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How Haptic Experiences Are Made

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Tor-Salve Dalsgaard: *How Haptic Experiences Are Made*

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The Clouds of Experience, digital art

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The typesetting of this thesis was inspired by Michael Mitchell and Susan Wightman's *Book Typography: A designer's manual*.

Ich hab' dich lieb, Mama.

Contents

Glossary

The terminology used throughout this thesis is relatively consistent with established work. However, since established works are not always consistent with themselves, clarification is in order.

senses of touch Relating to the perceptions that arise from receptors responding to mechanical stimulation. The proprioceptive, kinaesthetic, cutaneous, and nociceptive senses are instances of the senses of touch.

haptic Relating to the senses of touch, in this work specifically, in a technology-mediated context.

haptics The branch of research concerning the stimulation of the senses of touch, in this work specifically, in a technology-mediated context.

haptic stimulus A technology-mediated signal that directly influences the receptors of touch, causing electrical signals to be sent to the human brain.

haptic sensation An immediate, conscious interpretation of a proximal haptic stimulus.

haptic experience The conscious perception arising from a (multi-)sensory configuration that includes a haptic stimulus at an abstract, conceptual level.

Haptic Experience The branch of haptics concerning the perception and design of haptic experiences, analogous to broader User Experience research.

haptic inference A mental process in which the brain consciously infers information to mean something. *Sensory inference* infers the immediate information a haptic stimulus provides to elicit a haptic sensation. *Perceptual inference* processes a sensory situation composed of one or more haptic sensations to perceive a haptic experience.

haptic design A design process in which a designer creates a haptic stimulus enabling an experience. *Elicitation design* refers to the design of haptic stimuli with the purpose of eliciting a haptic sensation. *Experience design* refers to the design of a sensory configuration that enables a specific haptic experience.

Please note that the papers and manuscripts presented in Chapters 3, 6, 9, 12 and 14 might not adhere to this glossary and the general vocabulary presented in the thesis, as they are research articles written in a different context and state of mind.

Abstract

Haptic experiences are elicited when humans use and interact with haptic technology. With ever-developing technology, the dream of an all-purpose haptic display comes closer to fruition. Yet, what it is like to experience such a display is in discourse. The senses of touch profoundly impact social relations, bodily comfort, and human development; how to facilitate this impact through haptic technology is still subject to research. Due to the potential impact, it is imperative for those who design, use, and evaluate haptic technology to understand how haptic experiences are made.

The interest in haptic experiences is clear; however, the terminology and approach to haptic experiences are mudded. In this thesis, I aim to provide an overview of what haptic experiences are and what they are not. I present the Inference-Design Model for Haptic Experience, defining the relation between haptic stimulation, sensation, and experience as a two-way model of inference and design. Inference, the conscious process of making sense of the world, is subject to the question of *how* haptic experiences are made, while design, the process of creating a haptic system, is subject to the question of how haptic experiences are *made*. These two concepts present themselves as two sides of the same coin; design aims to convey an intended experience, inference yields the experience apparent to the perceiving human.

I discuss the Inference-Design Model for Haptic Experience and its implications in depth, presenting a clearer terminology and approach to designing, using, and evaluating haptic experiences. As a basis for this discussion serve five research projects, covering different aspects of inference and design. The journal paper *A User-Derived Mapping for Mid-Air Haptic Experiences* [63] forms the empirical basis for the model; the manuscript *Ultrasound can deliver chemical stimulants to the skin and modulate their perception* [65] proposes a novel way of producing haptic sensations; the journal paper *Haptic Magnetism* [68] shows the potential of haptic feedback for sensory augmentation; the short paper *A Touch of the Future: The TOUCHLESS Hackathon 2022* [67] presents novice designers' approach to designing for haptic experiences; and the manuscript *A Unified Model for Haptic Experience* [71] extends the principles of user experience to the haptic context.

This thesis proposes the Inference-Design Model for Haptic Experience as a theoretical construct for understanding haptic experiences. It also serves as a practical thinking tool for designing, using, and evaluating haptic technologies and devices. I speculate about the future of haptic experiences, particularly related to the dream of an all-purpose haptic display. In the end, I offer a new way of seeing haptic technology as part of a narrative spun by the designer that contributes to understanding how haptic experiences are made.

Resumé

Haptiske oplevelser opstår, når mennesker bruger og interagerer med haptisk teknologi. Med den stadig udviklende teknologi kommer drømmen om en alsidig haptisk enhed tættere på virkeligheden. Hvordan det er at opleve en sådan enhed er dog stadig uklar. Sanserne for berøring påvirker sociale relationer, kropslig komfort og menneskelig udvikling; hvordan man faciliterer denne påvirkning gennem haptisk teknologi, er stadig genstand for forskning. På grund af den potentielle påvirkning er det afgørende for dem, der designer, bruger og evaluerer haptisk teknologi, at forstå, hvordan haptiske oplevelser bliver til.

Interessen for haptiske oplevelser er tydelig; dog er terminologien og tilgangen til haptiske oplevelser mudret. I denne afhandling sigter jeg mod at give et overblik over, hvad haptiske oplevelser er, og hvad de ikke er. Jeg præsenterer en inferens-designmodel for haptisk oplevelse, der definerer forholdet mellem haptisk stimulation, sensation og oplevelse som en tovejsmodel for inferens og design. Inferens, den bevidste proces der giver mening til verden, relaterer til spørgsmålet om, *hvordan* haptiske oplevelser bliver til, mens design, processen med at skabe et haptisk system, relaterer til spørgsmålet om, hvordan haptiske oplevelser *bliver til*. Disse to begreber er som to sider af samme mønt; design sigter mod at formidle en tilsigtet oplevelse, inferens lader oplevelsen opstå for det opfattende menneske.

Jeg diskuterer inferens-designmodellens implikationer og præsenterer en klar terminologi og tilgang til design, brug og evaluering af haptiske oplevelser. Som grundlag præsenteres fem artikler, der dækker forskellige aspekter af inferens og design. Artiklen *A User-Derived Mapping for Mid-Air Haptic Experiences* [63] udgør det empiriske grundlag for modellen; manuskriptet *Ultrasound can deliver chemical stimulants to the skin and modulate their perception* [65] foreslår en ny måde at producere haptisk stimulans på; artiklen *Haptic Magnetism* [68] viser potentialet for haptisk feedback til sensorisk augmentation; artiklen *A Touch of the Future: The TOUCHLESS Hackathon 2022* [67] præsenterer designeres tilgang til design af haptiske oplevelser; og manuskriptet *A Unified Model for Haptic Experience* [71] udvider principperne for brugeroplevelse til den haptiske kontekst.

Denne afhandling foreslår inferens-designmodellen som en teoretisk konstruktion som skaber forståelse for haptiske oplevelser. Den fungerer også som et praktisk tænkeværktøj til design, brug og evaluering af haptiske teknologier. Jeg spekulerer over fremtiden for haptiske oplevelser, især i forhold til drømmen om den alsidige haptisk enhed. Til sidst kommer jeg med en ny måde at se på haptisk teknologi – som en del af en fortælling fortalt af designeren, der bidrager til forståelsen af, hvordan haptiske oplevelser bliver til.

Significance Statement

I have tried to explain my PhD research to family and friends. However, I have not always succeeded – I will try again.

How Haptic Experiences are Made. This thesis describes how haptic experiences emerge in the human mind and how they can be designed for. Haptic, in this context, refers to the stimulation of the senses of touch through technology – think of your phone vibrating when getting a text message or, maybe in the future, shaking your conversation partner's hand in a videocall. For a long time, researchers and practitioners alike have built haptic devices and techniques. Now, the technology is in a promising state, such that we can start thinking about how humans perceive the use of haptic technology and how we can design for particular haptic experiences. And that is exactly the aim of this thesis: thinking about how haptic experiences are made.

Hvordan haptiske oplevelser bliver til. Denne afhandling beskriver, hvordan haptiske oplevelser opstår i det menneskelige sind, og hvordan de kan designes. I denne sammenhæng beskriver 'haptisk' til stimuleringen af føle sanserne gennem teknologi – tænk på din telefon, der vibrerer, når du modtager en sms, eller, måske i fremtiden, at give din samtalepartner hånden i en videokald. I lang tid har forskere og designere bygget haptiske enheder og teknikker. Nu er teknologien i en så lovende tilstand, så vi kan begynde at tænke over, hvordan mennesker opfatter brugen af haptisk teknologi, og hvordan vi kan designe til specifikke haptiske oplevelser. Og det er netop formålet med denne afhandling: at finde ud af, hvordan haptiske oplevelser bliver til.

Wie haptische Erlebnisse entstehen. Diese Abhandlung beschreibt, wie haptische Erlebnisse im menschlichen Geist entstehen und wie sie designt werden können. Haptik bezieht sich in diesem Zusammenhang auf die Stimulation der Tastsinne durch Technologie – denk zum Beispiel daran, wie dein Telefon vibriert, wenn du eine Textnachricht erhältst, oder vielleicht in der Zukunft, wenn Sie Ihrem Gesprächspartner in einem Videoanruf die Hand schütteln. Seit Langem entwickeln Forscher und Praktiker gleichermaßen haptische Geräte und Techniken. Jetzt befindet sich die Technologie in einem vielversprechenden Zustand, sodass wir darüber nachdenken können, wie Menschen die Verwendung von haptischer Technologie wahrnehmen und wie wir für bestimmte haptische Erlebnisse designen können. Und genau das ist das Ziel dieser Abhandlung: Darüber nachzudenken, wie haptische Erlebnisse entstehen.

Preface

I like to work with my hands. Feel stuff. Shape stuff. Create stuff. It is immensely satisfying to see something that I have been part of making with my hands come to fruition. I have planted plants and trees; I have built a wall-sized bookshelf; I constructed a research lab. Now, I have written a PhD thesis. All with my hands and the help of others.

My fascination for the senses of touch stems from such experiences. Many experiences of touch are burned into my consciousness. Just seeing the potting machine at my family's plant nursery brings back memories of feeling the moisture and texture of the mulch and the delicateness of tiny tomato plants while potting them. Tomato plants have tiny hairs growing from the stem, making their leaves feel rough and fluffy at the same time. Just describing it makes me believe I feel the mulch and the tomato again. These *memories of touch* are what we try to evoke when creating with technologies that stimulate the senses of touch—haptic technologies. Yet, these memories are individual—after all, I would not expect everybody to have a similar shared experience of planting tomatoes, apart from my brother, maybe—which makes designing with haptic technologies tricky. And that is what this thesis is about: ~~giving people their own tomato planting experience.~~ building a thinking tool for haptic experience designers, alleviating some of the challenges embedded in the design process.

Writing a thesis on 'haptic' and 'experience' comes with a lot of headaches. Both terms have some air of elucivity around them. What 'haptic' is considered to be depends on the research field and context, and there is nothing harder to explain than what makes up the human 'experience'. The combination is even worse; I could probably get away with stating that 'haptic experiences' are those experiences elicited by haptic technology. However, that somehow does not consider the embodied knowledge that humans bring into the experienced situation. In addition, there is a severe imbalance: Haptic designers think very hard about the intended haptic experience, but humans using haptic technology do not explicitly think about their experiences as haptic experiences. This thesis serves as my headache relief pill: It will to clear my head and get all the thoughts out.

I am excited for the next time I get to make stuff and for the adventures to come. Experiences are made in doing. Experiences are made by the individual. Let the experience begin.

Tor-Salve Dalsgaard

31 May 2024, Copenhagen

Acknowledgements

The journey culminating in this PhD thesis felt short and long at the same time, mountainous and flat, slippery and steadfast. Many people helped me find safe ground.

Thank you, Katka, for being.

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Thanks to my co-authors for their effort, patience, and tenacity.
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Thanks to the HXLab, all its members, and Oliver for letting me stay for a summer and learn.

The journey would have been less enjoyable without you all.
Hier fängt die Geschichte an.

Publications

The main content of this thesis is based on two peer-reviewed and published journal articles, one peer-reviewed and published short paper, and two manuscripts currently under review. Listed in alphabetical order:

[63] **Tor-Salve Dalsgaard**, Joanna Bergström, Marianna Obrist, and Kasper Hornbæk. 2022. A User-Derived Mapping for Mid-Air Haptic Experiences. *International Journal of Human-Computer Studies*. DOI: 10.1016/j.ijhcs.2022.102920.

[65] **Tor-Salve Dalsgaard**, Arpit Bhatia, Lei Gao, Ryuji Hirayama, Sriram Subramanian, Joanna Bergström, and Kasper Hornbæk. [n. d.] Ultrasound can deliver chemical stimulants to the skin and modulate their perception. *In Progress*.

[67] **Tor-Salve Dalsgaard**, Arpit Bhatia, and Martin Maunsbach. 2023. A Touch of the Future: The TOUCHLESS Hackathon 2022. In *Proceedings of the 7th International Conference on Game Jams, Hackathons and Game Creation Events* (ICGJ '23). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3610602.3610607.

[68] **Tor-Salve Dalsgaard**, Kasper Hornbæk, and Joanna Bergström. 2023. Haptic Magnetism. *IEEE Transactions on Haptics*. DOI: 10.1109/TOH.2023.3299528.

[71] **Tor-Salve Dalsgaard** and Oliver Schneider. [n. d.] A Unified Model for Haptic Experience. *Under Review*.

Research Transparency

During my work, I got excited about open science. Thus, I have published all data collected during my research according to the FAIR principles. Listed are repositories containing the open data and preregistrations of the studies:

[64] **Tor-Salve Dalsgaard**, Joanna Bergström, Marianna Obrist, and Kasper Hornbæk. 2022. A User-Derived Mapping for Mid-Air Haptic Experiences - Dataset. DOI: 10.17894/ucph.57bf8bb1-98ac-4e5b-b3ec-47b3575815b8.

[66] **Tor-Salve Dalsgaard**, Arpit Bhatia, Lei Gao, Ryuji Hirayama, Sriram Subramanian, Joanna Bergström, and Kasper Hornbæk. [n. d.] Ultrasound can deliver chemical stimulants to the skin and modulate their perception - Preregistration & dataset.

[69] **Tor-Salve Dalsgaard**, Kasper Hornbæk, and Joanna Bergström. 2023. Haptic Magnetism - Dataset. DOI: 10.17605/OSF.IO/62PYJ.

Concurrent Publications

Throughout my PhD studies, I contributed to a number of other works; these are, however, out of scope for this thesis. Listed in alphabetical order:

[10] Annarita Ghosh Andersen, Laila Rahmoui, **Tor-Salve Dalsgaard**, Morten Bo Søndergaard Svendsen, Paul Frost Clementsen, Lars Konge, and Flemming Bjerrum. 2023. Preparing for Reality: A Randomized Trial on Immersive Virtual Reality for Bronchoscopy Training. *Respiration*. DOI: 10.1159/000528319.

[28] Joanna Bergström, **Tor-Salve Dalsgaard**, Jason Alexander, and Kasper Hornbæk. 2021. How to Evaluate Object Selection and Manipulation in VR? Guidelines from 20 Years of Studies. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (CHI '21). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3411764.3445193.

[70] **Tor-Salve Dalsgaard**, Jarrod Knibbe, and Joanna Bergström. 2021. Modeling Pointing for 3D Target Selection in VR. In *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology*. Association for Computing Machinery. DOI: 10.1145/3489849.3489853.

[168] Xinyue Hu, **Tor-Salve Dalsgaard**, and Kasper Hornbæk. [n. d.] "A False Reality"? A Micro-phenomenology of Avatars in VR. *Under Review*.

[216] Marie Høxbro Knudsen, Niklas Breindahl, **Tor-Salve Dalsgaard**, Dan Isbye, Anne Grethe Mølbak, Gerhard Tiwald, Morten Bo Søndergaard Svendsen, Lars Konge, Joanna Bergström, and Tobias Todsen. 2023. Using Virtual Reality Head-Mounted Displays to Assess Skills in Emergency Medicine: Validity Study. *Journal of Medical Internet Research*. DOI: 10.2196/45210.

Dissemination

I have presented my work on many occasions – industry fairs, public outreach events, a conference demo, a hackathon, a podcast episode, a tutorial, and the department's 50th anniversary. The conference demo was published as follows:

[51] Sean Chew, **Tor-Salve Dalsgaard**, Martin Maunsbach, Hasti Seifi, Joanna Bergström, Kasper Hornbæk, Josu Irisarri, Iñigo Ezcurdia, Naroa Iriarte, Asier Marzo, William Frier, Orestis Georgiou, Anna Sheremetieva, Kamil Kwarciak, Maciej Stroinski, Daria Joanna Hemmerling, Mykola Maksymenko, Antonio Cataldo, Marianna Obrist, Patrick Haggard, and Sriram Subramanian. 2023. TOUCHLESS: Demonstrations of Contactless Haptics for Affective Touch. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems* (CHI EA '23). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3544549.3583913.

Disclaimer

I hereby declare that this thesis is my own work. All texts quoted directly or paraphrased have been indicated by in-text citations. Full bibliographic details are given in the reference list at the end of the thesis. Below, I list my funding sources and conflicts of interest. In addition, I provide an overview of the ethical approvals obtained to conduct the research described in this thesis.

Funding

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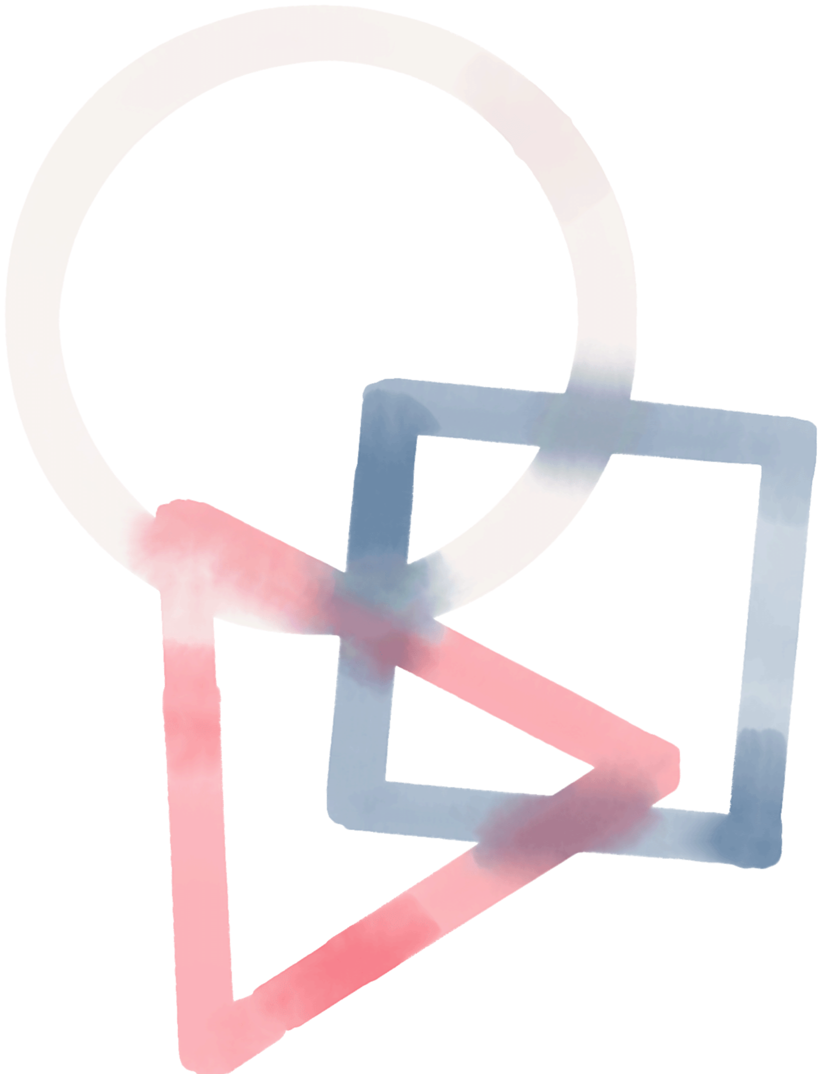
- Christian og Ottilia Brorsons Rejselegat for yngre videnskabsmænd og -kvinder
  Journal number 12038-1

Conflicts of Interest

I have no conflicts of interest to disclose.

Ethics Statement

This thesis presents research based on human subjects. All conducted research followed the ethical guidelines of the University of Copenhagen and was approved by the Research Ethics Committee of Science and Health, University of Copenhagen. The approvals can be found in Appendix A.



Part I

Introduction

We know with confidence
only when we know little;
with knowledge, doubt increases.
– Johann Wolfgang von Goethe

One might wonder about the authorial audacity to call this thesis *How Haptic Experiences Are Made*, despite some of the world's greatest thinkers' long efforts to define what makes up an 'experience' to begin with. Fair enough. In this work, I will venture closer to what Chalmers [47] called the *extra ingredient* that makes up conscious experience—at least for haptic experiences—something missing that would be able to explain "what sort of physical properties are relevant to the emergence of experience, and just what sort of experience we should expect any given physical system to yield" [47, p. 17], an endeavour Scott and Waddell compares to catching a slippery fish [340, pp. 10–27]. I will, however, fall short of providing a detailed account of the physical and mental processes of consciousness that make up a rich inner life, as I am a mere novice in this mystical world of experience – I'm sorry[1].

1. The Inference-Design Model for Haptic Experience

Haptic experiences—technology-mediated experiences of touch—are becoming more and more integrated with everyday life. This development is exciting, as touch plays such an important role in the human experience of being. Interpersonal touch is crucial for early human development [100], reduces stress and increases well-being [101]. Humans can identify objects [211] and extract object properties, such as weight, smoothness, temperature, and roundness, solely through touch [226]. As designers, we can create a space in which a specific experience can occur – what people experience is individual and their own [340]. Nevertheless, the design of interactive experiences has shaped the research in human-computer interaction of the 21st century. In particular, the question of how to design 'good' interactive experiences has been prominent [79, 84, 139, 265, 423]. Research within haptic experiences is similarly concerned with eliciting positive experiences, while the role of functional haptics is not to be downplayed – for instance, in the design of haptic feedback for medical devices. My work is focused on the elicitation of haptic experiences, inspired by Marianna Obrist and colleagues' work on tactile and multi-sensory experiences [284, 285, 396, 400], Oliver Schneider and colleagues' work on establishing the field of Haptic Experience [206, 330, 334, 355], Karon MacLean and colleagues' work of affective haptics [244, 245, 246, 247].

A good first question to consider is: 'What is a haptic experience?'. What seems a simple question has a lot of depth and nuance. Through this thesis, I aim to get closer to what constitutes a haptic experience, but let us consider a few viewpoints from which to approach the term. The first viewpoint might be linguistic; 'haptic', a word borrowed from Latin, meaning "the science

[1] I have been made aware that irony does not translate well in written text: I'm not sorry.

of touch"[2], while 'experience', in relation to this thesis, refers to "the conscious events that make up an individual life"[3]. Thus, haptic experience refers to 'the conscious events of touch that make up an individual life'. Hidden in this is the second, philosophical, viewpoint, relating to the question, 'What is consciousness?' – a question too big to answer here, but I will explore it later. For now, I note that the concept of 'conscious events of touch' seems too specific, as it is hard to separate them from 'conscious events of seeing' or 'conscious events of hearing'. Neuroscience, as a third viewpoint, explains experience as a physical process in the brain, as an interpretation of the sensory environment around us [197, 254]. How exactly this process is shaped and where it takes place in the brain is under debate [20, 22]. The last, fourth viewpoint is within human-computer interaction; haptics refers to programmable touch technology [333] or, more general, technology-mediated touch. The challenge here is the word 'experience' due to the word construction 'user experience', relating to a research field concerned with the usability and hedonic quality of technology use [142]. This poses two semantic challenges for this thesis. First, it requires me to distinguish between 'haptic experience' and 'Haptic Experience': haptic experience refers to experiences elicited by haptic technology, while Haptic Experience is the field of research concerned with the usability and hedonic quality of haptic technology [206]. Second, 'haptic experience' as a word construction implies a direct relation between haptic technology and perception of an experience; such an implication does not consider the multi-sensory nature of human experience. I thus interpret a haptic experience as a conscious event that is produced during interaction with haptic technology. Three notes: **(1)** I will use 'haptic' to refer to technology-mediated touch rather than touch in general; **(2)** an experience, haptic or not, is multi-sensory and occurs in the context of a given situation; **(3)** haptic designers do not design haptic experiences but design *for* haptic experiences, as I shall later argue; and **(4)** I follow Hornbæk and Oulasvirta's understanding of interaction, as it "interaction concerns two entities that determine each other's behavior over time" [165, p. 10]. While the first note is a stylistic choice, the other three impact my interpretation of the world; thus, I will discuss these notes throughout this thesis.

Haptic experiences are often less noticed by the perceiving human than other technology-mediated experiences [396]. This discrepancy is interesting, given the constant sensations humans receive through their senses of touch. The challenge of stimulating the sense of touch through technology is manifold: First, the senses of touch are distributed across the body, requiring the "ultimate haptic display" to provide haptic stimulation on the whole body [295, pp.

[2] https://www.merriam-webster.com/dictionary/haptic, accessed 25th April 2024.
[3] https://www.merriam-webster.com/dictionary/experience, accessed 25th April 2024.

Figure 1.1. The Inference-Design Model for Haptic Experience describing the inference process following a haptic stimulus, eliciting a haptic experience. The stimulus elicits sensations through sensory inference, which in turn elicits experiences through perceptual inference.

323–326]. Second, sensing never halts, making it hard for users to withdraw from most haptic technologies, unlike closing one's eyes in a visual experience [23]. Third, the perception of touch is highly contextual and individual, requiring technology to be adaptable and customisable [206, 334]. Last, haptic feedback is difficult to design, as the pathway between haptic stimuli and a human's perception thereof has not been mapped out. In this thesis, I attempt to tackle this last challenge by mapping out how haptic experiences are made.

1.1. Contribution

Throughout my work, I have worked on the core elements of how haptic experiences are made: A haptic experience is inferred through haptic sensations and elicited by haptic stimuli. These core elements form a model that relates stimuli to sensations and sensations to experiences through inference processes (Figure 1.1). I will refer to this model as the Inference-Design Model for Haptic Experience. The model is bi-directional, describing both how haptic experiences are made through psychophysics and through design. However simple and naive this Inference-Design Model might seem, it allows me to reason about the individual components of haptic experience, as there is a lot to unpack within the components. The Inference-Design Model states that humans perceive haptic stimuli as haptic sensations through a process of sensory inference and that sensations are assigned meaning (i.e., experiences) through a process of perceptual inference. The model arose from my work on haptic experiences [63], but also aligns with established models from neuroscience, such as the perception model described by Mather [254, p. 5]. With this thesis, I thus humbly contribute to the field of haptics by providing the Inference-Design Model for Haptic Experience as a thinking tool for how haptic experiences are made.

With this thesis, I will argue that the model has formative and generative power [26, 317], enabling discussions about concepts for the design of haptic experiences and informing design through the inference processes it describes. It is able to explain the haptic experiences elicited by haptic designs and aid the design of new ones through counterfactual reasoning [291]. Therefore, the main contribution of this thesis is the Inference-Design Model for Haptic Experience. Through the papers and manuscripts included in this thesis, I argue for the individual components and explain how the model was constructed. The journal paper *A User-Derived Mapping for Mid-Air Haptic Experiences* [63] serves as the basis for the model, initially defining the components and staging the scene for the sensory and perceptual inference processes. The manuscript *Ultrasound can deliver chemical stimulants to the skin and modulate their perception* [65] describes a method to deliver haptic stimuli through the levitation of chemicals known to elicit haptic sensations. The journal paper *Haptic Magnetism* [68] provides a concept of how haptic sensations can be designed to afford interactions in and of themselves. The manuscript *A Unified Model for Haptic Experience* [71] presents the unification of theoretical models from user and haptic experience research to describe components and considerations for haptic designs. The short paper *A Touch of the Future: The TOUCHLESS Hackathon 2022* [67] describes a hackathon conducted with novice haptic designers, showcasing how broad and varied haptic experiences are imagined to be.

In total, this thesis contributes a conceptual model for how haptic experiences are made. However, let me emphasize that the model is not complete, as it needs to undergo a further iterative process in which the constructed concepts and principles are used for design processes and thereby evaluated, as Beaudouin-Lafon et al. [26] suggested. This thesis also contributes a practical approach to design *for* haptic experiences based on the novel concept of narrative haptic design.

