726–743. ISSN: 1939-1277, 0096-1523. DOI: 10.1037/0096-1523.19.4.726.

Roberta L. Klatzky, Susan J. Lederman, and Catherine Reed (1987). “There’s more to touch than meets the eye: The salience of object attributes for haptics with and without vision.” In: *Journal of Experimental Psychology: General* 116.4, pp. 356–369. DOI: 10.1037/0096-3445.116.4.356.

Pascal Kockwelp, Anna Junga, Dimitar Valkov, Bernhard Marschall, Markus Holling, and Benjamin Risse (2022). “Towards VR Simulation-Based Training in Brain Death Determination.” In: *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 287–292. DOI: 10.1109/VRW55335.2022.00065.

Luv Kohli (2013). “Redirected touching.” PhD thesis. The University of North Carolina at Chapel Hill.

Luv Kohli, Eric Burns, Dorian Miller, and Henry Fuchs (2005). “Combining Passive Haptics with Redirected Walking.” In: *Proceedings of the 2005 International Conference on Augmented Tele-Existence*. ICAT ’05. Christchurch, New Zealand: Association for Computing Machinery, pp. 253–254. ISBN: 0473106574. DOI: 10.1145/1152399.1152451.

Georgios Korres, Tamas Aujeszky, and Mohamad Eid (2017). “Characterizing tactile rendering parameters for ultrasound based stimulation.” In: *2017 IEEE World Haptics Conference (WHC)*. Munich, Germany: IEEE, pp. 293–298. ISBN: 978-1-5090-1425-5. DOI: 10.1109/WHC.2017.7989917.

Georgios Korres and Mohamad Eid (2016). “Haptogram: Ultrasonic Point-Cloud Tactile Stimulation.” In: *IEEE Access* 4, pp. 7758–7769. ISSN: 2169-3536. DOI: 10.1109/ACCESS.2016.2608835.

Robert Kovacs, Eyal Ofek, Mar Gonzalez Franco, Alexa Fay Siu, Sebastian Marwecki, Christian Holz, and Mike Sinclair (2020). “Haptic PIVOT: On-Demand Handhelds in VR.” In: *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. UIST ’20. Virtual Event, USA: Association for Computing Machinery, pp. 1046–1059. ISBN: 9781450375146. DOI: 10.1145/3379337.3415854.

Joseph B. Kruskal (1964). “Multidimensional scaling by optimizing goodness of fit to a nonmetric hypothesis.” In: *Psychometrika* 29.1, pp. 1–27. ISSN: 0033-3123, 1860-0980. DOI: 10.1007/BF02289565.

Rakhesh Singh Kshetrimayum (2005). “A brief intro to metamaterials.” In: *IEEE Potentials* 23.5, pp. 44–46. DOI: 10.1109/MP.2005.1368916.

Katherine J. Kuchenbecker (2008). “Haptography: Capturing the Feel of Real Objects to Enable Authentic Haptic Rendering (Invited Paper).” In: *Proceedings of the First International Conference on Ambient Media and Systems*. Quebec, Canada: ICST. ISBN: 978-963-9799-16-5. DOI: 10.4108/ICST.AMBISYS2008.2815.

Katherine J. Kuchenbecker, Jonathan Fiene, and Günter Niemeyer (2006). “Improving contact realism through event-based haptic feedback.” In: *IEEE Transactions on Visualization and Computer Graphics* 12.2, pp. 219–230. ISSN: 1077-2626. DOI: 10.1109/TVCG.2006.32.

Katherine J. Kuchenbecker, Joseph Romano, and William McMahan (2011). “Haptography: Capturing and Recreating the Rich Feel of Real Surfaces.” In: *Robotics Research*. Ed. by Cédric Pradalier, Roland Siegwart, and Gerhard Hirzinger. Vol. 70. Springer Tracts in Advanced Robotics. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 245–260. ISBN: 978-3-642-19456-6. DOI: 10.1007/978-3-642-19457-3_15.

Ron Kurtus (2005). *Determining the Coefficient of Friction.* URL: https://nfsi.org/wp-content/uploads/2013/10/Determining.pdf (visited on 2022-08-10).

Eun Kwon, Gerard J. Kim, and Sangyoon Lee (2009). "Effects of sizes and shapes of props in tangible augmented reality." In: *2009 8th IEEE International Symposium on Mixed and Augmented Reality.* Orlando, FL, USA: IEEE, pp. 201–202. ISBN: 978-1-4244-5390-0. DOI: 10.1109/ISMAR.2009.5336463.

Jochen Lang and Sheldon Andrews (2011). "Measurement-Based Modeling of Contact Forces and Textures for Haptic Rendering." In: *IEEE Transactions on Visualization and Computer Graphics* 17.3, pp. 380–391. ISSN: 1077-2626. DOI: 10.1109/TVCG.2010.52.

Gierad Laput, Xiang 'Anthony' Chen, and Chris Harrison (2015). "3D Printed Hair: Fused Deposition Modeling of Soft Strands, Fibers, and Bristles." In: *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology.* UIST '15. Charlotte, NC, USA: Association for Computing Machinery, pp. 593–597. ISBN: 9781450337793. DOI: 10.1145/2807442.2807484.

Eldy S. Lazaro Vasquez, Netta Ofer, Shanel Wu, Mary Etta West, Mirela Alistar, and Laura Devendorf (2022). "Exploring Biofoam as a Material for Tangible Interaction." In: *Designing Interactive Systems Conference.* Virtual Event Australia: ACM, pp. 1525–1539. ISBN: 978-1-4503-9358-4. DOI: 10.1145/3532106.3533494.

Mathieu Le Goc, Lawrence H. Kim, Ali Parsaei, Jean-Daniel Fekete, Pierre Dragicevic, and Sean Follmer (2016). "Zooids: Building Blocks for Swarm User Interfaces." In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology.* UIST '16. Tokyo, Japan: Association for Computing Machinery, pp. 97–109. ISBN: 9781450341899. DOI: 10.1145/2984511.2984547.

Anatole Lecuyer, Sabine Coquillart, Abderrahmane Kheddar, Paul Richard, and Philippe Coiffet (2000). "Pseudo-haptic feedback: can isometric input devices simulate force feedback?" In: *Proceedings IEEE Virtual Reality 2000 (Cat. No.00CB37048).* New Brunswick, NJ, USA: IEEE Computer Society, pp. 83–90. ISBN: 978-0-7695-0478-0. DOI: 10.1109/VR.2000.840369.

Anatole Lécuyer (2009). "Simulating Haptic Feedback Using Vision: A Survey of Research and Applications of Pseudo-Haptic Feedback." In: *Presence: Teleoperators and Virtual Environments* 18.1, pp. 39–53. ISSN: 1054-7460. DOI: 10.1162/pres.18.1.39.

Susan J. Lederman and Susan G. Abbott (1981). "Texture perception: Studies of intersensory organization using a discrepancy paradigm, and visual versus tactual psychophysics." In: *Journal of Experimental Psychology: Human Perception and Performance* 7.4, pp. 902–915. DOI: 10.1037/0096-1523.7.4.902.

Susan J. Lederman and Roberta L. Klatzky (1987). "Hand movements: A window into haptic object recognition." In: *Cognitive Psychology* 19.3, pp. 342–368. ISSN: 0010-0285. DOI: https://doi.org/10.1016/0010-0285(87)90008-9.

Susan J. Lederman and Roberta L. Klatzky (2009). "Haptic perception: A tutorial." In: *Attention, Perception & Psychophysics* 71.7, pp. 1439–1459. ISSN: 1943-3921, 1943-393X. DOI: 10.3758/APP.71.7.1439.

Susan J. Lederman, Georgie Thorne, and Bill Jones (1986). "Perception of texture by vision and touch: Multidimensionality and intersensory integration." In: *Journal of Experimental Psychology: Human Perception and Performance* 12.2, pp. 169–180. DOI: 10.1037/0096-1523.12.2.169.

David Ledo, Miguel A. Nacenta, Nicolai Marquardt, Sebastian Boring, and Saul Greenberg (2012). "The HapticTouch Toolkit: Enabling Exploration of Haptic Interactions." In: *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction.* TEI '12. Kingston, Ontario, Canada: Association for Computing Machinery, pp. 115–122. ISBN: 9781450311748. DOI: 10.1145/2148131.2148157.

Chi-Jung Lee, Hsin-Ruey Tsai, and Bing-Yu Chen (2021). "HairTouch: Providing Stiffness, Roughness and Surface Height Differences Using Reconfigurable Brush Hairs on a VR Controller." In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems.* Yokohama Japan: ACM, pp. 1–13. ISBN: 978-1-4503-8096-6. DOI: 10.1145/3411764.3445285.

Jaebong Lee and Seungmoon Choi (2012). "Evaluation of vibrotactile pattern design using vibrotactile score." In: *2012 IEEE Haptics Symposium (HAPTICS).* Vancouver, BC, Canada: IEEE, pp. 231–238. ISBN: 978-1-4673-0809-0. DOI: 10.1109/HAPTIC.2012.6183796.

Jaebong Lee, Jonghyun Ryu, and Seungmoon Choi (2009). "Vibrotactile score: A score metaphor for designing vibrotactile patterns." In: *World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic*

Interfaces for Virtual Environment and Teleoperator Systems. Salt Lake City, UT, USA: IEEE, pp. 302–307. ISBN: 978-1-4244-3858-7. DOI: 10.1109/WHC.2009.4810816.

Jaeyeon Lee, Mike Sinclair, Mar Gonzalez-Franco, Eyal Ofek, and Christian Holz (2019). "TORC: A Virtual Reality Controller for In-Hand High-Dexterity Finger Interaction." In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems.* CHI '19. Glasgow, Scotland Uk: Association for Computing Machinery, pp. 1–13. ISBN: 9781450359702. DOI: 10.1145/3290605.3300301.

Akiko Iesaki, Akihiro Somada, Asako Kimura, Fumihisa Shibata, and Hideyuki Tamura (2008). "Psychophysical Influence on Tactual Impression by Mixed-Reality Visual Stimulation." In: *2008 IEEE Virtual Reality Conference.* Reno, NV, USA: IEEE, pp. 265–266. ISBN: 978-1-4244-1971-5. DOI: 10.1109/VR.2008.4480793.

Rui Li, Robert Platt, Wenzhen Yuan, Andreas ten Pas, Nathan Roscup, Mandayam A. Srinivasan, and Edward Adelson (2014). "Localization and manipulation of small parts using GelSight tactile sensing." In: *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 3988–3993. DOI: 10.1109/iros.2014.6943123.

Anan Lin, Meike Scheller, Feng Feng, Michael J Proulx, and Oussama Metatla (2021). "Feeling Colours: Crossmodal Correspondences Between Tangible 3D Objects, Colours and Emotions." In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems.* Yokohama Japan: ACM, pp. 1–12. ISBN: 978-1-4503-8096-6. DOI: 10.1145/3411764.3445373.

Robert W. Lindeman (1999). "Bimanual Interaction, Passive-Haptic Feedback, 3D Widget Representation, and Simulated Surface Constraints for Interaction In Immersive Virtual Environments." PhD thesis. Washington, DC, USA: George Washington University.

Lijuan Liu, Jiahao Guo, Chao Zhang, Zhangzhi Wang, Pinqi Zhu, Tuo Fang, Junwu Wang, Cheng Yao, and Fangtian Ying (2021). "ElectroPaper: Design and Fabrication of Paper-Based Electronic Interfaces for the Water Environment." In: *Electronics* 10.5. ISSN: 2079-9292. DOI: 10.3390/electronics10050604.

Jo-Yu Lo, Da-Yuan Huang, Chen-Kuo Sun, Chu-En Hou, and Bing-Yu Chen (2018). "RollingStone: Using Single Slip Taxel for Enhancing Active Finger Exploration with a Virtual Reality Controller." In: *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology.* UIST '18. Berlin, Germany: Association for Computing Machinery, pp. 839–851. ISBN: 9781450359481. DOI: 10.1145/3242587.3242627.

Gwilym Lockwood and Mark Dingemanse (2015). "Iconicity in the lab: a review of behavioral, developmental, and neuroimaging research into sound-symbolism." In: *Frontiers in Psychology* 6. ISSN: 1664-1078. DOI: 10.3389/fpsyg.2015.01246.

Lofelt (2021). *Lofelt Studio.* URL: https://lofelt.com/design.

Benjamin Long, Sue Ann Seah, Tom Carter, and Sriram Subramanian (2014). "Rendering Volumetric Haptic Shapes in Mid-Air Using Ultrasound." In: *ACM Trans. Graph.* 33.6. ISSN: 0730-0301. DOI: 10.1145/2661229.2661257.

Robert Longo (1995). *Johnny Mnemonic.* URL: https://www.imdb.com/title/tt0113481/ (visited on 2022-08-01).

Jack M. Loomis and Susan J. Lederman (1986). "Tactual perception." In: *Handbook of perception and human performance, Vol. 2: Cognitive processes and performance.* Oxford, England: John Wiley & Sons, pp. 1–41. ISBN: 0-471-82956-0.

Pedro Lopes and Patrick Baudisch (2017a). "Immense Power in a Tiny Package: Wearables Based on Electrical Muscle Stimulation." In: *IEEE Pervasive Computing* 16.03, pp. 12–16. ISSN: 1558-2590. DOI: 10.1109/MPRV.2017.2940953.

Pedro Lopes and Patrick Baudisch (2017b). "Interactive Systems Based on Electrical Muscle Stimulation." In: *Computer* 50.10, pp. 28–35. ISSN: 1558-0814. DOI: 10.1109/MC.2017.3641627.

Pedro Lopes, Alexandra Ion, and Patrick Baudisch (2015a). "Impacto: Simulating Physical Impact by Combining Tactile Stimulation with Electrical Muscle Stimulation." In: *Proceedings of the 28th Annual ACM Symposium on User Interface Software and Technology.* UIST '15. Charlotte, NC, USA: Association for Computing Machinery, pp. 11–19. ISBN: 9781450337793. DOI: 10.1145/2807442.2807443.

Pedro Lopes, Patrik Jonell, and Patrick Baudisch (2015b). "Affordance++: Allowing Objects to Communicate Dynamic Use." In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems.*

CHI '15. Seoul, Republic of Korea: Association for Computing Machinery, pp. 2515–2524. ISBN: 9781450331456. DOI: 10.1145/2702123.2702128.

Pedro Lopes, Sijing You, Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch (2017). "Providing Haptics to Walls & Heavy Objects in Virtual Reality by Means of Electrical Muscle Stimulation." In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. Denver, Colorado, USA: Association for Computing Machinery, pp. 1471–1482. ISBN: 9781450346559. DOI: 10.1145/3025453.3025600.

Pedro Lopes, Sijing You, Alexandra Ion, and Patrick Baudisch (2018). "Adding Force Feedback to Mixed Reality Experiences and Games Using Electrical Muscle Stimulation." In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: Association for Computing Machinery, pp. 1–13. ISBN: 9781450356206. DOI: 10.1145/3173574.3174020.

Lin Lu, Andrei Sharf, Haisen Zhao, Yuan Wei, Qingnan Fan, Xuelin Chen, Yann Savoye, Changhe Tu, Daniel Cohen-Or, and Baoquan Chen (2014). "Build-to-Last: Strength to Weight 3D Printed Objects." In: *ACM Trans. Graph.* 33.4. ISSN: 0730-0301. DOI: 10.1145/2601097.2601168.

Shihan Lu, Mianlun Zheng, Matthew C. Fontaine, Stefanos Nikolaidis, and Heather Marie Culbertson (2022). "Preference-Driven Texture Modeling Through Interactive Generation and Search." In: *IEEE Transactions on Haptics*, pp. 1–1. DOI: 10.1109/TOH.2022.3173935.

Zhou Ma and Pinhas Ben-Tzvi (2015). "RML Glove—An Exoskeleton Glove Mechanism With Haptics Feedback." In: *IEEE/ASME Transactions on Mechatronics* 20.2, pp. 641–652. ISSN: 1083-4435, 1941-014X. DOI: 10.1109/TMECH.2014.2305842.

Karon Maclean and Mario Enriquez (2003). "Perceptual design of haptic icons." In: *Proceedings of Eurohaptics*, pp. 351–363. URL: https://citeseer.ist.psu.edu/viewdoc/summary?doi=10.1.1.138.6172.

Karon E. MacLean (1996). "The 'haptic' camera: a technique for characterizing and playing back haptic properties of real environments." In: *Proceedings ASME Dynamic Systems and Control Division DSC*. Vol. 58. Atlanta, Georgia, United States: The American Society of Mechanical Engineers, pp. 459–467.

Karon E. MacLean (2008). "Haptic Interaction Design for Everyday Interfaces." In: *Reviews of Human Factors and Ergonomics* 4.1, pp. 149–194. ISSN: 1557-234X, 2163-3134. DOI: 10.1518/155723408X342826.

Karon E. MacLean, Oliver S. Schneider, and Hasti Seifi (2017). "Multisensory haptic interactions: understanding the sense and designing for it." In: *The Handbook of Multimodal-Multisensor Interfaces: Foundations, User Modeling, and Common Modality Combinations - Volume 1*. Ed. by Sharon Oviatt, Björn Schuller, Philip R. Cohen, Daniel Sonntag, Gerasimos Potamianos, and Antonio Krüger. ACM, pp. 97–142. ISBN: 978-1-970001-67-9. DOI: 10.1145/3015783.3015788.

Vivek Maheshwari and Ravi F. Saraf (2006). "High-resolution thin-film device to sense texture by touch." In: *Science* 312.5779, pp. 1501–1504.

Akhmajon Makhsadov, Donald Degraen, André Zenner, Felix Kosmalla, Kamila Mushkina, and Antonio Krüger (2022). "VRySmart: a Framework for Embedding Smart Devices in Virtual Reality." In: *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI EA '22. New Orleans, LA, USA: Association for Computing Machinery, pp. 1–8. ISBN: 9781450391566. DOI: 10.1145/3491101.3519717.

Nicholas D. Marchuk, J. Edward Colgate, and Michael A. Peshkin (2010). "Friction measurements on a Large Area TPaD." In: *2010 IEEE Haptics Symposium*. Waltham, MA, USA: IEEE, pp. 317–320. ISBN: 978-1-4244-6821-8. DOI: 10.1109/HAPTIC.2010.5444636.

Filippo Tommaso Marinetti (2014). *The Futurist Cookbook*. Penguin Modern Classics. London, England: Penguin Classics.

David Marino, Paul Bucci, Oliver S. Schneider, and Karon E. MacLean (2017). "Voodle: Vocal Doodling to Sketch Affective Robot Motion." In: *Proceedings of the 2017 Conference on Designing Interactive Systems*. DIS '17. Edinburgh, United Kingdom: Association for Computing Machinery, pp. 753–765. ISBN: 9781450349222. DOI: 10.1145/3064663.3064668.

Jonatan Martinez, Arturo Garcia, Miguel Oliver, Jose Pascual Molina, and Pascual Gonzalez (2016). "Identifying Virtual 3D Geometric Shapes with a Vibrotactile Glove." In: *IEEE Computer Graphics and Applications* 36.1, pp. 42–51. ISSN: 0272-1716. DOI: 10.1109/MCG.2014.81.

Jonàs Martínez, Jérémie Dumas, and Sylvain Lefebvre (2016). “Procedural Voronoi Foams for Additive Manufacturing.” In: *ACM Trans. Graph.* 35.4. ISSN: 0730-0301. DOI: 10.1145/2897824.2925922.

Jonàs Martínez, Samuel Hornus, Haichuan Song, and Sylvain Lefebvre (2018). “Polyhedral Voronoi Diagrams for Additive Manufacturing.” In: *ACM Trans. Graph.* 37.4. ISSN: 0730-0301. DOI: 10.1145/3197517.3201343.

Jonatan Martínez, Arturo S. García, Miguel Oliver, José P. Molina, and Pascual González (2014). “VITAKI: A Vibrotactile Prototyping Toolkit for Virtual Reality and Video Games.” In: *International Journal of Human-Computer Interaction* 30.11, pp. 855–871. ISSN: 1044-7318, 1532-7590. DOI: 10.1080/10447318.2014.941272.