1.2. Synopsis

In this thesis, I devote a part to each component of the Inference-Design Model, defining each component through previous work and refining it with the work presented as part of this thesis. Each part consists of an introduction, a relevant paper, and a contextualisation of the paper relative to the model. Macpherson's taxonomy of different philosophical approaches to individuate the senses [248] serves as a framework to devide the parts. Macpherson finds four criteria typically used to separate the senses: the sense organ criterion, the proximal stimulus criterion, the representational criterion, and the phenomenal character criterion. Yet, as Macpherson argues, these criteria are not to be seen as strict separators but rather as ways of describing different aspects of sensing.

Part II discusses *haptic stimuli*: technology-mediated activations of one or more receptors. Within haptics, researchers differentiate between cutaneous and kinaesthetic stimulation, referring to the two afferent perceptual subsystems activated through the stimulation of the sense organs of touch [227]. The part discusses primarily cutaneous proximal stimulation, as this is the modality I have worked with throughout. Most commonly, cutaneous stimulation is achieved through skin vibration for many different purposes, such as modulation of emotions (e.g., [201, 243, 285, 344]) and perception (e.g., [106, 204, 360]). My contribution to the induction of haptic stimuli is the manuscript titled *Ultrasound can deliver chemical stimulants to the skin and modulate their perception* [65]. In it, we describe a method of delivering chemical stimulants to the skin. We show that these stimulants can be perceived and are perceived as being different to vibrotactile stimulation. With this, we introduce a novel method for the delivery of haptic stimulants and expand the range of perceived sensations. At the end of the part, I discuss ways of providing proximal stimuli and the uses of chemical stimulants to provide haptic sensations.

Part III describes two mental inference processes: *sensory inference*, the low-level inference process of sensory information, and *perceptual inference*, the high-level inference process of sensory information. I define sensory inference as a physical process in which the brain assigns meaning, a sensation, to a haptic stimulus. In this part, I discuss the effect of action [227], as well as passive and active touch [112], on sensory inference. I similarly define perceptual inference as a process that assigns meaning to a sensation and thereby yields an experience. The process is partially based on the perceived sensations of a haptic stimulus; however, in this part, I discuss the complexities influencing perceptual inference. Past experience [20, 21], context [63], psychological needs [143, 325] and a number of other factors play a crucial role in perceptual inference. This part also describes two design processes: *elicitation design*, the design processes aiming to elicit specific sensations, and *experience design*, the design process aiming to design for a particular experience. Elicitation design is typically powered by haptic libraries relating stimuli to sensations (e.g., [137, 347]) or computational models for differentiating haptic stimuli (e.g., [234]), informing designers about the design space of haptic stimuli. Similarly, experience design relates to the design process of creating a haptic system with the intention of eliciting a specific haptic experience. Many principles and methods for designing haptic experiences have been suggested, such as Kim and Schneider's Haptic Experience Model [206] or Schneider et al.'s definition Haptic Experience Design [334]. The Inference-Design Model, in particular sensory and perceptual inference, is based on the research I contributed in the journal paper titled *A User-Derived Mapping for Mid-Air Haptic Experiences* [63]. In this work, we asked participants to describe their sensations and experiences in depth, allowing us to draw a distinction between the two components and develop insights into the sensory and perceptual inference processes. I present a notion for thinking about haptic inferences and design, namely as information spaces, based on Chalmers [47] argument around consciousness. Through this notion, I argue for the structure of the Inference-Design Model.

Part IV elaborates on *haptic sensation* – a conscious perception resulting from haptic stimuli through the process of sensory inference. Contrary to experiences are sensations immediate and automatic [254, pp. 3–7]. Humans encounter technology-mediated haptic sensations in their everyday lives when their smartphone vibrates while playing a game or receiving a message. In these situations, the haptic stimulus mediates a sense of urgency, drawing attention to the haptic device. In other situations, haptic stimuli display other representations of touch: weight, roughness, shape, and the like [226]. In the journal paper titled *Haptic Magnetism* [68], we explore the extent to which users can associate vibrotactile feedback to sensations of pseudo-attraction and -repulsion. Haptic Magnetism, as a concept, relies on the immediateness of sensations to guide or nudge users towards objects. In this work, we build on Hollan and Stornetta's [159] argument that mimicry of the physical world through technology need not be the gold standard for future interaction. In this part, I thus argue that the purposeful design of haptic sensations can elicit rich interactions by going beyond mimicry and, thereby, beyond the physical information touch presents.

Part V explains my view on *haptic experiences*. Haptic experiences are conscious perceptions of one or more haptic sensations processed through perceptual inference. Contrary to sensations, experiences take time and may require effort to form [254, pp. 3–7]. Through perceptual inference, the encounter with the smartphone while playing a game or receiving a message becomes an experience: a won game becomes a pleasant experience and the text from a loved one becomes a meaningful experience. However, the phenomenal character of touch is made through the context of the situation. This part presents ways of approaching research on technology-mediated experiences, through the lenses of positive psychology (e.g., [181, 326]), neuroscience (e.g., [45, 254]), human-computer interaction (e.g., [79, 139, 165, 416, 423]), and haptics (e.g, [92, 206, 245, 285, 334]). Based on the manuscript titled *A Unified Model for Haptic Experience* [71], I argue that haptic experiences are more difficult to design than haptic sensations and present a model for the design of haptic experiences. The Unified Model combines theories from user experience and haptic experience research, aiding haptic designers in reasoning about their designs and facilitating future discussions about haptic experiences. This manuscript serves as the theoretical grounding for Part V, yet lacks deeper considerations for the context of an experience and ethical considerations when stimulating the senses of touch. This I provide in this thesis. The short paper titled *A Touch of the Future: The TOUCHLESS Hackathon 2022* [67] serves as a practical account of haptic designers working with haptic experiences. It describes a hackathon planned and conducted in 2022, in which novice haptic designers used mid-air haptic technology to prototype haptic applications. The applications these designers created showed how these vibrotactile stimuli can elicit varied haptic experiences. Based on the theoretical and practical accounts, I propose a novel way of approaching design for haptic experience: through narration. Building a strong narrative supports the design for specific haptic experiences.

Part VI brings the components together and discusses their relation. The Inference-Design Model for Haptic Experience was constructed through the five papers and manuscripts presented as part of this thesis. I present the process of construction and relate the Inference-Design Model to established models and theories in phenomenology, neural sciences, and human-computer interaction. With these theoretical underpinnings in mind, I present an example of using the Inference-Design Model as a practical thinking tool, showing its generative power [26] and use for counterfactual reasoning [291]. At last, I give an outlook of the future and speculate how the Inference-Design Model for Haptic Experience might become an Inference-Design Theory for Haptic Experience. As the main contribution of this thesis, I present the formalisation of the relation between haptic stimulus, sensation, and experience through the model and the practical application of the model, which is useful for designers designing for haptic experiences. While much research still needs to be done, this thesis charts out how haptic experiences are made from a human-centric perspective.

1.3. Approach

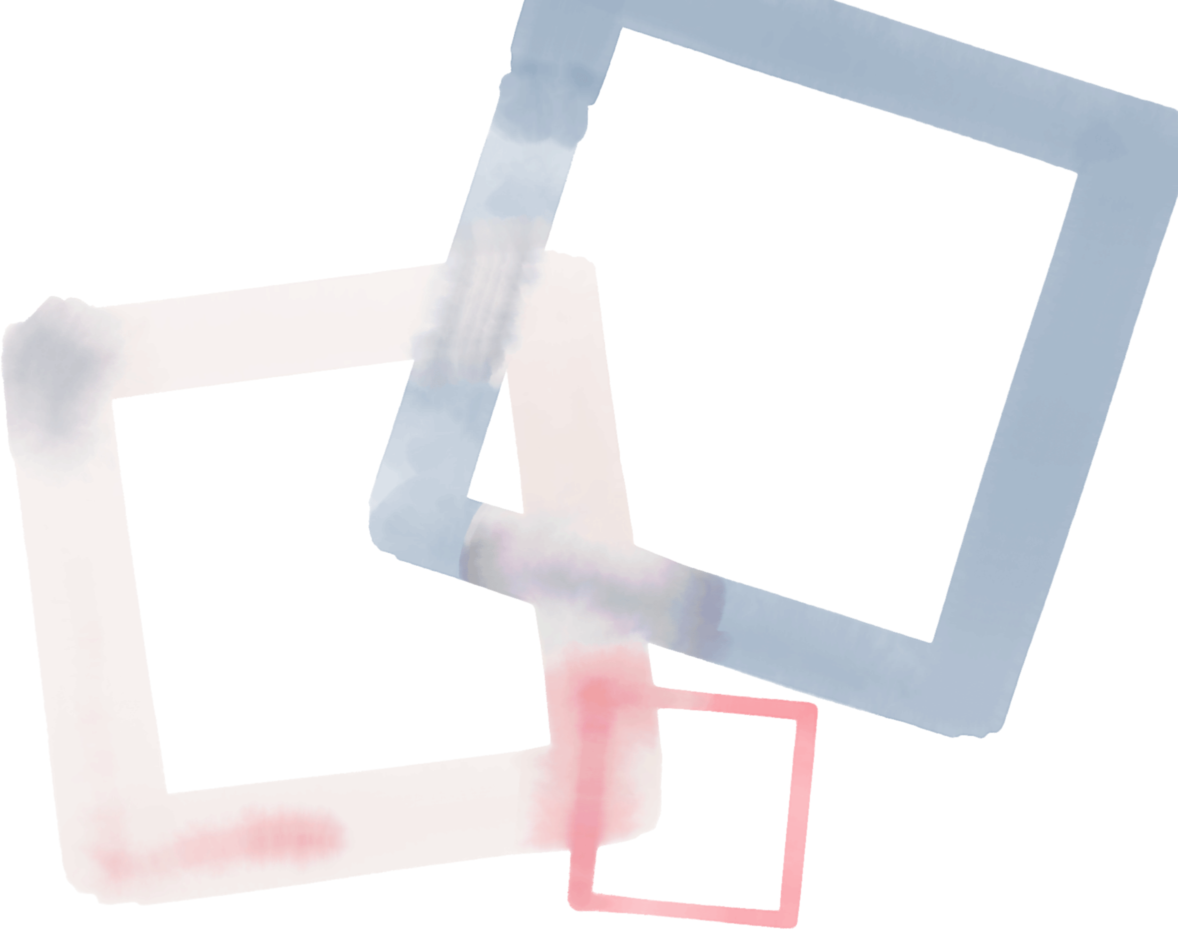
My work is within haptic experiences and the design thereof. In my research, I follow a pragmatist view, drawing on theories and methods from multiple disciplines to conduct my research. Throughout my work, I present both empirical, conceptual, and constructive problems that I attempt to solve through a method or theory that fits my research problem. With this, I am following Oulasvirta and Hornbæk's [290] argument that human-computer interaction is a problem-solving field. It has been important to me to develop my thinking through engagement with views on research other than mine; Frauenberger's [105] concepts of Entanglement, for instance, has broadened my outlook on the different ways of knowledge production regarding the relationship between human and technology. I find a lot of inspiration in the many works on the topic of 'experience', a concept so foundational to human life yet so elusive. In my work on the experience phenomenon, I have been inspired by many works; I would, however, like to highlight a few: Martin Heidegger's *Being and Time* [149] did open the world of metaphysics and phenomenology to me. David J. Chalmers' thoughts on conscious experiences [47, 48] have had an undeniable influence on my work. And Lisa Feldman Barrett's *How emotions are made* [21] did not only inspire the name of this thesis but made me believe much more that experiences are constructed through context and situation.

Most of my work is empirical; I do, however, find theory development appealing, as I believe that the field of haptics, similarly to the field of human-computer interaction, lacks strong concepts [161] and conducts too much research that can not be falsified [164]. Early in my PhD studies, I encountered a differentiation in the perception of haptic stimuli; haptic perceptions have a low- and a high-level component. In my first publication, *A User-Derived Mapping for Mid-Air Haptic Experiences* [63], this is expressed as the distinction between sensations (*'how a haptic stimulus felt'*; rough, light, round) and experiences (*'what a haptic stimulus felt like'*; pleasant, meaningful, helpful). Now, at the end of my studies, this notion has been translated to the Inference-Design Model for Haptic Experience, framing the work I have conducted in past years. While the model is relatively simple, it has the potential to stir some controversies. For instance, one might ask, *'What about emotions?'*, *'What about the context in which the stimulus is administered?'*, or *'Do all sensations lead to an experience?'*[4]. But that is the strength of the model exactly. It allows us to question the core of the issue, to make assumptions about the processes of making haptic experiences, and to reason about our haptic designs; in short, it allows for abductive, inductive, and counterfactual reasoning [291]. The aforementioned questions are, however, valid and should be addressed.

My latest conviction is the notion of model-centric research versus result-centric research paradigms. Devezer and Buzbas [80] urged psychological researchers to address the generalizability issues of empirical studies. The discussion is not new [25, 113], but I find the model-centric research paradigm Devezer and Buzbas proposed very appealing. The basic criticism of the current empirical research paradigm is placing fact-like results at the centre of knowledge production—building many tiny islands of knowledge without the ability to bridge the sea between them. The model-centric paradigm, on the other hand, places models and their epistemic iteration at the centre of knowledge production. In this paradigm, the explicit goal is to build, evaluate, and refine models. I have used this paradigm in the manuscript titled *A Unified Model for Haptic Experience* [71] to evaluate and refine existing models for Haptic Experience and to build the Inference-Design Model that encapsulates the contributions of my PhD studies.

Overall, I strongly believe that research approaches are and need to be diverse. I do not value my approach more than a positivistic or interpretivistic one—I will argue in later parts that refining the Inference-Design Model requires both approaches to develop and become useful.

[4] Don't worry, I'll get back to these in later parts of the thesis.



Part II

Haptic Stimulus

The first haptic interface
that really works will be
world-changing magic.
– *Michael Abrash*

haptic stimulus A technology-mediated signal that directly influences the receptors of touch, causing electrical signals to be sent to the human brain.

At the beginning of a sensation of touch stands a stimulus of touch. Stimulation is a two-part affair: A proximal stimulus elicits the activation of a sense organ. In the case of touch, the proximal stimulus might be pressure, vibration, or temperature radiating from an object, a human, or a haptic device. The sense organs of touch, on the other hand, are buried in the human skin. A variety of receptors are activated by different forms of stimuli, creating electric signals that are passed through the central nervous system to be interpreted by the human mind. These sense organs are 'always-on'; sensing never halts, allowing the human to draw inferences about their bodily surroundings. The senses of touch are not easily suppressed [299, pp. 59–77] – the analogue of closing one's eyes or ears does not exist for touch, as receptors responsible for touch are distributed across all parts of the body. Stimulation of the senses of touch thus arises constantly and across the human body [295, pp. 13–18].

In Chapter 2, I will describe the sense organs of touch throughout the body and the proximal stimuli elicited through haptic technology. Through the exploration of the sense organs of touch, I find opportunities for using uncommon proximal stimuli, which I describe in the context of the work I report in the manuscript *Ultrasound can deliver chemical stimulants to the skin and modulate their perception* [65] (presented in Chapter 3). In Chapter 4, I motivate the use of haptic stimuli as a component of the Inference-Design Model for Haptic Experience through this and other work.

2. Stimulating the Senses of Touch

To understand the design of haptic stimuli, we need to understand the sense organs of touch. While research on the sense organ is a neuroscientific affair, haptic research can contribute with ways of stimulating those receptors deemed interesting for the sense of touch. The most classical approach to haptic stimulation is through the mechanoreceptors in the human skin, capable of perceiving vibrations and force. The receptive field of the somatosensory system bounds the technological innovation within haptics. However, new findings within neuroscience extend these bounds and thus challenge haptic designers to create novel stimuli targeting receptors. Exemplary are the C tactile afferents, first described by Vallbo et al. [392] and later shown to be related to affective touch [300, 332], promising great potential for interpersonal haptic communication [310]. Another kind of receptors, currently underutilised in haptics research, are the chemoceptors—receptors activated by chemical components to elicit sensations of itch, pain, and temperature.

In this chapter, I will discuss the duality of what I understand as haptic stimulation in relation to the Inference-Design Model. On one side stands the proximal stimulus, on the other, the sense organ. When stimulus and organ meet, the organ is activated, sending bits of information to the central nervous system in the form of electrical signals. The brain makes sense of these signals, inferring sensations from the sensory environment, but let me not get ahead of myself; I will return to what constitutes a sense of touch in a later part. For now, I will consider the sensory organ for touch: the skin. It is common to discuss mechanoreceptors within haptics, as they are stimulated through pressure and vibration. In addition to these, I will discuss chemoceptors, as they promise novel haptic stimuli. Further, I will discuss the kinds of proximal stimuli haptic designers have available.

2.1. The Sense Organ

The skin is the sense organ of touch. Quite simplified, receptors in the skin convert mechanical stimulation to electrical potential. When the potential crosses a threshold, the receptor fires and sends information through the central nervous system to the brain's somatosensory cortex. Contrary to other sense organs, the sense organ of touch provides a range of sensory modalities; the skin provides information about mechanical touch (somatosensation), body position and movement (proprioception), and pain (nociception). Within the skin, several different receptors can be found that are more or less related to the sensory modalities the sense of touch provides [254, p. 349–365]. There is much to be said about the different sensory receptors and pathways; I can not do the descriptions justice, so I refer to neuroscientific works, such as Corniani and Saal's work on tactile innervation density [59], Kandel et al.'s grand overview of the principles of neural science [197], Mather' overview of sensation and perception [254], and Vallbo and Johansson's seminal work on the mechanoreceptors in the human skin [391]. I will explain this much: Typical receptors are nerve endings encapsulated within an end organ and connected to the nervous system through specialized fibres. Receptors convert a stimulus into an electrical signal processed by the sensory cortex. Within the skin, however, there are free nerve endings (or, bare never endings) that are not encapsulated in a specialised end-organ; however, how they transduce a stimulus to an electrical signal is not well understood [254, p. 352].

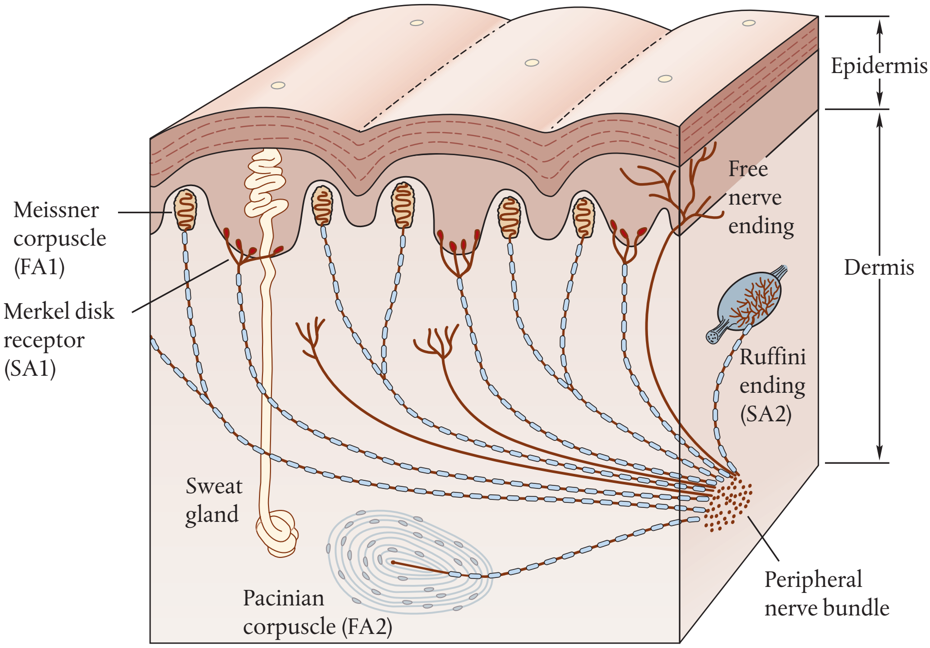


Figure 2.1. Tactile innervation of the glabrous skin in humans. A cross section of the glabrous skin shows the principal receptors for touch in the human hand. All of these are innervated by large-diameter Aβ myelinated fibers. The Meissner corpuscles and Merkel cells lie in the superficial layers of the skin at the base of the epidermis, 0.5 to 1.0 mm below the skin surface. The Meissner corpuscles are located in the dermal papillae that border the edges of each papillary ridge. The Merkel cells form dense bands below the intermediate ridge surrounding the sweat gland ducts along the center of the papillary ridges. The RA1 and SA1 fibers that innervate these receptors at their terminals so that each fiber innervates several nearby receptor organs. The Pacinian and Ruffini corpuscles lie within the dermis (2–3 mm thick) and in deeper tissues. The RA2 and SA2 fibers that innervate these receptors each innervate only one receptor organ. (Abbreviations: **RA1**, fast adapting type 1; **RA2**, fast adapting type 2; **SA1**, slowly adapting type 1; **SA2**, slowly adapting type 2.)

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Haptic research, in particular, often focuses on the somatosensory receptors in the hand. This is due to the hand being the primary body part for physical interaction with other humans and objects and, thus, for touching them. The hand contains four mechanoreceptors – receptors that activate on mechanical stimulation. These are illustrated in Figure 2.1, along with their location in the skin. Mechanoreceptors are categorised by fibre; slowly adapting (SA) fibres respond to sustained stimuli, while rapidly adapting (RA) fibres respond to changing stimuli [197, p. 437]. SA receptors respond to pressure and force applied to the skin, such as when grabbing a coffee mug, whereas FA receptors respond to vibrations, such as when moving the finger over sandpaper. Further, mechanoreceptors are categorised by type, depending on size and location in the skin. The end organs of type 1 receptors are small and located close to the skin surface, while the end organs of type 2 receptors are larger and buried deep in the skin. Type 1 receptors are distributed densely across the hand, particularly in the fingertips. Type 2 receptors, on the other hand, are sparsely distributed; nevertheless, they are large enough to sense displacement at the skin's surface [197, p. 437–438]. The cross of fibre and type yields the four mechanoreceptors: Merkel cells (SA1), Meissner corpuscles (RA1), Ruffini endings (SA2), and Pacinian corpuscles (RA2) [197, p. 437–450]. Kandel et al. highlight the importance of the mechanoreceptors:

> At the first touch, the peripheral sensory apparatus deconstructs the object into tiny segments, distributed over a large population of approximately 20,000 sensory nerve fibers. The SA1 system provides high-fidelity information about the object's spatial structure that is the basis of form and texture perception. The SA2 system provides information about the hand conformation and posture during grasping and other hand movements. The RA1 system conveys information about motion of the object in the hand, which enables us to manipulate it skillfully. Together with RA2 receptors, they sense vibration of objects that allows us to use them as tools. [197, p. 467]

Thus, it is no surprise that much haptic research explicitly or implicitly stimulates these mechanoreceptors to produce haptic experiences.

Apart from the function of the receptors, an important aspect to consider when designing haptic systems is the sensitivity, receptive field, and acuity of the receptors. Individual receptors have a limited area in which they are activated – the receptive field. Type 1 receptors have small and localized receptive fields, whereas type 2 receptors have large receptive fields. Figure 2.2 illustrates so-called 'homunculi' of the whole body and the hand, respectively, in which individual body areas are scaled to the receptor density in those parts of the skin. From the illustrations, it becomes evident why haptic stimulation of the hands works well: the receptor density is much

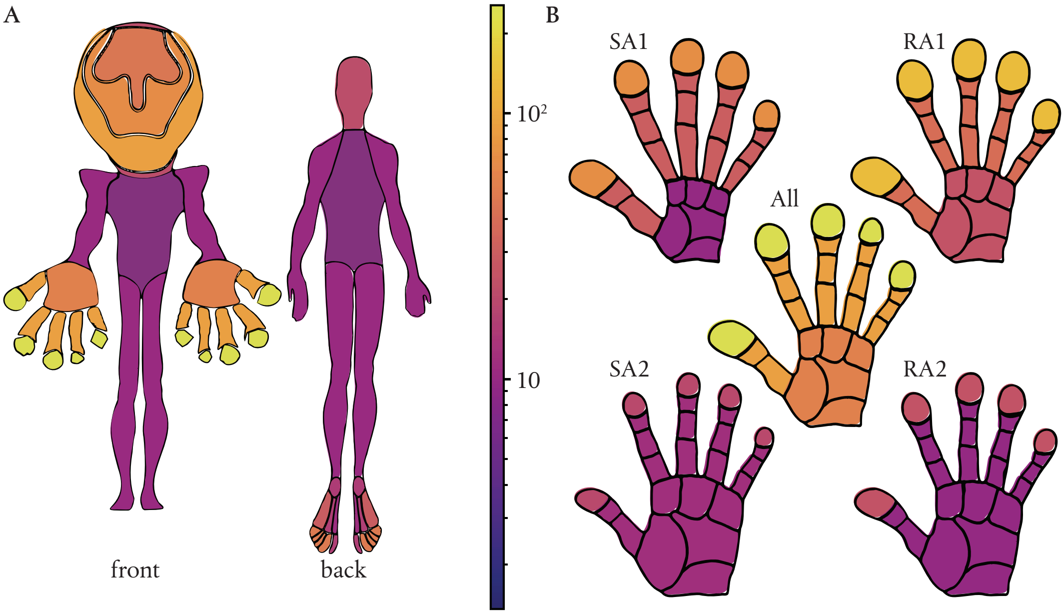

Figure 2.2. Illustration of the peripheral innervation homunculus for the whole body and the hand. Each area is scaled and coloured by its innervation density (units/cm^2) to reveal the "homunculus" of the body.

A. Whole-body tactile innervation densities. The colour and scaling of each body area denote its innervation density, combining both slowly adapting (SA) and fast-adapting (FA) fibres.
B. Innervation densities for the palmar surface of the human hand. Both slowly adapting type I (SAI) and fast-adapting type I (FAI) fibres are densely packed in the distal ends of the fingertips and much less so in the palm, while the two other afferent classes are more evenly spread throughout the hand and exhibit much lower innervation density overall.

Figure and caption reproduced and adapted, with permission, from Corniani and Saal [59]. Copyright © 2020 Corniani and Saal, used under CC BY 4.0. *Notation adapted for consistency.*

higher than in the rest of the body [59]. In particular, the fingertips are highly sensitive to touch. The reason for such high sensitivity in the hands is believed to be found within evolution – humans use their hands as a primary interaction interface with objects, tools, and other humans [197]. Dexterity is essential to being able to control tools well. Thus, the hands are good candidates for haptic stimulation because of the high tactile sensitivity and the potential use for interaction. However, other places on the body are also useful candidates for interactive haptic stimulation. For instance, Shen et al. [351] stimulated the mouth and lips in an entertainment VR experience. Ziat et al. [430] stimulated the soles of the feet to immerse people in an artistic painting, while Strohmeier et al. [361] stimulated the foot through a specialised shoe. Hassan et al. [138] used low-frequency sound to stimulate chest and feet. The potential is there, converting to practical application; however, it seems to be less common.

Lastly, I will mention the free nerve endings again, as these also have the potential for haptic stimulation. The free nerve endings are located throughout the skin but have no end organ that translates stimuli to electrical signals, as illustrated in Figure 2.1. It is not well understood how this translation happens in the free nerve endings; however, some classes of free nerve endings respond specifically to heat, some to cold, some to chemical irritants, and some to mechanical skin contact [254, p. 351–352]. Interesting for haptic research, in particular, are those free nerve endings with C fibres [392]. ‘C-tactile’ fibres, a class of C fibres, have been shown to be correlated to positive and pleasant touch sensations [254, 300, 332]. In particular, for affective touch, stimulation of the C-tactile fibres has great potential for applications in affective haptics. As we shall see later, free nerve endings that respond to chemical irritants, such as capsaicin, menthol, and others, also have the potential for haptic interactions.

2.2. Proximal Stimulus

Sense organs are stimulated by proximal stimuli – physical phenomena acting on the body’s receptors [248]. Typical proximal stimuli for the sense of touch are mechanical pressure and temperature, which are the stimuli that activate the receptors of touch, the free nerve endings, or both. Having illuminated the inner workings of the sense organs of touch, the question of how to use technology to stimulate the senses of touch remains. I will give an account of common technologies and techniques but focus on those relevant to the work conducted during my PhD studies. For a full account of technology-mediated touch stimulation, I refer to the works by Parisi [295] and Paterson [299].

Producing proximal stimuli of touch through technology fundamentally requires the delivery of mechanical pressure, a chemical substance, or a change in temperature on the skin to activate the sense organs of touch. On a technical level, there are many ways to achieve touch stimulation, whether through vibration motors or kinaesthetic actuators, thermoelectric devices, or a chemical stimulant. These technologies and techniques are sometimes embedded in general-purpose devices, such as smartphones or video game controllers, or specialized hardware, such as haptic vests or gloves. The list of such devices goes on – from surface haptic devices [24], mid-air haptic devices [312], grounded force-feedback devices [345], wearable haptic devices [117], elastic displays [196], to magnetic devices [223, 262, 360]. While each type of device has advantages and in their own right are promising, none can fulfil the Sutherland’s vision of an ‘ultimate display’ [363]; the haptic device capable of creating a chair to sit in or even be fatal [295, pp. 1–5]. No matter whether one believes Sutherland’s vision is an achievable or even desirable goal, it illustrates the grand challenge in haptics research: no general-purpose haptic device analogue to the general-purpose visual devices, XR headsets, exists.

There are two general challenges for designing haptic devices: (1) receptors are distributed across the body, and (2) the sense organs of touch facilitate at least three modalities: mechanical, chemical, and thermal. Many individual subproblems to these challenges have been solved with current technology; however, combining them into one solution is not practically feasible[5]. This does, however, not deteriorate the attempts to solve these challenges, as we do not have to accept Sutherland's vision of the 'ultimate display' to be the sole motivation for creating haptic systems. Despite not being general-purpose, haptic devices have a great influence in practice, for instance, in surgical robots or accessibility. In the following chapter, I will suggest an alternative approach to the design of haptic devices: acoustic levitation can deliver chemical stimulants to the skin.

[5] In the realm of speculation, one might see brain-computer interfaces as a pathway towards solving these challenges, similar to Tanaka et al.'s work [367]. This would change the proximal stimulus paradigm to a visceral stimulus paradigm. However, it also requires a better understanding of the somatosensory cortex, as the brain-computer interface needs to emulate the electrical signals otherwise emitted from the receptors of the skin.

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3. Ultrasound can deliver chemical stimulants to the skin and modulate their perception

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Abstract. When applied to the skin, chemical stimulants can evoke haptic sensations. However, they need to be applied continuously using pads in fixed locations, limiting their usefulness as a general haptic technology. To overcome these limitations, we introduce an ultrasound-based system for the precise acoustophoresis of droplets of chemical stimulants to the skin. We show that such droplets can indeed produce distinct haptic sensations. In addition, the system can use ultrasound to stimulate the area of the skin where the stimulants have been applied. We show that this increases the perceived intensity. Taken together, these results demonstrate the promise of non-contact delivery and modulation of chemical stimulants, not only as a haptic technology but also to provide deeper insights into the interaction of the chemical and mechanical senses.

Significance Statement. Chemicals have been used to create sensations on the skin. This is useful in studies of haptic perception and for virtual reality. Chemicals are usually applied by a piece of paper or a pad. This means that their haptic sensations are accompanied by those of the delivery device and makes it difficult to place and move the sensations. We present a system that uses ultrasound to levitate the chemicals onto the skin, overcoming these difficulties. We show how it can produce several haptic sensations and how the ultrasound can be used to change the haptic sensations without touching the skin. This system will enable new studies of haptic perception and richer haptic sensations to be added to virtual reality.

Keywords. Acoustophoresis, Topical Stimulants, Haptic Sensations

Citation. Tor-Salve Dalsgaard, Arpit Bhatia, Lei Gao, Ryuji Hirayama, Sriram Subramanian, Joanna Bergström, and Kasper Hornbæk. 2024. Ultrasound can deliver chemical stimulants to the skin and modulate their perception. *In Progress.*

3.1. Introducton

Chemical stimulants, such as menthol, capsaicin, and cinnemal, can induce haptic sensations when applied to the skin [118, 119, 120, 121, 122, 158, 279]. Chemicals have been used to activate the somatosensory system in the mucosal skin regions (like the mouth, eyelids, and nostrils) [260], inducing sensations of itching, warmth, and coolness [15, 158, 408], as well as in non-mucosal areas of the body with thin epidermis layers, such as the volar forearm [121, 158, 279] and the lips [45].

The most common way to deliver the chemicals to soak a sheet of filter paper or a cotton pad with the chemical and place it on the skin [118, 119, 120, 121, 122, 158, 279]. However, these delivery methods pose significant limitations for inducing rich haptic sensations. First, physical contact with a paper or a cotton pad induces a sensation of touch in addition to the sensations induced by the chemical. Therefore, controlling or studying the formation of sensations induced purely by the chemical is not possible. Second, as the skin remains covered by the paper or cotton pad, the chemicals cannot be combined with other technologies for inducing haptic sensations, such as mechanical vibration or friction from moving on a textured surface. Therefore, inducing or studying haptic sensations beyond the single chemical solution at a time is not possible. Third, the chemicals are only delivered at the specific location of the pad and for the duration that the solution on the pad carries. Therefore, more dynamic application both temporally (e.g., sustaining the delivery of the chemical for a longer time, stopping the delivery after a small quantity) and spatially (e.g., delivering the chemical in a very small or a larger region, dynamically moving the point of delivery) is not possible to control. These constraints limit the study and applications of chemical stimulants for rich haptic sensations.

To overcome these limitations and unlock new possibilities for chemical haptics, we propose the use of ultrasound as a novel delivery and modulation mechanism for haptic chemicals. Acoustophoresis uses acoustic radiation forces exerted by sound waves, such as ultrasound, to suspend objects and liquids in mid-air (i.e., "levitate") [11]. Recent advances in acoustophoresis have enabled the spatiotemporal manipulation of liquids [153, 321, 400], even in the presence of sound-scattering objects [152]. By leveraging the unique advantages of acoustophoresis, we can achieve contactless, interactive, and dynamic delivery of liquid chemicals onto the skin.

We study whether the chemical stimulants delivered by ultrasound acoustophoresis to the skin can induce haptic sensations, and whether the pure sensation can be modulated by simultaneous mechanical stimulation by ultrasound. In the first study, ultrasound acoustophoresis is used for the contactless delivery of three chemical stimulants shown in previous work to induce sensations with delivery via cotton pads: menthol, capsaicin, and cinnemaldehyde. The chemicals are dissolved in ethanol and it is also used as a baseline condition for a total of four chemicals. In the second study, we deliver cinnemaldehyde using ultrasound acoustophoresis and also apply ultrasonic haptic feedback at the point of application. In a third study, we only apply ultrasonic haptic feedback to be able to compare pure haptic feedback with the combination of chemical and haptic feedback. All studies follow a similar data collection procedure consisting of participants rating the perceived intensity on a 10cm visual analogue scale ranging from "no intensity" to "maximum imaginable intensity" for five minutes. After the five minutes have passed, the participants also describe the sensation they experienced by picking words from a given list. Overall, the studies show that chemical stimulants delivered to the skin with acoustophoresis are perceivable and that mechanism used for delivery—ultrasound—can further be used to modulate the perception.

3.2. Results

We invited a total of 160 participants across three pre-registered studies to report on the perceived intensity of any kind of sensation of a stimulus over time. The studies were conducted with identical apparatus (Figure 3.1A) and procedure (Figure 3.1B); however, they were conducted with varying stimuli. The first study investigated the perception of four solutions of chemical stimulants: ethanol (the solvent), capsaicin, cinnamal, and menthol. The second study investigated the perception of one chemical (cinnamal) in conjunction with an acoustic stimulus modulated to 50 Hz and 200 Hz, respectively. The third study investigated the perception of an acoustic stimulation modulated to 50 Hz and 200 Hz, respectively, alone.

We analyse the data using a generalised additive mixed model (GAMM) [263]. To evaluate the model, we employ the Wald test [415], allowing us to draw inferences on the perceivability of the stimuli. To draw inferences from the frequencies of words used to describe the sensation, we employ a χ^2 test, determining the difference in frequency within and between conditions. In addition, as an exploratory measure, we use time-intensity analysis (TI) [238] to compare stimulus intensity perception between participants. We employed the Kruskal-Wallis test, with a Dunn post-hoc analysis, to determine significant differences. Figure 3.2 shows an overview of the TI analysis. A statistical significance was defined as $p < .05$.

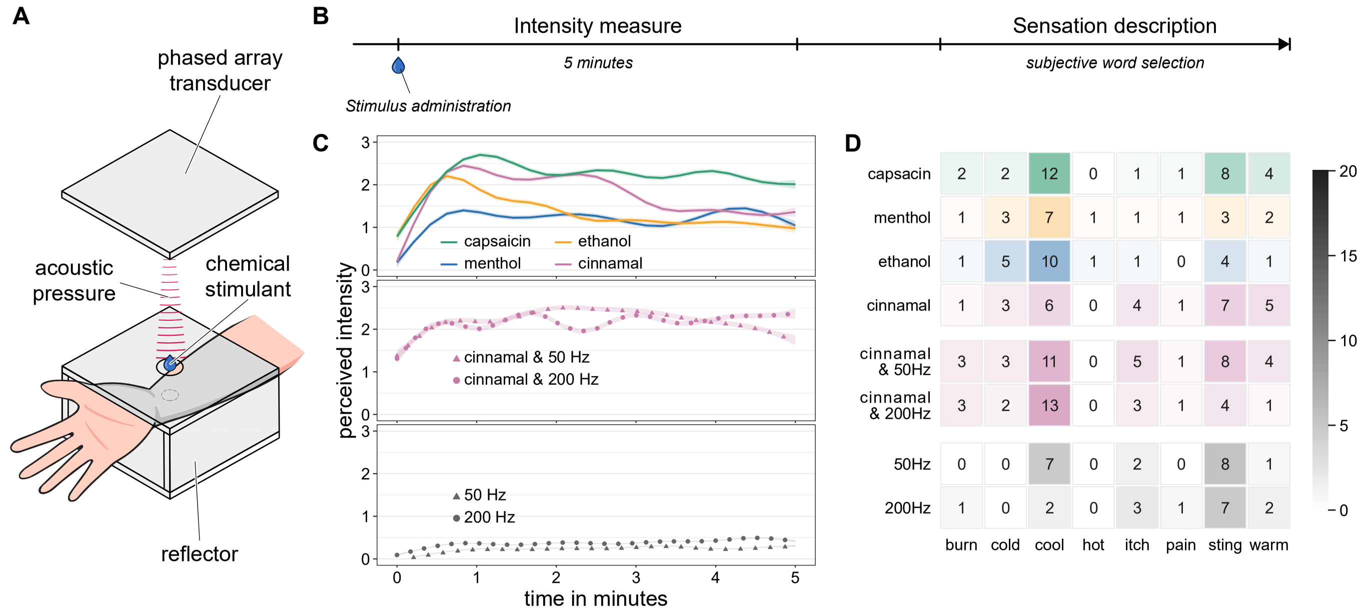

Figure 3.1. (A) Experimental setup. The chemical was applied to the forearm using acoustic levitation. (B) Experimental protocol. Participants were asked to rate the perceived intensity of any given sensation for five minutes on a visual analogue scale (VAS 0–10 cm), where 0 represented no intensity and 10 represented the maximum imaginable intensity [158]. After reporting on their perception, participants selected from a set of words that described any sensation perceived during the five minutes. (C) Plots of the GAMM smooths of the perceived intensity of haptic sensations and 95% pointwise confidence intervals for the smooth. The curve indicates the trend in the intensity data. *(top)* Perception of ethanol, capsaicin, cinnamal, and menthol; *(middle)* perception of cinnamal in combination with 50 Hz and 200 Hz acoustic stimulation. Smooth for the perception of cinnamal added for reference; and *(bottom)* perception of 50 Hz, and 200 Hz acoustic stimulation. (D) Frequency plots of the words participants selected to describe any sensation perceived during the study. *(top)* Words related to the perception of ethanol, capsaicin, cinnamal, and menthol; *(middle)* words related to the perception of cinnamal in combination with 50 Hz and 200 Hz ultrasound stimulation; and *(bottom)* words related to the perception of 50 Hz and 200 Hz ultrasound stimulation.

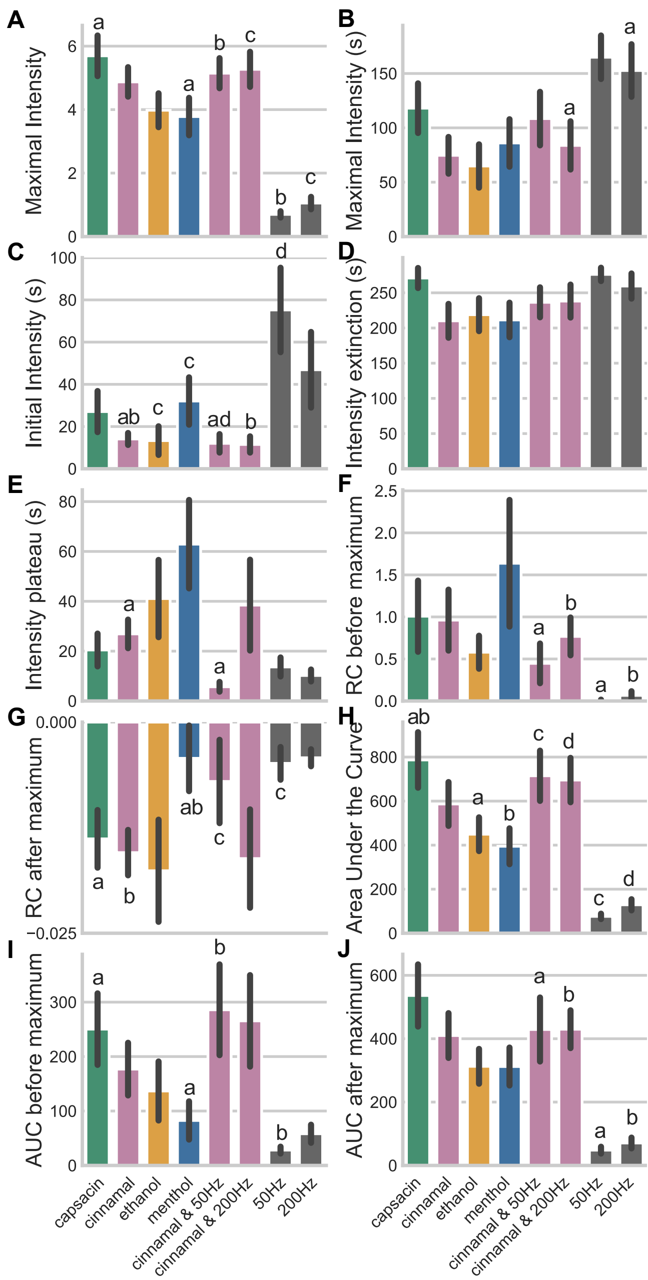

Figure 3.2. Time-intensity analysis for all three studies. (A) The maximal reported intensity. (B) The time at which the maximal intensity occurs. (C) The time at which the stimulant is initially perceived. (D) The time at which the stimulant is not perceived any more. (E) The number of seconds around the maximal intensity at which the reported intensity plateaus. (F) The rate of change before the maximal intensity occurred. (G) The rate of change after the maximal intensity occurred. (H) The area under the mean curve. (I) The area under the mean curve before the maximal intensity occurred. (J) The area under the mean curve after the maximal intensity occurred. Mean area with *same* letters indicate a significant difference at $p < .05$. Error bars represent standard errors of the means.

3.2.1. Chemical Perception

The majority of participants reported perceiving the chemical stimulant applied to their skin; for capsaicin, 17 participants out of 20 reported perceiving any sensation from the stimulus, and for cinnamal, menthol, and ethanol, 18 reported so. The GAMM smooths (Figure 3.1C, top) show the temporal development of the perceived intensity of each chemical stimulant. We found that all four chemicals are perceivable (ethanol: $W(8.82) = 169.3$, $p < .001$; capsaicin: $W(8.69) = 140.8$, $p < .001$; cinnamal: $W(8.84) = 285.9$, $p < .001$; and menthol: $W(8.62) = 62.5$, $p < .001$). However, the degrees of freedom and the Wald statistic are relatively high due to the large perceptual variance between participants.

The capsaicin condition was perceived stronger than the menthol and ethanol conditions: The maximal perceived intensity was significantly higher in the capsaicin condition ($M = 4.84$, $SD = 3.20$) than in the menthol condition ($M = 3.40$, $SD = 2.64$; $p = .046$, $CL = 0.70$) and the time to the initial perception in the ethanol condition ($M = 13.35s$, $SD = 28.81s$) was significantly lower than the menthol condition ($M = 32.09s$, $SD = 47.65s$; $p = .026$, $CL = 0.28$). In addition, we found that the total AUC was significantly higher for the capsaicin condition ($M = 668.86$, $SD = 557.74$) than for the ethanol ($M = 404.69$, $SD = 337.40$; $p = .039$, $CL = 0.29$) and menthol conditions ($M = 355.41$, $SD = 348.91$; $p = .014$, $CL = 0.75$).

Participants described their perception after reporting intensity. Figure 3.1D shows the frequency of words used by the participants for sensations felt throughout the five-minute span. We found that the distribution of words is similar across all chemical conditions, except for the menthol condition. Overall, the word ‘cool’ was used to describe the perceived sensation across most chemical conditions, followed by the word ‘sting’; however, there are no significant differences. Anecdotally, some participants described the sensation as ‘tingling’, ‘tickling’, and ‘vibrating’.

Overall, capsaicin is perceived as the strongest but comparable to cinnamal. The perceived strength generally weakens over time.

3.2.2. Perception Modulation

Applying cinnamal in conjunction with acoustic stimulation is perceivable (50Hz: $W(8.83) = 33.97$, $p < .001$ and 200Hz: $W(8.26) = 66.25$, $p < .001$). The perception of cinnamal is strengthened through acoustic stimulation (Figure 3.1C, middle). Overall, acoustic stimulation elicited a higher perceived intensity at the moment of onset and sustained it for longer. The perceived intensity in the cinnamal & 50Hz condition is 0.39 units ($SE = 0.01$) higher than the cinnamal condition, $t(19) = 27.18$, $p < .001$, while the cinnamal & 200Hz condition is 0.45 units ($SE = 0.01$) higher, $t(19) = 30.85$, $p < .001$.

The time to the initial perception in the cinnamal & 50Hz ($M = 12.05s, SD = 19.08s$; $p = 0.028$, $CL = 0.29$) and cinnamal & 200Hz conditions ($M = 11.52s, SD = 17.23s$; $p = 0.034$, $CL = 0.30$) was significantly shorter compared to the pure cinnamal condition ($M = 14.12s, SD = 12.04s$). The time in which the perceived intensity plateaus around the maximal perceived intensity is significantly higher in the cinnamal condition ($M = 54.23s$, $SD = 87.15s$) than in the cinnamal & 50Hz condition ($M = 20.42s$, $SD = 66.33s$; $p = 0.003$, $CL = 0.21$).

There is a significant difference in the distribution of words used to describe the sensation elicited by cinnamal and the sensation elicited by cinnamal & 200Hz, $\chi^2(8, N = 20) = 26.08, p = 0.001$. This leads to the inference that the acoustic stimulation enhanced the 'cool' sensation. We observed a similar effect for cinnamal & 50Hz; this difference is, however, not significant, $\chi^2(8, N = 20) = 3.05, p = 0.931$.

Overall, these results suggest that added acoustic stimulation shortens the time till perception and increases the time at peak perception of cinnamal.

3.2.3. The Effect of Acoustic Stimulation

Acoustic stimulation was perceivable (50Hz: $W(8.46) = 121.20$, $p < .001$ and 200Hz: $W(8.76) = 144.80$, $p < .001$). The smooth of the perceived sensation of the 50Hz condition is 1.93 units ($SE = 0.01$) lower than the cinnamal & 50Hz condition, while the 200Hz condition is 1.84 units ($SE = 0.01$) lower than the cinnamal & 200Hz condition. We found that the maximal perceived intensity in the cinnamal & 50Hz condition ($M = 4.89, SD = 2.32$) is significantly higher than in the 50Hz condition ($M = 0.63, SD = 0.46$; $p < .001$, $CL = 0.99$). The same is true for the cinnamal & 200Hz condition ($M = 5.27, SD = 2.47$) and the 200Hz condition ($M = 0.90, SD = 0.84$; $p < .001$, $CL = 0.94$).

The time to the initial perception in the cinnamal & 50Hz condition ($M = 12.05s, SD = 19.08s$) is significantly lower than the 50Hz condition ($M = 75.24s, SD = 84.89s$; $p < .001$, $CL = 0.13$). The total AUC was significantly higher for both corresponding pairs of conditions. Cinnamal & 50Hz condition ($M = 679.31, SD = 509.76$) has a higher AUC than in the 50Hz condition ($M = 68.88, SD = 54.69$; $p < .001$, $CL = 0.98$), and cinnamal & 200Hz condition ($M = 695.59, SD = 450.77$) has a higher AUC than in the 200Hz condition ($M = 109.76, SD = 106.93$; $p < .001$, $CL = 0.92$). For the AUC before the maximal perceived intensity, the cinnamal & 50Hz condition ($M = 271.67, SD = 359.50$) is higher than in the 50Hz condition ($M = 25.39, SD = 26.90$; $p = 0.004$, $CL = 0.77$). The area after the maximal perceived intensity was also significantly higher for both corresponding pairs of conditions. The cinnamal & 50Hz condition ($M = 407.65, SD = 439.17$) is higher than in the 50Hz condition ($M = 43.49, SD = 45.94$; $p < .001$, $CL = 0.90$), and the cinnamal & 200Hz condition ($M = 429.99, SD = 266.70$) is higher than than in the 200Hz condition ($M = 60.26, SD = 69.54$; $p < .001$, $CL = 0.95$).

Participants described the sensations differently between the cinnamal & 50Hz and 50Hz conditions ($\chi^2(8, N = 20) = 97.71, p < .001$) and the cinnamal & 200Hz and 200Hz conditions ($\chi^2(8, N = 20) = 25.72, p < .001$). In Figure 3.1D, we see that the two chemical conditions are rated 'cool', 'itch', and 'sting' more often.

Overall, we found the acoustic perception alone to be perceived as weak, yet noticeable. Acoustic stimuli alone are perceived significantly less on almost all TI parameters compared to the chemical and acoustic stimulation counterpart.

3.3. Discussion and Conclusion

We have demonstrated that chemical stimulants delivered by ultrasonic levitation can be perceived. The application of ultrasound to the chemicals modulates the perceived intensity of the delivered sensation. Furthermore, the combination of ultrasound and chemicals can speed up the onset of the sensation, increase the perceived intensity at onset, and maintain the sensation for longer.

3.3.1. Perception

The first study showed that droplet-sized topical stimulants can be transported to the skin and produce a noticeable effect. This removes the need for papers or pads to deliver the chemicals, allows the stimulation to be moved around, and helps separate the effect of the stimulant from the continued pressure of a paper or pad.

The magnitude of perception in the first study is weaker than similar studies (e.g., [118, 121, 158]) that use the same amount of concentration and data collection methods. This difference is likely due to the difference in delivery method, as soaked patches prevent evaporation and impact a larger area of skin. Despite this weakness, liquids delivered through ultrasonic levitation are still perceivable and perform better than ultrasonic stimulation only (Study 3). The reported intensity is low compared to previous work; Højland et al. [158], for instance, reported a moderate peak intensity for cinnamal (M=5.18, SD=0.32). This is to be expected given the smaller quantities of chemical stimulants administered in this work.

The word 'cool' was used by a majority of participants to describe the sensations in the experiment. This is likely due to the solvent, ethanol, which is known to feel cold on the skin due to evaporation [129, 331]. Menthol and capsaicin, which are commonly said to feel cold and hot respectively were not rated high for those words, however, this is consistent with previous studies [121] where capsaicin may also feel cool to certain individuals. Cinnamal being rated high for 'itch' is also consistent with previous studies [158, 279]. Thus, the novel delivery mechanism does not change the qualities of the perception.

3.3.2. Modulation

The addition of ultrasonic stimulation to the chemical stimulant cinnamal led to a sharp rise at the beginning of the intensity curve. The intensity curve for pure ultrasonic feedback also starts from zero. Though the graph's peak does not change, the area under it is greater than the area for the sum of the individual sensations. The reason for this phenomenon requires further studies. It is also opposite to the phenomenon of reduction in sensation when chemical and mechanical stimuli are combined [45].

We found that the 200Hz signal was not significantly different than the 50Hz signal. This is surprising given these signals target different receptors. The exact relationship between the ultrasonic wave frequency and its effect on the chemical stimulus still needs further investigation. This relationship may vary for the different stimulants, and hence, future studies are needed to investigate different stimulants.

3.3.3. Opportunities

Delivering chemical stimulants to the skin by ultrasound acoustophoresis presents new opportunities for haptics compared to other delivery mechanisms such as manually application using cotton pads or wearable chemical haptic devices [241].

First, acoustophoresis enables dynamic mixing of tactile stimuli. For example, we showed that chemical stimuli can be mixed and modulated by mechanical stimuli, namely ultrasound haptics. Similarly, different chemical stimuli could be mixed with each other as a cocktail, or acoustophoresis could add other types of mechanical stimuli, such as levitating particles and shooting those on the skin [108, 109].

Second, acoustophoresis enables temporal modulation of the chemical stimuli. We demonstrated that a single droplet can be perceived, and showed that this perception changes over time. The stimuli could be for instance applied multiple times and its frequency modulated, such as to strengthen or elongate the sensation with multiple droplets.

Third, acoustophoresis enables spatial modulation of the stimuli. We applied a single droplet onto a single location on the skin. However, the droplets could be applied simultaneously or sequentially to multiple locations on the skin, or atomized to spread a single droplet onto a larger area on the skin.

Combined, these three opportunities could be used to create dynamic mixtures of chemical sensations on the skin or to study the formation of the sensations (e.g., the thermal grill illusion by applying hot and cold inducing chemicals spatially next to each other, alternating temporally them on the same location, or as a mixture).

3.4. Materials and Methods

We ran three studies with an identical apparatus and procedure, however, changing the stimulus.

3.4.1. Apparatus

We built a device capable of acoustic levitation and ultrasound stimulation, both of which are facilitated through the same phased-array transducer (PAT). The PAT is comprised of 16×16 Murata MA40S4S transducers (40 KHz, 10.5 mm diameter (≈ 1.2 λ), delivering ≈ 8.1 Pa at 1 m distance when driven at 20 Vpp). The PAT produces a focal point of high pressure through ultrasound, which can be utilised to suspend matter in mid-air [152]. An increase in amplitude and control of the modulation frequency of the focal point is perceivable on the skin [312].

The device is based on the top-sided PAT arrangement and scattering levitation solver [152], which allows for the creation of levitation points with a sound-scattering object in the sound field, contrary to most acoustophoretic systems that only allow empty levitation space to avoid sound-field distortion by external sound-scattering objects. This solver, however, requires geometrical information of the scattering object to pre-compute the levitation scattering contribution from the object. This process is, however, not real-time. Thus, it was not feasible to model each participant's forearm as a scattering object. Instead, we place a hollow box (see Figure 3.1A) as a fixed and solid scattering reflector, with a hole with 2 cm diameter on top to allow for stimulation to occur. We implemented the scattering levitation solver based on the hardware and software framework provided by the OpenMPD platform [269].

During the study, a drop of a chemical stimulant was injected 2 cm above the box at a distance of 4 cm to the centre of the hole in the reflector. The key to manipulating liquid droplets by the acoustophoretic system is not only to make the acoustic radiation force overcome gravity but also to adjust the ratio of acoustic radiation force to the interfacial force of droplet to avoid droplet atomization [104, 152].

3.4.2. *Procedure*

We conducted three studies in sequential order. The studies differ only in the stimulus participants received. Both followed a between-subject design, such that each subject would evaluate the sensation of one stimulus condition to avoid confounding factors of a chemical stimulant being perceived for an extensive amount of time. A Latin square design determined the order of stimuli administered between subjects. All subjects received written and oral information about the experiment before giving their written consent. To counteract acoustic levitation's novelty effect, the experimenter demonstrated the levitation capabilities using a 2mm polystyrene bead and answered the subjects' questions.

Subjects were seated in front of the acoustophoretic device such that their right arm could reach inside the hollow reflector. Shortly after reaching into the reflector and placing their arm at the correct position, the experimenter administered the stimulus on the volar aspects of the subject's forearm. Subjects were asked to assess the perceived intensity of any given sensation on the forearm on a visual analogue scale (VAS 0-10 cm) on a tablet computer, where 0 presents no intensity at all and 10 the maximal imaginable intensity [158]. The subject would adjust the scale continuously over a period of five minutes (see the *Supplemental Materials* for reasoning). The perceived intensity was recorded with a sampling frequency of 60 Hz.