S. Maruo, K. Ikuta, and T. Ninagawa (2001). “Multi-polymer Microstereolithography for Hybrid Opto-MEMS.” In: *Technical Digest. MEMS 2001. 14th IEEE International Conference on Micro Electro Mechanical Systems (Cat. No.01CH37090).* Interlaken, Switzerland: IEEE, pp. 151–154. ISBN: 978-0-7803-5998-7. DOI: 10.1109/MEMSYS.2001.906501.

Thomas H. Massie and J. K. Salisbury (1994). “The PHANToM haptic interface: A device for probing virtual objects.” In: *Proceedings of the ASME Dynamic Systems and Control Division*, pp. 295–301.

John C. McClelland, Robert J. Teather, and Audrey Girouard (2017). “Haptobend: Shape-Changing Passive Haptic Feedback in Virtual Reality.” In: *Proceedings of the 5th Symposium on Spatial User Interaction.* SUI ’17. Brighton, United Kingdom: Association for Computing Machinery, pp. 82–90. ISBN: 9781450354868. DOI: 10.1145/3131277.3132179.

Francis McGlone and David Reilly (2010). “The cutaneous sensory system.” In: *Neuroscience & Biobehavioral Reviews* 34.2, pp. 148–159. ISSN: 01497634. DOI: 10.1016/j.neubiorev.2009.08.004.

William McMahan and Katherine J. Kuchenbecker (2009a). “Displaying realistic contact accelerations via a dedicated vibration actuator.” In: *World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems.* Salt Lake City, UT, USA: IEEE, pp. 613–614. ISBN: 978-1-4244-3858-7. DOI: 10.1109/WHC.2009.4810909.

William McMahan and Katherine J. Kuchenbecker (2009b). “Haptic display of realistic tool contact via dynamically compensated control of a dedicated actuator.” In: *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems.* St. Louis, MO, USA: IEEE, pp. 3170–3177. ISBN: 978-1-4244-3803-7. DOI: 10.1109/IROS.2009.5354607.

W.A. McNeely (1993). “Robotic graphics: a new approach to force feedback for virtual reality.” In: *Proceedings of IEEE Virtual Reality Annual International Symposium.* Seattle, WA, USA: IEEE, pp. 336–341. ISBN: 978-0-7803-1363-7. DOI: 10.1109/VRAIS.1993.380761.

Michael Meehan, Brent Insko, Mary Whitton, and Frederick P. Brooks (2002). “Physiological Measures of Presence in Stressful Virtual Environments.” In: *ACM Trans. Graph.* 21.3, pp. 645–652. ISSN: 0730-0301. DOI: 10.1145/566654.566630.

R Melnikova, A Ehrmann, and K Finsterbusch (2014). “3D printing of textile-based structures by Fused Deposition Modelling (FDM) with different polymer materials.” In: *IOP Conference Series: Materials Science and Engineering* 62, p. 012018. ISSN: 1757-8981, 1757-899X. DOI: 10.1088/1757-899X/62/1/012018.

Moritz Alexander Messerschmidt, Sachith Muthukumarana, Nur Al-Huda Hamdan, Adrian Wagner, Haimo Zhang, Jan Borchers, and Suranga Chandima Nanayakkara (2022). “ANISMA: A Prototyping Toolkit to Explore Haptic Skin Deformation Applications Using Shape-Memory Alloys.” In: *ACM Transactions on Computer-Human Interaction* 29.3, pp. 1–34. ISSN: 1073-0516, 1557-7325. DOI: 10.1145/3490497.

David J. Meyer, Michael A. Peshkin, and J. Edward Colgate (2016). “Tactile Paintbrush: A procedural method for generating spatial haptic texture.” In: *2016 IEEE Haptics Symposium (HAPTICS).* Philadelphia, PA, USA: IEEE, pp. 259–264. ISBN: 978-1-5090-0903-9. DOI: 10.1109/HAPTICS.2016.7463187.

Jussi Mikkonen (2013). “Printed Material and Dabric.” In: DOI: 10.21606/nordes.2013.033.

Paul Milgram and Fumio Kishino (1994). “A Taxonomy of Mixed Reality Visual Displays.” In: *IEICE Trans. Information Systems* vol. E77-D, no. 12, pp. 1321–1329.

Kouta Minamizawa, Souichiro Fukamachi, Hiroyuki Kajimoto, Naoki Kawakami, and Susumu Tachi (2007a). “Gravity Grabber: Wearable Haptic Display to Present Virtual Mass Sensation.” In: *ACM SIGGRAPH 2007*

Emerging Technologies. SIGGRAPH '07. San Diego, California: Association for Computing Machinery, 8–es. ISBN: 9781450318242. DOI: 10.1145/1278280.1278289.

Kouta Minamizawa, Souichiro Fukamachi, Hiroyuki Kajimoto, Naoki Kawakami, and Susumu Tachi (2007b). "Wearable Haptic Display to Present Virtual Mass Sensation." In: *ACM SIGGRAPH 2007 Sketches*. SIGGRAPH '07. San Diego, California: Association for Computing Machinery, pp. 133–138. ISBN: 9781450347266. DOI: 10.1145/1278780.1278833.

Margaret Minsky, Ouh-young Ming, Oliver Steele, Frederick P. Brooks, and Max Behensky (1990). "Feeling and Seeing: Issues in Force Display." In: *SIGGRAPH Comput. Graph.* 24.2, pp. 235–241. ISSN: 0097-8930. DOI: 10.1145/91394.91451.

Viktor Miruchna, Robert Walter, David Lindlbauer, Maren Lehmann, Regine von Klitzing, and Jörg Müller (2015). "GelTouch: Localized Tactile Feedback Through Thin, Programmable Gel." In: *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. UIST '15. Charlotte, NC, USA: Association for Computing Machinery, pp. 3–10. ISBN: 9781450337793. DOI: 10.1145/2807442.2807487.

Abhijeet Mishra, Piyush Kumar, Jainendra Shukla, and Aman Parnami (2022). "HaptiDrag: A Device with the Ability to Generate Varying Levels of Drag (Friction) Effects on Real Surfaces." In: *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 6.3, pp. 1–26. ISSN: 2474-9567. DOI: 10.1145/3550310.

Motoki Miyoshi, Parinya Punpongsanon, Daisuke Iwai, and Kosuke Sato (2021). "SoftPrint: Investigating Haptic Softness Perception of 3D Printed Soft Object in FDM 3D Printers." In: *Journal of Imaging Science and Technology* 65.4, pp. 1–8. ISSN: 1943-3522. DOI: 10.2352/J.ImagingSci.Technol.2021.65.4.040406.

Ashley Montagu (1986). *Touching: the human significance of the skin*. 3rd ed. New York: Perennial Library. ISBN: 978-0-06-015535-3.

Catarina Mota (2011). "The rise of personal fabrication." In: *Proceedings of the 8th ACM conference on Creativity and cognition - C&C '11*. Atlanta, Georgia, USA: ACM Press, p. 279. ISBN: 978-1-4503-0820-5. DOI: 10.1145/2069618.2069665.

Camille Moussette and Richard Banks (2010). "Designing through Making: Exploring the Simple Haptic Design Space." In: *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '11. Funchal, Portugal: Association for Computing Machinery, pp. 279–282. ISBN: 9781450304788. DOI: 10.1145/1935701.1935763.

Muhanna A. Muhanna (2015). "Virtual reality and the CAVE: Taxonomy, interaction challenges and research directions." In: *Journal of King Saud University - Computer and Information Sciences* 27.3, pp. 344–361. ISSN: 13191578. DOI: 10.1016/j.jksuci.2014.03.023.

Takaki Murakami, Tanner Person, Charith Lasantha Fernando, and Kouta Minamizawa (2017). "Altered Touch: Miniature Haptic Display with Force, Thermal and Tactile Feedback for Augmented Haptics." In: *ACM SIGGRAPH 2017 Emerging Technologies*. SIGGRAPH '17. Los Angeles, California: Association for Computing Machinery. ISBN: 9781450350129. DOI: 10.1145/3084822.3084836.

Yuichi Muramatsu, Mihoko Niitsuma, and Trygve Thomessen (2012). "Perception of tactile sensation using vibrotactile glove interface." In: *2012 IEEE 3rd International Conference on Cognitive Infocommunications (CogInfoCom)*. Kosice, Slovakia: IEEE, pp. 621–626. ISBN: 978-1-4673-5188-1. DOI: 10.1109/CogInfoCom.2012.6422054.

Joseph T. Muth, Daniel M. Vogt, Ryan L. Truby, Yiğit Mengüç, David B. Kolesky, Robert J. Wood, and Jennifer A. Lewis (2014). "Embedded 3D Printing of Strain Sensors within Highly Stretchable Elastomers." In: *Advanced Materials* 26.36, pp. 6307–6312. ISSN: 09359648. DOI: 10.1002/adma.201400334.

Sachith Muthukumarana, Don Samitha Elvitigala, Juan Pablo Forero Cortes, Denys J.C. Matthies, and Suranga Nanayakkara (2020). "Touch Me Gently: Recreating the Perception of Touch Using a Shape-Memory Alloy Matrix." In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI '20. Honolulu, HI, USA: Association for Computing Machinery, pp. 1–12. ISBN: 9781450367080. DOI: 10.1145/3313831.3376491.

Sachith Muthukumarana, Moritz Alexander Messerschmidt, Denys J.C. Matthies, Jürgen Steimle, Philipp M. Scholl, and Suranga Nanayakkara (2021). "ClothTiles: A Prototyping Platform to Fabricate Customized Actuators on Clothing Using 3D Printing and Shape-Memory Alloys." In: *Proceedings of the 2021 CHI*

Conference on Human Factors in Computing Systems. CHI '21. Yokohama, Japan: Association for Computing Machinery. ISBN: 9781450380966. DOI: 10.1145/3411764.3445613.

Fumitaka Nakaizumi, Haruo Noma, Kenichi Hosaka, and Yasuyuki Yanagida (2006). "SpotScents: A Novel Method of Natural Scent Delivery Using Multiple Scent Projectors." In: *IEEE Virtual Reality Conference (VR 2006)*. Alexandria, VA, USA: IEEE, pp. 207–214. ISBN: 978-1-4244-0224-3. DOI: 10.1109/VR.2006.122.

Somang Nam and Deborah Fels (2016). "Design and Evaluation of an Authoring Tool and Notation System for Vibrotactile Composition." In: *Universal Access in Human-Computer Interaction. Interaction Techniques and Environments*. Ed. by Margherita Antona and Constantine Stephanidis. Vol. 9738. Lecture Notes in Computer Science. Cham: Springer International Publishing, pp. 43–53. ISBN: 978-3-319-40243-7. DOI: 10.1007/978-3-319-40244-4_5.

Niels Nilsson, Rolf Nordahl, and Stefania Serafin (2016). "Immersion revisited: A review of existing definitions of immersion and their relation to different theories of presence." In: *Human Technology* 12.2, pp. 108–134. DOI: 10.17011/ht/urn.201611174652.

Niels Christian Nilsson, André Zenner, and Adalberto L. Simeone (2021). "Propping Up Virtual Reality With Haptic Proxies." In: *IEEE Computer Graphics and Applications* 41.5, pp. 104–112. DOI: 10.1109/MCG.2021.3097671.

Sajid Nisar, Melisa Orta Martinez, Takahiro Endo, Fumitoshi Matsuno, and Allison M. Okamura (2019). "Effects of Different Hand-Grounding Locations on Haptic Performance With a Wearable Kinesthetic Haptic Device." In: *IEEE Robotics and Automation Letters* 4.2, pp. 351–358. ISSN: 2377-3766, 2377-3774. DOI: 10.1109/LRA.2018.2890198.

Martin Nisser, Yashaswini Makaram, Lucian Covarrubias, Amadou Bah, Faraz Faruqi, Ryo Suzuki, and Stefanie Mueller (2022). "Mixels: Fabricating Interfaces using Programmable Magnetic Pixels." In: *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology*. UIST '22. Bend, Oregon, USA: Association for Computing Machinery. DOI: 10.48550/ARXIV.2208.03804.

Romain Nith, Shan-Yuan Teng, Pengyu Li, Yujie Tao, and Pedro Lopes (2021). "DextrEMS: Increasing Dexterity in Electrical Muscle Stimulation by Combining It with Brakes." In: *The 34th Annual ACM Symposium on User Interface Software and Technology*. UIST '21. Virtual Event, USA: Association for Computing Machinery, pp. 414–430. ISBN: 9781450386357. DOI: 10.1145/3472749.3474759.

Aditya Shekhar Nittala, Klaus Kruttwig, Jaeyeon Lee, Roland Bennewitz, Eduard Arzt, and Jürgen Steimle (2019). "Like A Second Skin: Understanding How Epidermal Devices Affect Human Tactile Perception." In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Glasgow, Scotland Uk: Association for Computing Machinery, pp. 1–16. ISBN: 9781450359702. DOI: 10.1145/3290605.3300610.

Michael W. O'Boyle and Robert D. Tarte (1980). "Implications for phonetic symbolism: The relationship between pure tones and geometric figures." In: *Journal of Psycholinguistic Research* 9.6, pp. 535–544. ISSN: 0090-6905, 1573-6555. DOI: 10.1007/BF01068115.

Marcia K. O'Malley and Abhishek Gupta (2008). "Chapter 2 - haptic interfaces." In: *HCI beyond the GUI*. Ed. by Philip Kortum. Interactive technologies. San Francisco: Morgan Kaufmann, pp. 25–73. ISBN: 978-0-12-374017-5. DOI: https://doi.org/10.1016/B978-0-12-374017-5.00002-X.

Ian Oakley, Marilyn Rose McGee, Stephen Brewster, and Philip Gray (2000). "Putting the feel in 'look and feel'." In: *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '00*. The Hague, The Netherlands: ACM Press, pp. 415–422. ISBN: 978-1-58113-216-8. DOI: 10.1145/332040.332467.

Marianna Obrist, Sue Ann Seah, and Sriram Subramanian (2013). "Talking about tactile experiences." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. Paris France: ACM, pp. 1659–1668. ISBN: 978-1-4503-1899-0. DOI: 10.1145/2470654.2466220.

Yoichi Ochiai, Takayuki Hoshi, and Jun Rekimoto (2014). "Pixie Dust: Graphics Generated by Levitated and Animated Objects in Computational Acoustic-Potential Field." In: *ACM Trans. Graph.* 33.4. ISSN: 0730-0301. DOI: 10.1145/2601097.2601118.

Masa Ogata (2018). “Magneto-Haptics: Embedding Magnetic Force Feedback for Physical Interactions.” In: *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*. Berlin Germany: ACM, pp. 737–743. ISBN: 978-1-4503-5948-1. DOI: 10.1145/3242587.3242615.

Masa Ogata and Yuki Koyama (2021). “A Computational Approach to Magnetic Force Feedback Design.” In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. Yokohama Japan: ACM, pp. 1–12. ISBN: 978-1-4503-8096-6. DOI: 10.1145/3411764.3445631.

Shogo Okamoto, Hikaru Nagano, and Yoji Yamada (2013). “Psychophysical Dimensions of Tactile Perception of Textures.” In: *IEEE Transactions on Haptics* 6.1, pp. 81–93. ISSN: 1939-1412. DOI: 10.1109/TOH.2012.32.

Allison M. Okamura, Mark R. Cutkosky, and Jack Tigh Dennerlein (2001). “Reality-based models for vibration feedback in virtual environments.” In: *IEEE/ASME Transactions on Mechatronics* 6.3, pp. 245–252. DOI: 10.1109/3516.951362.

Simon Olberding, Sergio Soto Ortega, Klaus Hildebrandt, and Jürgen Steimle (2015). “Foldio: Digital Fabrication of Interactive and Shape-Changing Objects With Foldable Printed Electronics.” In: *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. UIST ’15. Charlotte, NC, USA: Association for Computing Machinery, pp. 223–232. ISBN: 9781450337793. DOI: 10.1145/2807442.2807494.

Manuel M. Oliveira, Gary Bishop, and David McAllister (2000). “Relief Texture Mapping.” In: *Proceedings of the 27th Annual Conference on Computer Graphics and Interactive Techniques*. SIGGRAPH ’00. USA: ACM Press/Addison-Wesley Publishing Co., pp. 359–368. ISBN: 1581132085. DOI: 10.1145/344779.344947.

Anke van Oosterhout, Miguel Bruns, and Eve Hoggan (2020). “Facilitating Flexible Force Feedback Design with Feelix.” In: *Proceedings of the 2020 International Conference on Multimodal Interaction*. ICMI ’20. Virtual Event, Netherlands: Association for Computing Machinery, pp. 184–193. ISBN: 9781450375818. DOI: 10.1145/3382507.3418819.

OpenStax (2021). *Psychology*. URL: https://openstax.org/books/psychology/pages/5-5-the-other-senses#Figure_05_05_Touch (visited on 2022-07-10).

Charles E. Osgood, George J. Suci, and Percy H. Tannenbaum (1957). *The Measurement of Meaning*. Oxford, England: University of Illinois Press, p. 342.

Per-Anders Oskarsson, Lars Eriksson, and Otto Carlander (2012). “Enhanced Perception and Performance by Multimodal Threat Cueing in Simulated Combat Vehicle.” In: *Human Factors: The Journal of the Human Factors and Ergonomics Society* 54.1, pp. 122–137. ISSN: 0018-7208, 1547-8181. DOI: 10.1177/0018720811424895.

Jifei Ou, Gershon Dublon, Chin-Yi Cheng, Felix Heibeck, Karl Willis, and Hiroshi Ishii (2016). “Cilllia: 3D Printed Micro-Pillar Structures for Surface Texture, Actuation and Sensing.” In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. San Jose California USA: ACM, pp. 5753–5764. ISBN: 978-1-4503-3362-7. DOI: 10.1145/2858036.2858257.

Jifei Ou, Daniel Oran, Don Derek Haddad, Joseph Paradiso, and Hiroshi Ishii (2019). “SensorKnit: Architecting Textile Sensors with Machine Knitting.” In: *3D Printing and Additive Manufacturing* 6.1, pp. 1–11. ISSN: 2329-7662, 2329-7670. DOI: 10.1089/3dp.2018.0122.

Claudio Pacchierotti, Gionata Salvietti, Irfan Hussain, Leonardo Meli, and Domenico Prattichizzo (2016). “The hRing: A wearable haptic device to avoid occlusions in hand tracking.” In: *2016 IEEE Haptics Symposium (HAPTICS)*. Philadelphia, PA, USA: IEEE, pp. 134–139. ISBN: 978-1-5090-0903-9. DOI: 10.1109/HAPTICS.2016.7463167.

Claudio Pacchierotti, Stephen Sinclair, Massimiliano Solazzi, Antonio Frisoli, Vincent Hayward, and Domenico Prattichizzo (2017). “Wearable Haptic Systems for the Fingertip and the Hand: Taxonomy, Review, and Perspectives.” In: *IEEE Transactions on Haptics* 10.4, pp. 580–600. ISSN: 1939-1412, 2329-4051, 2334-0134. DOI: 10.1109/TOH.2017.2689006.

Dinesh K. Pai and Peter Rizun (2003). “The WHaT: a wireless haptic texture sensor.” In: *11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2003. HAPTICS 2003. Proceedings.* Pp. 3–9. DOI: 10.1109/HAPTIC.2003.1191210.

Sabrina A. Panëels, Margarita Anastassova, and Lucie Brunet (2013). “TactiPEd: Easy Prototyping of Tactile Patterns.” In: *Human-Computer Interaction – INTERACT 2013*. Ed. by Paula Koté, Gary Marsden, Gitte

Lindgaard, Janet Wesson, and Marco Winckler. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 228–245. ISBN: 978-3-642-40480-1. DOI: 10.1007/978-3-642-40480-1_15.

Sabrina A. Panëels, Jonathan C. Roberts, and Peter J. Rodgers (2010). "HITPROTO: a tool for the rapid prototyping of haptic interactions for haptic data visualization." In: *2010 IEEE Haptics Symposium*. Waltham, MA: IEEE, pp. 261–268. ISBN: 978-1-4244-6821-8. DOI: 10.1109/HAPTIC.2010.5444647.

Julian Panetta, Qingnan Zhou, Luigi Malomo, Nico Pietroni, Paolo Cignoni, and Denis Zorin (2015). "Elastic Textures for Additive Fabrication." In: *ACM Trans. Graph.* 34.4. ISSN: 0730-0301. DOI: 10.1145/2766937.