After the five minutes had passed, subjects were asked to select any words from a list related to their perceived sensations over the period. Subjects could select none and write additional words in an open-ended format if they wished to. The listed words were presented in random order and with a description adapted from Green and Flammer [121]. Words and descriptions are listed in the the *Supplemental Materials Table* 3.1.

3.4.3. *Study 1: Chemical Perception*

The first study investigated the temporal perception of chemical stimulants applied to the skin.

3.4.3.1. Participants. We recruited a total of 81 subjects for the first study (38 female, 42 male, range 18-50y, 25.75 ± 5.26) primarily from the student body at local universities and social media posts as paid volunteers. One subject was excluded, as they did not follow the study protocol. We recruited only participants who reported no impairments or chronic or current pain in the right volar aspects of the forearm and no known food allergies. The room temperature was 23.70°C ± 1.17°C, while the surface skin temperature of the subjects was 36.28°C ± 0.33°C. See the *Supplemental Materials* for sample size considerations.

3.4.3.2. Stimulation. In this study, we stimulated participants with one of four chemical stimulants soluted in ethanol: cinnamal (5% solution by volume [158]), menthol (40% solution weight by volume [279]), capsaicin (0.25% solution by weight [121]), or ethanol (carrier). Additional details are listed in the *Supplemental Materials Table* 3.2.

3.4.4. Study 2: Modulation of Perception

The second study investigated the potential effect of ultrasound stimulation on the temporal perception of chemical stimulants on the skin.

3.4.4.1. Participants. We recruited a total of 40 subjects for the second study (19 female, 21 male, range 20-35y, 25.93 ± 3.58) primarily from the student body at local universities as paid volunteers. We recruited only participants who reported no impairments or chronic or current pain in the right volar aspects of the forearm and no known food allergies. The room temperature was 23.15°C ± 0.93°C, while the surface skin temperature of the subjects was 36.34°C ± 0.38°C. See the *Supplemental Materials* for sample size considerations.

3.4.4.2. Stimulation. In this study, we used cinnamal (5% solution by volume [158]) as a chemical stimulant (see the *Supplemental Materials* for reasoning). After the application of the chemical, we stimulated the participant's skin with an amplitude-modulated focal point [312], vibrating the skin with either a 50Hz or 200Hz modulation, constantly over the five-minute study period. These modulation frequencies stimulate two specific mechanoreceptors in the skin: the Meissner corpuscle with a peak vibration sensitivity at 50Hz and the Pacinian corpuscle with a peak vibration sensitivity at 200Hz [132, 197].

3.4.5. Study 3: Acoustic Perception

The third study investigated the potential effect of ultrasound stimulation on the wrist.

3.4.5.1. Participants. We recruited a total of 40 subjects for the second study (15 female, 24 male, one non-binary, range 21-57y, 29.77 ± 7.56) primarily from the student body at local universities as paid volunteers. We recruited only participants who reported no impairments or chronic or current pain in the right volar aspects of the forearm. The room temperature was 22.46°C ± 0.89°C, while the surface skin temperature of the subjects was 36.37°C ± 0.22°C. See the *Supplemental Materials* for sample size considerations.

3.4.5.2. Stimulation. We stimulated the participant's skin with an amplitude-modulated focal point [312], vibrating the skin with either a 50Hz or 200Hz modulation, identically to the second study.

3.4.6. Data Analysis

We used a generalised additive mixed model (GAMM) [263] to model the intensity data and used a χ^2-test to test for differences in word distributions across conditions, as pre-registered. As an exploratory analysis, we conducted Time Intensity (TI) [238] analysis to gain detailed insights into the perception of the stimulation.

The GAMM was fitted in R using the `mgcv`-library [415] and the formula `gamm(intensity ~ stimulant + s(time, by = stimulant), data = data)`.

We conducted the χ^2-test using the SciPy package in Python [403] and the function `scipy.stats.chisquare`, comparing the word distributions.

We report on the intensity curve through TI analysis. We analyse the maximally perceived intensity across participants (Figure 3.2A) and the time at which the maximal intensity occurs (Figure 3.2B). We analyse the time of initial perception, the first time the intensity value exceeded 5% (the significance level) of the maximal intensity (Figure 3.2C), and the time of the extinction of perception, the first time the intensity value falls below 5% of the maximal intensity after the maximal intensity occurred (Figure 3.2D). Next we analyse the plateau around the maximal intensity, i.e., time duration around the maximal where the measured intensity is greater than 95% of the maximal intensity (Figure 3.2E). In addition, we report the slope of a linear fit on the intensity values from the initial to the maximal intensity and from the maximal to the extinction in Figure 3.2F and Figure 3.2G, respectively. Last, we report on the area under the curve (AUC), both in total (Figure 3.2H), before the maximal intensity (Figure 3.2I), and after the maximal intensity (Figure 3.2J).

3.4.7. Ethics Statement

The experiments were approved by the local ethics committee at the University of Copenhagen (504-0376/23-5000) and were conducted in accordance with the Declaration of Helsinki (2013). All studies were pre-registered at osf.io/a9erb.

3.4.8. Data Availability

Data and source code are available at osf.io/a9erb.

Acknowledgements

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3.5. Supplemental Material

3.5.1. Sample size consideration

McKeown and Sneddon [263] describe a study design similar to ours, although they investigate the emotional valence of video clips. They suggest that 20 to 30 participants per condition would have been sufficient for their study to achieve a large effect size.

3.5.2. Pilot studies

3.5.2.1. Determining study duration. Subjects were asked to rate perceived intensity during a five-minute window. This duration was found suitable in a pilot study conducted prior to the first study. We recruited a total of 12 subjects for the pilot study (6 female, 6 male, range 22-32y, 27.25 ± 3.05). We recruited only participants who reported no impairments or chronic or current pain in the right volar aspects of the forearm and no known food allergies. The room temperature was $23.42°C \pm 0.47°C$, while the surface skin temperature of the subjects was $36.37°C \pm 0.42°C$.

We administered a drop of either menthol, capsaicin, cinnemal, or ethanol to the volar forearm of the subjects. Subjects were asked to indicate two points in time by pressing a button: when they started perceiving sensations different from their normal perception and when they stopped perceiving sensations different from their normal perception. On average, subject stopped perceiving menthol after $94.80s$ (SD=$54.00s$), capsaicin after $888.61s$ (SD=$1342.22s$), cinnemal after $195.64s$ (SD=$117.02s$), and ethanol after $31.80s$ (SD=$13.89s$). Note that the capsaicin condition was heavily influenced by one participant who perceived a sensation for roughly 40 minutes. Such a long effect was not observed during any of the following studies. We decided on the five-minute window for rating the perceived intensity of the chemical stimulants as $> 90\%$ of subjects perceived the stimulation for shorter than five minutes.

3.5.2.2. Selecting a candidate stimulant for study 2. Subjects of study 2 were administered with cinnamal in conjunction with ultrasound stimulation, due to the results of a pilot study. We recruited a total of 24 subjects for the pilot study (8 female, 12 male, range 23-44y, 29.17 ± 4.73). We recruited only participants who reported no impairments or chronic or current pain in the right volar aspects of the forearm and no known food allergies. The room temperature was $22.39°C \pm 0.58°C$, while the surface skin temperature of the subjects was $36.60°C \pm 0.17°C$.

Based on the results of the first study, we selected cinnamal and capsaicin as candidates for our modulation technique using ultrasound stimulation. Thus, we conducted a between-subject study with two independent variables, chemical stimulant and ultrasound modulation frequency, similar to the following study 2 described in the main paper. The chemical stimulant variable had two levels, cinnamal and capsaicin, and the ultrasound modulation frequency was either 50Hz or 200Hz. We used a generalised additive mixed model (GAMM) [263, 415] to model the perceived intensity and found the effect of modulating cinnamal to be more promising, as the perceived intensity of the cinnamal & 50Hz was 0.43 units higher than the capsaicin & 50Hz and the cinnamal & 200Hz was 0.80 units higher than the capsaicin & 200Hz.

Table 3.1. The list of words shown after each trial for the subjects to describe their sensations during the five-minute trial period. Subjects could select any number of words to describe their sensations. Subjects had the option to select none and describe sensations in their own words. The words were shown with a description of the word. * indicates word-descriptions by Green and Flammer [121, 122]. ** indicates word-descriptions not present in related work. These were created by following the structure of existing definitions and dictionary meanings.

Sensation	Description
Itch	The sensation associated with a desire to scratch.*
Sting/prick	Sharp sensations similar to those produced by an insect bite or a pin-prick, which may be constant or intermittent.*
Burn	The sensation produced by extreme temperatures or chemical irritants, which may or may not be associated with a thermal sensation (either hot or cold*
Pain	Any sensation that 'hurts'.*
Cool	A moderately cold sensation; neither warm nor cold.**
Cold	The sensation of an uncomfortable lack of warmth.**
Warm	The sensation of a moderate degree of heat.**
Hot	The sensation of great bodily heat.**

Table 3.2. The used chemicals and their solutions. Capsaicin, menthol, and cinnamaldehyde are soluted in ethanol. We reference the papers using the same solution and the commercial distributor of the chemical.

Chemical	Purity	Concen.	Solution	Reference	Source
Capsaicin	> 60.0%	0.25%	by weight	[121]	TCI Europe N.V., Zwijndrecht, Belgium; PN: M1149
Menthol	> 98.0%	40%	weight by volume	[279]	TCI Europe N.V., Zwijndrecht, Belgium; PN: M0321
trans-Cinnamaldehyde	> 98.0%	5%	by volume	[158]	TCI Europe N.V., Zwijndrecht, Belgium; PN: C0352
Ethanol	96.0%		by volume		Les Grandes Distilleries de Charleroi N.V., Jumet, Belgium

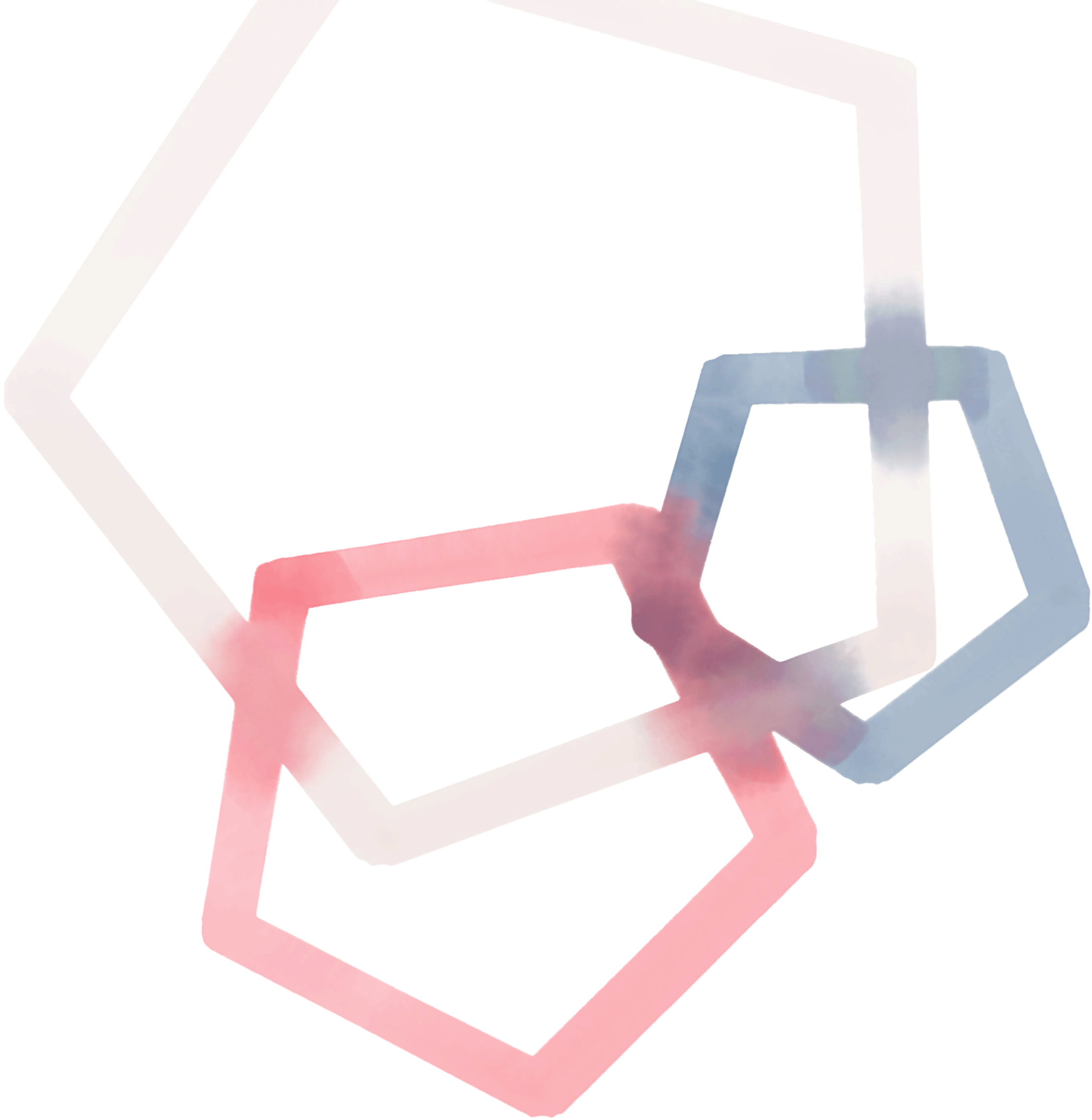
4. Haptic Stimulation

Creating haptic stimuli that elicit an intended perception is a challenging affair, as it depends on the technological development of haptic devices and the physiological parameters of the receptors of touch, such as the sensitivity and receptive fields of such receptors. Designers of haptic stimuli need to understand these challenges to be able to convey their intent [245, 334]. Much work within haptics concerns the ease of these challenges, and different ways have been found to address them. Schneider et al. [334], for instance, put forward a need for better prototyping possibilities as a crucial driver for haptic development. Others have proposed better haptic design tools (e.g., [193, 228, 236, 335, 336, 343]) and haptic rendering algorithms (e.g., [235, 256, 376]). In this chapter, I discuss the uses of chemical stimulants for prototyping and an observation regarding the design of haptic stimuli.

With the presented manuscript *Ultrasound can deliver chemical stimulants to the skin and modulate their perception* [65], we show the potential for chemical stimulants as proximal stimuli for the haptic senses. These stimulants can be induced and modulated and are thus a new tool in the toolbox of haptic designers. We propose acoustic levitation as a delivery method; however, Lu et al. [241] showed use of an elaborate pumping system to deliver stimulation. The possibilities of device designs and chemical stimulation candidates lay unexplored – at least in the realm of human-computer interaction. Findings presented in neuroscientific literature propose, among others, methyl salicylate [122], sanshool [45, 231], and eucalyptol [102], in addition to the presented menthol [89, 118, 120, 224, 279], cinnamal [102, 158, 279], and capsaicin [121]. Filiou et al. [102], in particular, showed that the mixture of eucalyptol and cinnamal is perceived differently from the individual components, opening another avenue for research in the use of chemical stimulants for haptic stimulation. Haptics research remains reliant on findings from neuroscience to develop novel ways of stimulation. Such novel ways of stimulation have the potential to allow for rapid prototyping, yet the link between chemical stimulants and haptic sensation is to be explored.

An interesting, seemingly banal, observation I have made from creating the Inference-Design Model is an underlying factor to all haptic designs: Haptic designers only have direct control over the proximal stimulus. Haptic stimulation is often designed with little knowledge of the environment, social setting, or context of use [334], nor the body or embodied knowledge of the perceiving human – the perception of haptic stimulation, however, is deeply embedded in these and other factors. Haptic designers can make qualified guesses, particularly when the haptic device is specialized for a particular use case or context. For instance, a haptic designer working with vibrotactile feedback for video games knows some things about probable configurations where use occurs and aims to make a game more immersive or enjoyable. They know the 'look and feel' of the game itself, can anticipate the social context in a single- or multi-player setting, and can reasonably assume that the game is played while on a living room sofa. However, the perceiving human is the unknown in this equation – the diversity of perception is difficult to adjust for in practice. Another conceptually similar example is haptic feedback in surgical robots. The fidelity requirements of haptic feedback are much higher than in a video game, and the environment and context are much more defined. Nevertheless, the perceiving human is the unknown – What is their expertise level? Are they fatigued? Haptic designers design haptic feedback but must also design a story about the haptic stimulation. Designing a haptic stimulus always has the goal of feeling like something. Perceptually, the stimulus does not stand alone – the story of its occurrence in a given context must also be told.

The connection between the designer and perceiving humans is made through that story. It shows the human how the designed world is supposed to work but does not tell the human how to feel [340, pp. 28–47]. In that way, the human can bring their embodied knowledge into the experience, guided by the designer's intent. Much research work has lifted different forms of haptic design from the low-level stimuli to the high-level experiences (e.g., [206, 245, 334]). Yet, in the end, it is important not to forget that haptic designers can *only* control the haptic stimulus and 'just' design *for* haptic experiences [340, 416]. Haptic designers need to consider their role in the perceived experience—they can control the stimulus and shape the context configuration—haptic designers are experience designers, whether they like it or not.



Part III

Inference and Design

Life is messy,

and we need to design for it.

– *Adam Scott and Dave Waddell*

haptic inference A mental process in which the brain consciously infers information to mean something. *Sensory inference* infers the immediate information a haptic stimulus provides to elicit a haptic sensation. *Perceptual inference* processes a sensory situation composed of one or more haptic sensations to perceive a haptic experience.

haptic design A design process in which a designer creates a haptic stimulus enabling an experience. *Elicitation design* refers to the design of haptic stimuli with the purpose of eliciting a haptic sensation. *Experience design* refers to the design of a sensory configuration that enables a specific haptic experience.

Something happens between haptic stimulation and experiences. But what? And how do we design the *something*? I seek to answer these and many other questions in this part of the thesis. To begin with, what we know about the *something* is that it describes a link between the neural signal received by the brain through the sensory environment and the conscious perception of the environment. This link appears in literature from different fields, such as neuroscience [20, 198, 254], psychology [325], philosophy [48, 77], and human-computer interaction [85, 143, 259], however, it is hard to pinpoint an exact definition. Some suggest a purely physical, neurological process [75, 254], others cite needs and motivation to influence the link [143, 325], while yet others argue that experiences are so fundamental to being, that the link is hardly definable [48]. In short, the link is complicated to navigate. Nevertheless, a human can somehow consciously assign meaning to a stimulus. And, fundamental to haptic design is the belief that particular stimuli can be designed to elicit a particular meaning, might that be affective [92, 245], social [172, 395], functional [68, 278], or any other inferred information from a perceived touch.

In my view, human perception can yield two separate perceptual constructs, which I have labelled sensation and experience. I will discuss both in later parts. Further, perceivable proximal stimuli will yield sensations through a process I name *sensory inference* since the sensory environment informs the inference process. Lastly, I name the process that infers an experience from sensations as *perceptual inference*, as a given perceptual state forms an experience of the world. Together, these form the conscious inference process responsible for generating experiences in the human mind. In addition, I define two analogous design processes, *elicitation design* and *experience design*. Elicitation design refers to the design process aiming to elicit haptic sensations, while experience design relates to the process of creating a context in which a particular haptic experience occurs. Within haptics research, some research has gone into design practice and theory, in particular, related to Haptic Experience [12, 206, 330, 334] and affective haptics [92, 174, 175, 245, 285]. Examples of research on elicitation design are sensation libraries, mapping haptic stimuli to sensations (e.g., [137, 347]). My notion of haptic experience design is related to Schneider et al.'s notion of Haptic Experience Design [334]; however, I differentiate in some cases.

In Chapter 5, I present both inference and design in depth. I explore the two inference processes, particularly what seems to inform the link between neural signals and conscious perception. A question emerges for haptics research: How can haptic designs leverage the two inference processes? I attempt to tackle this question by describing the two design processes: elicitation and experience design. Chapter 6 is a reprint of the journal paper *A User-Derived Mapping for Mid-Air Haptic Experiences* [63], in which we provide empirical data on the separation between stimuli, sensation, and experience. From the separation follows a connection, a link that is non-trivial. The paper provides rich and detailed descriptions of what haptic stimuli feel like and how previous experiences are linked to the current experience. Lastly, in Chapter 7, I explore the isomorphic nature of the relationship between stimuli, sensations, and experiences by exploring the inference and design processes in depth through the notion of information spaces.

5. The Making of Haptic Experiences

At the core interest of haptic design is how haptic experiences are made. For humans to perceive experiences as intended by haptic designers, the designers need to understand humans. However, the challenge for designers is to strike a balance between the intent of a design and how the design appears to the human [140]. In this chapter, I will let you participate in my speculations about the inference processes in the human mind and how we can leverage the distinction between sensations and experiences for design. Fundamental to this speculation is *ex nihilo nihil fit* – nothing comes from nothing.

5.1. The Making of Inference

Humans assign meaning to the world based on the sensory environment [396, pp. 14–27]. The inferred sense-making of the world lays the foundation for acting upon the world, making the inference process incredibly influential in our daily lives. Barrett describes inference to be informed by an internalised, mental *concept* of elements of the environment around the human [21, pp. 25–41]. The concept of a tree, for instance, includes not only information about what a tree looks and feels like but also the relation to other concepts related to trees, such as nature, hike, leaf, and calmness. The concept and the relations are constructed by past experiences and refined by the current. This inference from these mental concepts guides human action in new contexts and situations—"concepts are a primary tool for [the] brain to guess the meaning of incoming sensory inputs" [21, p. 28]. Experiencing the tree is a multi-sensory affair: Humans see the green leaves, hear the tree rustle in the wind, feel the roughness of the bark, and so on. The individual components might be broken down into a visual, auditory, or tactile experience, but together, they make up the experience of a tree. That is not to say people can not experience a tree without seeing it, but the mental construction becomes more robust when sensory modalities play well together [396, pp. 14–27]. This concept of multi-sensory integration is well-studied in relation to technology use [58, 396].

Barrett's stance of constructionism requires humans to be able to both re-experience and categorize concepts, as they serve as a reference for future inference. This implies a relation between stimulus and experience in some way. In creating the Inference-Design Model for Haptic Experience, I am arguing for categorising concepts into low-level sensations and high-level experiences. There are a number of concepts that are related to other concepts more often than others. These are for the senses of touch concepts of temperature, pressure, shape and movement at the surface of the human body [248, p. 132], such as cold, weight, sting, vibration, roughness, and the like [200, 226]. I denote these as sensations[6]. I thus extend the implication from before: There is a relation between stimuli, sensations, and experiences – experiences are relational.

The relation takes the form of two inference processes: one between stimulus and sensation—sensory inference—and one between sensation and experience—perceptual inference. Sensory inference, within touch, makes sense of the physical signals originating from the sense organs to concepts relating to *'how does it feel?'*. Back to the tree: Touching the bark brings an immediate sensation of roughness and dryness to mind. This inference process is immediate and allows humans to react [47]. For instance, a sudden increase in signals from the free nerve endings might prevent burns from a hot surface, or changing signals from the FA1 receptors might result in a tighter grip on a slippery object. In short, the sensory inference engages with sense-making for awareness, "the functional correlate of conscious experience" [47, p. 8], informing conscious behaviour. But, as Chalmers [47] stated, this does not offer an explanation for the formation experience itself.

[6] My "definition" is deliberately vague, as I have no empirical evidence for the boundaries of what constitutes a sensation compared to an experience. With the definition, I offer more questions than answers. In the following chapter, presenting the journal paper *A User-Derived Mapping for Mid-Air Haptic Experiences* [63], I engage with the concepts of sensation and experience empirically, however, without concluding a robust definition.

Perceptual inference is a more abstract process; it makes sense of a sensory environment, consisting of psychological and physical sensations, to an experience. Perceptual inference is a considered, conscious process relating to *'what does this feel like?'*. Following Barrett's stance, previous experiences play a central role in forming experiences [21]. This suggests that experiences are highly individual, but nevertheless, humans can articulate experiences, and thus, they can be categorised [143, 217]. Again, the tree: Seeing, hearing, and touching the tree gives a sense of calmness that originates in the surrounding peaceful nature. Chalmers [47] believed inference to be deterministic, i.e. if a psychological and physical setting is exactly recreated, an experience can be re-experienced. Stances to the contrary exist [77]; however, that would not bode well for haptic experience design, as experience design designs exactly the psychological and physical setting in which an experience can emerge [105, 140, 340]. Subject to more research is the question of what kinds of (sensory) information influence the inference processes. There are candidates, such as previous experience [21], need fulfilment [143], and context [86], but it remains unclear.

5.2. The Making of Design

If we accept the notion of inference as presented, we, as haptic designers, face the challenge of creating designs that support the inference processes. The Inference-Design Model for Haptic Experience differentiate between *elicitation design*, the design process that designs for sensory inference, yielding a sensation based on the induction of a stimulus, and *experience design*, the design process that designs for perceptual inference, yielding an experience based on, among others, sensations, context, and previous experiences. In my view, haptic researchers work on three problems: **(1)** How to stimulate the receptors of the skin, by for instance, developing novel devices (e.g., [53, 220, 296, 351]) or novel ways of stimulating haptic sense organs (e.g., [65, 189, 241]), **(2)** how stimulation elicits perception by building correlation libraries (e.g., [63, 137, 347]) or deriving computational models for the perception of stimulation (e.g., [4, 234, 375]), and **(3)** how to design for haptic experiences by creating design tools (e.g., [336, 343]) or by defining design models and guidelines (e.g., [206, 245, 334]). The model captures all three problems: Problem 1 relates to the stimulus component, problem 2 to elicitation design, and problem 3 to experience design. These problem definitions help motivate the differentiation between elicitation design and experience design, although they are not independent. Elicitation design and sensations inform experience design; take, for instance, the work by Tsai et al. [382], in which the haptic sensation directional force was used to increase the experience of immersion in a virtual ball game.

Designing for haptic experiences starts with solving problem 1, meaning choosing or creating a stimulation method. There are many devices to choose from—the Haptipedia project [345] lists over 100 grounded force feedback devices alone—however, it is not easy, yet important, to be aware of the affordances a given haptic device has at the beginning of a design process [341, 346]. The design of novel haptic devices is important for research in haptic experiences, as there is a technological dependency, similar to how research in virtual reality is driven by the development of novel virtual reality devices. But enough about devices and their challenges, Part II gave an overview.

Elicitation design directly relates to problem 2. It encapsulates efforts to determine causation between haptic stimulation and sensation, finding those stimuli that reliably create a particular sensation. From the haptics perspective, contributions to elicitation design knowledge are often weighted matrices, mapping stimuli and sensations. The VibViz project [347], for instance, lists 120 vibrotactile patterns and their associated sensations. This approach requires much data, as the design space of designing haptic stimuli is large [63]. Thus, recently, more and more speculation on the use of crowdsourcing to study haptic sensations has emerged [4, 222, 337, 389]. However, the design space is *really* large, in particular considering the spatiotemporal nature of haptic stimuli. To remedy this issue, Lim and Park [234] proposed a model able to predict the perceptual similarity of haptic stimuli, allowing the scope of the search of the design space. Thus it is possible to determine causations between stimuli and sensations, with current methodologies. What remains is to determine a device-agnostic syntax to describe haptic stimuli. Strohmeier and colleagues [360, 361, 362] suggest a parametric approach, describing (vibrotactile) stimulation by amplitude and frequency, as well as spatial and temporal features, analogous to how hue, saturation, and luminosity describes visual stimuli. As an alternative direction, I suggest describing haptic stimuli by the sensation they elicit, analogous to a colour wheel. These directions are not orthogonal but cater to different audiences: the parametric approach informs technical haptic work, whereas the qualitative approach informs haptic designers.

On the topic of problem 3, work has been conducted to describe what haptic experience design is. These descriptions often take user experience research as a baseline to define what is special about haptic experience research. Consider the definition of Haptic Experience Design by Schneider et al. [334]:

> [Haptic Experience Design is] the design (planning, development, and evaluation) of user experiences deliberately connecting interactive technology to one or more perceived senses of touch, possibly as part of a *multisensory experience*. [334, p. 5].