Gunhyuk Park and Seungmoon Choi (2017). "A Physics-Based Vibrotactile Feedback Library for Collision Events." In: *IEEE Transactions on Haptics* 10.3, pp. 325–337. ISSN: 1939-1412, 2329-4051, 2334-0134. DOI: 10.1109/TOH.2016.2614804.

Mark Paterson (2007). *The Senses of Touch*. ISBN: 9781845204792.

Huaishu Peng, Jennifer Mankoff, Scott E. Hudson, and James McCann (2015). "A Layered Fabric 3D Printer for Soft Interactive Objects." In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Seoul, Republic of Korea: Association for Computing Machinery, pp. 1789–1798. ISBN: 9781450331456. DOI: 10.1145/2702123.2702327.

Alvaro G. Perez, Daniel Lobo, Francesco Chinello, Gabriel Cirio, Monica Malvezzi, Jose San Martin, Domenico Prattichizzo, and Miguel A. Otaduy (2017). "Optimization-Based Wearable Tactile Rendering." In: *IEEE Transactions on Haptics* 10.2, pp. 254–264. ISSN: 1939-1412, 2329-4051, 2334-0134. DOI: 10.1109/TOH.2016.2619708.

Alvaro G. Perez, Daniel Lobo, Francesco Chinello, Gabriel Cirio, Monica Malvezzi, Jose San Martin, Domenico Prattichizzo, and Miguel A. Otaduy (2015). "Soft finger tactile rendering for wearable haptics." In: *2015 IEEE World Haptics Conference (WHC)*. Evanston, IL: IEEE, pp. 327–332. ISBN: 978-1-4799-6624-0. DOI: 10.1109/WHC.2015.7177733.

Hannah Perner-Wilson and Mika Satomi (2012). *Involving the machines*. URL: https://www.kobakant.at/?p=432 (visited on 2022-09-23).

Franklin Pezutti-Dyer and Leah Buechley (2022). "Extruder-Turtle: A Library for 3D Printing Delicate, Textured, and Flexible Objects." In: *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '22. Daejeon, Republic of Korea: Association for Computing Machinery. ISBN: 9781450391474. DOI: 10.1145/3490149.3501312.

Michal Piovarči (2020). "Perception-Aware Computational Fabrication: Increasing The Apparent Gamut of Digital Fabrication." PhD thesis. Lugano, Switzerland: Università della Svizzera italiana.

Michal Piovarči, Danny M. Kaufman, David I. W. Levin, and Piotr Didyk (2020). "Fabrication-in-the-loop co-optimization of surfaces and styli for drawing haptics." In: *ACM Transactions on Graphics* 39.4. ISSN: 0730-0301, 1557-7368. DOI: 10.1145/3386569.3392467.

Michal Piovarči, David I. W. Levin, Danny M. Kaufman, and Piotr Didyk (2018). "Perception-aware modeling and fabrication of digital drawing tools." In: *ACM Transactions on Graphics* 37.4, pp. 1–15. ISSN: 0730-0301, 1557-7368. DOI: 10.1145/3197517.3201322.

Michal Piovarči, David I. W. Levin, Jason Rebello, Desai Chen, Roman Ďurikovič, Hanspeter Pfister, Wojciech Matusik, and Piotr Didyk (2016). "An interaction-aware, perceptual model for non-linear elastic objects." In: *ACM Transactions on Graphics* 35.4, pp. 1–13. ISSN: 0730-0301, 1557-7368. DOI: 10.1145/2897824.2925885.

Ivan Poupyrev, Nan-Wei Gong, Shiho Fukuhara, Mustafa Emre Karagozler, Carsten Schwesig, and Karen E. Robinson (2016). "Project Jacquard: Interactive Digital Textiles at Scale." In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI '16. San Jose, California, USA: Association for Computing Machinery, pp. 4216–4227. ISBN: 9781450333627. DOI: 10.1145/2858036.2858176.

Ivan Poupyrev, Tatsushi Nashida, Shigeaki Maruyama, Jun Rekimoto, and Yasufumi Yamaji (2004). "Lumen: interactive visual and shape display for calm computing." In: *ACM SIGGRAPH 2004 Emerging technologies on - SIGGRAPH '04*. Los Angeles, California: ACM Press, p. 17. DOI: 10.1145/1186155.1186173.

Narjes Pourjafarian, Marion Koelle, Fjolla Mjaku, Paul Strohmeier, and Jürgen Steimle (2022). "Print-A-Sketch: A Handheld Printer for Physical Sketching of Circuits and Sensors on Everyday Surfaces." In: *Proceedings of the*

2022 CHI Conference on Human Factors in Computing Systems. CHI '22. New Orleans, LA, USA: Association for Computing Machinery. ISBN: 9781450391573. DOI: 10.1145/3491102.3502074.

Emmi Pouta and Jussi Ville Mikkonen (2022). "Woven ETextiles in HCI — a Literature Review." In: *Designing Interactive Systems Conference*. DIS '22. Virtual Event, Australia: Association for Computing Machinery, pp. 1099–1118. ISBN: 9781450393584. DOI: 10.1145/3532106.3533566.

Mark B. Powers and Paul M.G. Emmelkamp (2008). "Virtual reality exposure therapy for anxiety disorders: A meta-analysis." In: *Journal of Anxiety Disorders* 22.3, pp. 561–569. ISSN: 08876185. DOI: 10.1016/j.janxdis.2007.04.006.

Domenico Prattichizzo, Francesco Chinello, Claudio Pacchierotti, and Monica Malvezzi (2013). "Towards Wearability in Fingertip Haptics: A 3-DoF Wearable Device for Cutaneous Force Feedback." In: *IEEE Transactions on Haptics* 6.4, pp. 506–516. ISSN: 1939-1412. DOI: 10.1109/TOH.2013.53.

Kathrin Probst, Michael Haller, Kentaro Yasu, Maki Sugimoto, and Masahiko Inami (2014). "Move-It Sticky Notes Providing Active Physical Feedback through Motion." In: *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction*. TEI '14. Munich, Germany: Association for Computing Machinery, pp. 29–36. ISBN: 9781450326353. DOI: 10.1145/2540930.2540932.

Uwe Proske and Simon C. Gandevia (2012). "The Proprioceptive Senses: Their Roles in Signaling Body Shape, Body Position and Movement, and Muscle Force." In: *Physiological Reviews* 92.4, pp. 1651–1697. ISSN: 0031-9333, 1522-1210. DOI: 10.1152/physrev.00048.2011.

Parinya Punpongsanon, Daisuke Iwai, and Kosuke Sato (2015). "SoftAR: Visually Manipulating Haptic Softness Perception in Spatial Augmented Reality." In: *IEEE Transactions on Visualization and Computer Graphics* 21.11, pp. 1279–1288. ISSN: 1077-2626, 1941-0506, 2160-9306. DOI: 10.1109/TVCG.2015.2459792.

Ismo Rakkolainen, Euan Freeman, Antti Sand, Roope Raisamo, and Stephen Brewster (2021). "A Survey of Mid-Air Ultrasound Haptics and Its Applications." In: *IEEE Transactions on Haptics* 14.1, pp. 2–19. ISSN: 1939-1412, 2329-4051, 2334-0134. DOI: 10.1109/TOH.2020.3018754.

Vilayanur S. Ramachandran and Edward M. Hubbard (2003). "Hearing Colors, Tasting Shapes." In: *Scientific American* 288.5, pp. 52–59. DOI: 10.1038/scientificamerican0503-52.

Raf Ramakers, Kashyap Todi, and Kris Luyten (2015). "PaperPulse: An Integrated Approach for Embedding Electronics in Paper Designs." In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Seoul, Republic of Korea: Association for Computing Machinery, pp. 2457–2466. ISBN: 9781450331456. DOI: 10.1145/2702123.2702487.

Nimesha Ranasinghe and Ellen Yi-Luen Do (2016). "Digital Lollipop: Studying Electrical Stimulation on the Human Tongue to Simulate Taste Sensations." In: *ACM Trans. Multimedia Comput. Commun. Appl.* 13.1. ISSN: 1551-6857. DOI: 10.1145/2996462.

Nimesha Ranasinghe, Pravar Jain, Nguyen Thi Ngoc Tram, Koon Chuan Raymond Koh, David Tolley, Shienny Karwita, Lin Lien-Ya, Yan Liangkun, Kala Shamaiah, Chow Eason Wai Tung, Ching Chiuan Yen, and Ellen Yi-Luen Do (2018). "Season Traveller: Multisensory Narration for Enhancing the Virtual Reality Experience." In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: Association for Computing Machinery, pp. 1–13. ISBN: 9781450356206. DOI: 10.1145/3173574.3174151.

Nimesha Ranasinghe, Ryohei Nakatsu, Hideaki Nii, and Ponnampalam Gopalakrishnakone (2012). "Tongue Mounted Interface for Digitally Actuating the Sense of Taste." In: *2012 16th International Symposium on Wearable Computers*. Newcastle, United Kingdom: IEEE, pp. 80–87. ISBN: 978-0-7695-4697-1. DOI: 10.1109/ISWC.2012.16.

Jun Rekimoto (2013). "Traxion: A Tactile Interaction Device with Virtual Force Sensation." In: *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology*. UIST '13. St. Andrews, Scotland, United Kingdom: Association for Computing Machinery, pp. 427–432. ISBN: 9781450322683. DOI: 10.1145/2501988.2502044.

Michael Rietzler, Florian Geiselhart, Jan Gugenheimer, and Enrico Rukzio (2018). "Breaking the Tracking: Enabling Weight Perception Using Perceivable Tracking Offsets." In: *Proceedings of the 2018 CHI Conference on*

Human Factors in Computing Systems. CHI '18. Montreal QC, Canada: Association for Computing Machinery, pp. 1–12. ISBN: 9781450356206. DOI: 10.1145/3173574.3173702.

Michael Rietzler, Katrin Plaumann, Taras Kränzle, Marcel Erath, Alexander Stahl, and Enrico Rukzio (2017). "VaiR: Simulating 3D Airflows in Virtual Reality." In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. Denver, Colorado, USA: Association for Computing Machinery, pp. 5669–5677. ISBN: 9781450346559. DOI: 10.1145/3025453.3026009.

Michael A. Riley, Jeffrey B. Wagman, Marie-Vee Santana, Claudia Carello, and M. T. Turvey (2002). "Perceptual Behavior: Recurrence Analysis of a Haptic Exploratory Procedure." In: *Perception* 31.4, pp. 481–510. ISSN: 0301-0066, 1468-4233. DOI: 10.1068/p3176.

Michael L. Rivera and Scott E. Hudson (2019). "Desktop Electrospinning: A Single Extruder 3D Printer for Producing Rigid Plastic and Electrospun Textiles." In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Glasgow, Scotland Uk: Association for Computing Machinery, pp. 1–12. ISBN: 9781450359702. DOI: 10.1145/3290605.3300434.

Michael L. Rivera, Melissa Moukperian, Daniel Ashbrook, Jennifer Mankoff, and Scott E. Hudson (2017). "Stretching the Bounds of 3D Printing with Embedded Textiles." In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. Denver, Colorado, USA: Association for Computing Machinery, pp. 497–508. ISBN: 9781450346559. DOI: 10.1145/3025453.3025460.

Gabriel Robles-De-La-Torre (2006). "The Importance of the Sense of Touch in Virtual and Real Environments." In: *IEEE Multimedia* 13.3, pp. 24–30. ISSN: 1070-986X. DOI: 10.1109/MMUL.2006.69.

Irvin Rock and Jack Victor (1964). "Vision and Touch: An Experimentally Created Conflict between the Two Senses." In: *Science* 143.3606, pp. 594–596. DOI: 10.1126/science.143.3606.594.

Joseph M. Romano and Katherine J. Kuchenbecker (2012). "Creating Realistic Virtual Textures from Contact Acceleration Data." In: *IEEE Transactions on Haptics* 5.2, pp. 109–119. ISSN: 1939-1412. DOI: 10.1109/TOH.2011.38.

David Rosen and Austina Nguyen (2005). "Simulation Methods for Formable Crust Skins of Digital Clay Human-Computer Interface Devices." In: *Volume 3: 25th Computers and Information in Engineering Conference, Parts A and B*. Long Beach, California, USA: ASMEDC, pp. 1099–1109. ISBN: 978-0-7918-4740-4. DOI: 10.1115/DETC2005-84455.

Barbara O. Rothbaum, Larry F. Hodges, Rob Kooper, Dan Opdyke, James S. Williford, and Max North (1995). "Effectiveness of computer-generated (virtual reality) graded exposure in the treatment of acrophobia." In: *Am J Psychiatry* 152.4, pp. 626–628.

Isa Rutten, William Frier, Lawrence Van den Bogaert, and David Geerts (2019). "Invisible Touch: How Identifiable Are Mid-Air Haptic Shapes?" In: *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI EA '19. Glasgow, Scotland Uk: Association for Computing Machinery, pp. 1–6. ISBN: 9781450359719. DOI: 10.1145/3290607.3313004.

Jonghyun Ryu and Seungmoon Choi (2008). "posVibEditor: Graphical authoring tool of vibrotactile patterns." In: *2008 IEEE International Workshop on Haptic Audio visual Environments and Games*. Ottawa, ON, Canada: IEEE, pp. 120–125. ISBN: 978-1-4244-2668-3. DOI: 10.1109/HAVE.2008.4685310.

L Sabantina, F Kinzel, A Ehrmann, and K Finsterbusch (2015). "Combining 3D printed forms with textile structures - mechanical and geometrical properties of multi-material systems." In: *IOP Conference Series: Materials Science and Engineering* 87, p. 012005. ISSN: 1757–899X. DOI: 10.1088/1757-899X/87/1/012005.

Satoshi Saga (2015). "Lateral-force-based haptic display." In: *SIGGRAPH Asia 2015 Haptic Media And Contents Design*. Kobe Japan: ACM, pp. 1–3. ISBN: 978-1-4503-3932-2. DOI: 10.1145/2818384.2818391.

Riad Sahli, Aubin Prot, Anle Wang, Martin H. Müser, Michal Piovarči, Piotr Didyk, and Roland Bennewitz (2020). "Tactile perception of randomly rough surfaces." In: *Scientific Reports* 10.1, p. 15800. ISSN: 2045-2322. DOI: 10.1038/s41598-020-72890-y.

Maki Sakamoto, Junya Yoshino, Ryuichi Doizaki, and Masaharu Haginoya (2016). "Metal-like texture design evaluation using sound symbolic words." In: *International Journal of Design Creativity and Innovation* 4.3–4, pp. 181–194. ISSN: 2165-0349, 2165-0357. DOI: 10.1080/21650349.2015.1061449.

Mark Salada, J. Edward Colgate, Peter Vishton, and Frankel Eviatar (2005). “An Experiment on Tracking Surface Features with the Sensation of Slip.” In: *Proceedings. First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics Conference.* Los Alamitos, CA, USA: IEEE Computer Society, pp. 132–137. DOI: 10.1109/WHC.2005.22.

Mark Salada, Peter Vishton, J. Edward Colgate, and Eviatar Frankel (2004). “Two experiments on the perception of slip at the fingertip.” In: *12th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2004.* HAPTICS ’04, pp. 146–153. DOI: 10.1109/HAPTIC.2004.1287190.

Kenneth Salisbury, David L. Brock, Thomas H. Massie, N. Swarup, and Craig Buchanan Zilles (1995). “Haptic Rendering: Programming Touch Interaction with Virtual Objects.” In: *Proceedings of the 1995 symposium on Interactive 3D graphics.* SI3D ’95. Monterey, California, United States: ACM Press, pp. 123–130. ISBN: 978-0-89791-736-0. DOI: 10.1145/199404.199426.

Eva-Lotta Sallnäs, Kirsten Rassmus-Gröhn, and Calle Sjöström (2000). “Supporting Presence in Collaborative Environments by Haptic Force Feedback.” In: *ACM Trans. Comput.-Hum. Interact.* 7.4, pp. 461–476. ISSN: 1073-0516. DOI: 10.1145/365058.365086.

Antti Sand, Ismo Rakkolainen, Poika Isokoski, Jari Kangas, Roope Raisamo, and Karri Palovuori (2015). “Head-Mounted Display with Mid-Air Tactile Feedback.” In: *Proceedings of the 21st ACM Symposium on Virtual Reality Software and Technology.* VRST ’15. Beijing, China: Association for Computing Machinery, pp. 51–58. ISBN: 9781450339902. DOI: 10.1145/2821592.2821593.

Andreas Sandström, Amir Asadpoordarvish, Jenny Enevold, and Ludvig Edman (2014). “Spraying Light: Ambient-Air Fabrication of Large-Area Emissive Devices on Complex-Shaped Surfaces.” In: *Advanced Materials* 26.29, pp. 4975–4980. ISSN: 09359648. DOI: 10.1002/adma.201401286.

Ryoko Sasamoto (2019). *Onomatopoeia and Relevance.* Springer International Publishing. DOI: 10.1007/978-3-030-26318-8.

Makoto Sato (2002). “Development of String-based Force Display: SPIDAR.” In: *International Conference on Virtual Systems and Multimedia.* Vol. 8, p. 6.

Robert F. Schmidt, ed. (1986). *Fundamentals of Sensory Physiology.* Berlin, Heidelberg: Springer Berlin Heidelberg. ISBN: 978-3-540-15870-7. DOI: 10.1007/978-3-642-82598-9.

Oliver Schneider, Bruno Fruchard, Dennis Wittchen, Bibhushan Raj Joshi, Georg Freitag, Donald Degraen, and Paul Strohmeier (2022). “Sustainable Haptic Design: Improving Collaboration, Sharing, and Reuse in Haptic Design Research.” In: *CHI Conference on Human Factors in Computing Systems Extended Abstracts.* CHI EA ’22. New Orleans, LA, USA: Association for Computing Machinery. ISBN: 9781450391566. DOI: 10.1145/3491101.3503734.

Oliver Schneider, Karon MacLean, Colin Swindells, and Kellogg Booth (2017). “Haptic experience design: What hapticians do and where they need help.” In: *International Journal of Human-Computer Studies* 107, pp. 5–21. ISSN: 10715819. DOI: 10.1016/j.ijhcs.2017.04.004.

Oliver S. Schneider, Ali Israr, and Karon E. MacLean (2015). “Tactile Animation by Direct Manipulation of Grid Displays.” In: *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology.* UIST ’15. Charlotte, NC, USA: Association for Computing Machinery, pp. 21–30. ISBN: 9781450337793. DOI: 10.1145/2807442.2807470.

Oliver S. Schneider and Karon E. MacLean (2014). “Improvising design with a Haptic Instrument.” In: *2014 IEEE Haptics Symposium (HAPTICS).* Houston, TX, USA: IEEE, pp. 327–332. ISBN: 978-1-4799-3131-6. DOI: 10.1109/HAPTICS.2014.6775476.

Oliver S. Schneider and Karon E. MacLean (2016). “Studying design process and example use with Macaron, a web-based vibrotactile effect editor.” In: *2016 IEEE Haptics Symposium (HAPTICS).* Philadelphia, PA, USA: IEEE, pp. 52–58. ISBN: 978-1-5090-0903-9. DOI: 10.1109/HAPTICS.2016.7463155.

Samuel B. Schorr and Allison M. Okamura (2017). “Fingertip Tactile Devices for Virtual Object Manipulation and Exploration.” In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems.* CHI ’17. Denver, Colorado, USA: Association for Computing Machinery, pp. 3115–3119. ISBN: 9781450346559. DOI: 10.1145/3025453.3025744.

Thomas Schubert, Frank Friedmann, and Holger Regenbrecht (2001). "The Experience of Presence: Factor Analytic Insights." In: *Presence: Teleoperators and Virtual Environments* 10.3, pp. 266–281. ISSN: 1054-7460. DOI: 10.1162/105474601300343603.

Christian Schumacher, Bernd Bickel, Jan Rys, Steve Marschner, Chiara Daraio, and Markus Gross (2015). "Microstructures to Control Elasticity in 3D Printing." In: *ACM Trans. Graph.* 34.4. ISSN: 0730-0301. DOI: 10.1145/2766926.

Sue Ann Seah, Diego Martinez Plasencia, Peter D. Bennett, Abhijit Karnik, Vlad Stefan Otrocol, Jarrod Knibbe, Andy Cockburn, and Sriram Subramanian (2014). "SensaBubble: A Chrono-Sensory Mid-Air Display of Sight and Smell." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '14. Toronto, Ontario, Canada: Association for Computing Machinery, pp. 2863–2872. ISBN: 9781450324731. DOI: 10.1145/2556288.2557087.

Hasti Seifi (2019). *Personalizing Haptics: From Individuals' Sense-Making Schemas to End-User Haptic Tools*. Springer Series on Touch and Haptic Systems. Cham: Springer International Publishing. ISBN: 978-3-030-11378-0. DOI: 10.1007/978-3-030-11379-7.

Hasti Seifi, Chamila Anthonypillai, and Karon E. MacLean (2014). "End-user customization of affective tactile messages: A qualitative examination of tool parameters." In: *2014 IEEE Haptics Symposium (HAPTICS)*. Houston, TX, USA: IEEE, pp. 251–256. ISBN: 978-1-4799-3131-6. DOI: 10.1109/HAPTICS.2014.6775463.

Hasti Seifi, Matthew Chun, Colin Gallacher, Oliver Schneider, and Karon E. MacLean (2020a). "How Do Novice Hapticians Design? A Case Study in Creating Haptic Learning Environments." In: *IEEE Transactions on Haptics* 13.4. 11 citations (Semantic Scholar/DOI) [2022-07-09], pp. 791–805. ISSN: 1939-1412, 2329-4051, 2334-0134. DOI: 10.1109/TOH.2020.2968903.

Hasti Seifi, Farimah Fazlollahi, Michael Oppermann, John Andrew Sastrillo, Jessica Ip, Ashutosh Agrawal, Gunhyuk Park, Katherine J. Kuchenbecker, and Karon E. MacLean (2019). "Haptipedia: Accelerating Haptic Device Discovery to Support Interaction & Engineering Design." In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Glasgow, Scotland Uk: Association for Computing Machinery, pp. 1–12. ISBN: 9781450359702. DOI: 10.1145/3290605.3300788.

Hasti Seifi and Karon E. MacLean (2017). "Exploiting haptic facets: Users' sensemaking schemas as a path to design and personalization of experience." In: *International Journal of Human-Computer Studies* 107. Multisensory Human-Computer Interaction, pp. 38–61. ISSN: 1071-5819. DOI: https://doi.org/10.1016/j.ijhcs.2017.04.003.

Hasti Seifi, Michael Oppermann, Julia Bullard, Karon E. MacLean, and Katherine J. Kuchenbecker (2020b). "Capturing Experts' Mental Models to Organize a Collection of Haptic Devices: Affordances Outweigh Attributes." In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: Association for Computing Machinery, pp. 1–12. ISBN: 9781450367080. URL: https://doi.org/10.1145/3313831.3376395.

Hasti Seifi, Kailun Zhang, and Karon E. MacLean (2015). "VibViz: Organizing, visualizing and navigating vibration libraries." In: *2015 IEEE World Haptics Conference (WHC)*. Evanston, IL: IEEE, pp. 254–259. ISBN: 978-1-4799-6624-0. DOI: 10.1109/WHC.2015.7177722.

Thomas B. Sheridan (1992). *Telerobotics, Automation, and Human Supervisory Control*. MIT. ISBN: 9780262193160.

Yuxiang Shi, Fan Wang, Jingwen Tian, Shuyao Li, Engang Fu, Jinhui Nie, Rui Lei, Yafei Ding, Xiangyu Chen, and Zhong Lin Wang (2021). "Self-powered electro-tactile system for virtual tactile experiences." In: *Science Advances* 7.6, eabe2943. ISSN: 2375–2548. DOI: 10.1126/sciadv.abe2943.

Kazuhiro Shimonomura (2019). "Tactile Image Sensors Employing Camera: A Review." In: *Sensors (Basel, Switzerland)* 19.18, p. 3933. ISSN: 1424-8220. DOI: 10.3390/s19183933.

Sunghwan Shin and Seungmoon Choi (2018). "Effects of haptic texture rendering modalities on realism." In: *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*. Tokyo Japan: ACM, pp. 1–5. ISBN: 978-1-4503-6086-9. DOI: 10.1145/3281505.3281520.

Sunghwan Shin and Seungmoon Choi (2020). "Hybrid Framework for Haptic Texture Modeling and Rendering." In: *IEEE Access* 8, pp. 149825–149840. ISSN: 2169-3536. DOI: 10.1109/ACCESS.2020.3015861.

David M. Sidhu and Penny M. Pexman (2018). “Five mechanisms of sound symbolic association.” In: *Psychonomic Bulletin & Review* 25.5, pp. 1619–1643. ISSN: 1069-9384, 1531-5320. DOI: 10.3758/s13423-017-1361-1.

Adalberto L. Simeone, Eduardo Velloso, and Hans Gellersen (2015). “Substitutional Reality: Using the Physical Environment to Design Virtual Reality Experiences.” In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems.* CHI ’15. Seoul, Republic of Korea: Association for Computing Machinery, pp. 3307–3316. ISBN: 9781450331456. DOI: 10.1145/2702123.2702389.

Mike Sinclair, Eyal Ofek, Mar Gonzalez-Franco, and Christian Holz (2019). “CapstanCrunch: A Haptic VR Controller with User-Supplied Force Feedback.” In: *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology.* UIST ’19. New Orleans, LA, USA: Association for Computing Machinery, pp. 815–829. ISBN: 9781450368162. DOI: 10.1145/3332165.3347891.

Pitchaya Sitthi-Amorn, Javier E. Ramos, Yuwang Wangy, Joyce Kwan, Justin Lan, Wenshou Wang, and Wojciech Matusik (2015). “MultiFab: A Machine Vision Assisted Platform for Multi-Material 3D Printing.” In: *ACM Trans. Graph.* 34.4. ISSN: 0730-0301. DOI: 10.1145/2766962.

Alexa F. Siu, Eric J. Gonzalez, Shenli Yuan, Jason B. Ginsberg, and Sean Follmer (2018). “ShapeShift: 2D Spatial Manipulation and Self-Actuation of Tabletop Shape Displays for Tangible and Haptic Interaction.” In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems.* CHI ’18. Montreal QC, Canada: Association for Computing Machinery, pp. 1–13. ISBN: 9781450356206. DOI: 10.1145/3173574.3173865.

Lisa Skedung, Martin Arvidsson, Jun Young Chung, Christopher M. Stafford, Birgitta Berglund, and Mark W. Rutland (2013). “Feeling Small: Exploring the Tactile Perception Limits.” In: *Scientific Reports* 3.1, p. 2617. ISSN: 2045-2322. DOI: 10.1038/srep02617.

Lisa Skedung, Kathryn L. Harris, Elizabeth S. Collier, and Mark W. Rutland (2020). “The finishing touches: the role of friction and roughness in haptic perception of surface coatings.” In: *Experimental Brain Research* 238.6, pp. 1511–1524. ISSN: 1432-1106. DOI: 10.1007/s00221-020-05831-w.

Mel Slater (1999). “Measuring Presence: A Response to the Witmer and Singer Presence Questionnaire.” In: *Presence: Teleoperators and Virtual Environments* 8.5, pp. 560–565. ISSN: 1054-7460. DOI: 10.1162/105474699566477.

Mel Slater (2009). “Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments.” In: *Philosophical Transactions of the Royal Society B: Biological Sciences* 364.1535, pp. 3549–3557. DOI: 10.1098/rstb.2009.0138.

Mel Slater, Vasilis Linakis, Martin Usoh, and Rob Kooper (1996). “Immersion, Presence and Performance in Virtual Environments: An Experiment with Tri-Dimensional Chess.” In: *Proceedings of the ACM Symposium on Virtual Reality Software and Technology.* VRST ’96. Hong Kong: Association for Computing Machinery, pp. 163–172. ISBN: 0897918258. DOI: 10.1145/3304181.3304216.

Mel Slater and Anthony Steed (2000). “A Virtual Presence Counter.” In: *Presence: Teleoperators and Virtual Environments* 9.5, pp. 413–434. ISSN: 1054-7460. DOI: 10.1162/105474600566925.

Mel Slater, Martin Usoh, and Anthony Steed (1994). “Depth of Presence in Virtual Environments.” In: *Presence: Teleoperators and Virtual Environments* 3.2, pp. 130–144. ISSN: 1054–7460. DOI: 10.1162/pres.1994.3.2.130.

Mel Slater and Sylvia Wilbur (1997). “A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments.” In: *Presence: Teleoperators and Virtual Environments* 6.6, pp. 603–616. ISSN: 1054-7460. DOI: 10.1162/pres.1997.6.6.603.

Allan Smith, Geneviève Gosselin, and Bryan Houde (2002). “Deployment of fingertip forces in tactile exploration.” In: *Experimental Brain Research* 147.2, pp. 209–218. ISSN: 0014-4819, 1432-1106. DOI: 10.1007/s00221-002-1240-4.

Rajinder Sodhi, Ivan Poupyrev, Matthew Glisson, and Ali Israr (2013). “AIREAL: Interactive Tactile Experiences in Free Air.” In: *ACM Trans. Graph.* 32.4. ISSN: 0730-0301. DOI: 10.1145/2461912.2462007.

Iain Softley (1995). *Hackers.* URL: https://www.imdb.com/title/tt0113243/ (visited on 2022-08-01).

Massimiliano Solazzi, Antonio Frisoli, and Massimo Bergamasco (2010). “Design of a novel finger haptic interface for contact and orientation display.” In: *2010 IEEE Haptics Symposium.* Waltham, MA, USA: IEEE, pp. 129–132. ISBN: 978-1-4244-6821-8. DOI: 10.1109/HAPTIC.2010.5444667.

Massimiliano Solazzi, William R. Provancher, Antonio Frisoli, and Massimo Bergamasco (2011). “Design of a SMA actuated 2-DoF tactile device for displaying tangential skin displacement.” In: *2011 IEEE World Haptics Conference*. Istanbul: IEEE, pp. 31–36. ISBN: 978-1-4577-0299-0. DOI: 10.1109/WHC.2011.5945457.

Moshe Solomonow, John Lyman, and Amos Freedy (1977). “Electrotactile two-point discrimination as a function of frequency, body site, laterality, and stimulation codes.” In: *Annals of Biomedical Engineering* 5.1, pp. 47–60. ISSN: 0090-6964, 1573-9686. DOI: 10.1007/BF02409338.

Marco Speicher, Jan Ehrlich, Vito Gentile, Donald Degraen, Salvatore Sorce, and Antonio Krüger (2019a). “Pseudo-Haptic Controls for Mid-Air Finger-Based Menu Interaction.” In: *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI EA ’19. Glasgow, Scotland, UK: Association for Computing Machinery, pp. 1–6. ISBN: 9781450359719. DOI: 10.1145/3290607.3312927.

Marco Speicher, Christoph Rosenberg, Donald Degraen, Florian Daiber, and Antonio Krüger (2019b). “Exploring Visual Guidance in 360-Degree Videos.” In: *Proceedings of the 2019 ACM International Conference on Interactive Experiences for TV and Online Video*. TVX ’19. Salford (Manchester), United Kingdom: Association for Computing Machinery, pp. 1–12. ISBN: 9781450360173. DOI: 10.1145/3317697.3323350.

Charles Spence (2011). “Crossmodal correspondences: A tutorial review.” In: *Attention, Perception, & Psychophysics* 73.4, pp. 971–995. ISSN: 1943-3921, 1943-393X. DOI: 10.3758/s13414-010-0073-7.

Charles Spence and Cesare V. Parise (2012). “The Cognitive Neuroscience of Crossmodal Correspondences.” In: *i-Perception* 3.7, pp. 410–412. ISSN: 2041-6695, 2041-6695. DOI: 10.1068/i0540ic.

Misha Sra, Sergio Garrido-Jurado, Chris Schmandt, and Pattie Maes (2016). “Procedurally Generated Virtual Reality from 3D Reconstructed Physical Space.” In: *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology*. VRST ’16. Munich, Germany: Association for Computing Machinery, pp. 191–200. ISBN: 9781450344913. DOI: 10.1145/2993369.2993372.

Mandayam A. Srinivasan and Cagatay Basdogan (1997). “Haptics in Virtual Environments: Taxonomy, Research Status, and Challenges.” In: *Computers & Graphics* 21.4, pp. 393–404. ISSN: 00978493. DOI: 10.1016/S0097-8493(97)00030-7.

Andrew A. Stanley, Kenji Hata, and Allison M. Okamura (2016). “Closed-loop shape control of a Haptic Jamming deformable surface.” In: *2016 IEEE International Conference on Robotics and Automation (ICRA)*. Stockholm, Sweden: IEEE, pp. 2718–2724. ISBN: 978-1-4673-8026-3. DOI: 10.1109/ICRA.2016.7487433.

Andrew A. Stanley and Allison M. Okamura (2015). “Controllable Surface Haptics via Particle Jamming and Pneumatics.” In: *IEEE Transactions on Haptics* 8.1, pp. 20–30. DOI: 10.1109/TOH.2015.2391093.

Anthony Steed, Sebastian Friston, Vijay Pawar, and David Swapp (2020). “Docking Haptics: Extending the Reach of Haptics by Dynamic Combinations of Grounded and Worn Devices.” In: *26th ACM Symposium on Virtual Reality Software and Technology*. VRST ’20. Virtual Event, Canada: Association for Computing Machinery. ISBN: 9781450376198. DOI: 10.1145/3385956.3418943.

Carolin Stellmacher (2021). “Haptic-Enabled Buttons Through Adaptive Trigger Resistance.” In: *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. Lisbon, Portugal: IEEE, pp. 201–204. ISBN: 978-1-66544-057-8. DOI: 10.1109/VRW52623.2021.00044.

Carolin Stellmacher, Michael Bonfert, Ernst Kruijff, and Johannes Schöning (2022). “Triggermuscle: Exploring Weight Perception for Virtual Reality Through Adaptive Trigger Resistance in a Haptic VR Controller.” In: *Frontiers in Virtual Reality* 2, p. 754511. ISSN: 2673–4192. DOI: 10.3389/frvir.2021.754511.

Andrew Stockman and Lindsay T. Sharpe (2000). “The spectral sensitivities of the middle- and long-wavelength-sensitive cones derived from measurements in observers of known genotype.” In: *Vision Research* 40.13, pp. 1711–1737. ISSN: 00426989. DOI: 10.1016/S0042-6989(00)00021-3.

Patrick L. Strandholt, Oana A. Dogaru, Niels C. Nilsson, Rolf Nordahl, and Stefania Serafin (2020). “Knock on Wood: Combining Redirected Touching and Physical Props for Tool-Based Interaction in Virtual Reality.” In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. Honolulu HI USA: ACM, pp. 1–13. ISBN: 978-1-4503-6708-0. DOI: 10.1145/3313831.3376303.

Paul Strohmeier, Sebastian Boring, and Kasper Hornbæk (2018). “From Pulse Trains to “Coloring with Vibrations”: Motion Mappings for Mid-Air Haptic Textures.” In: *Proceedings of the 2018 CHI Conference on Human Factors *in Computing Systems*. Montreal QC Canada: ACM, pp. 1–13. ISBN: 978-1-4503-5620-6. DOI: 10.1145/3173574.3173639.

Paul Strohmeier, Seref Güngör, Luis Herres, Dennis Gudea, Bruno Fruchard, and Jürgen Steimle (2020). “BARefoot: Generating Virtual Materials Using Motion Coupled Vibration in Shoes.” In: *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. UIST ’20. Virtual Event, USA: Association for Computing Machinery, pp. 579–593. ISBN: 9781450375146. DOI: 10.1145/3379337.3415828.

Paul Strohmeier and Kasper Hornbæk (2017). “Generating Haptic Textures with a Vibrotactile Actuator.” In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. Denver Colorado USA: ACM, pp. 4994–5005. ISBN: 978-1-4503-4655-9. DOI: 10.1145/3025453.3025812.

Yuqian Sun, Shigeo Yoshida, Takuji Narumi, and Michitaka Hirose (2019). “PaCaPa: A Handheld VR Device for Rendering Size, Shape, and Stiffness of Virtual Objects in Tool-Based Interactions.” In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI ’19. Glasgow, Scotland Uk: Association for Computing Machinery, pp. 1–12. ISBN: 9781450359702. DOI: 10.1145/3290605.3300682.

Ivan E. Sutherland (1965). “The Ultimate Display.” In: *Proceedings of the Congress of the International Federation for Information Processing*. Vol. 2, pp. 506–508.

Ivan E. Sutherland (1968). “A Head-Mounted Three Dimensional Display.” In: *Proceedings of the AFIPS Fall Joint Computing Conference*. ACM, pp. 757–764.

Ryo Suzuki, Hooman Hedayati, Clement Zheng, James L. Bohn, Daniel Szafir, Ellen Yi-Luen Do, Mark D. Gross, and Daniel Leithinger (2020). “RoomShift: Room-Scale Dynamic Haptics for VR with Furniture-Moving Swarm Robots.” In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI ’20. Honolulu, HI, USA: Association for Computing Machinery, pp. 1–11. ISBN: 9781450367080. DOI: 10.1145/3313831.3376523.

Ryo Suzuki, Koji Yatani, Mark D. Gross, and Tom Yeh (2018). “Tabby: Explorable Design for 3D Printing Textures.” In: *Pacific Graphics Short Papers*. arXiv:1810.13251 [cs], 4 pages. DOI: 10.2312/pg.20181273.

Colin Swindells, Evgeny Maksakov, Karon E. MacLean, and Victor Chung (2006). “The Role of Prototyping Tools for Haptic Behavior Design.” In: *2006 14th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp. 161–168. DOI: 10.1109/HAPTIC.2006.1627084.

Colin Swindells, Seppo Pietarinen, and Arto Viitanen (2014). “Medium fidelity rapid prototyping of vibrotactile haptic, audio and video effects.” In: *2014 IEEE Haptics Symposium (HAPTICS)*. Houston, TX, USA: IEEE, pp. 515–521. ISBN: 978-1-4799-3131-6. DOI: 10.1109/HAPTICS.2014.6775509.

László Szirmay-Kalos and Tamás Umenhoffer (2008). “Displacement Mapping on the GPU — State of the Art.” In: *Computer Graphics Forum* 27.6, pp. 1567–1592. DOI: https://doi.org/10.1111/j.1467-8659.2007.01108.x.

Akifumi Takahashi, Jas Brooks, Hiroyuki Kajimoto, and Pedro Lopes (2021). “Increasing Electrical Muscle Stimulation’s Dexterity by Means of Back of the Hand Actuation.” In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. CHI ’21. Yokohama, Japan: Association for Computing Machinery. ISBN: 9781450380966. DOI: 10.1145/3411764.3445761.

Haruki Takahashi and Jeeeun Kim (2019). “3D Printed Fabric: Techniques for Design and 3D Weaving Programmable Textiles.” In: *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. UIST ’19. New Orleans, LA, USA: Association for Computing Machinery, pp. 43–51. ISBN: 9781450368162. DOI: 10.1145/3332165.3347896.

Haruki Takahashi and Homei Miyashita (2016). “Thickness Control Technique for Printing Tactile Sheets with Fused Deposition Modeling.” In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. Tokyo Japan: ACM, pp. 51–53. ISBN: 978-1-4503-4531-6. DOI: 10.1145/2984751.2985701.

Emi Tamaki, Takashi Miyaki, and Jun Rekimoto (2011). “PossessedHand: Techniques for Controlling Human Hands Using Electrical Muscles Stimuli.” In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’11. Vancouver, BC, Canada: Association for Computing Machinery, pp. 543–552. ISBN: 9781450302289. DOI: 10.1145/1978942.1979018.

Yoshihiro Tanaka, Wouter M. Bergmann Tiest, Astrid M. L. Kappers, and Akihito Sano (2014). "Contact Force and Scanning Velocity during Active Roughness Perception." In: *PLoS ONE* 9.3. Ed. by François Tremblay, e93363. ISSN: 1932-6203. DOI: 10.1371/journal.pone.0093363.

Yudai Tanaka, Arata Horie, and Xiang 'Anthony' Chen (2020). "DualVib: Simulating Haptic Sensation of Dynamic Mass by Combining Pseudo-Force and Texture Feedback." In: *26th ACM Symposium on Virtual Reality Software and Technology.* VRST '20. Virtual Event, Canada: Association for Computing Machinery. ISBN: 9781450376198. DOI: 10.1145/3385956.3418964.