With this definition, Schneider et al. aimed to outline the process employed by haptic designers. Unclear in this definition is why the 'design' term is overloaded with terms related to workflow and why the relatively vague term 'connecting' finds itself in the gap between user experiences and interactive technology. Schneider et al.'s definition stands in contrast to other established definitions of experience design, such as Rossman and Duerden's definition:

> Experience design is the process of intentionally orchestrating experience elements to provide opportunities for participants to co-create and sustain interaction that lead to results desired by the participant and the designer. [319, p. 14]

Both definitions put the notion of 'design as a process' in the fore; however, Rossman and Duerden focus on the creation and co-creation aspects of the design process. Comparing these definitions yields the questions of why haptic experience design needs its own definition and what would make haptic experience design different from experience design other than the technology used to elicit experiences. My answer to the first question is, no, haptic experience design does not need its own definition, but it needs clarification of what 'experience elements' influence haptic experience and how to align the expectations of the participants and designers 'desired results' in practice. Such clarifications yield insights into the answer to the second question: designers need to have an overview of the experiences haptic technology can elicit to decide to include haptic stimulation in their designs. The haptic experience design process, as a component of the Inference-Design Model, by Rossman and Duerden's definition, needs to take the participant's needs into account, best in a co-creation process. Similarly, it should not ignore the inherent multisensory nature of haptic experiences that not only Schneider et al. argue for; Velasco and Obrist emphasises that "in a way, all experiences are multisensory" [396, p. 25] and MacLean et al. state that "the haptic signal can play several roles as part of a 'team' of sensory channels involved in a [multisensory] design" [247, p. 107]. In the end, haptic experience design has many challenges. However, it has proven effective: Obrist et al. [285] used a co-creation approach to design haptic patterns that convey emotions, while Price et al. [308] employed a flexible prototype to communicate affection using a multi-sensory approach.

Solving the three aforementioned problems requires help, according to MacLean [245] and Schneider et al. [334], help from neuroscientists and psychologists. Not because haptic designers are helpless but because designing for haptic experiences requires an overview from many perspectives. There are considerations of the sense organ and receptors, available technology, experience design, and application-specific needs [245]. In addition, the design process is costly; often, many design iterations are required to find a 'good' haptic stimulation [234, 334]. In one way or another, these issues relate to the problems that haptic researchers are working on. The biggest challenge for haptic designers is the lack of a common haptic language, which is currently diffused due to the many perspectives that influence haptic experience design. The Inference-Design Model can help designers formulate their needs, showing that the model carries generative power [26] and can facilitate counterfactual thinking [291].

The next chapter is a reprint of the journal paper *A User-Derived Mapping for Mid-Air Haptic Experiences* [63]. Within it, we present two empirical studies on how haptic stimuli are perceived by participants. The first relates to sensory inference, while the second relates to perceptual inference. Together, the paper informs the basic structure of the Inference-Design Model.

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6. A User-Derived Mapping for Mid-Air Haptic Experiences

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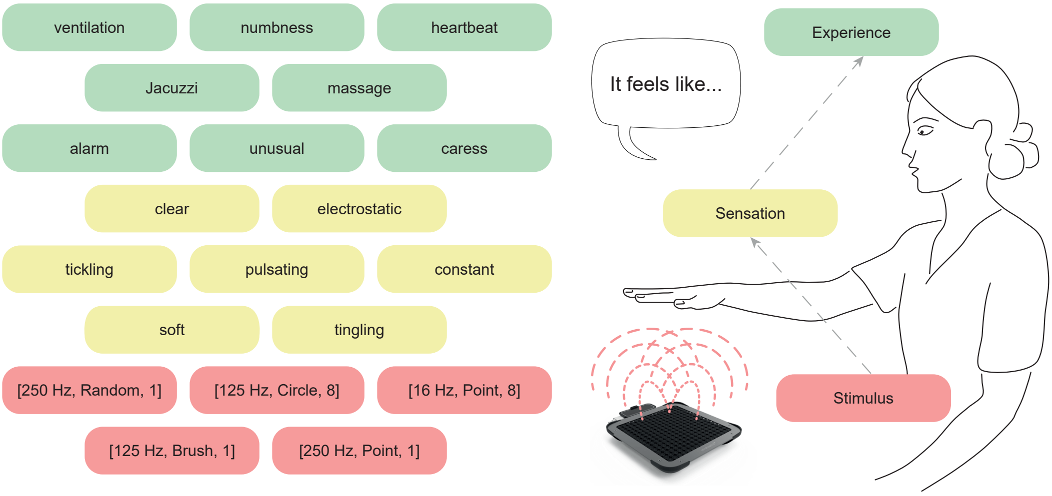

Figure 6.1. A mid-air haptic device produces a *stimulus*. The stimulus is formed by the settings of device parameters. We selected five stimuli to generate a mapping. The settings of their three parameters, frequency, pattern, and repetitions, are presented on the left in red. The stimulus causes vibrations on the skin that results in a haptic *sensation*. The haptic sensation is based on the activation of the mechanoreceptors in the user's skin. Some example connections from the stimuli to the sensations that the mapping includes are presented in yellow. Through the sensation, the user *experiences* the mid-haptic stimulus. Examples of these are presented in green.

Abstract. Mid-air haptic stimulation can enrich user experience during human-computer interaction. However, the design space of such stimuli is large due to the number and range of stimulation parameters. It therefore remains difficult for designers to select a stimulus to induce an intended experience. We derive a mapping for mid-air experiences based on two user studies. In the first study, participants rated 36 stimuli varied across three parameters (frequency, pattern, and repetitions). These ratings allowed us to determine a set of five experientially distinct stimuli. In the second study, participants vocalized their experiences with those five stimuli. This allows us to generate a mapping of 17 sensations and 23 experiences related to the stimuli. Finally, we discuss how the mapping can inform designers and researchers working with mid-air haptic technologies.

Keywords. mid-air haptics, user experience, tactile experience

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6.1. Introduction

Mid-air haptic devices can stimulate the skin without physical contact. Currently, the most common devices are based on ultrasound. However, the stimulation parameters of ultrasonic haptic devices differ from those with physical contact, such as vibration motors, in terms of force-feedback and spatial freedom. Therefore, the literature on designing haptic experiences (e.g., [206, 334]) can only to a limited extent inform the selection of parameters of mid-air haptic stimuli and the consequences of those for user experience.

Ultrasonic mid-air haptic devices stimulate the sense of touch by emitting ultrasonic acoustic waves. The tactile focal point, created by these waves, causes vibrations on the skin that results in a haptics sensation and ultimately a haptic experience (Figure 6.1). Previous work in mid-air haptics has focused mostly on the first step: how people *sense* changes in the stimulation parameters. For example, moving stimuli appear to have lower detection thresholds compared to static stimuli [365], and slower moving stimuli are perceived stronger compared to rapidly moving stimuli [106]. Other studies show small or no effect of varying stimulation parameters when it comes to detection or recognition of mid-air haptic patterns [239, 323]. As previous work has so far covered only a small portion of the possible stimulation parameters, identifying those that people sense and thus possibly also experience differently is challenging.

Earlier work on mid-air haptic experiences roots their choice of stimulation parameters in neuropsychological properties of the human skin, such as the activation of mechanoreceptors (e.g., [128, 284]). For example, [284] used this approach to relate one parameter of mid-air haptic stimulus, frequency (at 16 Hz and 250 Hz), to 14 distinct experiences. In a later work, they leveraged users' past experiences to define the best-fitting mid-air haptic stimuli for specific emotions [285]. However, it remains unclear how other stimulation parameters, such as spatial and temporal patterns, or combinations of these influence user experiences.

We conduct two studies (1) to find a set of experientially different stimuli and (2) to create a mapping of haptic experiences related to those stimuli. In the first study, we ask participants to rate stimuli on their experiential value. We base the experiential value on a subjective rating scheme. The possible parameter space is large with choices of any pattern and continuous values of frequency and repetitions. We vary the stimuli in 36 combinations of three frequencies, four patterns, and three repetitions. This allows us to choose a smaller set of combinations based on how they vary in experiential value. A smaller set of stimuli is necessary to study in-depth how each is experienced in the second study. The ratings also form our first contribution, linking three stimulation parameters to three dimensions of experiential value. In the second study, we employ a micro-phenomenological interview [309] to encourage participants to describe their haptic experiences of five stimuli (from the first study) in depth. We analyse user descriptions by combining two approaches. First, we give an overall account of themes in the interviews and describe individual experiences in depth. Second, we do natural language analysis of the interviews to find keywords associated with particular stimuli. This forms our second contribution: A user-derived mapping for mid-air haptic experiences. As the mapping consists of five stimuli, it is not covering the full space of mid-air haptic stimuli. Nevertheless, we do cover a previously unexplored sample of stimuli with new spatial and temporal patterns, and can relate the five stimuli to 17 distinct sensations and 23 distinct experiences. We discuss how the ratings of stimulation parameters and the mapping can inform designers about the types of experiences they can induce with mid-air haptics.

6.2. Related Work

The design space of mid-air haptic stimuli is large, and it remains unclear how mid-air haptic stimuli relate to user experiences. We first present some key prior research on how mid-air haptic stimuli induce changes in sensations. We then discuss approaches to support the design of mid-air haptic experiences.

6.2.1. Creating Mid-Air Haptic Sensations

Ultrasonic mid-air haptic devices stimulate the sense of touch by emitting ultrasonic acoustic waves, using an array of transducers. The waves collide in a focal point above the device, creating a field of high pressure. The focal point lets the skin vibrate when touched, resulting in a tactile sensation. By modulating the vibration intensity, frequency, position, and other parameters over time, designers can create a wide range of different stimuli.

In past research, three strategies have emerged to structure the modulation. With amplitude modulation, the first strategy, the vibration is modulated on a sinusoidal waveform, varying intensity over time [166]. Takahashi et al. [365] proposed lateral modulation, a second strategy for modulating the lateral position of the focal point. The third strategy is called spatiotemporal modulation, as it modulates the focal point position rapidly along a predefined path with fixed intensity, rendering tactile patterns on the skin [106]. Although designers have access to these different modulation strategies, it remains unclear how to modulate parameters to induce specific sensations. This unclarity is due to the large space of parameters and the vast range of settings for these.

Previous work has identified spatiotemporal modulation of the focal point to be influential on detection thresholds [365] and on perceived strength [106]. Frier et al. [106] highlighted that the perceived strength of stimuli is dependent not only on the spatial pattern but also on the temporal parameters of rendering these on the skin (e.g., slow circular patterns are perceived as strong). Another body of work has investigated the recognizability of mid-air haptic patterns [219, 239, 323]. Rutten et al. [323], for instance, showed that it is hard for users to differentiate between similarly shaped patterns, and argued that this is due to the missing visual modality. While all these works show that each stimulation parameter has an effect on the perceived sensation, they cover only a small portion of possible parameters. Therefore, identifying those parameter settings that people sense and thus possibly also experience different is challenging.

We aim to tackle the large parameter space in our first study. We include three parameters: frequency, repetition, and pattern, which all have been shown to influence haptic sensation in the previous work above. We vary frequency in three levels within known perceptual limits, repetition of the stimulus in three levels, and use four distinct patterns. To assess whether these parameters can result in changes in sensations and possibly also experiences, we ask the participants to rate the stimuli in their experiential value based on the semantic differential created by Osgood et al. [289]. The ratings are given with polar adjectives "Pleasant" and "Unpleasant", "Strong" and "Weak", and "Excitable" and "Calm" [288]. These three sets of adjectives align with earlier work reporting on haptic user experiences (e.g., [106, 284, 334]), where pleasantness and strength of stimuli are measured. These ratings how the stimulation parameters play together in how distinct they are experienced. However, the three dimensions of experiential differences cannot provide insight into the nuances and variability of all that the users may experience about mid-air haptic stimuli. This insight is important for making decisions in designing stimuli.

6.2.2. Designing Mid-Air Haptic Experiences

Design of haptic experiences has been discussed in literature (e.g., [206, 334]). For example, Schneider et al. [334] identified prominent design challenges. They explain, for instance, that it is challenging to create consistent haptic experiences across individual perceptions and to assess the quality of the designed experiences. Asking users to talk about haptic stimuli in their own language is one promising way of capturing related experiences [182, 284].

Guidelines for designing mid-air haptic experiences for different domains have been proposed in recent years. Young et al. [425] created a set of stimuli and hand gesture combinations, fitting car controls. In the AR domain, Van den Bogaert and Geerts [393] employed user elicitation to create a set of stimuli and gesture combinations for input. Both works provide insights, guides, and hints to designing mid-air haptic experiences in their respective domains. Our work is different in the sense, that we aim to investigate the haptic stimuli, isolated from other modalities (i.e., we do not stimulate the visual or auditory system). We are also not looking to design haptic stimuli for specific functional uses (like car controls or AR input), as the aim is to generate descriptions of stimuli, independent of functional use.

Obrist et al. [284] created a vocabulary for mid-air haptic stimuli, which relates two stimuli to 14 experiences. Although being limited to one stimulation parameter (frequency), this vocabulary solves the challenge of consistency and quality for the two explored stimuli, and thus serves as a guide for designers when creating mid-air haptic experiences by varying the frequency of the stimuli. In later work Obrist et al. [285] showed that users can relate even complex experiences, such as emotions, to mid-air haptic stimuli.

Our work builds on the work of Obrist et al. [284] by expanding the parameters of mid-air haptic stimuli as described above. Like Obrist et al., we also ask users to vocalise their experiences about mid-air haptics. We expand their approach by asking the participants to describe, relate, and interpret their experience with different mid-air haptic stimuli in a micro-phenomenological interview. Moreover, we combine the interview approach with both statement analysis and natural language analysis. Based on these, we present a mapping that connects haptic stimuli to conscious experiences.

6.3. Stimulation Parameters

We investigate the relation between mid-air haptic stimuli and user experience by using an ultrasonic haptic device. Due to the large design space of stimuli the ultrasonic haptic device can produce, we have to limit our investigation to a set of stimulation parameters. Here we describe the design space and explain the set of parameters included in our studies.

Each stimulus induced by ultrasonic mid-air haptic devices consists of a set of primary and secondary parameters. The primary parameters are the focal point intensity and position. Intensity is in essence the amplitude of the wave emitted by the ultrasound speakers. In our study, the intensity of the focal point is modulated on a sinusoidal waveform, with a fixed amplitude of the highest possible setting for the used device, approximately 155 dB [167, 323]. The focal point position can be modulated by emitting ultrasound from an array of speakers. Both the amplitude and the focal point can also be modulated over time. This brings us to a set of secondary parameters. For example, we can vary the frequency of the wave amplitude (how often the wave reaches its full amplitude) or the sequence and tempo in which the focal point is set onto a number of positions.

Because of this complexity of the stimuli, designing even seemingly simple stimuli requires many decisions. Let us take producing a circular pattern as an example. In this example, a designer has already decided on how to modulate the two primary parameters over time: they will use amplitude modulation to reach a certain intensity and a number of points are stimulated in such a sequence that they form a circle (i.e., taking the nearest point next and proceeding to a single, clockwise direction). Next, the designer needs to define settings for the secondary parameters. As intensity is modulated using amplitude modulation, the designer needs to define the appropriate waveform, and frequency of the modulation, and as the position is modulated as a circular pattern, the designer needs to define at least the radius, centre, and the number of points to stimulate along the circular path (i.e., resolution). This exemplifies that designing mid-air haptic experiences is difficult and not intuitive.

In our studies, we focus on three parameters: amplitude frequency, spatial pattern, and the number of repetitions. With these parameters, we can build stimuli that have the potential to trigger diverse sensations and experiences. The parameter settings presented reflect the current common use of mid-air haptic technology, such as feedback for button-presses and interaction with virtual objects [312]. Additionally, these parameters are used often in previous work (e.g., [106, 284, 285, 323]).

We vary the *frequency* of the wave amplitude, with values of 16 Hz, 125 Hz, and 250 Hz. With these frequencies, we target two sets of fast-adapting mechanoreceptors in the human skin, responding to vibrotactile sensations [59, 391]. The peak sensitivities of these receptors are around 16 Hz an 250 Hz respectively [284], leading to the choice of these settings. A 125 Hz amplitude frequency has the potential to stimulate both sets of receptors, as the activation range of the re-

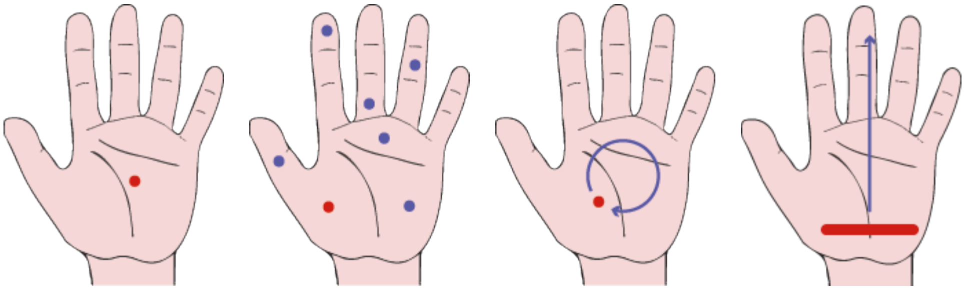

Figure 6.2. Spatiotemporal patterns used to stimulate participants: (a) the Point pattern; (b) the Random pattern; (c) the Circular pattern; and (d) the Brush pattern. Red marks a focal point position, while blue describes the spatiotemporal path of the focal point.

ceptors overlap [59, 110]. Additionally, a 125 Hz frequency amplitude modulation was used in the experiments by Rutten et al. [323].

We modulate the position in four different *patterns*. The patterns are inspired by the work of Frier et al. [106] and Rutten et al. [323]. Figure 6.2 shows the patterns. Except for the Point pattern, they are spatiotemporal patterns in the sense that they have a temporal sequence in which multiple locations are stimulated over time. The Point pattern (Figure 6.2a) is a statically positioned focal point in the centre of the palm, with a diameter of approximately 0.8 cm (the focal point width). The Random pattern (Figure 6.2b) is similar to the Point pattern, with the difference that the focal point is stimulating on random positions on the hand. Within one instance of the pattern, forty positions are randomly generated and the focal point is moved between these positions during the induction, such that the focal point is static at one position on the hand for a tenth of a second if the pattern is played for four seconds. The Circle pattern (Figure 6.2c) describes a circular path for the focal point, with center in the centre of the palm, and a radius of 2 cm. The Brush pattern (Figure 6.2d) is a 5 cm wide line moving from the wrist to the fingertips, where the illusion of a line is created by oscillating the focal point with a frequency of 100 Hz.

The stimulus length is fixed to four seconds. We vary the number of *repetitions* of the stimulus within this time frame, with values of one, four, and eight. In practice, this means that when the number of repetitions is four, the pattern is played four times within these four seconds. Thus, with four repetitions, the pattern is applied for 500 ms and paused for 500 ms, four times in a row. Patterns are completed exactly once every repetition (e.g., the focal point moves around the circular path once per repetition). We limit the stimulus length to keep the overall study duration short to counteract any fatigue during the study. With four seconds, the stimulus is long enough to repeat a pattern multiple times, while being short enough to not induce much fatigue during the overall study. The repetitions were chosen to represent a stimulus that is constantly on (when the repetition value is one), and a fast on-off stimulus (eight) which is still not that frequently repeated that it would be felt as being constantly on, as well as one value in between (four). The different number of repetitions are motivated by common uses of stimuli in haptic devices, such as for instance the vibration of mobile phones when an alarm is buzzing.

6.4. Study 1: Evaluating Experiential Differences of Stimuli

The purpose of this study is to identify a set of mid-air haptic stimuli that are experientially distinct. To do this, we ask participants to rate 36 stimuli based on their experiences. These ratings are used to cluster the stimuli based on experiential value using a *k*-means clustering algorithm. The final set of experientially distinct stimuli is derived from the clusters. The ratings are available in an open repository [63].

6.4.1. Method

6.4.1.1. Participants. We recruited 19 participants to rate 36 mid-air haptic stimuli. The participants were aged between 25 and 57 (mean: 33.21, std: 8.66). Of the participants, five were female and 14 were male. None of the participants reported any sensory impairments in the hand, nor any prior experiences with mid-air haptics. It took 27 minutes on average for the participants to complete the experiment. All participants were rewarded with a gift valued at $15.

6.4.1.2. Design. The study followed a within-subject design with the three independent variables: frequency, pattern, and repetitions. The parameters are varied in 36 combinations of stimuli: three frequencies, four patterns, and three repetitions. The settings for these independent variables are listed in the previous section. We also add one zero-intensity stimulus, serving as an attention control condition. All stimuli were presented in an order randomized for each participant to avoid order effects.

6.4.1.3. Measures. The participants rated each stimulus on the three dimensions *evaluation*, *potency*, and *activity*, based on the semantic differential. Evaluation is rated with the polar adjectives "Pleasant" and "Unpleasant", potency with "Strong" and "Weak", and activity with "Excitable" and "Calm" on 7-point scales [288]. These three sets of adjectives align well with earlier work on haptic user experiences (e.g., [106, 284, 334]), where pleasantness and strength of stimuli are measured.

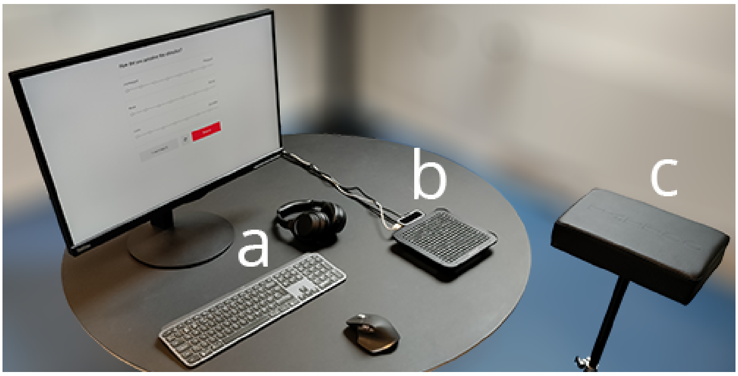

Figure 6.3. The setup in the first study, consisting of (a) a screen, keyboard, mouse and headphones; (b) the mid-air haptics device STRATOS Explore and Leap Motion controller; (c) and an armrest.

These sets of adjectives also capture the valence and arousal dimensions of the Valence-Arousal model [150, 264, 322] by measuring pleasantness and calmness.

6.4.1.4. Materials. The stimuli were given with the mid-air haptic device STRATOS Explore[7]. The device was placed on a table in front of the participant. An armrest was placed next to the participant, such that their dominant hand could be positioned consistently 20 cm above the haptic device. The distance of 20 cm between hand and device was shown to be best for stimulus perception by Obrist et al. [284]. The ratings were given with a desktop computer. Its 27" screen, mouse, and keyboard were placed on the table as depicted in Figure 6.3. The study was conducted seated in a room with little visual and auditory distractions.

6.4.1.5. Procedure. The participants were first introduced to the aim of the study, asked to sign an informed consent form, and fill out a demographics questionnaire. The participants were then instructed to wear a set of noise-cancelling headphones playing pink noise, so as to not become distracted by audible noise from the haptic device. A simple point stimulus was played before starting so that the participants had time to familiarise themselves with the sensation of mid-air haptic stimuli.

The mid-air haptic stimuli were applied to the dominant hand. To negate alignment issues, the dominant hand was tracked with a Leap Motion controller[8]. Stimuli were presented relative to the centre of the dominant hand. The participants were informed that they would not have to be very precise with the placement of the dominant hand during stimulus application, as the

[7] https://www.ultraleap.com/product/stratos-explore/ (accessed February 14, 2022)
[8] https://www.ultraleap.com/product/leap-motion-controller/ (accessed February 14, 2022)

Table 6.1. Minimal, median, and maximum ratings for evaluation, potency, and activity. Ratings range between 0 and 6.

		Rating	Frequency	Pattern	Repetitions
Evaluation Unpleasant (0) - Pleasant (6)	*min*	2.83	16 Hz	Circle	4
	median	3.68	250 Hz	Circle	4
	max	4.79	16 Hz	Brush	1
Potency Weak (0) - Strong (6)	*min*	0.00	16 Hz	Circle	4
	median	2.95	125 Hz	Circle	1
	max	4.58	250 Hz	Brush	8
Activity Calm (0) - Excitable (6)	*min*	2.29	16 Hz	Point	1
	median	3.05	250 Hz	Point	8
	max	4.84	125 Hz	Random	8

hand would be tracked automatically, as long as they placed their arm on the armrest and the hand over the device.

The study consisted of rating the 36 stimuli, each lasting four seconds. After a stimulus was played, a computer screen in front of them displayed the rating form for three dimensions of experiential value. The three ratings were given using the dominant hand and the mouse. Using the dominant hand to both controls the mouse and receive the stimuli ensured that the dominant hand was "distracted" between stimuli. The participants were allowed to take their time to rate the stimulus and to replay them. After submitting the three ratings, the participant had five seconds to place their dominant hand over the device, before the next stimulus was played. In addition to the three dimensions for ratings, participants had the option to indicate that they could not feel the induced stimulus and the option to be induced with stimuli again as often as they wanted.

6.4.2. *Results*

The collected data consists of 684 ratings for 36 stimuli. In this section, we analyse the data using a *k*-means clustering algorithm. The clustered ratings are used to derive a set of stimuli that spans the experiential space, defined through the semantic differential ratings.

6.4.2.1. Stimulus Ratings. All participants indicated not to be able to feel the attention control condition, such that no data points related to specific participants were excluded completely. The collected data contains 44 data points where participants reported the stimuli to be imperceivable. Most often, these stimuli were induced with frequency setting 16 Hz (97.77%), rendered as a Point pattern (52.23%) and/or for the full stimulation time (i.e., one repetition, 52.23%). As these data points do not provide ratings, they are not included in further analysis.

Table 6.2. Selected stimuli through *k*-means clustering of participant ratings.

Cluster	Frequency	Pattern	Repetitions	Evaluation	Potency	Activity
#1	125 Hz	Brush	1	4.58	3.84	2.26
#2	16 Hz	Point	8	3.20	0.20	1.67
#3	125 Hz	Circle	8	3.84	2.95	3.79
#4	250 Hz	Random	8	3.47	3.79	4.47
#5	250 Hz	Point	1	3.37	1.68	1.89

The stimulus ratings were encoded to values between 0 and 6, such that low values indicate low evaluation, potency, and activity, and vice versa. Ratings were averaged per stimulus to yield an aggregate between participants. Averaging ratings lessens the influence of the novelty effect of mid-air haptics and potential rating inconsistencies within participant ratings. The variance between participants in ratings was 1.76 for evaluation, 1.41 for potency, and 1.59 for activity. Potency and activity ratings are strongly correlated ($r = 0.81$), evaluation and potency are moderately correlated ($r = 0.39$), and evaluation and activity are not correlated ($r = -0.11$). Table 6.1 shows the minimum, median, and maximum ratings for each of the dimensions and lists the stimulus resulting in these ratings.

6.4.2.2. Clustering Stimuli. The ratings describe the experiential value of each stimulus. The aim of the study is to select experientially distinct stimuli, that can be used for further analysis. We do this by clustering experientially related stimuli into five clusters, using a *k*-means algorithm. The number of clusters was determined by scree analysis. All stimuli in the same cluster carry similar experiential values.

Figure 6.4 shows all stimuli coloured by their respective clusters. Cluster #1 consists of the most pleasantly rated stimuli. All stimuli in this cluster are repeated once and Brush and Circle patterns (i.e., slowly moving patterns) are perceived as being pleasant. Cluster #2 groups together stimuli rated as very weak and it contains stimuli with Circle and Point patterns, all with an amplitude frequency setting of 16 Hz. Cluster #3 contains stimuli with Circle and Point patterns, high amplitude frequency (125 Hz and 250 Hz), and a high number of repetitions. These stimuli are rated around the middle of all three dimensions. Cluster #4 contains stimuli, that are rated high on potency and activity. All stimuli with Random patterns are found in this cluster, together with stimuli with Brush patterns and a high number of repetitions (four and eight). Cluster #5 contains stimuli with Point and Circle patterns and with high amplitude frequency and a low number of repetitions (one and four). These stimuli are rated pleasant, weak, and calm, in the middle ground between the other clusters.