Shan-Yuan Teng, Tzu-Sheng Kuo, Chi Wang, Chi-huan Chiang, Da-Yuan Huang, Liwei Chan, and Bing-Yu Chen (2018). "PuPoP: Pop-up Prop on Palm for Virtual Reality." In: *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology.* UIST '18. Berlin, Germany: Association for Computing Machinery, pp. 5–17. ISBN: 9781450359481. DOI: 10.1145/3242587.3242628.

Shan-Yuan Teng, Pengyu Li, Romain Nith, Joshua Fonseca, and Pedro Lopes (2021). "Touch&Fold: A Foldable Haptic Actuator for Rendering Touch in Mixed Reality." In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems.* Yokohama Japan: ACM, pp. 1–14. ISBN: 978-1-4503-8096-6. DOI: 10.1145/3411764.3445099.

Shan-Yuan Teng, Cheng-Lung Lin, Chi-huan Chiang, Tzu-Sheng Kuo, Liwei Chan, Da-Yuan Huang, and Bing-Yu Chen (2019). "TilePoP: Tile-Type Pop-up Prop for Virtual Reality." In: *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology.* UIST '19. New Orleans, LA, USA: Association for Computing Machinery, pp. 639–649. ISBN: 9781450368162. DOI: 10.1145/3332165.3347958.

Mihail Terenti and Radu-Daniel Vatavu (2022). "VIREO: Web-based Graphical Authoring of Vibrotactile Feedback for Interactions with Mobile and Wearable Devices." In: *International Journal of Human–Computer Interaction*, pp. 1–9. ISSN: 1044-7318, 1532-7590. DOI: 10.1080/10447318.2022.2109584.

David Ternes and Karon E. MacLean (2008). "Designing Large Sets of Haptic Icons with Rhythm." In: *Haptics: Perception, Devices and Scenarios.* Ed. by Manuel Ferre. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 199–208. ISBN: 978-3-540-69057-3.

Xavier de Tinguy, Claudio Pacchierotti, Mathieu Emily, Mathilde Chevalier, Aurelie Guignardat, Morgan Guillaudeux, Chloe Six, Anatole Lecuyer, and Maud Marchal (2019a). "How Different Tangible and Virtual Objects Can Be While Still Feeling the Same?" In: *2019 IEEE World Haptics Conference (WHC).* Tokyo, Japan: IEEE, pp. 580–585. ISBN: 978-1-5386-9461-9. DOI: 10.1109/WHC.2019.8816164.

Xavier de Tinguy, Claudio Pacchierotti, Maud Marchal, and Anatole Lecuyer (2019b). "Toward Universal Tangible Objects: Optimizing Haptic Pinching Sensations in 3D Interaction." In: *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR).* Osaka, Japan: IEEE, pp. 321–330. ISBN: 978-1-72811-377-7. DOI: 10.1109/VR.2019.8798205.

Warren S. Torgerson (1952). "Multidimensional scaling: I. Theory and method." In: *Psychometrika* 17.4, pp. 401–419. ISSN: 0033-3123, 1860-0980. DOI: 10.1007/BF02288916.

Cesar Torres, Tim Campbell, Neil Kumar, and Eric Paulos (2015). "HapticPrint: Designing Feel Aesthetics for Digital Fabrication." In: *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology.* UIST '15. Charlotte, NC, USA: Association for Computing Machinery, pp. 583–591. ISBN: 9781450337793. DOI: 10.1145/2807442.2807492.

Matteo Toscani and Anna Metzger (2022). "A Database of Vibratory Signals from Free Haptic Exploration of Natural Material Textures and Perceptual Judgments (ViPer): Analysis of Spectral Statistics." In: *Haptics: Science, Technology, Applications.* Ed. by Hasti Seifi, Astrid M. L. Kappers, Oliver Schneider, Knut Drewing, Claudio Pacchierotti, Alireza Abbasimoshaei, Gijs Huisman, and Thorsten A. Kern. Vol. 13235. Lecture Notes in Computer Science. Cham: Springer International Publishing, pp. 319–327. ISBN: 978-3-031-06248-3. DOI: 10.1007/978-3-031-06249-0_36.

Ryan L. Truby and Jennifer A. Lewis (2016). "Printing soft matter in three dimensions." In: *Nature* 540.7633, pp. 371–378. ISSN: 0028-0836, 1476-4687. DOI: 10.1038/nature21003.

N.G. Tsagarakis, T. Horne, and D.G. Caldwell (2005). "SLIP AESTHEASIS: A Portable 2D Slip/Skin Stretch Display for the Fingertip." In: *First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for*

Virtual Environment and Teleoperator Systems. Pisa, Italy: IEEE, pp. 214–219. ISBN: 978-0-7695-2310-1. DOI: 10.1109/WHC.2005.117.

Hsin-Ruey Tsai, Chieh Tsai, Yu-So Liao, Yi-Ting Chiang, and Zhong-Yi Zhang (2022). "FingerX: Rendering Haptic Shapes of Virtual Objects Augmented by Real Objects Using Extendable and Withdrawable Supports on Fingers." In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems.* CHI '22. New Orleans, LA, USA: Association for Computing Machinery. ISBN: 9781450391573. DOI: 10.1145/3491102.3517489.

Mohamed Yassine Tsalamlal, Paul Issartel, Nizar Ouarti, and Mehdi Ammi (2014). "HAIR: HAptic feedback with a mobile AIR jet." In: *2014 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 2699–2706. DOI: 10.1109/ICRA.2014.6907246.

Michael T. Turvey, Gregory Burton, Eric L. Amazeen, Matthew Butwill, and Claudia Carello (1998). "Perceiving the width and height of a hand-held object by dynamic touch." In: *Journal of Experimental Psychology: Human Perception and Performance* 24.1, pp. 35–48. DOI: 10.1037/0096-1523.24.1.35.

Michael T. Turvey and Claudia Carello (1995). "Dynamic Touch." In: *Perception of Space and Motion.* Elsevier, pp. 401–490. DOI: 10.1016/b978-012240530-3/50013-4.

Chelsea Tymms, Esther P. Gardner, and Denis Zorin (2018). "A Quantitative Perceptual Model for Tactile Roughness." In: *ACM Trans. Graph.* 37.5. ISSN: 0730-0301. DOI: 10.1145/3186267.

Chelsea Tymms, Siqi Wang, and Denis Zorin (2020). "Appearance-Preserving Tactile Optimization." In: *ACM Trans. Graph.* 39.6. ISSN: 0730-0301. DOI: 10.1145/3414685.3417857.

Unity Technologies (2022). *Unity Real-Time Development Platform | 3D, 2D VR & AR Engine.* URL: https://unity.com/ (visited on 2022-07-31).

Martin Usoh, Kevin Arthur, Mary C. Whitton, Rui Bastos, Anthony Steed, Mel Slater, and Frederick P. Brooks (1999). "Walking > Walking-in-Place > Flying, in Virtual Environments." In: *Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques.* SIGGRAPH '99. USA: ACM Press/Addison-Wesley Publishing Co., pp. 359–364. ISBN: 0201485605. DOI: 10.1145/311535.311589.

Martin Usoh, Ernest Catena, Sima Arman, and Mel Slater (2000). "Using Presence Questionnaires in Reality." In: *Presence: Teleoperators and Virtual Environments* 9.5, pp. 497–503. ISSN: 1054-7460. DOI: 10.1162/105474600566989.

Valve Corporation (2022). *SteamVR Unity Plugin.* URL: https://valvesoftware.github.io/steamvr_unity_plugin/index.html (visited on 2020-03-30).

Richard Q. Van der Linde, Piet Lammertse, Erwin Frederiksen, and B. Ruiter (2002). "The HapticMaster, a new high-performance haptic interface." In: *Proceedings of Eurohaptics.* Edinburgh University, pp. 1–5.

Yasemin Vardar, Christian Wallraven, and Katherine J. Kuchenbecker (2019). "Fingertip Interaction Metrics Correlate with Visual and Haptic Perception of Real Surfaces." In: *2019 IEEE World Haptics Conference (WHC).* Tokyo, Japan: IEEE, pp. 395–400. ISBN: 978-1-5386-9461-9. DOI: 10.1109/WHC.2019.8816095.

Velko Vechev, Juan Zarate, David Lindlbauer, Ronan Hinchet, Herbert Shea, and Otmar Hilliges (2019). "TacTiles: Dual-Mode Low-Power Electromagnetic Actuators for Rendering Continuous Contact and Spatial Haptic Patterns in VR." In: *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR).* Osaka, Japan: IEEE, pp. 312–320. ISBN: 978-1-72811-377-7. DOI: 10.1109/VR.2019.8797921.

Ronald T. Verrillo (1966). "Vibrotactile sensitivity and the frequency response of the Pacinian corpuscle." In: *Psychonomic Science* 4.1, pp. 135–136.

Victor G. Veselago (2002). "Electrodynamics of Media with Simultaneously Negative Electric Permittivity and Magnetic Permeability." In: *Advances in Electromagnetics of Complex Media and Metamaterials.* Ed. by Saïd Zouhdi, Ari Sihvola, and Mohamed Arsalane. Dordrecht: Springer Netherlands, pp. 83–97. ISBN: 978-94-007-1067-2. DOI: 10.1007/978-94-007-1067-2_5.

Eric Vezzoli, Chris Ullrich, Gijs Den Butter, and Rafal Pijewski (2022). *XR Haptics, Implementation and Design Guidelines.* Bowker Identifier Services. ISBN: 9780578391205.

Wei Dai Vian and Nancy L. Denton (2018). “Hardness Comparison of Polymer Specimens Produced with Different Processes.” In: *ASEE IL-IN Section Conference*. Vol. 3. ASEEIL IL-IN ’18. Indiana, USA: The American Society for Engineering Education. DOI: 10.5703/1288284316841.

Raquel Viciana-Abad, Arcadio Reyes Lecuona, and Matthieu Poyade (2010). “The Influence of Passive Haptic Feedback and Difference Interaction Metaphors on Presence and Task Performance.” In: *Presence: Teleoperators and Virtual Environments* 19.3, pp. 197–212. DOI: 10.1162/pres.19.3.197.

Yon Visell (2009). “Tactile sensory substitution: Models for enaction in HCI.” In: *Interacting with Computers* 21.1–2, pp. 38–53. ISSN: 09535438. DOI: 10.1016/j.intcom.2008.08.004.

Yon Visell, Keerthi Adithya Duraikkannan, and Vincent Hayward (2014). “A Device and Method for Multimodal Haptic Rendering of Volumetric Stiffness.” In: *Haptics: Neuroscience, Devices, Modeling, and Applications*. Ed. by Malika Auvray and Christian Duriez. Vol. 8618. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 478–486. ISBN: 9783662441923. DOI: 10.1007/978-3-662-44193-0_60.

Brad Walker (2011). *The anatomy of stretching: your illustrated guide to flexibility and injury rehabilitation*. 2nn. North Atlantic Books. ISBN: 1-58394-371-4.

Steven A. Wall and William S. Harwin (1999). “Modelling of Surface Identifying Characteristics Using Fourier Series.” In: *Dynamic Systems and Control*. Nashville, Tennessee, USA: American Society of Mechanical Engineers, pp. 65–71. ISBN: 978-0-7918-1634-9. DOI: 10.1115/IMECE1999-0009.

Christian Wallraven, Heinrich H. Bülthoff, Steffen Waterkamp, Loes van Dam, and Nina Gaißert (2014). “The Eyes grasp, the Hands see: Metric Category Knowledge transfers between Vision and Touch.” In: *Psychonomic Bulletin & Review* 21.4, pp. 976–985. ISSN: 1069-9384, 1531-5320. DOI: 10.3758/s13423-013-0563-4.

Brian A. Wandell (1995). *Foundations of Vision*. Sunderland, MA: Sinauer Associates.

Dangxiao Wang, Yuan Guo, Shiyi Liu, Yuru Zhang, Weiliang Xu, and Jing Xiao (2019). “Haptic Display for Virtual Reality: Progress and Challenges.” In: *Virtual Reality & Intelligent Hardware* 1.2, pp. 136–162. ISSN: 20965796. DOI: 10.3724/SP.J.2096-5796.2019.0008.

Dangxiao Wang, Kouhei Ohnishi, and Weiliang Xu (2020). “Multimodal Haptic Display for Virtual Reality: A Survey.” In: *IEEE Transactions on Industrial Electronics* 67.1, pp. 610–623. ISSN: 0278-0046, 1557-9948. DOI: 10.1109/TIE.2019.2920602.

Qi Wang and Vincent Hayward (2008). “Tactile Synthesis and Perceptual Inverse Problems Seen from the Viewpoint of Contact Mechanics.” In: *ACM Transactions on Applied Perception* 5.2. ISSN: 1544-3558. DOI: 10.1145/1279920.1279921.

Colin Ware, Kevin Arthur, and Kellogg S. Booth (1993). “Fish Tank Virtual Reality.” In: *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI ’93*. Amsterdam, The Netherlands: ACM Press, pp. 37–42. ISBN: 978-0-89791-575-5. DOI: 10.1145/169059.169066.

Junji Watanabe and Maki Sakamoto (2012). “Comparison between onomatopoeias and adjectives for evaluating tactile sensations.” In: *Proceedings of the 6th International Conference of Soft Computing and Intelligent Systems and the 13th International Symposium on Advanced Intelligent Systems (SCIS-ISIS 2012)*, pp. 2346–2348.

Junji Watanabe, Yuuka Utsunomiya, Hiroya Tsukurimichi, and Maki Sakamoto (2012). “Relationship between Phonemes and Tactile-emotional Evaluations in Japanese Sound Symbolic Words.” In: *Proceedings of the Annual Meeting of the Cognitive Science Society*. Vol. 34. 6.

Ernst Heinrich Weber (1834). *De Subtilitate Tactus*.

Ernst Heinrich Weber (1846). “Der Tastsinn und das Gemeingefühl.” In: *Handwörterbuch der Physiologie* 3, pp. 481–588.

Stanley Grauman Weinbaum (1935). “Pygmalion’s Spectacles.” In: *Wonder Stories*. Ed. by Hugo Gernsback. Continental Publications, pp. 28–39.

Malte Weiss, Chat Wacharamanotham, Simon Voelker, and Jan Borchers (2011). “FingerFlux: near-surface haptic feedback on tabletops.” In: *Proceedings of the 24th annual ACM symposium on User interface software and technology - UIST ’11*. Santa Barbara, California, USA: ACM Press, p. 615. ISBN: 978-1-4503-0716-1. DOI: 10.1145/2047196.2047277.

Michael Wessely, Ticha Sethapakdi, Carlos Castillo, Jackson C. Snowden, Ollie Hanton, Isabel P. S. Qamar, Mike Fraser, Anne Roudaut, and Stefanie Mueller (2020). “Sprayable User Interfaces: Prototyping Large-Scale Interactive Surfaces with Sensors and Displays.” In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI ’20. Honolulu, HI, USA: Association for Computing Machinery, pp. 1–12. ISBN: 9781450367080. DOI: 10.1145/3313831.3376249.

Eric Whitmire, Hrvoje Benko, Christian Holz, Eyal Ofek, and Mike Sinclair (2018). “Haptic Revolver: Touch, Shear, Texture, and Shape Rendering on a Reconfigurable Virtual Reality Controller.” In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI ’18. Montreal QC, Canada: Association for Computing Machinery, pp. 1–12. ISBN: 9781450356206. DOI: 10.1145/3173574.3173660.

Wikimedia Commons (2001). *The Cave Automatic Virtual Environment at EVL, University of Illinois at Chicago by Dave Pape*. URL: https://upload.wikimedia.org/wikipedia/commons/6/6d/CAVE_Crayoland.jpg (visited on 2022-08-07).

Wikimedia Commons (2009). *The Stockman and Sharpe (2000) 2°cone fundamentals, as found here, plotted against the sRGB spectrum by BenRG*. URL: https://commons.wikimedia.org/w/index.php?curid=7873848 (visited on 2022-07-11).

Wikimedia Commons (2018). *Friday Mosque, Malé, Maldives*. URL: https://commons.wikimedia.org/wiki/File:Male%27_Hukuru_Miskiy_1.jpg (visited on 2022-05-17).

E. J. Williams (1949). “Experimental Designs Balanced for the Estimation of Residual Effects of Treatments.” In: *Australian Journal of Chemistry* 2.2, pp. 149–168. DOI: 10.1071/CH9490149.

Anusha Withana, Daniel Groeger, and Jürgen Steimle (2018). “Tacttoo: A Thin and Feel-Through Tattoo for On-Skin Tactile Output.” In: *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*. UIST ’18. Berlin, Germany: Association for Computing Machinery, pp. 365–378. ISBN: 9781450359481. DOI: 10.1145/3242587.3242645.

Bob G. Witmer and Michael J. Singer (1998). “Measuring Presence in Virtual Environments: A Presence Questionnaire.” In: *Presence: Teleoperators and Virtual Environments* 7.3, pp. 225–240. DOI: 10.1162/105474698565686.

Dennis Wittchen, Katta Spiel, Bruno Fruchard, Donald Degraen, Oliver Schneider, Georg Freitag, and Paul Strohmeier (2022). “TactJam: An End-to-End Prototyping Suite for Collaborative Design of On-Body Vibrotactile Feedback.” In: *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction*. New York, NY, USA: Association for Computing Machinery. ISBN: 9781450391474. DOI: 10.1145/3490149.3501307.

Jeremy M. Wolfe, Keith Kluender, Dennis M. Levi, Linda Bartoshuk, Rachel S. Herz, Roberta L. Klatzky, and Daniel M. Merfeld (2018). *Sensation and Perception*. 5th ed. Sinauer Associates.

Akira Yakata, Yuichiro Shimizu, Masaharu Haginoya, and Maki Sakamoto (2013). “Method of evaluating metal textures by the sound symbolism of onomatopoeia.” In: *The Second Asian Conference on Information Systems*. 7. Phuket, Thailand, pp. 618–624. URL: https://saki.siit.tu.ac.th/acis2013/posts/read/52.

Shun Yamaguchi, Seitaro Kaneko, and Hiroyuki Kajimoto (2020). “Measurement of the Permissible Range of Consistency between Visual and Tactile Presentations of Line Grating Textures.” In: *Applied Sciences* 10.7. 0 citations (Semantic Scholar/DOI) [2022-07-09], p. 2494. ISSN: 2076-3417. DOI: 10.3390/app10072494.

Xin Yan, Lin Lu, Andrei Sharf, Xing Yu, and Yulu Sun (2021). “Man-made by Computer: On-the-Fly Fine Texture 3D Printing.” In: *Symposium on Computational Fabrication*. Virtual Event USA: ACM, pp. 1–10. ISBN: 978-1-4503-9090-3. DOI: 10.1145/3485114.3485119.

Xin Yan, Cong Rao, Lin Lu, Andrei Sharf, Haisen Zhao, and Baoquan Chen (2020). “Strong 3D Printing by TPMS Injection.” In: *IEEE Transactions on Visualization and Computer Graphics* 26.10, pp. 3037–3050. DOI: 10.1109/TVCG.2019.2914044.

Hsin-Yun Yao and Vincent Hayward (2010). “Design and analysis of a recoil-type vibrotactile transducer.” In: *The Journal of the Acoustical Society of America* 128.2, pp. 619–627. DOI: 10.1121/1.3458852.

Lining Yao, Ryuma Niiyama, Jifei Ou, Sean Follmer, Clark Della Silva, and Hiroshi Ishii (2013). “PneUI: Pneumatically Actuated Soft Composite Materials for Shape Changing Interfaces.” In: *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology*. UIST ’13. St. Andrews, Scotland, United Kingdom: Association for Computing Machinery, pp. 13–22. ISBN: 9781450322683. DOI: 10.1145/2501988.2502037.

Yuan Yao, Cheng Ding, Mohamed Aburaia, Maximilian Lackner, and Lanlan He (2021). *A 3D weaving infill pattern for fused filament fabrication.* DOI: 10.21203/rs.3.rs-295081/v1.

Kentaro Yasu (2017). "Magnetic Plotter: A Macrotexture Design Method Using Magnetic Rubber Sheets." In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems.* Denver Colorado USA: ACM, pp. 4983–4993. ISBN: 978-1-4503-4655-9. DOI: 10.1145/3025453.3025702.

Kentaro Yasu (2019). "Magnetact: Magnetic-Sheet-Based Haptic Interfaces for Touch Devices." In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems.* CHI '19. Glasgow, Scotland Uk: Association for Computing Machinery, pp. 1–8. ISBN: 9781450359702. DOI: 10.1145/3290605.3300470.

Kentaro Yasu (2020). "MagneLayer: Force Field Fabrication by Layered Magnetic Sheets." In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems.* Honolulu HI USA: ACM, pp. 1–9. ISBN: 978-1-4503-6708-0. DOI: 10.1145/3313831.3376552.

Kentaro Yasu and Masaya Ishikawa (2021). "Magnetact Animals: A Simple Kinetic Toy Kit for a Creative Online Workshop for Children." In: *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems.* Yokohama Japan: ACM, pp. 1–4. ISBN: 978-1-4503-8095-9. DOI: 10.1145/3411763.3451533.

Kentaro Yasu and Yuichiro Katsumoto (2015). "Bump ahead: easy-to-design haptic surface using magnet array." In: *SIGGRAPH Asia 2015 Emerging Technologies.* Kobe Japan: ACM, pp. 1–3. ISBN: 978-1-4503-3925-4. DOI: 10.1145/2818466.2818478.

Vibol Yem and Hiroyuki Kajimoto (2017). "Comparative Evaluation of Tactile Sensation by Electrical and Mechanical Stimulation." In: *IEEE Transactions on Haptics* 10.1, pp. 130–134. ISSN: 1939-1412. DOI: 10.1109/TOH.2016.2605084.

Vibol Yem, Ryuta Okazaki, and Hiroyuki Kajimoto (2016). "FinGAR: Combination of Electrical and Mechanical Stimulation for High-Fidelity Tactile Presentation." In: *ACM SIGGRAPH 2016 Emerging Technologies.* SIGGRAPH '16. Anaheim, California: Association for Computing Machinery. ISBN: 9781450343725. DOI: 10.1145/2929464.2929474.

Yan Yixian, Kazuki Takashima, Anthony Tang, Takayuki Tanno, Kazuyuki Fujita, and Yoshifumi Kitamura (2020). "ZoomWalls: Dynamic Walls That Simulate Haptic Infrastructure for Room-Scale VR World." In: *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology.* UIST '20. Virtual Event, USA: Association for Computing Machinery, pp. 223–235. ISBN: 9781450375146. DOI: 10.1145/3379337.3415859.

Sang Ho Yoon, Siyuan Ma, Woo Suk Lee, Shantanu Thakurdesai, Di Sun, Flávio P. Ribeiro, and James D. Holbery (2019). "HapSense: A Soft Haptic I/O Device with Uninterrupted Dual Functionalities of Force Sensing and Vibrotactile Actuation." In: *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology.* New Orleans LA USA: ACM, pp. 949–961. ISBN: 978-1-4503-6816-2. DOI: 10.1145/3332165.3347888.

Masaaki Yoshida (1968). "Dimensions of Tactual Impressions (1)." In: *Japanese Psychological Research* 10.3, pp. 123–137. ISSN: 1468-5884, 0021-5368. DOI: 10.4992/psycholres1954.10.123.

Shigeo Yoshida, Yuqian Sun, and Hideaki Kuzuoka (2020). "PoCoPo: Handheld Pin-Based Shape Display for Haptic Rendering in Virtual Reality." In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems.* CHI '20. Honolulu, HI, USA: Association for Computing Machinery, pp. 1–13. ISBN: 9781450367080. DOI: 10.1145/3313831.3376358.

Shunsuke Yoshimoto, Yoshihiro Kuroda, Masataka Imura, and Osamu Oshiro (2015). "Material Roughness Modulation via Electrotactile Augmentation." In: *IEEE Transactions on Haptics* 0.0, p. 12.

Takashi Yoshioka, Sliman J. Bensmaïa, James C. Craig, and Steven S. Hsiao (2007). "Texture perception through direct and indirect touch: An analysis of perceptual space for tactile textures in two modes of exploration." In: *Somatosensory & Motor Research* 24.1–2, pp. 53–70. ISSN: 0899-0220, 1369-1651. DOI: 10.1080/08990220701318163.

Eric M. Young, Amirhossein H. Memar, Priyanshu Agarwal, and Nick Colonnese (2019). "Bellowband: A Pneumatic Wristband for Delivering Local Pressure and Vibration." In: *2019 IEEE World Haptics Conference (WHC).* Tokyo, Japan: IEEE, pp. 55–60. ISBN: 978-1-5386-9461-9. DOI: 10.1109/WHC.2019.8816075.

Xinge Yu, Zhaoqian Xie, Yang Yu, Jungyup Lee, Abraham Vazquez-Guardado, Haiwen Luan, Jasper Ruban, Xin Ning, Aadeel Akhtar, Dengfeng Li, Bowen Ji, Yiming Liu, Rujie Sun, Jingyue Cao, Qingze Huo, Yishan Zhong, ChanMi Lee, SeungYeop Kim, Philipp Gutruf, Changxing Zhang, Yeguang Xue, Qinglei Guo, Aditya

Chempakasseril, Peilin Tian, Wei Lu, JiYoon Jeong, YongJoon Yu, Jesse Cornman, CheeSim Tan, BongHoon Kim, KunHyuk Lee, Xue Feng, Yonggang Huang, and John A. Rogers (2019). "Skin-integrated wireless haptic interfaces for virtual and augmented reality." In: *Nature* 575.7783, pp. 473–479. ISSN: 0028-0836, 1476-4687. DOI: 10.1038/s41586-019-1687-0.

Sungryul Yun, Suntak Park, Bongje Park, Semin Ryu, Seung Mo Jeong, and Ki-Uk Kyung (2020). "A Soft and Transparent Visuo-Haptic Interface Pursuing Wearable Devices." In: *IEEE Transactions on Industrial Electronics* 67.1, pp. 717–724. ISSN: 0278-0046, 1557-9948. DOI: 10.1109/TIE.2019.2898620.

Jonas Zehnder, Espen Knoop, Moritz Bächer, and Bernhard Thomaszewski (2017). "Metasilicone: Design and Fabrication of Composite Silicone with Desired Mechanical Properties." In: *ACM Trans. Graph.* 36.6. ISSN: 0730-0301. DOI: 10.1145/3130800.3130881.

André Zenner, Donald Degraen, Florian Daiber, and Antonio Krüger (2020). "Demonstration of Drag:On - A VR Controller Providing Haptic Feedback Based on Drag and Weight Shift." In: *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI EA '20. Honolulu, HI, USA: Association for Computing Machinery, pp. 1–4. ISBN: 9781450368193. DOI: 10.1145/3334480.3383145.

André Zenner and Antonio Krüger (2017). "Shifty: A Weight-Shifting Dynamic Passive Haptic Proxy to Enhance Object Perception in Virtual Reality." In: *IEEE Transactions on Visualization and Computer Graphics* 23.4, pp. 1285–1294. DOI: 10.1109/TVCG.2017.2656978.

André Zenner and Antonio Krüger (2019). "Drag:On: A Virtual Reality Controller Providing Haptic Feedback Based on Drag and Weight Shift." In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Glasgow, Scotland Uk: Association for Computing Machinery, pp. 1–12. ISBN: 9781450359702. DOI: 10.1145/3290605.3300441.

André Zenner, Marco Speicher, Sören Klingner, Donald Degraen, Florian Daiber, and Antonio Krüger (2018). "Immersive Notification Framework: Adaptive & Plausible Notifications in Virtual Reality." In: *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI EA '18. Montreal QC, Canada: Association for Computing Machinery, pp. 1–6. ISBN: 9781450356213. DOI: 10.1145/3170427.3188505.

Yiwei Zhao and Sean Follmer (2018). "A Functional Optimization Based Approach for Continuous 3D Retargeted Touch of Arbitrary, Complex Boundaries Haptic Virtual Reality." In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: Association for Computing Machinery, pp. 1–12. ISBN: 9781450356206. DOI: 10.1145/3173574.3174118.

Yiwei Zhao, Lawrence H. Kim, Ye Wang, Mathieu Le Goc, and Sean Follmer (2017). "Robotic Assembly of Haptic Proxy Objects for Tangible Interaction and Virtual Reality." In: *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces*. ISS '17. Brighton, United Kingdom: Association for Computing Machinery, pp. 82–91. ISBN: 9781450346917. DOI: 10.1145/3132272.3134143.

Clement Zheng and Ellen Yi-Luen Do (2018). "Mechamagnets: Tactile Mechanisms with Embedded Magnets." In: *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction*. Stockholm Sweden: ACM, pp. 57–64. ISBN: 978-1-4503-5568-1. DOI: 10.1145/3173225.3173268.

Clement Zheng, Jeeeun Kim, Daniel Leithinger, Mark D. Gross, and Ellen Yi-Luen Do (2019). "Mechamagnets: Designing and Fabricating Haptic and Functional Physical Inputs with Embedded Magnets." In: *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '19. Tempe, Arizona, USA: Association for Computing Machinery, pp. 325–334. ISBN: 9781450361965. DOI: 10.1145/3294109.3295622.

Yanling Zheng, Xu Huang, Jialiang Chen, Kechen Wu, Jianlei Wang, and Xu Zhang (2021). "A Review of Conductive Carbon Materials for 3D Printing: Materials, Technologies, Properties, and Applications." In: *Materials* 14.14, p. 3911. ISSN: 1996–1944. DOI: 10.3390/ma14143911.

Kening Zhu, Taizhou Chen, Feng Han, and Yi-Shiun Wu (2019). "HapTwist: Creating Interactive Haptic Proxies in Virtual Reality Using Low-Cost Twistable Artefacts." In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Glasgow, Scotland Uk: Association for Computing Machinery, pp. 1–13. ISBN: 9781450359702. DOI: 10.1145/3290605.3300923.