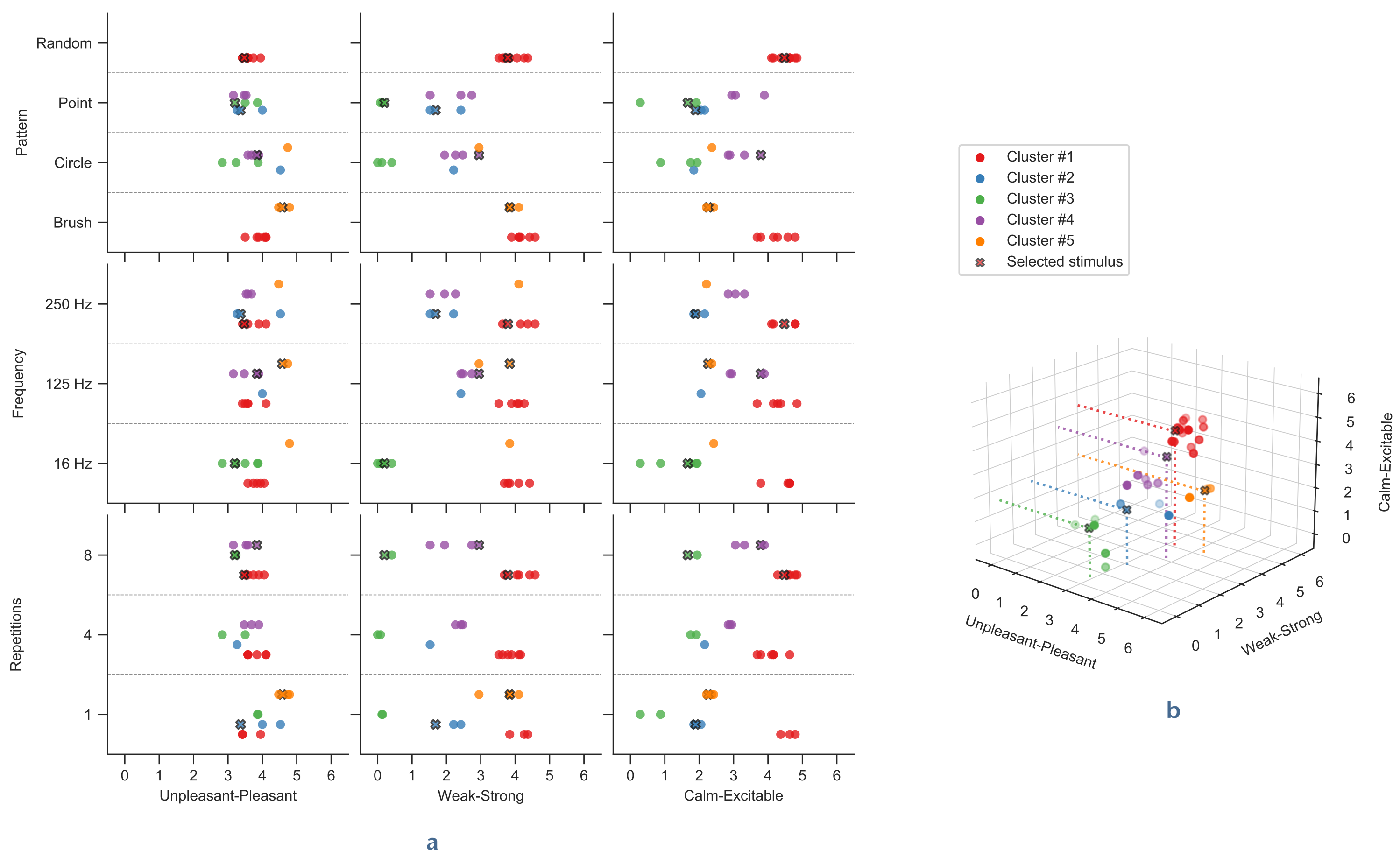

Figure 6.4. Stimuli ranked by rating and coloured by clusters, found by *k*-means clustering. Selected, experientially different stimuli are marked with a cross. In (a) each plot shows a parameter against an experiential rating dimension, i.e., each plot contains all 36 stimuli positioned by parameter and rating. We can, for instance, derive that stimuli in cluster #2 are consistently rated as being weak, as all blue scatters are grouped close to zero on the Weak-Strong axis, and having a frequency of 16 Hz, as all blue scatters are found within the boundary marking the 16 Hz stimuli. (b) shows each stimulus colored by cluster. Dotted guides mark the experiential rating of selected stimuli.

We select one stimulus per cluster for further analysis. We do this by counting the number of each frequency, pattern, and repetition setting in a cluster. We select the stimulus that within a cluster has settings that occur most often. Thus, for each cluster, we find the most common amplitude frequency, pattern, and repetitions settings. The stimulus consisting of the commonly occurring settings was considered as representative of the cluster. In the case of equally common settings, we selected the stimulus that has a minimal distance to the cluster centroid. Table 6.2 lists the settings and ratings of the selected stimuli. The selected set is varied across stimuli settings, although the repetition setting four is not present. This is expected, as the selection process does not guarantee full coverage of stimuli settings but rather prioritises variance in the experiential values of the stimuli.

6.5. Study 2: Generating a Mapping of Haptic Experiences

The purpose of this study is to generate a mapping of experiences for mid-air haptic stimuli. To do this, we ask participants to vocalize their experiences in interviews with the set of five stimuli found in the first study. The participant statements are then used to form a mapping through thematic and natural language analyses. Interview transcriptions are available in the original language, Danish, and in the English translation in an open repository [64].

6.5.1. Method

6.5.1.1. Participants. We invited 11 participants to talk about their experiences with mid-air haptics. Of these six were females and five males. The participants were aged between 21 and 43 (mean: 27.6, std: 5.8). Three participants reported that they had tried mid-air haptics one or two times before. There was no overlap between participants participating in the first and second studies. Five participants currently studied or had completed an education within the STEM fields, three within Arts, two within Social Sciences, and one within Humanities. All participants spoke in their native language during the study. None of the participants reported any sensory impairments in the hand. Each participant was rewarded with a gift valued at $25.

6.5.1.2. Approach. We use micro-phenomenological approach to conduct the interviews. Contrary to observational studies, micro-phenomenological studies do not rely on external observations of subjects experiences. This allows for in-depth questions about the subjective experience to generate rich and precise descriptions.

Petitmengin [303] crafted the *micro-phenomenology interview* technique based on the work of Vermersch [397, 398]. The micro-phenomenology interview is a technique for researchers to explore singular subjective experiences in depth. The interview is meant to focus the interviewee's attention on the experience, guiding them through the evocation of the experience, and directing their attention towards specific dimensions of the experience [309]. This structure invites interviewees to talk about the different sensory, cognitive, and affective inputs of a specific lived experience.

Recently, Prpa et al. [309] described how the interview technique has been used by HCI researchers. They exemplify previous approaches to micro-phenomenology in HCI and provide guidance for researchers using this technique. In HCI, for instance, Knibbe et al. [215] used the micro-phenomenological interview to generate descriptions of the moment of exciting Virtual Reality and Hogan et al. [155] explored information visualizations with the interview technique. Obrist et al. [284] used the micro-phenomenology interview to generate a vocabulary for mid-air haptics.

In the interviews, we ask the participants to describe, relate, and interpret their experiences with different mid-air haptic stimuli. The analysis of interviews (described by Petitmengin et al. [304]), is not perfectly suited for our study, because here the experience of a haptic stimulus is relatively short in time. Therefore, we adapt the questions from Petitmengin [303], Obrist et al. [284], Obrist et al. [283], Knibbe et al. [214], and Prpa et al. [309] to suit this type of experience. The aim of the questions was to uncover three underlying features of the experience: a subjective description, an experiential relation, and an interpretation. Examples of the questions asked are:

- "How would you describe the felt stimulus?"
- "What previous experience did the stimulus remind you of?"
- "How would you describe this to someone, who has not tried mid-air haptics at all?"
- "How was the first time you felt the stimulus different from the last?"

In addition to questions, we repeatedly reformulated descriptions given by the participants to stabilize their attention to the experience. This technique allows the participant to refocus their attention and to correct misunderstandings during the interview [303].

6.5.1.3. Procedure. The study was conducted in the same room as in the first study. The apparatus was also the same as in the first study, although the setup was re-arranged, such that participant and experimenter were sitting across from each other. This was done to focus the attention of the participant on the interview and stimulus, instead of the apparatus.

The participants were introduced to the aim of the study, signed an informed consent form, and filled out a demographics questionnaire. Afterwards, they were instructed to wear a set of noise-cancelling headphones playing pink noise during the time a stimulus was induced. A simple point stimulus was played before starting the interview on the set of selected stimuli so that the participants had time to familiarise themselves with the sensation of mid-air haptic stimuli.

During this second study, participants were presented with five stimuli selected in the first study (Table 6.2). The stimuli were presented one at a time in a randomized order to avoid order effects. Each trial was conducted in two phases: an induction and an interview phase. During the induction phase, participants felt the stimulus three times in a row with a 5-second delay between playbacks, such that the participant could get a firm impression of the stimulus. Participants were asked to wear a set of noise-cancelling headphones, playing pink noise, only during this phase. Immediately after the induction phase, the interview phase started; the interviews followed the micro-phenomenology interview protocol described above and lasted between 5 and 10 minutes for each stimulus. All interview sessions were audio-recorded. On average participants completed the full session in 46 minutes.

6.5.2. Data

We collected recordings of 11 interviews for each of the five selected stimuli, for a total of 55 stimuli-specific interviews. The interviews were transcribed for the qualitative analysis. The analysis was conducted on the transcriptions in the interviewee's native language. Translation to English was done by two of the authors.

We analyse the data with two approaches, qualitative analysis and natural language analysis. These analyses and the results are presented next.

6.5.3. Qualitative Analysis

We do a qualitative analysis of the transcribed interviews, following the approaches taken in earlier uses of micro-phenomenology in HCI (e.g., [214, 284]). This allows us to give an overall account of the themes in the interviews as well as participants' individual experiences in depth. The strength of this approach is to give rich, particular descriptions.

The analysis of the transcribed interviews shows five themes. Each theme spells out important aspects of participants' experience as captured by the interviews. In the following, we discuss those themes and use the notation [Participant, Frequency, Pattern, Repetitions] to indicate the participant identifier and felt stimulus (e.g., [P1, 125 Hz, Circle, 8]).

Table 6.3. Described sensations associated with stimuli. Words unique to a stimulus are highlighted in italics. The number of participants (out of 11) using the word is indicated in parenthesis.

Stimulus	Sensations
[250 Hz, Random, 8]	vibrating (4), mild (3), tingling (3), pulsating (2), *stuttering* (2), electrostatic (1), soft (1)
[125 Hz, Circle, 8]	vibrating (4), constant (3), mild (3), *clear* (2), soft (1)
[16 Hz, Point, 8]	pulsating (4), tingling (4), vibrating (4), mild (3), electrostatic (2), soft (2), tickling (2)
[250 Hz, Point, 1]	*prickling* (2), trembling (2), vibrating (2), electrostatic (1), soft (1), tingling (1)
[125 Hz, Brush, 1]	vibrating (5), soft (3), tickling (3), electrostatic (2), tingling (2), trembling (2), mild (1)

6.5.3.1. Sensations. Participants connect a variety of words to the sensation induced by the mid-air haptic stimuli. Table 6.3 shows an overview of these words. Words such as *vibration*, *mild*, and *soft* recur across stimuli, showing an overall positive sentiment towards the sensation. In general, many of the same words were used to describe the sensation across stimuli, with a few exceptions, for instance, *stuttering*: "*Like someone who blows, stuttering very much, while they are at it*" [P4, 125 Hz, Brush, 1]. Many participant stated that the sensation was "*not natural*" [P5, 125 Hz, Brush, 1] or "*unusual*" [P2, 250 Hz, Random, 8]. Some relate this to the fact, that the stimulus was produced by an artificial object:

> "*Everybody has tried, that someone is blowing on you. And you know that feeling well, but you have not tried a machine doing it before.*" [P2, 16 Hz, Point, 8]

Another participant clearly stated, that being touched involuntarily made the sensation unusual and unpredictable:

> "*Because it is rare that you come into contact with something new that you have not chosen yourself. It's more like that. It's unusual for me to sit here and feel a stimulus on my hand because I'm not used to my hands being exposed to things I do not expect to happen because it is often myself who decides what my hands [come in contact with].*" [P2, 16 Hz, Point, 8]

The linked words in Table 6.3 overlap with the previously generated vocabulary by Obrist et al. [284], showing that the same sensations transcend to these more complex stimuli. For instance, do words like "tingling", "soft", "ticking", and "pulsating" recur in results of both studies.

6.5.3.2. Spatial movements. Here we compare the experiences of the patterns to the played patterns (Figure 6.2), but do not consider the latter a "ground truth", as participants simply describe what they feel.

Both the [16 Hz, Point, 8] and [250 Hz, Point, 1] stimuli are described similar to: "*it felt like it was very specifically at one place*" [P4, 250 Hz, Point, 1] (in the middle of the hand). The descriptions differ in the number of times a "blow" was felt on the hand since the [250 Hz, Point, 1] stimulus was described as being continuously blowing, while the [16 Hz, Point, 8] stimulus is described as blowing multiple times on the same spot. These compare well to the pattern intended.

The [125 Hz, Brush, 1] stimulus was described consistently with the Brush pattern: "*[It] starts at the root of the hand, and then it moves up over the hand and over the fingers [...] in a fluid motion.*" [P9, 125 Hz, Brush, 1]

The descriptions of the [250 Hz, Random, 8] stimulus were less consistent. Many participants described the location of the focal point "*as if it were moving, to different places on the hand* " [P7, 250 Hz, Random, 8] or similar, but a smaller group of participants felt that the stimulus drew "*a pattern of what at least felt like linear movements in different directions over most of the palm*" [P8, 250 Hz, Random, 8] or similar descriptions of lines being drawn on the palm.

The movement of the [125 Hz, Circle, 8] stimulus is described in various ways, from feeling like a door key touching the hand with a rotational movement, to movements in a C- or an O-like pattern. The latter examples compare relatively close to the intended movement pattern. One participant described the movement very thoroughly:

> "*Something starts down at the end of your hand and then goes a bit forward, or you get blown air on the hand a bit in front of that, which then blows back on down the hand, and then next time you feel something that is further up on the hand, which breaths back further down the hand.*" [P10, 125 Hz, Circle, 8]

It seems that it is hard for participants to identify the displayed pattern. Even patterns with little spatiotemporal complexity (such as those displayed here) are difficult to recognize consistently. This finding is consistent with that of Rutten et al. [323], stating that the recognizability of mid-air haptic patterns is unreliable.

6.5.3.3. Experiences. Participants answered with a variety of earlier experiences that in different ways were thought to be similar to the sensation felt or that participants were reminded of based on the sensation.

A commonly mentioned relation was to an experience of blowing. One participant described how "*it's maybe a bit [like] a drunk man you would need to breathe into a breathalyzer, who just has to do it a few times before it gets a little random like that, well, that's the picture I get in my head*" [P2, 250 Hz, Random, 1]. Other participants emphasize the more localized experience of blowing, like through a straw (One participant had done so as part of practising to play the musical instrument Didgeridoo [P1, 250 Hz, Point, 1]), a weak bicycle pump [P3, 125 Hz, Circle, 8], a hand dryer [P10, 125 Hz, Brush, 1], or the ventilation in an aeroplane [P6, 250 Hz, Point, 1]. A few mentions emphasized that stimuli felt like blowing but non-localized, for instance like "*a small gust of wind*" [P11, 250 Hz, Point, 1].

Other relations were to technology. Participants frequently mentioned the similarity to the alarm in their phones or the vibrations from a pager. One said "*Okay, completely different experience. It's very funny. Well, it [makes me think of] the old Nokia 3310 when it rings, with, well, more like a blowing feeling [...]*" [P4, 16 Hz, Point, 8]. Three persons mentioned the feel of their phones ringing.

Table 6.4. Participants were induced with a stimulus three times in a row before interviews. This timeline shows the common themes, participants talked about when asked to remember back to the moment of induction. Numbers in parenthesis indicate the number of participants (out of 11) talking about a particular theme.

1st induction	2nd induction	3rd induction
Analogy (5)	Analogy (1)	Intensity (3)
Movement (4)		Internalization (2)
Sensation (2)		Analogy (1)

Participants also linked the stimuli to experiences with drawing, "*Yeah, so it might feel a bit like taking a pencil and then running lines across, but still just without touching…*" [P3, 250 Hz, Random, 8]. Similar comments were made about being touched with a feather and with a brush. The emphasis seems to be on the spatial analogies of the stimuli.

A final link was to the experience of touches on the body, in particular, to massage and caressing. One participant noted that the stroke was like being touched by another person.

> "*Yes, well, it was a lot…it was really funny, this feeling. It made me happy, that is. […] it could also be a feeling, where my partner is running their hand down over my hand, or like…, it was very much like safe or fun, or something, that feeling…*" [P2, 125 Hz, Brush, 1]

Other participants spoke about massage, as in "*it's very chill…when you just sit and run your hand, like, back and forth, and the feeling, I get, is a little bit like you just sitting and getting a gentle massage, [on] the palm of your hand.*" [P7, 250 Hz, Point, 1] Although one person spoke about a massage chair [P1, 125 Hz, Brush, 1], the emphasis here is on the similarity to human touch.

Participants can relate rich and varying experiences to the stimuli. This shows the flexibility of mid-air haptic stimuli, both relating to simple notifications to complex interhuman interactions. One participant wrapped up the experiences: "*This is pretty magical*" [P1, 250 Hz, Random, 8].

6.5.3.4. Analogies. Not all participants could relate a previous experience to all felt stimuli, stating for instance that they had no visual feedback as a reason for it being difficult to relate the felt haptic stimuli to previous experiences.

> "*Well, I do not think you use, well, like this, with this 'having to figure out what it is that could feel like this', of course, it requires thinking power in a completely different way than if you had something visual that could tell you what really happened, right?*" [P9, 250 Hz, Random, 8]

Other reasoned that the sensation felt "*very abstract*" ([P4, 250 Hz, Random, 8], [P7, 250 Hz, Point, 1], [P4, 250 Hz, Point, 1]) and that "*it does not feel natural, so it was not a feeling of, 'now that experience is something [I] would naturally experience in everyday life'*" [P3, 125 Hz, Brush, 1]. Here, we will take a closer look at the strategies used by participants to explain the felt stimuli, that proved difficult to relate to actual previous experiences.

One strategy to explain a felt stimulus was to use an analogy of sounds. To some participants, it seemed that the haptic and auditory feedback modalities are connected due to the rhythm, created by the combination of Pattern and Repetition. All three selected stimuli with the number of repetitions set to eight were associated with rhythmic sounds (i.e., music, alarms, or sounds from vibrating objects). The stimulus with a Random pattern is described in terms of music, for instance as "*some tone, music like*" [P10, 250 Hz, Random, 8], "*a bass playing [...] and you can feel that 'duf, duf, duf, duf'*" [P5, 250 Hz, Random, 8], and "*soccer battle cries, like 'dudu dududu, let's win'-ish*" [P10, 250 Hz, Random, 8]. Next to music, sounds from real world objects were used to relate an experience to a stimulus, by for instance associating with "*a sound, [...] [when] a fire engine [is] going past you*" [P5, 16 Hz, Point, 8] or "*a sprinkler, [...] that goes like 'prr prr prrr', as if it is rotating around*" [P5, 125 Hz, Circle, 8].

Despite being asked to relate to a previous experience, some participants related stimuli to imagined experiences. Inspiration for these experiences was gathered from, among others, Science Fiction movies, in which a character would get their hand, fingerprints or eyes scanned with a red laser to get through a secret door ([P7, 125 Hz, Brush, 1], [P10, 125 Hz, Brush, 1]). The analogy of a touchable laser was also used to relate a stimulus with a Point pattern to a "*laser light used to point at a blackboard*" [P1, 250 Hz, Point, 1]. At other times the stimulus with a Brush pattern was related to a "*lonely ocean wave*" [P8, 125 Hz, Brush, 1], that gave a "*soft, round feeling, [...and that] ran slowly [...] scanning the hand*" [P10, 125 Hz, Brush, 1]. Similarly the stimulus with a Circle pattern related to a constant soft wave ([P5, 125 Hz, Circle, 8], [P8, 125 Hz, Circle, 8]).

6.5.3.5. Temporal unfolding. During the interview, we asked the participants to recount the three repetitions of the stimulus induction at the beginning of the interview. We asked them to describe how their experience differed between the three repetitions of the played stimulus. Table 6.4 shows the timeline of the stimulus inductions and the identified themes for each time the stimulus was induced. Participants often reported that their related previous experience, or analogy, came to mind quickly, when first induced with a stimulus — "*It was in the first stimulus [...], that's what I associated it with right away*" [P7, 125 Hz, Circle, 8]. For others, the interpretation of stimulus came to mind during the second and third induction. The movement of the stimulus appeared to be in the focus during the first induction, as participants reported: "*So, the first time, I just had to figure out where it hit [...]*" [P5, 250 Hz, Random, 8].

Although being induced with the exact same stimulus, participants felt differences in perceived strength of a stimulus between inductions: "*[...] I felt right there at the very end that it came, like, stronger than the first [...]*" [P5, 250 Hz, Random, 8]. The third stimulus induction is also used by some participants to internalize the stimulus and finalize their opinion of the stimulus.

> "*Well, I can not very well distinguish between the first two, but the last one, it was like a little more 'Okay, this one is a little clearer', or, it feels stronger on your hand.*" [P3, 125 Hz, Brush, 1]

In general terms, at the first induction, intuition about the stimulus is formed. During the second and third induction, this intuition is consolidated and internalized.

6.5.4. *Language Analysis*

Here we present a natural language analysis of the transcribed interviews. The strength of this approach is to find particular words associated with individual stimuli.

The research field of Natural Language Processing (NLP) has for many years concerned itself with the analysis of natural human language. We use NLP to extract keywords relevant to each stimulus from participant statements. In this analysis, we extract the nouns, verbs, and adjectives, to generate keywords from each of these different parts of speech. As "nouns name substances; verbs name processes; and adjectives name qualities" [38], we assume that the participant derived nouns refer to the objects relate to stimuli, that the verbs refer to the felt sensation, and adjectives refer to the qualities of stimuli. In the following, we describe our methodology to find keywords, ensure that their context is considered, and provide an overview of keywords.

6.5.4.1. Methods. In our analysis, we leverage two techniques from within NLP to find keywords in the participant interviews. Before applying these techniques, we filter the corpus to include participant statements (excluding interviewer questions) and to not include stopwords. We use the Term Frequency Inverse Document Frequency (TF-IDF) score [147] to determine the importance of words within participant statements. TF-IDF scores words in a text document based on their frequency and on the inverse frequency within the document, where high scores imply a strong relation to the document. The technique is widely used for keyword selection (e.g., [147, 313]), although it is application dependent to select a threshold for the scores to include. The second technique is based on adjusted residuals, following Knibbe et al. [214] and Sharpe [350]. The absolute value of the adjusted residuals implies how much actual occurrences of a word differ from the expected distribution. The sign of the adjusted residual indicates whether the number of occurrences was lower or higher than expected. As the adjusted residuals are z-values, we convert them to corresponding probabilities using a normal distribution. Since we are doing multiple testing, we adjust each probability using the Bonferroni correction.

Thus we compute the TF-IDF score and the adjusted residuals for each stimulus and part of speech, with the full corpus of interviews as reference. We threshold TF-IDF > 0.5, to highlight words to be found important, and $p < 0.05$, to remove words that are used across interviews to talk about stimuli. Scoring words with both techniques, we gain two sets of words. We find the intersection between the sets to determine keywords that are deemed to be important and not commonly used between stimuli. We analyse the keywords manually based on the context in which they appear, to ensure that singular keywords are not misinterpreted. We disambiguate keywords by adding context or removing keywords when deemed misleading.

6.5.4.2. Disambiguating Keywords. Applying the methods above, we found 62 keywords, before filtering out 15, for a total of 47 contextually relevant keywords. We added contextual information to 14 keywords. All keywords are listed by the related stimulus in Table 6.5. We filtered words that are assigned the wrong part of speech due to word ambiguities in the origin language (e.g., "beating", as in "*a heart beating*" [P10, 125 Hz, Circle, 8] and "banks", the financial institution, use the same word) and words that relate to phrases in verbal language (e.g., *remember* as in "*[...] as far as I remember*"

Table 6.5. Keywords found through TF-IDF and adjusted residual, grouped by the stimulus. Words added in italics provide context to the keywords and numbers in parenthesis indicate how many participants (out of 11) used the keyword. Keywords are sorted by their TF-IDF score.

Stimulus	Nouns	Verbs	Adjectives
[250 Hz, Random, 8]	feedback (1), Jacuzzi (2), pattern (6), *sharpen* attention (1), line (2)	exposed *to stimulus* (2)	different *places* (9), random (2), unusual (1), *missing* visual (2)
[125 Hz, Circle, 8]	heartbeat (1), door key (1)	surprising (3), *weak bike* pump (1), comb *hair* (1), figure out *[purpose]* (2), drag *across the hand* (3)	pleasant (3), not unpleasant (2)
[16 Hz, Point, 8]	alarm (3), bass (1), middle *of the hand* (3), video game (2)	pulsating (2), vibrating (4)	not negative (2)
[125 Hz, Brush, 1]	movement (7), wave (2), movie (2), feather (2), hand dryer (3), gust of wind (2), vibration (4)	move (5), choppy (1), tickling (3), scanning (2)	wide (3), damp *hand* (1), unusual (1), electrostatic (1)
[250 Hz, Point, 1]	point (2)	pointing *at something* (1), numbness (1), prickly (4)	not physical (2), long time (4), mild (3)

[P9, 250 Hz, Random, 8]). The language analysis results in a mix of keywords mentioned by only one participant (e.g., *pump air* [125 Hz, Circle, 8]) and a large number of participants (e.g., *movement* [125 Hz, Brush, 1]). This shows that the keywords not only reflect common words between participants, but also individual phrases. In the following, we mark keywords in italics, although they can be found in the aforementioned table.

6.5.4.3. Stimulus Keywords. Each row in Table 6.5 shows how participants describe, related to and interpret haptic stimuli. The [250 Hz, Random, 8] stimulus is related to five nouns, that, in conjunction with five adjectives, describe the felt stimulus (*random pattern* moving in *lines* at *different* places on the hand), related experiences (e.g., "*[…feels] like putting your hand over the […] air bubble tube for […] a Jacuzzi*" [P9]), and what properties they attribute the stimulus (e.g., "*it sharpened the attention in various places of my hand*" [P1]).

Keywords found to describe the [125 Hz, Circle, 8] stimulus indicated that participants have difficulties relating previous experiences with the stimulus, as only the keywords *heartbeat* and *door key* were found. However, some participants described the stimulus, as if an object was dragged across their hand. The difficulty of relating to this stimulus is also reflected in a subset of the verb keywords, as participants can not *figure out* the purpose of the stimulus — "*Maybe because I do not have any associations to it, because I do not feel I can figure out what its purpose is*" [P10]. In any case, participants did report this stimulus to be *pleasant* or, at least, *not unpleasant*.

The [16 Hz, Point, 8] stimulus is typically described in terms of the position of the focal point at the *middle* of the hand). The resulting haptic experience is related to the vibrations and sounds of an *alarm* clock, the feeling of standing near a *bass* speaker at a concert, and vibrations emitted from *video game* controllers. The stimulus is sensed as *pulsating*, *vibrating*, or both, and it was "*[…] neither negative nor positive.*" [P7]

Also when describing the [125 Hz, Brush, 1] stimulus, participants focus on the pattern, specifically the *movement* of the pattern. The movement is described as a *wide wave*, *gust of wind*, or *feather*, touching and *moving* across the hand — "*[…] it is a static feather, to be very specific.*" [P4] The overall stimulation induced a *tickling* sensation, although the movement felt *choppy* or stuttering. Participants additionally related "*a slightly weak airblade […] that you run your hand up and down through, but just holding your hand still instead.*" [P9] Similarly focusing on the movement of the stimulus, participants described feeling like a device *scanning* their hand, as they had seen in the *movies*.

The [250 Hz, Point, 1] stimulus is perceived as being a *mild*, *prickly point*, with a feeling when "*[…] one's foot sleeps or hand sleeps, the one there such a slightly stinging feeling […].*" [P2] Similar to the other presented stimuli, this stimulus is described as being intangible, "*[b]ecause this feels more like such a gust of wind with vibrations, where physical touch feels more like such pressure and the feeling of skin to skin.*" [P3]

Overall, the stimuli are often spatially described by their pattern and as being *vibrating*, *tickling*, or *prickling*, although never as unpleasant nor as being tangible. Participants were reminded of a variety of previous experiences, most prominently an *gust of wind* blowing on their hand.

6.5.5. A User-Derived Mapping for Mid-Air Haptic Experiences

We generate a mapping linking the five selected stimuli and the found sensations and experiences from the insights gained through qualitative and language analyses. The mapping is presented in Figure 6.5. It is based on the keywords listed in the qualitative analysis (Table 6.3 and Section 6.5.3.3) and language analysis (Table 6.5). We categorised the keywords as being sensation or experience by three authors and grouped them by semantic meaning. To categorise keywords, we define a sensation as a mental process resulting from an immediate stimulation of mechanoreceptors, while an experience is the conscious response of said sensation. These definitions are adapted from Kandel et al. [198].