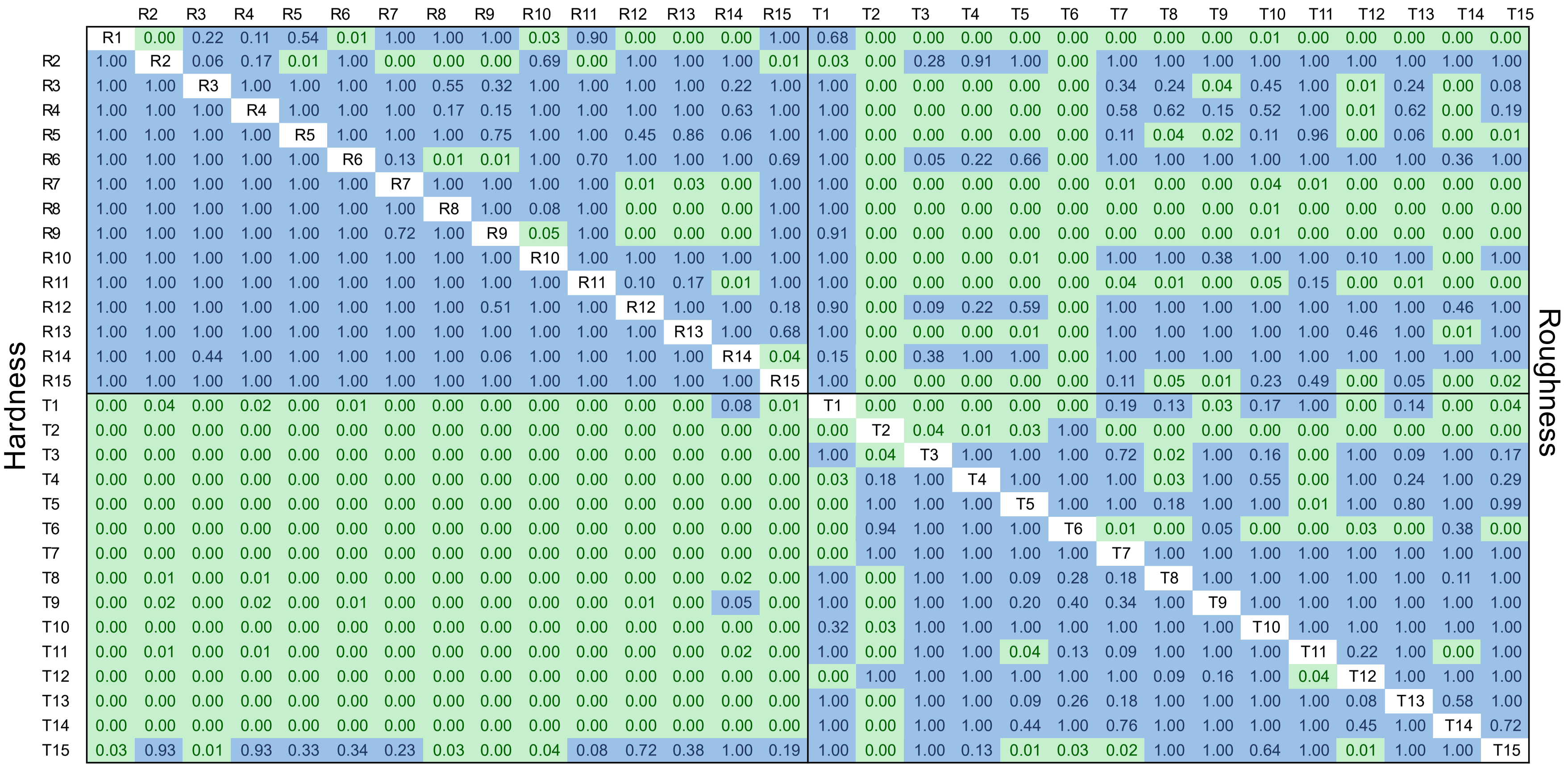
Part V

APPENDIX

a

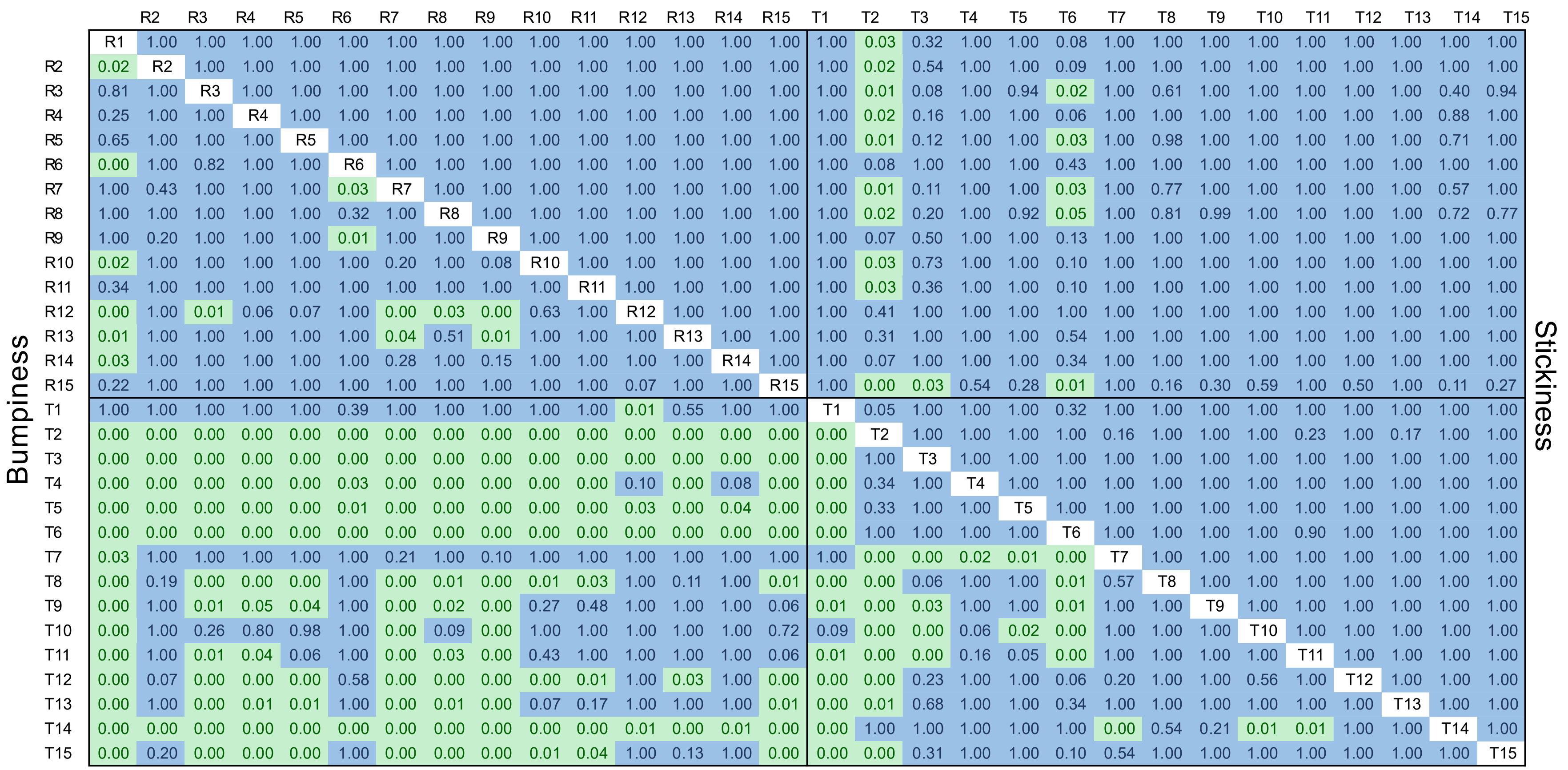
ANNEX: CAPTURING TACTILE PROPERTIES

A.1 INDIVIDUAL TACTILE RATINGS



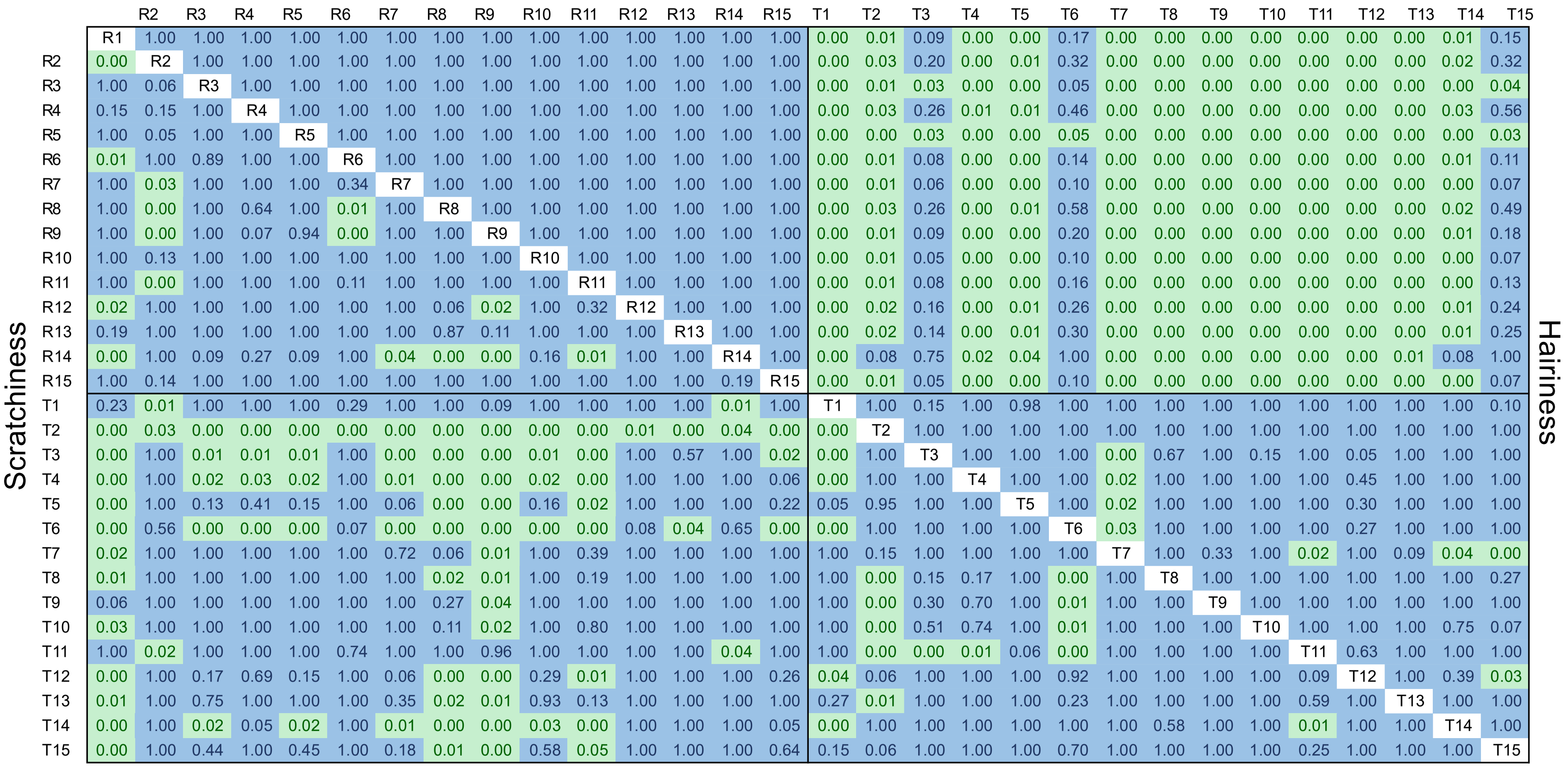
		R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15
	R1	0.00	0.22	0.11	0.54	0.01	1.00	1.00	1.00	0.03	0.90	0.00	0.00	0.00	1.00	0.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
R2	1.00	R2	0.06	0.17	0.01	1.00	0.00	0.00	0.00	0.69	0.00	1.00	1.00	1.00	0.01	0.03	0.00	0.28	0.91	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
R3	1.00	1.00	R3	1.00	1.00	1.00	1.00	0.55	0.32	1.00	1.00	1.00	1.00	0.22	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.34	0.24	0.04	0.45	1.00	0.01	0.24	0.00	0.08
R4	1.00	1.00	1.00	R4	1.00	1.00	1.00	0.17	0.15	1.00	1.00	1.00	1.00	0.63	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.58	0.62	0.15	0.52	1.00	0.01	0.62	0.00	0.19
R5	1.00	1.00	1.00	1.00	R5	1.00	1.00	1.00	0.75	1.00	1.00	0.45	0.86	0.06	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.11	0.04	0.02	0.11	0.96	0.00	0.06	0.00	0.01
R6	1.00	1.00	1.00	1.00	1.00	R6	0.13	0.01	0.01	1.00	0.70	1.00	1.00	1.00	0.69	1.00	0.00	0.05	0.22	0.66	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.36	1.00
R7	1.00	1.00	1.00	1.00	1.00	1.00	R7	1.00	1.00	1.00	1.00	0.01	0.03	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.04	0.01	0.00	0.00	0.00	0.00
R8	1.00	1.00	1.00	1.00	1.00	1.00	1.00	R8	1.00	0.08	1.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
R9	1.00	1.00	1.00	1.00	1.00	1.00	0.72	1.00	R9	0.05	1.00	0.00	0.00	0.00	1.00	0.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
R10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	R10	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.01	0.00	1.00	1.00	0.38	1.00	1.00	0.10	1.00	0.00	1.00
R11	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	R11	0.10	0.17	0.01	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.04	0.01	0.00	0.05	0.15	0.00	0.01	0.00	0.00
R12	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.51	1.00	1.00	R12	1.00	1.00	0.18	0.90	0.00	0.09	0.22	0.59	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.46	1.00
R13	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	R13	1.00	0.68	1.00	0.00	0.00	0.00	0.01	0.00	1.00	1.00	1.00	1.00	1.00	0.46	1.00	0.01	1.00
R14	1.00	1.00	0.44	1.00	1.00	1.00	1.00	1.00	0.06	1.00	1.00	1.00	1.00	R14	0.04	0.15	0.00	0.38	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
R15	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	R15	1.00	0.00	0.00	0.00	0.00	0.00	0.11	0.05	0.01	0.23	0.49	0.00	0.05	0.00	0.02
T1	0.00	0.04	0.00	0.02	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.01	T1	0.00	0.00	0.00	0.00	0.00	0.19	0.13	0.03	0.17	1.00	0.00	0.14	0.00	0.04
T2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	T2	0.04	0.01	0.03	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.04	T3	1.00	1.00	1.00	0.72	0.02	1.00	0.16	0.00	1.00	0.09	1.00	0.17
T4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.18	1.00	T4	1.00	1.00	1.00	0.03	1.00	0.55	0.00	1.00	0.24	1.00	0.29
T5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	T5	1.00	1.00	0.18	1.00	1.00	0.01	1.00	0.80	1.00	0.99
T6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.94	1.00	1.00	1.00	T6	0.01	0.00	0.05	0.00	0.00	0.03	0.00	0.38	0.00
T7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	T7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T8	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	1.00	0.00	1.00	1.00	0.09	0.28	0.18	T8	1.00	1.00	1.00	1.00	1.00	0.11	1.00
T9	0.00	0.02	0.00	0.02	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.05	0.00	1.00	0.00	1.00	1.00	0.20	0.40	0.34	1.00	T9	1.00	1.00	1.00	1.00	1.00	1.00
T10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.32	0.03	1.00	1.00	1.00	1.00	1.00	1.00	1.00	T10	1.00	1.00	1.00	1.00	1.00
T11	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	1.00	0.00	1.00	1.00	0.04	0.13	0.09	1.00	1.00	1.00	T11	0.22	1.00	0.00	1.00
T12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.09	0.16	1.00	0.04	T12	1.00	1.00	1.00
T13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	1.00	1.00	0.09	0.26	0.18	1.00	1.00	1.00	1.00	0.08	T13	0.58	1.00
T14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	1.00	1.00	0.44	1.00	0.76	1.00	1.00	1.00	1.00	0.45	1.00	T14	0.72
T15	0.03	0.93	0.01	0.93	0.33	0.34	0.23	0.03	0.00	0.04	0.08	0.72	0.38	1.00	0.19	1.00	0.00	1.00	0.13	0.01	0.03	0.02	1.00	1.00	0.64	1.00	0.01	1.00	1.00	T15

Figure a.1: P-values (green, < 0.05; blue, $>= 0.05$) of the Wilcoxon signed ranks tests (Bonferroni-Holm correction) for all comparisons for hardness (left) and roughness (right). The ratings of hardness and roughness were found to significantly differ depending on the sample (hardness, $\chi^2(29) = 445.83$, $p < .001$; roughness, $\chi^2(29) = 382.29$, $p < .001$).



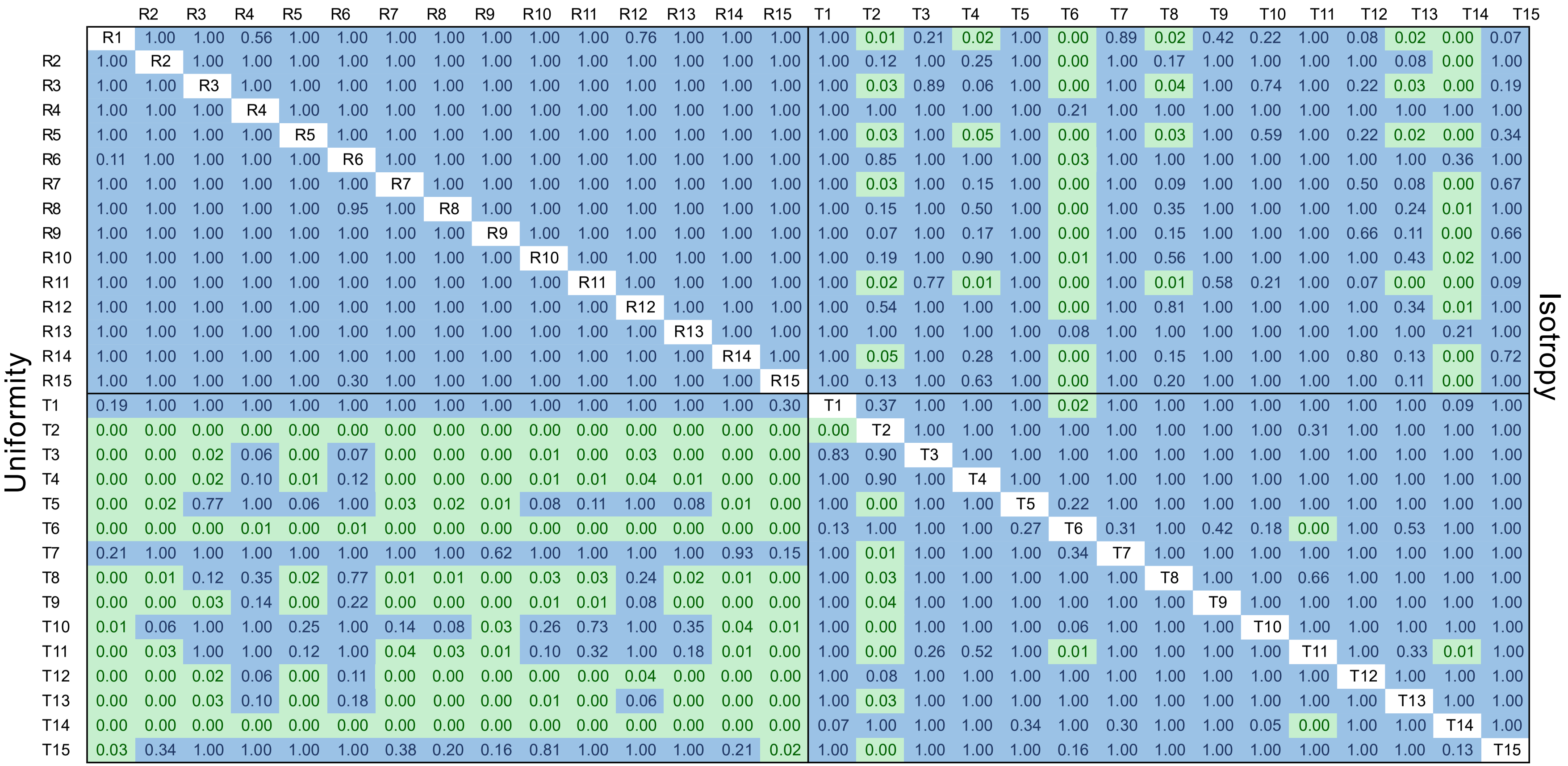
		R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15
	R1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.03	0.32	1.00	1.00	0.08	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
R2	0.02	R2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.02	0.54	1.00	1.00	0.09	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
R3	0.81	1.00	R3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.01	0.08	1.00	0.94	0.02	1.00	0.61	1.00	1.00	1.00	1.00	1.00	0.40	0.94
R4	0.25	1.00	1.00	R4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.02	0.16	1.00	1.00	0.06	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.88	1.00
R5	0.65	1.00	1.00	1.00	R5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.01	0.12	1.00	1.00	0.03	1.00	0.98	1.00	1.00	1.00	1.00	1.00	0.71	1.00
R6	0.00	1.00	0.82	1.00	1.00	R6	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.08	1.00	1.00	1.00	0.43	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
R7	1.00	0.43	1.00	1.00	1.00	0.03	R7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.01	0.11	1.00	1.00	0.03	1.00	0.77	1.00	1.00	1.00	1.00	1.00	0.57	1.00
R8	1.00	1.00	1.00	1.00	1.00	0.32	1.00	R8	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.02	0.20	1.00	0.92	0.05	1.00	0.81	0.99	1.00	1.00	1.00	1.00	0.72	0.77
R9	1.00	0.20	1.00	1.00	1.00	0.01	1.00	1.00	R9	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.07	0.50	1.00	1.00	0.13	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
R10	0.02	1.00	1.00	1.00	1.00	1.00	0.20	1.00	0.08	R10	1.00	1.00	1.00	1.00	1.00	1.00	0.03	0.73	1.00	1.00	0.10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
R11	0.34	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	R11	1.00	1.00	1.00	1.00	1.00	0.03	0.36	1.00	1.00	0.10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
R12	0.00	1.00	0.01	0.06	0.07	1.00	0.00	0.03	0.00	0.63	1.00	R12	1.00	1.00	1.00	1.00	0.41	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
R13	0.01	1.00	1.00	1.00	1.00	1.00	0.04	0.51	0.01	1.00	1.00	1.00	R13	1.00	1.00	1.00	0.31	1.00	1.00	1.00	0.54	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
R14	0.03	1.00	1.00	1.00	1.00	1.00	0.28	1.00	0.15	1.00	1.00	1.00	1.00	R14	1.00	1.00	0.07	1.00	1.00	1.00	0.34	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
R15	0.22	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.07	1.00	1.00	R15	1.00	0.00	0.03	0.54	0.28	0.01	1.00	0.16	0.30	0.59	1.00	0.50	1.00	0.11	0.27
T1	1.00	1.00	1.00	1.00	1.00	0.39	1.00	1.00	1.00	1.00	1.00	0.01	0.55	1.00	1.00	T1	0.05	1.00	1.00	1.00	0.32	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	T2	1.00	1.00	1.00	1.00	0.16	1.00	1.00	1.00	0.23	1.00	0.17	1.00	1.00
T3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	T3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T4	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.08	0.00	0.00	0.34	1.00	T4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T5	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.04	0.00	0.00	0.33	1.00	1.00	T5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	T6	1.00	1.00	1.00	1.00	0.90	1.00	1.00	1.00	1.00
T7	0.03	1.00	1.00	1.00	1.00	1.00	0.21	1.00	0.10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.02	0.01	0.00	T7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T8	0.00	0.19	0.00	0.00	0.00	1.00	0.00	0.01	0.00	0.01	0.03	1.00	0.11	1.00	0.01	0.00	0.00	0.06	1.00	1.00	0.01	0.57	T8	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T9	0.00	1.00	0.01	0.05	0.04	1.00	0.00	0.02	0.00	0.27	0.48	1.00	1.00	1.00	0.06	0.01	0.00	0.03	1.00	1.00	0.01	1.00	1.00	T9	1.00	1.00	1.00	1.00	1.00	1.00
T10	0.00	1.00	0.26	0.80	0.98	1.00	0.00	0.09	0.00	1.00	1.00	1.00	1.00	1.00	0.72	0.09	0.00	0.00	0.06	0.02	0.00	1.00	1.00	1.00	T10	1.00	1.00	1.00	1.00	1.00
T11	0.00	1.00	0.01	0.04	0.06	1.00	0.00	0.03	0.00	0.43	1.00	1.00	1.00	1.00	0.06	0.01	0.00	0.00	0.16	0.05	0.00	1.00	1.00	1.00	1.00	T11	1.00	1.00	1.00	1.00
T12	0.00	0.07	0.00	0.00	0.00	0.58	0.00	0.00	0.00	0.00	0.01	1.00	0.03	1.00	0.00	0.00	0.00	0.23	1.00	1.00	0.06	0.20	1.00	1.00	0.56	1.00	T12	1.00	1.00	1.00
T13	0.00	1.00	0.00	0.01	0.01	1.00	0.00	0.01	0.00	0.07	0.17	1.00	1.00	1.00	0.01	0.00	0.01	0.68	1.00	1.00	0.34	1.00	1.00	1.00	1.00	1.00	1.00	T13	1.00	1.00
T14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	1.00	1.00	1.00	1.00	1.00	0.00	0.54	0.21	0.01	0.01	1.00	1.00	T14	1.00
T15	0.00	0.20	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.01	0.04	1.00	0.13	1.00	0.00	0.00	0.00	0.31	1.00	1.00	0.10	0.54	1.00	1.00	1.00	1.00	1.00	1.00	1.00	T15

Figure a.2: P-values (green, < 0.05; blue, $>= 0.05$) of the Wilcoxon signed ranks tests (Bonferroni-Holm correction) for all comparisons for bumpiness (left) and stickiness (right). The ratings of bumpiness and stickiness were found to significantly differ depending on the sample (bumpiness, $\chi^2(29) = 393.01$, $p < .001$; stickiness, $\chi^2(29) = 172.08$, $p < .001$).



		R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15
	R1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.01	0.09	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.15
R2	0.00	R2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.03	0.20	0.00	0.01	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.32
R3	1.00	0.06	R3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.01	0.03	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04
R4	0.15	0.15	1.00	R4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.03	0.26	0.01	0.01	0.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.56
R5	1.00	0.05	1.00	1.00	R5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.03	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
R6	0.01	1.00	0.89	1.00	1.00	R6	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.01	0.08	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.11
R7	1.00	0.03	1.00	1.00	1.00	0.34	R7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.01	0.06	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07
R8	1.00	0.00	1.00	0.64	1.00	0.01	1.00	R8	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.03	0.26	0.00	0.01	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.49
R9	1.00	0.00	1.00	0.07	0.94	0.00	1.00	1.00	R9	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.01	0.09	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.18
R10	1.00	0.13	1.00	1.00	1.00	1.00	1.00	1.00	1.00	R10	1.00	1.00	1.00	1.00	1.00	0.00	0.01	0.05	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07
R11	1.00	0.00	1.00	1.00	1.00	0.11	1.00	1.00	1.00	1.00	R11	1.00	1.00	1.00	1.00	0.00	0.01	0.08	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13
R12	0.02	1.00	1.00	1.00	1.00	1.00	1.00	0.06	0.02	1.00	0.32	R12	1.00	1.00	1.00	0.00	0.02	0.16	0.00	0.01	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.24
R13	0.19	1.00	1.00	1.00	1.00	1.00	1.00	0.87	0.11	1.00	1.00	1.00	R13	1.00	1.00	0.00	0.02	0.14	0.00	0.01	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.25
R14	0.00	1.00	0.09	0.27	0.09	1.00	0.04	0.00	0.00	0.16	0.01	1.00	1.00	R14	1.00	0.00	0.08	0.75	0.02	0.04	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.08	1.00
R15	1.00	0.14	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.19	R15	0.00	0.01	0.05	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07
T1	0.23	0.01	1.00	1.00	1.00	0.29	1.00	1.00	0.09	1.00	1.00	1.00	1.00	0.01	1.00	T1	1.00	0.15	1.00	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.10
T2	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.04	0.00	0.00	T2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T3	0.00	1.00	0.01	0.01	0.01	1.00	0.00	0.00	0.00	0.01	0.00	1.00	0.57	1.00	0.02	0.00	1.00	T3	1.00	1.00	1.00	0.00	0.67	1.00	0.15	1.00	0.05	1.00	1.00	1.00
T4	0.00	1.00	0.02	0.03	0.02	1.00	0.01	0.00	0.00	0.02	0.00	1.00	1.00	1.00	0.06	0.00	1.00	1.00	T4	1.00	1.00	0.02	1.00	1.00	1.00	1.00	0.45	1.00	1.00	1.00
T5	0.00	1.00	0.13	0.41	0.15	1.00	0.06	0.00	0.00	0.16	0.02	1.00	1.00	1.00	0.22	0.05	0.95	1.00	1.00	T5	1.00	0.02	1.00	1.00	1.00	1.00	0.30	1.00	1.00	1.00
T6	0.00	0.56	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.08	0.04	0.65	0.00	0.00	1.00	1.00	1.00	1.00	T6	0.03	1.00	1.00	1.00	1.00	0.27	1.00	1.00	1.00
T7	0.02	1.00	1.00	1.00	1.00	1.00	0.72	0.06	0.01	1.00	0.39	1.00	1.00	1.00	1.00	1.00	0.15	1.00	1.00	1.00	1.00	T7	1.00	0.33	1.00	0.02	1.00	0.09	0.04	0.00
T8	0.01	1.00	1.00	1.00	1.00	1.00	1.00	0.02	0.01	1.00	0.19	1.00	1.00	1.00	1.00	1.00	0.00	0.15	0.17	1.00	0.00	1.00	T8	1.00	1.00	1.00	1.00	1.00	1.00	0.27
T9	0.06	1.00	1.00	1.00	1.00	1.00	1.00	0.27	0.04	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.30	0.70	1.00	0.01	1.00	1.00	T9	1.00	1.00	1.00	1.00	1.00	1.00
T10	0.03	1.00	1.00	1.00	1.00	1.00	1.00	0.11	0.02	1.00	0.80	1.00	1.00	1.00	1.00	1.00	0.00	0.51	0.74	1.00	0.01	1.00	1.00	1.00	T10	1.00	1.00	1.00	0.75	0.07
T11	1.00	0.02	1.00	1.00	1.00	0.74	1.00	1.00	0.96	1.00	1.00	1.00	1.00	0.04	1.00	1.00	0.00	0.00	0.01	0.06	0.00	1.00	1.00	1.00	1.00	T11	0.63	1.00	1.00	1.00
T12	0.00	1.00	0.17	0.69	0.15	1.00	0.06	0.00	0.00	0.29	0.01	1.00	1.00	1.00	0.26	0.04	0.06	1.00	1.00	1.00	0.92	1.00	1.00	1.00	1.00	0.09	T12	1.00	0.39	0.03
T13	0.01	1.00	0.75	1.00	1.00	1.00	0.35	0.02	0.01	0.93	0.13	1.00	1.00	1.00	1.00	0.27	0.01	1.00	1.00	1.00	0.23	1.00	1.00	1.00	1.00	0.59	1.00	T13	1.00	1.00
T14	0.00	1.00	0.02	0.05	0.02	1.00	0.01	0.00	0.00	0.03	0.00	1.00	1.00	1.00	0.05	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.58	1.00	1.00	0.01	1.00	1.00	T14	1.00
T15	0.00	1.00	0.44	1.00	0.45	1.00	0.18	0.01	0.00	0.58	0.05	1.00	1.00	1.00	0.64	0.15	0.06	1.00	1.00	1.00	0.70	1.00	1.00	1.00	1.00	0.25	1.00	1.00	1.00	T15

Figure a.3: P-values (green, < 0.05; blue, $>= 0.05$) of the Wilcoxon signed ranks tests (Bonferroni-Holm correction) for all comparisons for scratchiness (left) and hairiness (right). The ratings of scratchiness and hairiness were found to significantly differ depending on the sample (scratchiness, $\chi^2(29) = 315.01$, $p < .001$; hairiness, $\chi^2(29) = 394.38$, $p < .001$).