Figure 6.5 shows the five stimuli adjacent to their related sensations and experiences. From the figure, it becomes clear that participants have a shared language of talking about sensations across stimuli, as they often use similar words to describe stimuli, both across different stimuli and within the same stimulus. For instance, the keywords *mild*, *soft*, and *vibrating* are omnipresent, repeating across stimuli. On the other hand, when a sensation is unique to one stimulus, it has been repeated often across participants (e.g., the keyword *movement* was related to [125 Hz, Brush, 1] and mentioned by seven distinct participants).

Experiences are less consistent compared to sensations across participants and stimuli. Participants deliver distinct descriptions of what experience a particular stimulus reminds them of. However, it is possible to group those associations. For instance, [16 Hz, Point, 8] does remind some

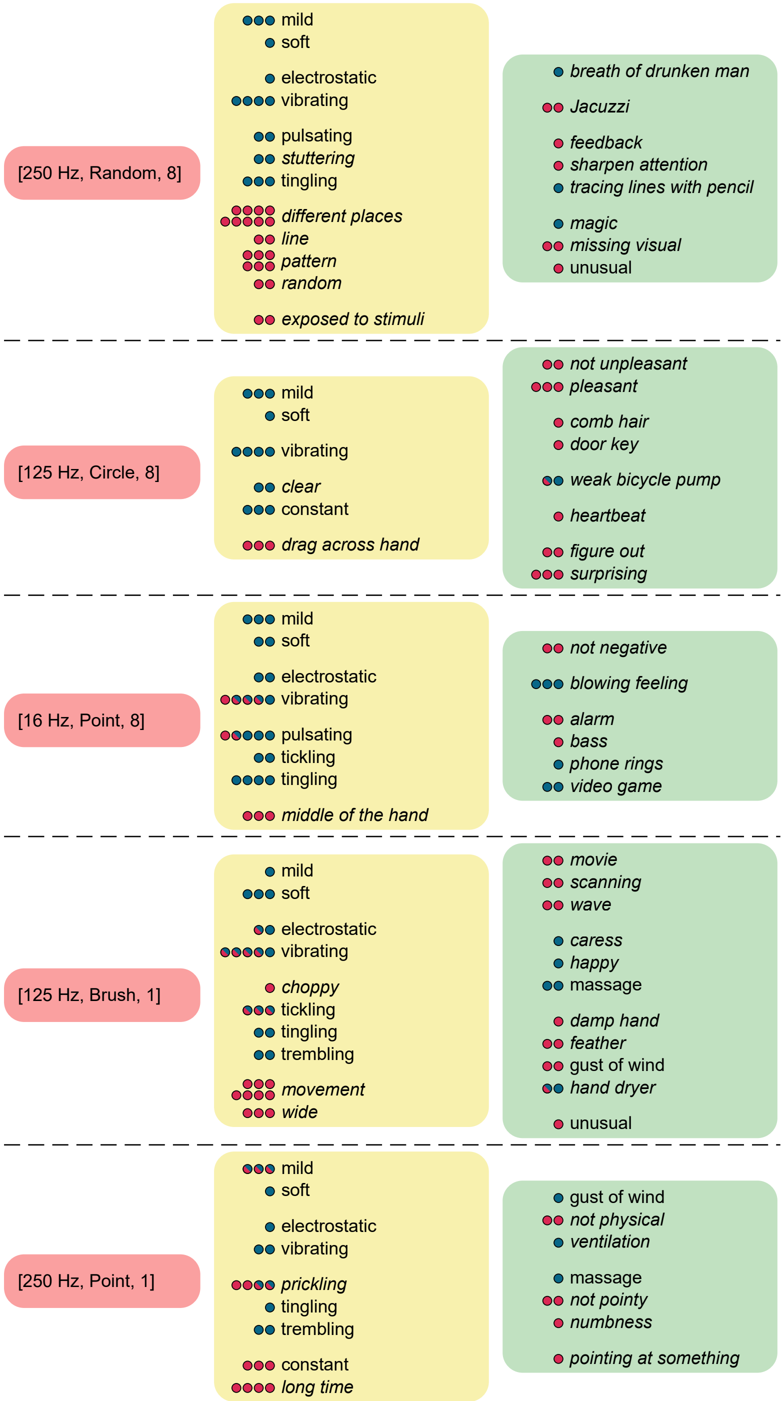

Figure 6.5. The user-derived mapping, consisting stimuli in red, sensations in yellow, and experiences in green. Keywords highlighted in *italics* are unique to one stimulus and keywords are grouped together by semantic meaning. Each dot next to a keyword represents one participant and is colour coded by the analysis method used to find the keyword. Blue dots mark keywords found through thematic analysis, red dots keywords found through language analysis, and mixed dots keywords found throughout both methodologies.

participants of an *alarm*, a *bass* sound, a *phone ringing*, and *video games*, all with similar underlying sensations (*vibrating*, in this case).

This mapping can help designers in creating mid-air haptic experiences and in evaluating mid-air haptic stimuli. Let us exemplify how designers could leverage the mapping with two use cases.

In the first use case, a person living in a remote location would like to communicate a touch on their loved one's hand either during a live conversation or as part of a message. The designer could provide the [125 Hz, Brush, 1] stimulus as one option as that has been connected with experiences of caressing. Similar to emojis, the designer has chosen a stimulus to represent semantic meaning, directly augmenting the communicated words in a conversation or a message. In the second use case, a parent and a child play a haptically augmented pattern guessing game remotely. The designer of such a game could provide the [250 Hz, Random, 8] stimulus as one option to communicate the patterns as that has been connected to experiences of someone drawing on the hand, as this stimulus is related to such a game. This could leverage the feelings of social touch in the remote interactions between users.

6.6. Discussion

Mid-air haptics faces opportunities for creative, diverse and novel experiences; at the same time, it faces an enormous design space. Because mid-air haptics is a new technology, user experience in this space is not well understood. Nonetheless, novice participants proved able to provide in-depth insights into their experience with mid-air haptic stimuli.

In the first study, participants provided ratings of mid-air haptic stimuli, enabling us to select a set of diverse stimuli based on their experiential value. In the second study, we interviewed participants about their experience with the selected stimuli, ultimately resulting in a mapping for mid-air haptic experiences.

6.6.1. *Informative and rich experiences*

In the studies, participants felt the mid-air haptic stimulation to be pleasant (or, at least not unpleasant) and frequently commented on the lack of haptic force. When asked, participants in the second study commented that stimulation was created by somebody else than themselves or an artificial object (a "machine"). Participants related these stimuli created by a machine to their phone or alarm clock ringing or felt that the stimulus was conveying some sort of information, suggesting that artificial stimulation has been normalized through everyday use.

When participants thought somebody else initiated the stimulus, some vocalized social and interpersonal experiences. These ranged between someone drawing with fingers on the participants back, for them to guess a shape, getting their hand massaged, or their partner caressing their hand. The latter one shows that experiences, possibly related to a strong positive emotion come to mind when feeling certain mid-air haptic stimuli. Stimulating purely the sense of touch can affect the emotional state of users and convey complex interpersonal experiences. The fact that participants relate both bland informative and rich social experiences to mid-air haptic stimuli speaks for the experiential diversity of the technology. This finding mirrors the finding of Obrist et al. [283], as they show that emotional meaning can be conveyed with mid-air haptics.

6.6.2. Talking about Tactile Experiences

Obrist et al. [284] presented the human-experiential vocabulary, tying two stimuli to 14 word-categories, describing users tactile experiences. In our interviews and analysis, we can see many of the same themes emerging, for instance when participants comment that a stimulus feels "tickling" or like an "air-conditioner". The participants across both Obrist et al. and our studies even share analogies, when comparing the feeling of the stimulus with a feeling of numbness in their hand (i.e., "hand is going to sleep"). Distinct in our results, we found that users also can relate complex social interactions with mid-air haptic stimuli. This is probably due to the difference in stimulus pattern, as we present our participants with multiple patterns with varying complexity, compared to a point on the hand. In general, this shows that both the expert users, interviewed by Obrist et al., and the novices, interviewed by us, have a similar language when talking about mid-air haptic sensations and experiences.

6.6.3. Experience Modelling

Kim and Schneider [206] define the Haptic Experience Model, consisting of the different aspects to consider when designing haptic experiences. Part of the model are five experiential dimensions; *Harmony*, *Expressivity*, *Autotelics*, *Immersion*, and *Realism*. Participants talk about these dimensions without being prompted specifically, showing that these dimensions also apply to mid-air haptics. Harmony is an important issue for participants, as many state that they would like a visual reference to more easily be reminded of an experience. Some even mention related auditory experiences, indicating that stimulating the full range of sensory channels is promising to yield rich experiences. The Expressivity and Autotelics dimensions are satisfied, as participants report distinct relations to experiences between stimuli and that stimuli feel "pleasant". We do not measure Immersion, but as participants provide very colourful descriptions of their experience, indicating some degree of immersion, most likely limited by the lack of sensory harmony. This limit also applies to the Realism dimension, although participants through the provision of analogies give examples of realistic experiences. Overall, these stimuli alone do not target all of Kim and Schneider's experiential dimensions, although they are able to influence experiential factors.

6.6.4. Methods for Studying Haptic Experiences

We use a variety of techniques to first rate and cluster stimuli, to then be able to explore the haptic experiences produced by stimuli. As reported before, the results of two experiential ratings do correlate, showing that there is little distinct information to be gained from measuring both. On the other hand, it shows that users associate the strength and excitability of mid-air haptic stimuli.

Another technique we used is the micro-phenomenological interview, which in its essence focuses the interviewee's attention to a specific lived experience and facilitates generating descriptions of the very same. We quickly discovered that inducing the stimulus only once at the beginning of the interview makes it challenging for participants to talk about the experience in-depth, as one stimulus is limited to four seconds in total induction length. We thus opted to let participants experience the stimulus three times in a row, to gain a basis for the diachronic structure to unfold.

6.6.5. *Limitations and Future Directions*

The mapping is not exhaustive, due to the vast design space of mid-air haptics and limitations in the sample of participants. An exhaustive mapping was never the goal, as it is not feasible to search the full space, using the methodology presented. Instead, we aimed to cover a previously unexplored sample of stimuli and succeeded at generating distinct descriptions of these in this subspace. As we only investigate a small sample in-depth, we can not reliably provide insights into the effect of individual parameter settings (e.g., comparing 125 Hz against 250 Hz frequency settings). This would require a larger sample, evaluated for instance through crowdsourcing, once ultrasonic mid-air haptic devices gain increased entry into the objects of everyday life.

No matter the size of the sample, the resulting mapping should be validated. We propose two approaches for validation of vocabularies concerned with mid-air haptics: (a) invite participants to assign a phrase, from a carefully selected set of phrases to a haptic stimulus and then check whether the assigned phrase overlaps with the corresponding set of phrases in the mapping; or (b) invite participants to create a haptic stimulus that subjectively matches the experience in question and then check whether (or to what degree) it matches the corresponding stimulus related to the experience, according to the mapping. The latter approach is inspired by the work of Obrist et al. [285], where participants are asked to create a mid-air haptic experience to mediate a specific emotion.

The results are also limited by the number of participants participating in the two studies. In the first study, the participants seem to agree on the ratings, as the reported standard deviations are low and the ratings cluster well. Assessing the consistency between participants in the second study, is more difficult, partly due to the nature of subjective reports and differences in tactile perception between humans. Although the set of participants interviewed in the seconds study is diverse in educational background, age, and sex, it would be meaningful to interview people with more diverse backgrounds, as tactile experiences can be individual. The naivety of the participants is also a limitation to our study, according to Rutten and Geerts [324], as mid-air haptic sensations are generally perceived more positive, when novel to the participant.

6.7. Conclusion

We formed a user-derived mapping for mid-air haptic experiences, through two user studies. Using the results of the first study, we derived a set of representative stimuli. In the second study, we leverage the phenomenology interview technique to gather rich descriptions of the haptic experience related to the interview. The mapping is formed by a consensus of qualitative and quantitative methods applied to the interviews. With the mapping, designers gained a tool for creating mid-air haptic experiences and for evaluating mid-air haptic stimuli. We discuss design implications of the mapping and compare participant statements to existing haptic experience frameworks.

Acknowledgements

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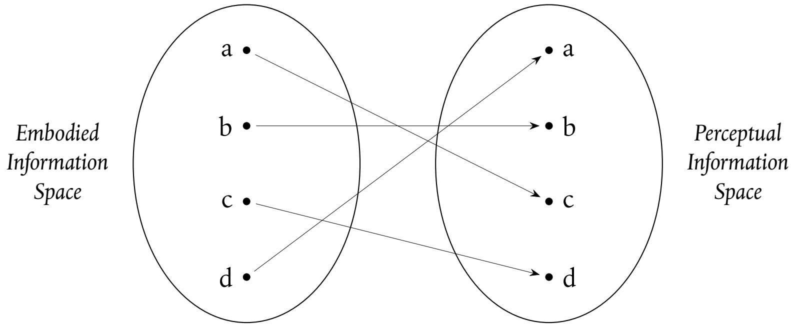


Figure 6.6. Exemplary configuration of the links between the embodied and perceptual information spaces.

7. Experience as an Information Space

The presented journal paper *A User-Derived Mapping for Mid-Air Haptic Experiences* [63], along with other works (e.g., [137, 307, 347]), suggest a mapping between haptic stimuli and sensations as a way of differentiating between sensory environments. Another way is cognitive modelling of the neural response of perception (e.g., [73, 379]) or the perceptual modelling of difference relation (e.g., [4, 234, 375]). Past experiences have shown to be influential to the formation of perception [20, 21], and thus must be part of the embodied state. Lastly, Dourish [86] argued for the importance of context to interactions and explained that context arises from activity, is bound to and formed by a situation, and changes dynamically. These concepts are not orthogonal to each other, yet somehow different – how pronounced the difference might be is unclear. In the journal paper *A User-Derived Mapping for Mid-Air Haptic Experiences* [63], we found that descriptions of experiences of particular haptic feedback patterns have several dissimilarities and similarities. The number of similarities is higher on a sensation level than on the experience level; nevertheless, it seems that there is a link between the experiences across humans, with some error margin. I explain the error margin primarily through the aforementioned factors of previous experience, context, and need fulfilment.

To reason about sensory and perceptual inference, let us consider stimuli, sensations, and experiences as *information states* embedded in an *information space*, following Chalmers [47] and Shannon [348]. Such a view entails two information spaces: the embodied information space comprised of physical, sensory states that are linked to experiential states in the perceptual information space. Consider the exemplary illustration of such spaces in Figure 6.6; a physical, embodied state links to a mental, perceptual state. Hassenzahl et al. [143] and McCarthy and Wright [259] argued for experiences being inseparable, as they are perceived continuously and argue that two experiences can never be alike. Hassenzahl et al. further argue experiences may nevertheless be categorized in terms of the basic psychological needs they fulfil. In contrast, Chalmers argues that the link between proximal stimulus and experience is deterministic. In a hypothetical, Chalmers [47, pp. 20-23] argued that if neural activity in the brain would be exactly duplicated, the qualitative experience would be identical [47, pp. 20-23], making experiences separable. In my view, these two supposedly opposite stances are not mutually exclusive; however, they argue at different ontological 'levels'. Chalmers is right in theory; experiences are repeatable and separable. However, from a designer's point of view, experiences will not be repeatable in practice, as duplicating neural activity is not practically feasible. Thus, Hassenzahl et al. and McCarthy and Wright are right in practice. This can be explained by the change in the embodied information state – human experiences are influenced by their past experiences [20]. Thus, to replicate an experience, designers would need to replicate the exact embodied state[9].

Such an observation shows the need to understand the composition of the embodied state and the perceptual state, as designing an embodied state that elicits a particular perceptual state is the goal of much haptic design. The notion of information spaces yields two distinct advantages here: **(1)** information spaces are structured as difference relations between the encapsulated states, i.e., characterisations of whether states are similar or different and **(2)** Shannon [348] defined information spaces to be isomorphic, leading Chalmers [47] to suggest that a particular embodied state corresponds to a particular perceptual state. Both these advantages yield questions to research. The first advantage implies a way of distinguishing between states in the embodied information space and between states in the perceptual information space. The challenge is to define the differences; the embodied states are characterised by the bodily state, including the sensory environment, the past experience, and the context. The sensory environment is an outcome of (haptic) stimulation, which can be defined by amplitude, frequency, location, and temporality [361]. Such a parametrisation is helpful for designers [334, 361], and has been the subject of research before.

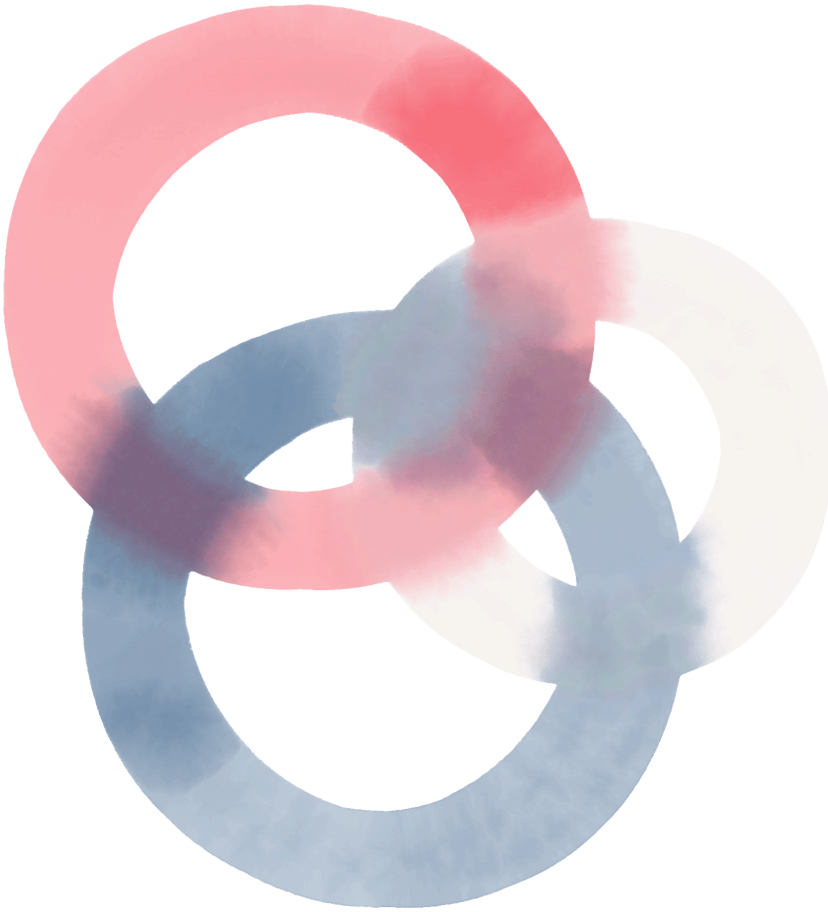
The perceptual information space is much harder to define; it consists of the *qualia* of the functional and subjective experience [388]. The qualia describes what it is like to undergo a particular embodied state. Wright et al. [416] identified four interwoven threads of experience: the compositional thread, the sensual thread, the emotional thread, and the spatiotemporal thread. The compositional thread describes the holistic perception of qualia and how they relate to the given situation as a whole, while the sensual thread describes the sensory engagement in the situation. The emotional thread describes the emotional response to a situation, and the spatiotemporal thread relates to the aspects of the situation's time and place. To elaborate on the perceptual information space, I argue for a functional thread describing the actionable information in a situation – this notion overlaps with Wright et al.'s compositional thread; however, in my view, there is more to the story, as allostasis plays a role in consciousness [20]. Allostasis describes the neuro-scientific understanding of the core function of the brain: The regulation of the body to maintain a balance of energy consumption [20]. Thus, qualia have an underlying aspect related to the functional maintenance of the body, an aspect that interprets actionable information for decision-making. With such a composition, it seems plausible to design for experiences through, for instance, haptic feedback. The idea of treating experience and qualia as information spaces is derived from Chalmers [47]; yet, whether or not embodied and perceptual information states are the same is hotly debated[10].

[9] Such a replication requires one of two things: designerly control over the spacetime continuum *or* a general sensoric display, such as those described by O'Shiel [282, p. 183] or Sutherland [363]. Both seem unlikely in the foreseeable future.

[10] Chalmers [47, 48] argued against, Dennett [76, 77] argued for. It's a whole thing, and somehow zombies got dragged into the story [76, 388].

The second advantage states that an embodied state corresponds to a perceptual state and vice versa due to the isomorphism of information states. This statement is to be taken as philosophical – in practice, replicating an embodied state exactly seems implausible, as it requires to 'reset' human consciousness to a previous state, in which the to-be-replicated experience has not happened, following Hassenzahl et al. [143] and McCarthy and Wright [259] as before. Taken together, the information spaces seem infinitely large; however, we, as designers, must assume that there are clusters of isomorphic relations between embodied and perceptual information spaces such that similar embodied states arrive at similar perceptual states. Otherwise, a reductionistic approach would not yield any results. The grand research challenge that follows is to dissect the embodied state and find how changes in the embodied state are reflected in the perceptual state. A low-level example: how do changes in the frequency of a vibrotactile stimulus affect the perceived intensity of the stimulus? A high-level example: how do changes in the social context affect the perception of haptic technology use? As mentioned before, libraries of haptic patterns and their associated perceptual state (e.g., [27, 137, 307, 347] and *A User-Derived Mapping for Mid-Air Haptic Experiences* [63]) and perceptual models (e.g., [4, 234, 375]) are beginning to shape the understanding of the embodied state. Similarly important, research in affective haptics (e.g., [174, 175, 245]; overview by Eid and Al Osman [92]) and relatedly social touch technology (e.g., [172, 258, 308]; overview by van Erp and Toet [395]), as lead to better understanding of the social aspects of experience. However, more research is needed to determine the effects of stimulation, context, and previous experience.

The Inference-Design Model for Haptic Experience hides the complexity of information spaces on the surface yet reflects the two advantages of the notion of information spaces in its inclusion of the inference and design processes. With it, designers gain the understanding that stimuli, sensations, and experiences are related. When creating a system that induces haptic feedback, it is important to be aware of the relation, as such a system will *always* elicit an experience. "Rest assured that no matter whether we want to focus on experience or not, technology will always create some" [145, p. 209], as Hassenzahl et al. put it.



Part IV

Haptic Sensation

Variation,
not uniformity,
is the norm.
– *Lisa Feldman Barrett*

haptic sensation An immediate, conscious interpretation of a proximal haptic stimulus.

Aristotle's classical five senses—smell, sight, touch, taste, and hearing—have long formed the foundation for our understanding of the somatosensory system. While this understanding is still taught in primary schools and somehow feels intuitive, it is also understating the complexities of human sensing. Take, for instance, the sense of balance, a sense that is not directly related to the Aristotelian Five but, in fact, very important to the essential functioning of modern humans – it allows them to read information from a mobile device while walking down the street without looking up [254, pp. 331–344]. Or, the sense of presence, which is heavily researched within human-computer interaction and haptics [184, 357] – also not a sense, according to Aristotle, yet one could argue what constitutes a sense in the first place, and if 'presence' qualifies as a sense. Macpherson [248] called the Aristotelian view on the senses sparse and argued against discrete categorisation of sensations. The question is, then, what distinguishes the senses? Macpherson argued that we should describe what senses are like with regard to four criteria: the *sense organ*, the physical organ through which the sense is perceived; the *proximal stimulus*, the stimulus activating the sense; the *representation*, the objects and properties the sense presents; and the *phenomenal character*, the experiences the sense elicits. In the previous Part II, I described the sense organs and proximal stimuli of touch; in the next Part V, I will discuss the phenomenal character; and in this, I explain the properties of touch presents to the perceiving human–the representations of touch.

Chapter 8 presents the notion of the representation of touch, dissecting the Aristotelean notion of common and proper sensibles [248] and Lederman and Klatzky notion of exploratory procedures [226]. Touch makes functional and actionable information perceivable; a feature essential to the Inference-Design Model for Haptic Experience. In Chapter 9, I show how to extend the notion of representations of touch using the concept of sensory substitution and augmentation. The journal paper *Haptic Magnetism* [68] presents a conceptual framework for designing sensations that can only be perceived through haptic technology while maintaining the functional and actionable nature of the information sensed through touch. Lastly, Chapter 10 continues beyond the representation of touch. The design space for 'unrealistic' haptic sensations is largely undefined; however, designing sensations that go beyond the ordinarily considered perceivable is the great potential of haptic technology, in my view. The chapter argues for the potential and provides examples of the very same.

8. Representations of Touch

While Aristotle may not have been entirely successful in differentiating between all senses, the search for the difference nevertheless yielded an interesting taxonomy of perceptible objects and properties. Aristotle proposed three types of perceptible properties: *common*, *proper*, and *accidental*

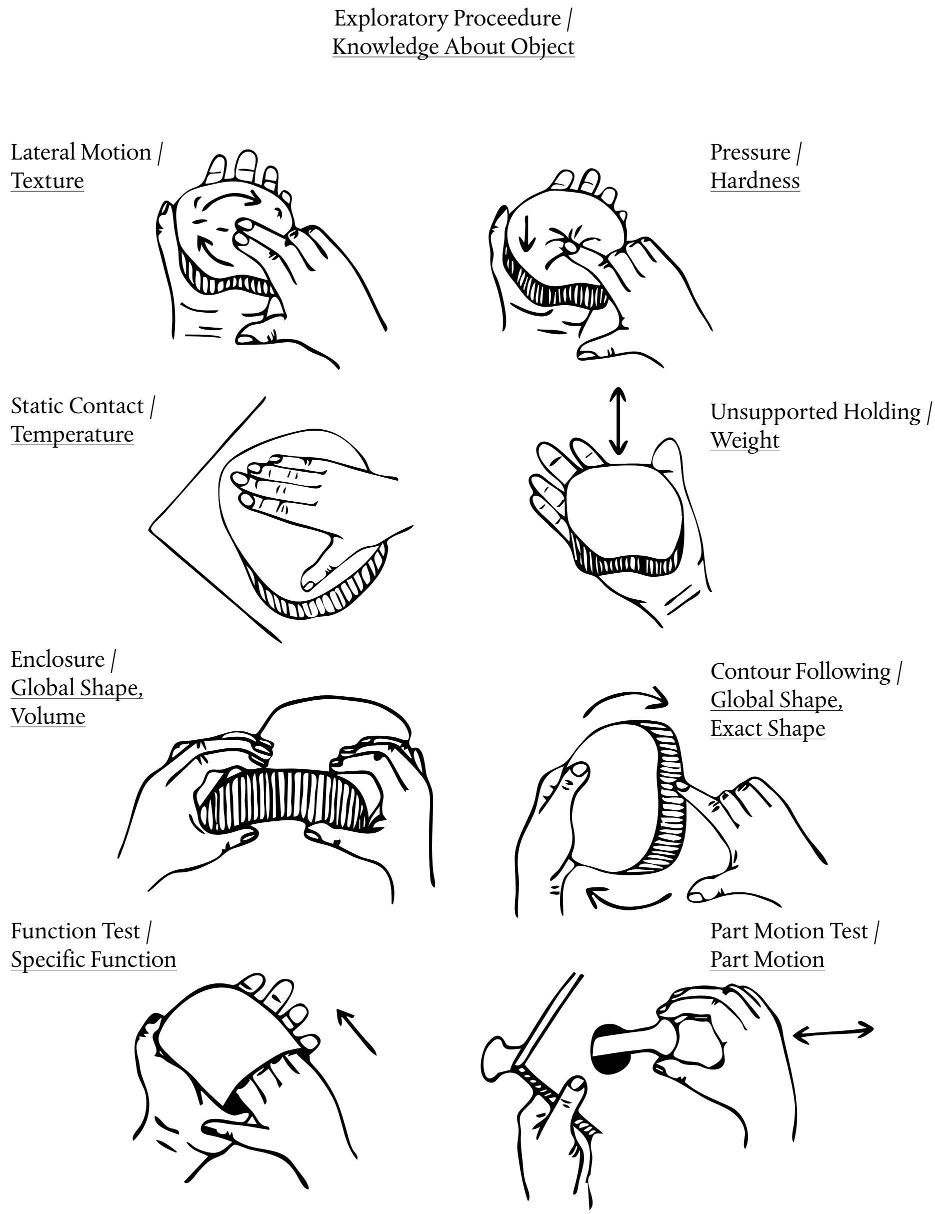


Figure 8.1. Exploratory procedures and associated properties.
Reproduced, with permission, from Lederman and Klatzky [226, p. 31]. Copyright © 1993 Elsevier.

sensibles [97, 292]. It is not entirely clear what Aristotle meant by accidental sensibles [292]; however, common sensibles are those perceivable properties shared between senses—motion, rest, magnitude, unity, shape, size, and time [248, 292]—while proper sensibles refer to the properties perceivable through a single sense. Macpherson explains, "[according to Aristotle], the proper sensibles of hearing, tasting, smelling, and seeing are sound, flavor, odor, and color, respectively" [248, p. 129]. Touch, however, falls out of this categorisation, as it has multiple proper sensibles, according to Aristotle: dry, fluid, hot, and cold [248]. Aristotle's categorisations of senses and sensibles are quite neat and handy in explaining the difference between senses; however, given some headwind, 'havoc' is created as Macpherson put it. Instances of havoc are systems for sensory substitution [249], replacing the sensory input from one sense to another. Take braille, a tactile writing system that maps information otherwise gathered through the visual sense to the tactile sense [295] or tactile-visual sensory substitution devices that display visual information on the tongue [17, 249]. In both cases, the representation of the visual sense is conveyed through the senses of touch, which does not exactly confirm Aristotle's taxonomy of senses and sensibles.