		R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15
	R1	1.00	1.00	0.56	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.76	1.00	1.00	1.00	1.00	0.01	0.21	0.02	1.00	0.00	0.89	0.02	0.42	0.22	1.00	0.08	0.02	0.00	0.07
R2	1.00	R2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.12	1.00	0.25	1.00	0.00	1.00	0.17	1.00	1.00	1.00	1.00	0.08	0.00	1.00
R3	1.00	1.00	R3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.03	0.89	0.06	1.00	0.00	1.00	0.04	1.00	0.74	1.00	0.22	0.03	0.00	0.19
R4	1.00	1.00	1.00	R4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.21	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
R5	1.00	1.00	1.00	1.00	R5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.03	1.00	0.05	1.00	0.00	1.00	0.03	1.00	0.59	1.00	0.22	0.02	0.00	0.34
R6	0.11	1.00	1.00	1.00	1.00	R6	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.85	1.00	1.00	1.00	0.03	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.36	1.00
R7	1.00	1.00	1.00	1.00	1.00	1.00	R7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.03	1.00	0.15	1.00	0.00	1.00	0.09	1.00	1.00	1.00	0.50	0.08	0.00	0.67
R8	1.00	1.00	1.00	1.00	1.00	0.95	1.00	R8	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.15	1.00	0.50	1.00	0.00	1.00	0.35	1.00	1.00	1.00	1.00	0.24	0.01	1.00
R9	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	R9	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.07	1.00	0.17	1.00	0.00	1.00	0.15	1.00	1.00	1.00	0.66	0.11	0.00	0.66
R10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	R10	1.00	1.00	1.00	1.00	1.00	1.00	0.19	1.00	0.90	1.00	0.01	1.00	0.56	1.00	1.00	1.00	1.00	0.43	0.02	1.00
R11	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	R11	1.00	1.00	1.00	1.00	1.00	0.02	0.77	0.01	1.00	0.00	1.00	0.01	0.58	0.21	1.00	0.07	0.00	0.00	0.09
R12	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	R12	1.00	1.00	1.00	1.00	0.54	1.00	1.00	1.00	0.00	1.00	0.81	1.00	1.00	1.00	1.00	0.34	0.01	1.00
R13	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	R13	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.08	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.21	1.00
R14	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	R14	1.00	1.00	0.05	1.00	0.28	1.00	0.00	1.00	0.15	1.00	1.00	1.00	0.80	0.13	0.00	0.72
R15	1.00	1.00	1.00	1.00	1.00	0.30	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	R15	1.00	0.13	1.00	0.63	1.00	0.00	1.00	0.20	1.00	1.00	1.00	1.00	0.11	0.00	1.00
T1	0.19	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.30	T1	0.37	1.00	1.00	1.00	0.02	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.09	1.00
T2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	T2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.31	1.00	1.00	1.00	1.00
T3	0.00	0.00	0.02	0.06	0.00	0.07	0.00	0.00	0.00	0.01	0.00	0.03	0.00	0.00	0.00	0.83	0.90	T3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T4	0.00	0.00	0.02	0.10	0.01	0.12	0.00	0.00	0.00	0.01	0.01	0.04	0.01	0.00	0.00	1.00	0.90	1.00	T4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T5	0.00	0.02	0.77	1.00	0.06	1.00	0.03	0.02	0.01	0.08	0.11	1.00	0.08	0.01	0.00	1.00	0.00	1.00	1.00	T5	0.22	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T6	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13	1.00	1.00	1.00	0.27	T6	0.31	1.00	0.42	0.18	0.00	1.00	0.53	1.00	1.00
T7	0.21	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.62	1.00	1.00	1.00	1.00	0.93	0.15	1.00	0.01	1.00	1.00	1.00	0.34	T7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T8	0.00	0.01	0.12	0.35	0.02	0.77	0.01	0.01	0.00	0.03	0.03	0.24	0.02	0.01	0.00	1.00	0.03	1.00	1.00	1.00	1.00	1.00	T8	1.00	1.00	0.66	1.00	1.00	1.00	1.00
T9	0.00	0.00	0.03	0.14	0.00	0.22	0.00	0.00	0.00	0.01	0.01	0.08	0.00	0.00	0.00	1.00	0.04	1.00	1.00	1.00	1.00	1.00	1.00	T9	1.00	1.00	1.00	1.00	1.00	1.00
T10	0.01	0.06	1.00	1.00	0.25	1.00	0.14	0.08	0.03	0.26	0.73	1.00	0.35	0.04	0.01	1.00	0.00	1.00	1.00	1.00	0.06	1.00	1.00	1.00	T10	1.00	1.00	1.00	1.00	1.00
T11	0.00	0.03	1.00	1.00	0.12	1.00	0.04	0.03	0.01	0.10	0.32	1.00	0.18	0.01	0.00	1.00	0.00	0.26	0.52	1.00	0.01	1.00	1.00	1.00	1.00	T11	1.00	0.33	0.01	1.00
T12	0.00	0.00	0.02	0.06	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	1.00	0.08	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	T12	1.00	1.00	1.00
T13	0.00	0.00	0.03	0.10	0.00	0.18	0.00	0.00	0.00	0.01	0.00	0.06	0.00	0.00	0.00	1.00	0.03	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	T13	1.00	1.00
T14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	1.00	1.00	1.00	0.34	1.00	0.30	1.00	1.00	0.05	0.00	1.00	1.00	T14	1.00
T15	0.03	0.34	1.00	1.00	1.00	1.00	0.38	0.20	0.16	0.81	1.00	1.00	1.00	0.21	0.02	1.00	0.00	1.00	1.00	1.00	0.16	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.13	T15

Figure a.4: P-values (green, < 0.05; blue, $>= 0.05$) of the Wilcoxon signed ranks tests (Bonferroni-Holm correction) for all comparisons for uniformity (left) and isotropy (right). The ratings of uniformity and isotropy were found to significantly differ depending on the sample (uniformity, $\chi^2(29) = 329.88$, $p < .001$; isotropy, $\chi^2(29) = 189.08$, $p < .001$).

b

ANNEX: EXPRESSING TACTILE FEEDBACK

B.1 PILOT STUDY

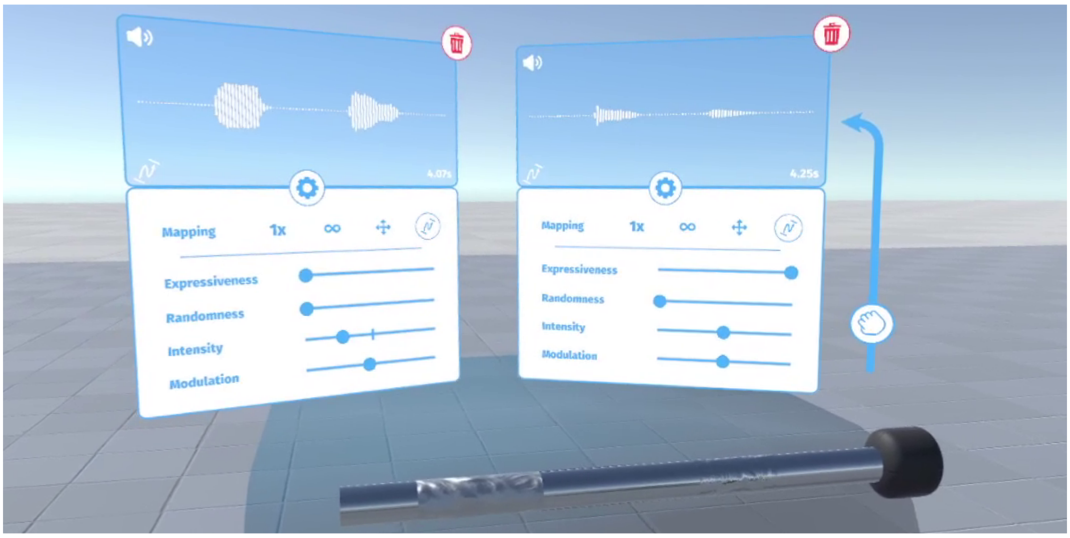
Category	Actions	Object		#Objects
Push	flick	paper football		5
		marble		
	push	small	box	
		medium		
		large		
Slide	sliding finger over	smooth	textured surface	6
		rough		
		rougher		
	sliding hand over	smooth	textured surface	
		rough		
		rougher		
Rotate	mix	water	in cup with finger	3
		sand		
	waving	fan		
Pull	stretch with fingers	soft	elastic band	6
		strong		
		textured hairtie		
	stretch with hands	soft	exercise band	
		strong		
	pull	feet of small tripod		
Passive Feel	touch	base	toothbrush	3
		tip		
	pour water	bottle		
Tool Slide	slide	small coin	table	4
		large coin		
	slide	boxcutter knife		
		camera trolley		
Tool Rotate	rotate	(smooth) potentiometer		5
		servomotor		
		stepper motor		
		dial (boxcutter)		
	turn with both hands	steering wheel		
Tool Pull/Push	pull	bike pump		4
	open	door		
	open	drawer		
	open	scissors		
Tool Press	push	small	button	4
		medium		
		large		
	press	pressure pen		
Press	press finger	soft	sponge	5
		stiff		
	squeeze	soft	sponge	
		stiff		
	pressing two hands	pregnancy ball		

Figure b.1: List of actions and objects used in the pilot study.

C

ANNEX: PROTOTYPING VIBROTACTILE FEEDBACK

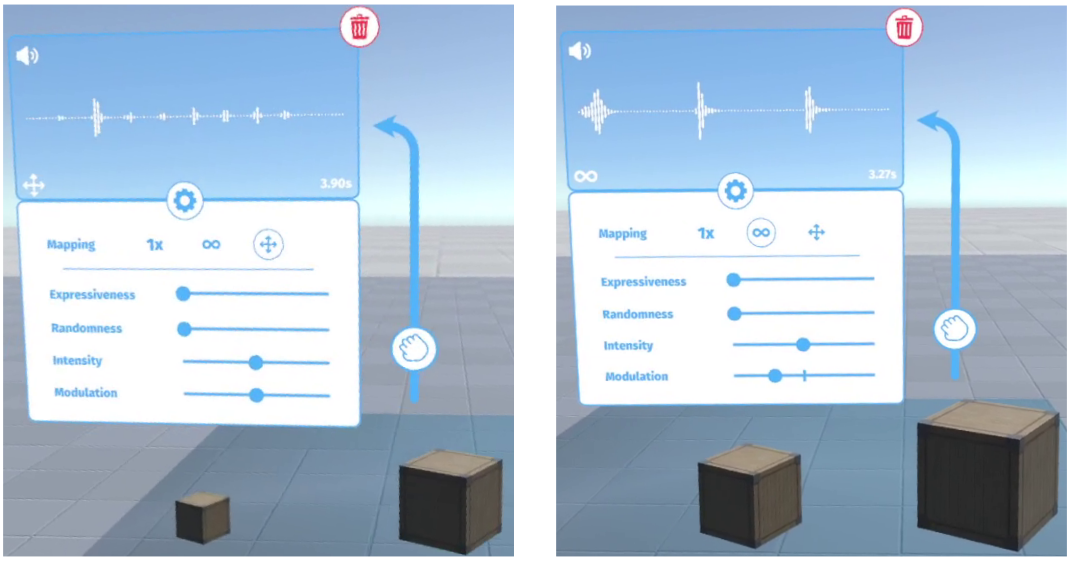
C.1 PARTICIPANT DESIGN EXAMPLES



(a) Design of vibrotactile feedback for a slider with textures on top. Here, the difference in vocalization strength (see waveform) is balanced out using the expressiveness and intensity modifiers

(b) Design of vibrotactile feedback for a virtual lightsaber. Here, a layer with a continuous mapping provides active background vibrations, while a layer using a motion mapping emphasizes the swing of the lightsaber.

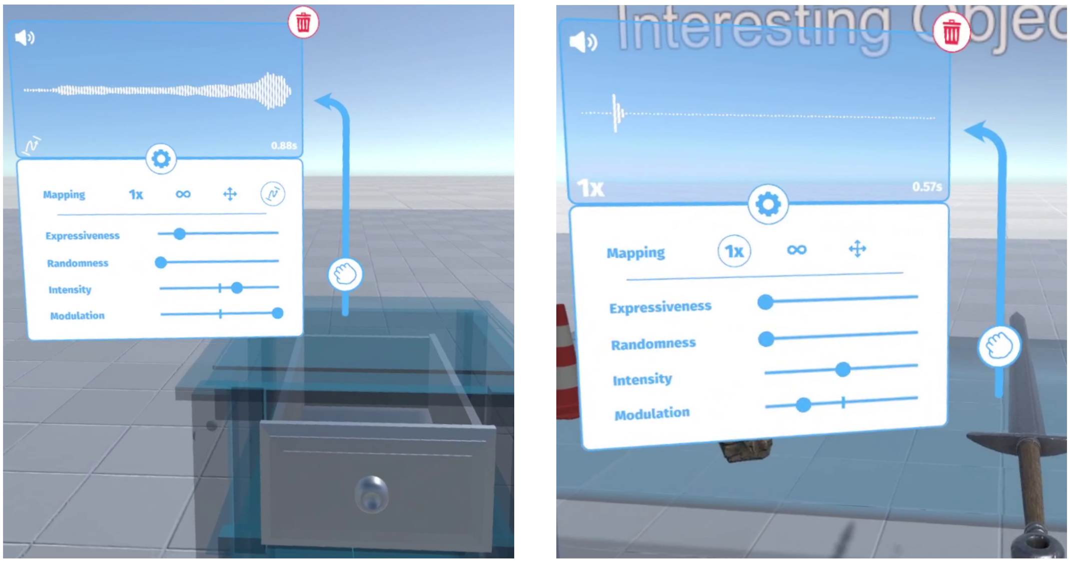
Figure c.1: Example designs using multi-layered approaches.



(a) Illusion of pebbles inside a box. Here, the initial vocalization provided the intended result, as no modifiers were changed.

(b) Illusion of a rock inside a box. Here, the modulation modifier was used to provide a sharper sensations.

Figure c.2: Example designs for simulating illusions inside boxes.



(a) A smooth, continuous sensation ends with a “boom” upon opening the drawer and reaching the end.

(b) Here, the participant aimed to create a sensation when dropping the sword, indicating a limitation of the current framework.

Figure c.3: Example designs for a metallic drawer and a metal sword.

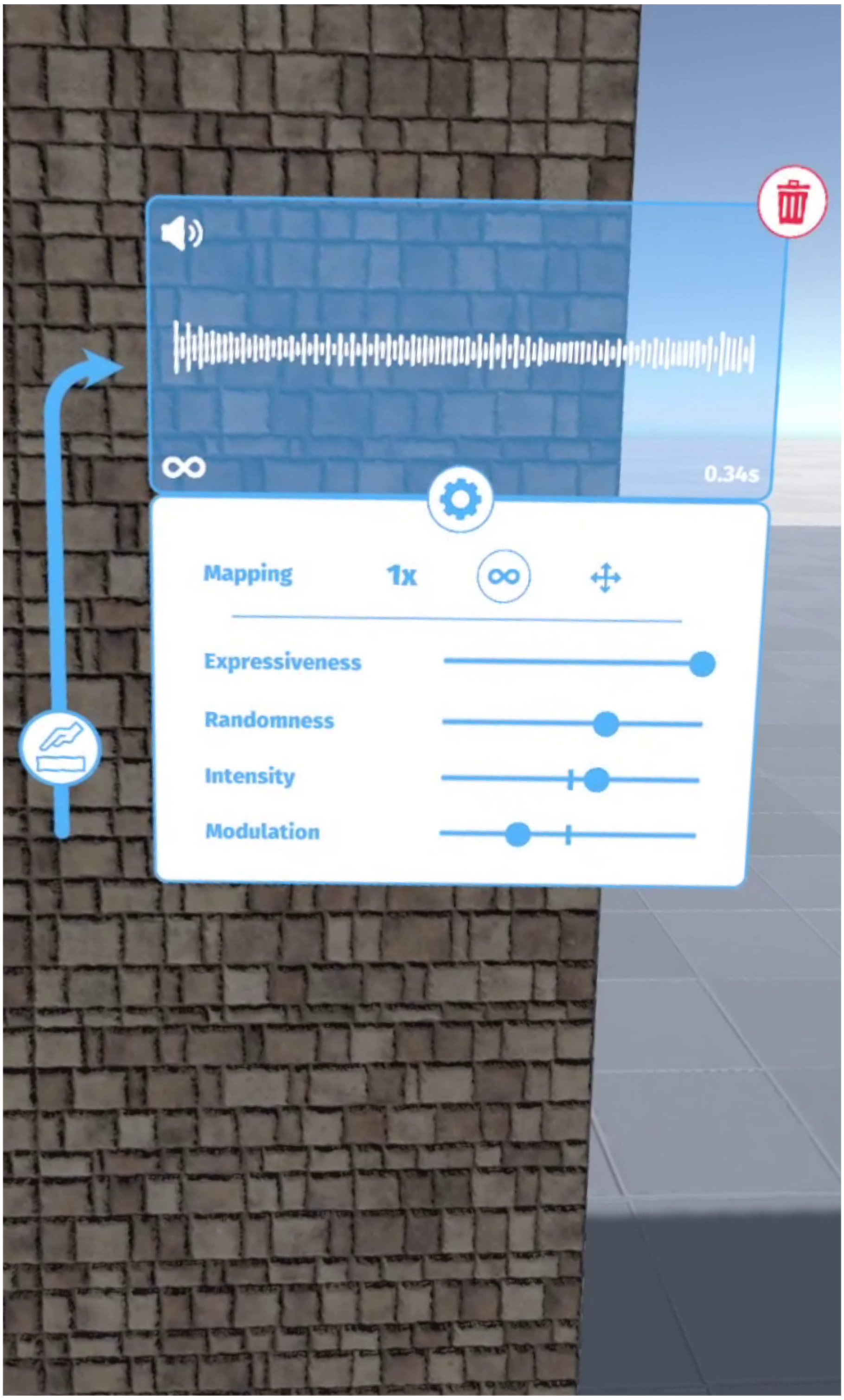


Figure c.4: Design of vibrotactile feedback for touching a brick wall. Here, the modifiers were extensively changed to enhance the experience. Note the high amount of randomness aimed at providing the sensation of touching stone features.

rip and tear
until it is done

COLOPHON

This document was typeset using the typographical look-and-feel `classicthesis` developed by André Miede and Ivo Pletikosić. The style was inspired by Robert Bringhurst's seminal book on typography "*The Elements of Typographic Style*". `classicthesis` is available for both LaTeX and LyX:

https://bitbucket.org/amiede/classicthesis/