While Aristotle's take on representations of touch is off, questions relating to the purpose of touch are still frequently asked, particularly what properties of objects are perceivable through touch. Quite famous are the works of psychologists Susan J. Lederman and Roberta L. Klatzky, defining a taxonomy of how tactile exploration yields insights into the object's properties [212, 225, 226] and showing the great potential of touch for object recognition [209, 210, 211]. Figure 8.1 shows Lederman and Klatzky's taxonomy of tactile exploration, listing texture, hardness, temperature, weight, shape, volume, function, and motion as properties perceivable through touch [226]. While this taxonomy might not be the definite list of perceivable properties, it shows the diversity of the representations touch can deliver. These representations are what I call sensations.

Haptic sensations arise from the interaction between perceiving human and a technological object. However, the perception of sensations is affected by the mode of interaction: whether the human engages with the object passively or actively affects the perception of the object [112]. Gibson [112] famously differentiated between *touching*, active touch, and *being touched*, passive touch. Active touch is informed by exploration, a notion that Lederman and Klatzky used to build the taxonomy shown in Figure 8.1 and generally has sparked much research in the field of haptics (e.g., [172, 185, 244, 294, 314, 426]). Active touch prompts differentiable neural activity compared to passive touch [353] and provides information about an object's texture, shape, and hardness. A substantial body of work within haptic research is dedicated to mimicking the outcome of these exploratory procedures of active touch: weight perception (e.g., [190, 338]), shape recognition (e.g., [99, 128, 296, 323]), roughness (e.g., [27, 78, 126, 195]), and many other properties are well studied [200]. Kappers and Bergmann Tiest [200] further elaborated Lederman and Klatzky's taxonomy to expand on the perceivable properties mentioned by Lederman and Klatzky and to relate those properties to cases of passive and active touch. Table 8.1 lists Kappers and Bergmann Tiest's interpretation of haptic representations – it focuses on material, spatial, and numerical representations, but also introduces illusions as a haptic representation.

Table 8.1. Properties perceivable by touch, as described by Kappers and Bergmann Tiest [200].

Material Properties	Spatial Properties	Numerousity	Illusions and after-effects
Roughness	Shape	Numerousity	Geometric optical illusions in touch
Compliance	Curvature		Curvature after-effect
Coldness	Length		Temperature illusion
Friction	Volume		Location illusion
Viscosity	Orientation		
Density and weight			

There is much to be said about haptic perception, and to give an adequate account of it has filled books; I refer to David Parisi's *Archaeologies of Touch: Interfacing with Haptics from Electricity to Computing* [295], Mark Paterson's *The Senses of Touch: haptics, affects, and technologies* [299], and Mounia Ziat's *Haptics for Human-Computer Interaction: From the Skin to the Brain* [429] in this matter. Instead, the purpose of this chapter is to introduce my understanding of sensations. Haptic sensations are functional and actionable, and they form the basis of how humans form their experiences and make decisions. A sensation becomes functional when it informs about an object's properties, such as the perception of weight or roughness (e.g., [90, 126, 190]), and becomes actionable when the sensation facilitates the perceiving human decide on further action; for instance, the judgement of an object's friction allows for tightening their grip [31]. Within the Inference-Design Model, sensations take an essential place between stimuli and experiences, indicating that experiences are perceived based on the functional and actionable information provided by the sensations.

Macpherson warns that to define all forms of touch representations requires "thinking through a large number of examples of instances of [...] touch" [248, p. 129], suggesting that a thorough definition might be found through listing all the possible sensations perceivable. Kappers and Bergmann Tiest's [200] and Lederman and Klatzky's [226] taxonomies are nevertheless useful and do not claim to be a thorough definition. For instance, sensory substitution and augmentation are not present in the mentioned taxonomies, yet these techniques have grand potential in the haptic space. As an example of the potential for sensory augmentation, I introduce the journal paper *Haptic Magnetism* [68] in the next chapter, presenting a concept of the same name. Haptic Magnetism thereby goes beyond the representations of touch presented by Kappers and Bergmann Tiest and Lederman and Klatzky.

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9. Haptic Magnetism

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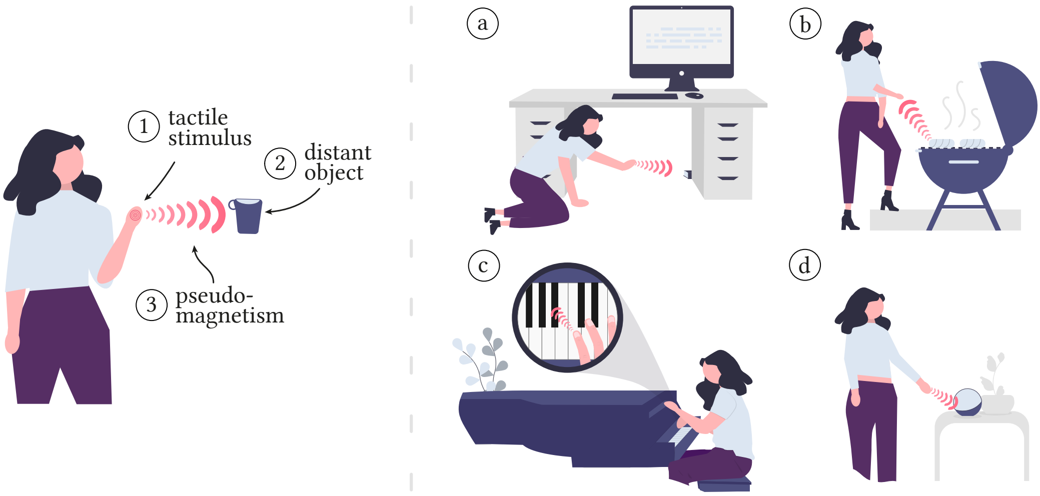

Figure 9.1. *Left:* The three principles of Haptic Magnetism: A tactile stimulus (◎) enables the user to interact with a distant object (▼) through an experience of a pseudo-magnetic attraction (»») and repulsion («««). *Right:* Examples of interactions using Haptic Magnetism. A user being (a) attracted to find an occluded object, (b) repulsed to avoid a dangerous object, (c) attracted to select a particular object, and (d) attracted to discover an interactable object.

Abstract. New interactions are often developed by mimicking the real world. Therefore, many researchers in haptics have focused on creating a realistic experience of contact between users and objects. However, dispensing with mimicry may allow us to develop novel haptic interactions. We present *Haptic Magnetism*, an interaction modality that delivers sensations of distant objects through tactile stimulation and enables interactions through pseudo-magnetic attraction and repulsion. To show the feasibility of Haptic Magnetism, we designed 12 pseudo-magnetic stimuli and assessed them in two studies. In the first study, we show that participants gain a sense of distant objects. In the second study, we evaluate a subset of stimuli to show that participants can interact with the objects based on experiences of pseudo-magnetic attraction and repulsion. Finally, we discuss how Haptic Magnetism supports guiding movements, nudging users, and revealing affordances.

Keywords. Human-Computer Interaction, Design, Haptic Rendering, Perception and Psychophysics

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9.1. Introduction

Creating plausible experiences of touching objects has been the goal of numerous works (e.g., [98, 275, 334, 372, 411]). Central to most of this work is the assumption that we should create haptic experiences that *mimic* the contact between objects, say, a user's finger and an object in virtual reality. That assumption may be challenged. Hollan and Stornetta [159] famously argued that face-to-face communication need not be a golden standard for electronic media. Following this argument, haptic feedback can be an experience in itself rather than a mimicry of realistic contact. We, too, are inspired by this idea.

We present Haptic Magnetism, an interaction modality that enables users to sense objects at a distance solely through the sense of touch. Similar to Haptic Magnetism, researchers have created systems for using the sense of touch to sense things that cannot be usually sensed. For example, Nagel et al. [278] created the feelSpace belt, which provides haptic feedback of magnetic north, and Grönvall et al. [123] created the FeltRadio, which provides haptic feedback to sense radio waves present around the user. Although these examples can be considered instances of Haptic Magnetism, the modality can seve as an umbrella, or strong concept [161], for a wider range of interactions.

In Haptic Magnetism, interactions are enabled through experiences of pseudo-magnetic attraction and repulsion (Figure 9.1 left). The feeling of this modality would be equivalent to holding a magnet in hand and moving it closer to another magnet, exerting attracting and repulsing forces. Gaining a sense of attraction and repulsion can be useful, for instance, for guiding a user to find an occluded or otherwise invisible objects, such as lost keys in another room (Figure 9.1a), or navigating their hand to avoid a hot cooking plate (Figure 9.1b). It can also be useful for nudging the user to select the right key on a piano (Figure 9.1c) or for discovering interactable objects in augmented reality in an otherwise passive real-world scene (Figure 9.1d).

In two studies, we show the feasibility of Haptic Magnetism. To investigate whether the basic feeling of pseudo-magnetism can be induced at all, we test Haptic Magnetism as the sole feedback for interactions (i.e., without visual probes). Initially, we designed 12 haptic stimuli as candidates for producing the sensations of attraction and repulsion. Then, in the first user study, we quantified how well these stimuli induce sensations of objects at a distance. We asked participants to rate their sensations of the distant object, that sensation changing with movement, and about feeling a sensation of a pull toward or a push away from the object. The three stimuli that the participants rated most frequently to provide pseudo-magnetic sensations were selected for the second study. In the second study, we ask a new set of participants to select between attracting, repulsing, and neutral stimuli in a forced choice task. The results show that users can distinguish attractive stimuli when prompted. We also ask participants to locate an attractive stimulus on a plane. We find that the participants can accurately locate the stimulus. These two findings suggest that Haptic Magnetism can enable interactions with distant objects through experiences of pseudo-magnetic attraction and repulsion solely based on the sense of touch.

Our main contributions are the concept of Haptic Magnetism and the two studies validating the concept. We discuss the feasibility of Haptic Magnetism and how the concept can help hapticians design stimuli for pseudo-magnetic sensations and to interact with distant objects.

9.2. Haptic Magnetism

Haptic Magnetism is an interaction modality relying solely on the sense of touch. Figure 9.1, left, depicts the three principles of Haptic Magnetism that guide the design of stimuli for pseudo-magnetic sensations to interact with distant objects:

(1) *Haptic Magnetism relies on providing tactile stimuli to the haptic sense.* These stimuli are produced by generic haptic devices (for a definition of generic haptic devices, see Muender et al. [275]). Thereby, Haptic Magnetism is based on illusory sensations rather than physically pulling or shearing the skin. The stimuli should express relations between the user and an object, such as the distance between them or a direction toward the object. A change in the relation should result in a change in one or more stimulus design parameters, for instance, intensity or frequency. In real magnetism, the change of the attracting or repulsing force is exponential in relation to the magnets' distance. In Haptic Magnetism, however, the change can be of any rate (e.g., linear, polynomial).

(2) *Haptic Magnetism delivers sensations of objects at a distance.* The sensation changes based on the user's movement in relation to the object, giving a constant sense of it without mimicking touch. The sensation is thus not of contact (e.g., texture or shape) but of location (e.g., distance or direction).

(3) *Haptic Magnetism enables interactions through experiences of pseudo-magnetic attraction and repulsion.* The two modes of attraction and repulsion make up the interaction modality. The modes allow users to interact with objects at a distance. The interactions include guidance, navigation, nudging, and discovery (Figure 9.1).

Haptic Magnetism can be used alone or in combination with other interaction modalities. For example, when objects are occluded, locating them becomes difficult even with augmented visual feedback [233]. Haptic Magnetism can provide additional guidance in such tasks.

Haptic Magnetism can also be used in real or virtual environments. As the haptic sense is less dominant than vision or audio (the commonly stimulated senses), using haptics can be less intrusive and less likely to break immersion in a virtual experience [298]. Similarly, when introduced into the real world, designers can create more subtle interactions with Haptic Magnetism compared to audiovisual ones.

In the following, we expand on the scenarios presented in Figure 9.1, where Haptic Magnetism enables interaction. These scenarios range from urgent to subtle interactions. Haptic Magnetism can be used for guidance, leading the user towards a book that fell behind their writing desk or towards their lost keys hidden in the fridge (Figure 9.1a). Here the occluded or hidden object attracts a user so as to be found. Conversely, Haptic Magnetism is useful for repulsing the user away from dangerous objects to avoid them. This could be hot items on a grill or leaking gas pipes in a workplace environment (Figure 9.1b). In these two application areas, the interaction is urgent. If the user wants to find their keys right now or needs to be warned in a dangerous situation immediately, urgency is desired such that the user can act on the information gained in a timely manner. Here the interaction is not sought after for pleasure but by necessity; users thus desire the interaction to be efficient and precise. In other scenarios, a different form of interaction is desired. Haptic Magnetism can be used to nudge the user, to support learning by reinforcing the selection of correct objects or to support decision-making. If, for instance, the user wishes to learn to play the piano, they can be attracted to hit the right key (Figure 9.1c). Or, if they would be baking a delicious cupcake, Haptic Magnetism could repulse the user from the salt jar, placed dangerously close to the sugar jar. Similarly, Haptic Magnetism is useful for revealing affordances of objects, for instance, by supporting the discovery of multiple interactable objects through attraction but not dictating a selection of any particular one (Figure 9.1d). In these scenarios, users want to learn a skill and the pseudo-magnetic stimulus supports the learning process.

These scenarios tell about the potential of Haptic Magnetism. Haptic interactions are commonly associated with proximity and intimacy [298], whereas Haptic Magnetism is an interaction modality allowing designers to create haptic interactions with objects at a distance.

Our description of the interaction modality Haptic Magnetism serves as a strong concept [161]. The three principles describe a class of possible user interfaces, which is more general than a concrete user interface and more specific than a theory of haptic perception. In particular, the Haptic Magnetism generalize earlier user interface ideas such as FeltRadio [123] and feelSpace belt [278], while at the same time being more concrete than general principles of sensory substitution. The three principles of Haptic Magnetism have generative power [26] in that they can be applied to make decisions about how magnetism may be used in particular applications. This also makes them differ from specific user interface ideas and general principles.

9.3. Related Work

In this section, we discuss work related to the three principles of Haptic Magnetism. First, we discuss realistic stimuli pushing or pulling the fingers in relation to an object. Next, we discuss studies about touching remote entities; objects, people, or phenomena. Finally, we discuss previous work that uses haptics for sensory augmentation about entities that cannot otherwise be sensed, such as the direction of the magnetic north.

9.3.1. Inducing Realistic Tactile Stimuli

The sense of touch can be stimulated with different technologies, such as vibration motors, force feedback devices, or ultrasonic haptic devices. The technologies have an influence on the perceived realism of haptic stimuli. Muender et al. [275] relate perceived realism to the specificity of haptic devices, such that devices built to produce a specific haptic stimulus are perceived as more realistic than generic devices. Such custom devices have been used to mimic realistic renderings of haptic stimuli in different contexts. For instance, Whitmire et al. [411] created the Haptic Revolver, built to provide sensations of texture, shear and direction by rotating a surface underneath the fingertip. The "Tactile Sleeve for Social Touch" [172] set out to mimic realistic touch sensations in social settings, by users receiving haptic stimuli on the forearm. Wolverine [53] and Wireality [98] are examples of purpose-built devices for realistic haptic experiences in virtual reality that physically stop the fingers at a grasped object's surface. Central to these devices is the assumption that we should create haptic experiences that mimic reality. However, without devices that are customised to pull or push the hand, it is unclear how to best stimulate the skin to convey an experience of magnetism.

9.3.2. Remote and Virtual Touch

Virtual objects or people with virtual presence cannot be directly touched. Introducing haptics to these contexts has been suggested to enhance the experience, as the typically primarily audio-visual computer interface becomes multi-sensory, allowing for a greater information flow to the user [298]. For example, receiving haptic feedback when performing a remote task through a robot has been shown to improve task-specific performance (e.g., [232, 274, 276]), and adding haptics to virtual handshakes and other forms of remote social interactions (e.g., [173, 298]) has been shown to improve presence and immersion in the social contexts.

Similarly, a sense of touch has been discussed in relation to virtual objects. Already in the Tangible Bits, Ishii and Ullmer [188] use a physical proxy that can be directly grasped to manipulate the corresponding virtual object on a tabletop display. Such passive proxies have also been used in virtual reality to provide realistic feedback of grasping objects. For example, the user's virtual hands or fingers can be redirected in a way that they touch a physical cube at the same time as the corresponding virtual cube at a different location [16] or of different size [29]. Lopes et al. [240] extends the sense of touch to provide information on how an object can be used. They present the concept of "Affordance++", which allows users to discover the affordances of objects once they are grasped. However, in all of these works the haptic feedback displays contact between the hand and the object. Even if the object or the person in these works is remote or virtual, they are not shown at a distance from the user's hand. In Haptic Magnetism, the object is sensed at a distance, and that sensation changes when moving closer or farther from the object.

9.3.3. Sensory Augmentation with Haptics

Macpherson [249] defines sensory substitution as the replacement of a missing sense by delivering information usually gathered by the missing sense to an available sense. As an extension to this idea, Macpherson describes sensory augmentation as creating a novel sense, delivered through an existing sense [249, pp. 1-10].

The idea of sensory augmentation becomes more approachable in everyday use cases. For instance, the feelSpace belt [278] delivers a sense of magnetic north, used for pedestrian navigation, and the FeltRadio [123] delivers a sense of radio waves present around the user. Applications are often within accessibility (e.g., [125, 194, 270, 278]). Instead of presenting a physical property of the real world, Culbertson et al. [61] created an illusory force with a set of wearable vibration motors to direct the user's movements. All these works can be considered instances of Haptic Magnetism, although they are not always stringently following the three principles presented. Nagel et al. [278] built a system without any notion of pulling or pushing. [125] on the other hand employed these pseudo-magnetic sensations to guide users with a custom device.

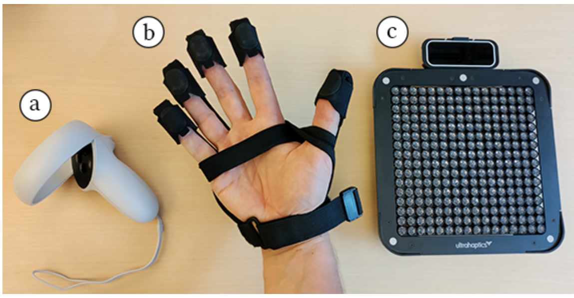

Figure 9.2. The three devices used in the study: (a) a virtual reality controller, (b) a haptic glove, and (c) a mid-air haptic device.

The novelty of Haptic Magnetism is that it can enable *interactions with distant objects* through *experiences of pseudo-magnetism* solely through *the sense of touch*. It is an interaction modality for pseudo-magnetism since it uses the haptic modality to provide a sense of magnetism. It not only provides a sense of an object at a distance, but also changes that sensation depending on the distance (e.g., when moving closer to the magnet), and has modes for both magnetic forces of attraction and repulsion. Finally, it does so solely through the sense of touch, using generic haptic technologies.

9.4. Study 1: Producing Sensations of Objects at a Distance

We design 12 tactile stimuli as candidates for delivering pseudo-magnetic sensations (Principle 1). The stimuli are designed based on ideas from related work and on the technical capabilities of three haptic devices: a controller, a haptic glove, and a mid-air haptic device. Participants rate the stimuli on four subjective scales, indicating their sensation of the object at a distance and its magnetic properties. The purpose of this study is to show that Haptic Magnetism can deliver sensations of objects at a distance (Principle 2) using different haptic devices.

9.4.1. Participants

We recruited 21 participants to rate the 12 haptic stimuli. The participants were between 18 and 58 years of age (mean: 29.10, std: 9.04). Seven participants self-reported as female and 14 as male. The experiment took 32 minutes on average to complete. All participants were rewarded with a gift valued at $15.

9.4.2. Study Design

The study investigates an independent variable containing 12 levels, each corresponding to one of the designed haptic stimuli. Each stimulus is dependent on a haptic device, as it is designed specifically to work on one device. We used three different devices, controller, glove, and mid-air, since each of them has a different level of versatility in producing skin vibrations on the hand. The first device was a hand-held *controller* (Figure 9.2a) with a vibration motor, representing the most common haptic feedback device, as found in mobile phones and game controllers. The second was a haptic *glove* (Figure 9.2b) with multiple vibration motors, meant for use in augmented and virtual

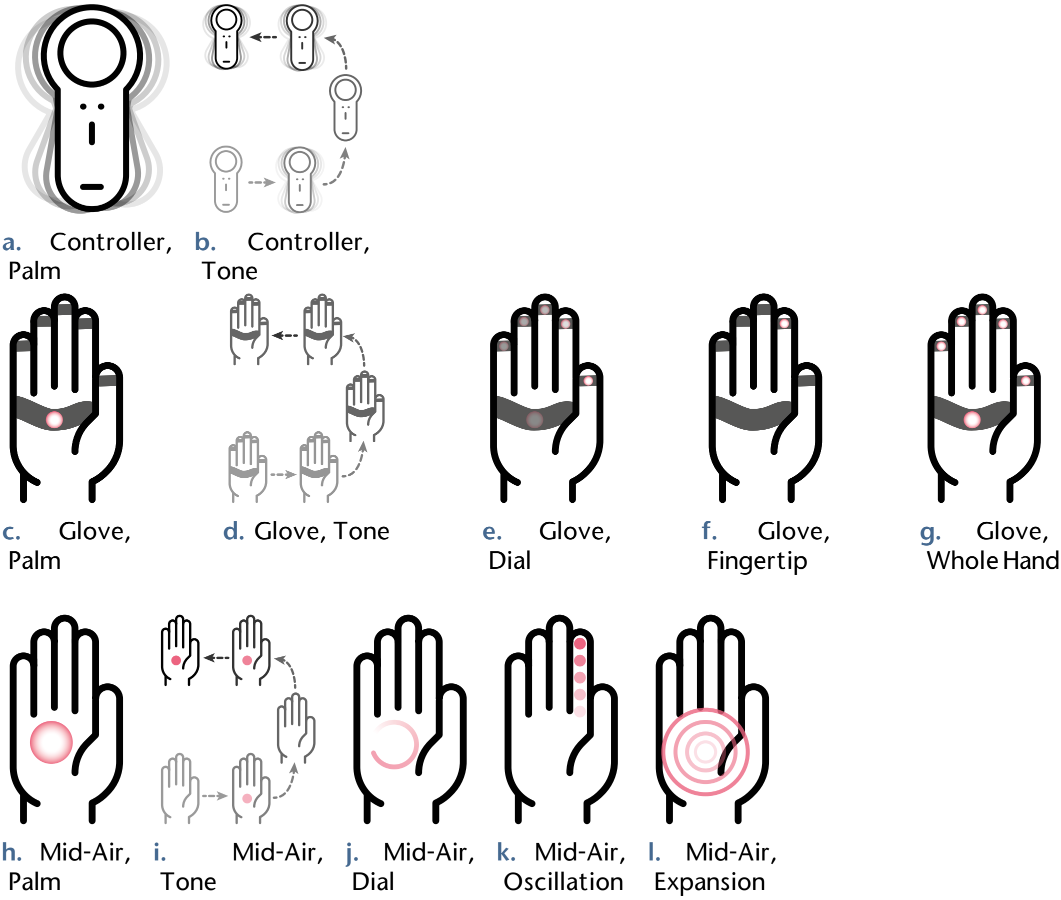

Figure 9.3. The 12 candidate designs for pseudo-mangetic haptic stimuli. Rows indicate haptic device, used to induce the stimulus, columns indicate the comparable haptic stimuli across devices.

reality. The third was a *mid-air* (Figure 9.2c) haptic device, which induces skin vibrations through ultrasonic sound waves anywhere on the hand. For details on the devices, we refer to the supplementary materials.

During the study, participants were tasked to explore the sensation of a distant object. They were asked about their perception of that object and its pseudo-magnetic properties. A trial consisted of a 20-second exploration of a candidate stimulus and of answering a questionnaire, in which participants rated the stimulus. Each stimulus was induced three times, for a total of 36 trials. The study followed a within-subjects study design, where all participants evaluated all stimuli using all devices. Conditions were blocked according to the devices, such that participants did not need to switch devices after every trial. The order of devices was randomised according to a Latin square and, for each device, the stimuli were presented in random order.

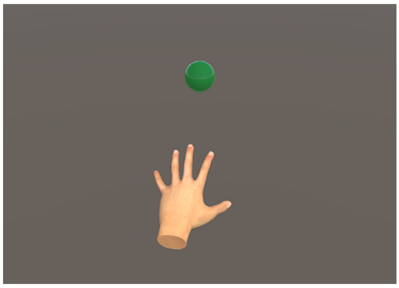

Figure 9.4. The virtual reality scene used in the first study. A participant is moving their hand toward a virtual object.

9.4.3. *Design of Stimuli*

For the study, we designed 12 haptic stimuli for the three devices. The design is limited by the capabilities of the devices, such that the number of stimuli designed for the controller is smaller than for the glove or mid-air conditions. We aimed both to design stimuli that are comparable across devices and stimuli that take advantage of the technological capabilities of the devices. By the principles of Haptic Magnetism, a pseudo-magnetic stimulus has its source in a distant object. All stimuli used in this study are designed to convey a sense of the distance between hand and object through different haptic patterns and modulations. This distance relation produces a linear change in the modulation, i.e., the parameter is linearly increasing or decreasing based on the distance between hand and object. For detailed descriptions of the stimuli, we refer to the supplementary materials.

The stimuli are visualised in Figure 9.3. For all three devices, we designed a stimulus that is centred on the palm of the user and modulate intensity, such that the sensation is strong when close to the object or weak when far away (Figure 9.3a, Figure 9.3c, and Figure 9.3h). Similarly, for all three devices, we designed a stimulus with constant intensity, but changing periodical beat (Figure 9.3b, Figure 9.3d, and Figure 9.3i), such that the excitation frequency is high when close to the object, similar to the sound of a metal detector.

For the haptic glove and the mid-air haptic device, we designed a set of comparable stimuli: a circular stimulus, with increased drawing speed as the user's hand, is moved closer to the object (Figure 9.3e and Figure 9.3j). Lastly, we designed four stimuli taking advantage of features unique to each haptic device. For the haptic glove, we designed a stimulus on the index fingertip, with intensity modulation (Figure 9.3f), such that intensity is high when close to the object, and a stimulus using all six actuators in the glove at once, also with intensity modulation (Figure 9.3g). For the mid-air haptic device, we designed a point stimulus on the index finger, moving along the finger, when moving closer to the object (Figure 9.3k) and a circular stimulus, with radius modulation (Figure 9.3l), such that the circle becomes smaller when closer to the object.

9.4.4. *Task*

In the study, participants were tasked with exploring a stimulus and rating their perception of a distant object and its pseudo-magnetic properties. Virtual reality was used to control the environment from other objects and the view of the haptic devices. The stimulus originated from a sphere with a diameter of 10 cm, posing as the distant object. Participants could at any time see a virtual representation of their hand and, during the trial, see the virtual object, as depicted in Figure 9.4. The virtual object was placed 70 cm away from the participant (i.e., out of arms reach) at approximately chest height. Participants were asked to move their hands to an initial starting point, indicated by a translucent hand. Afterwards, they could freely explore the stimulus by moving their hand towards and away from the object for 20 seconds. When that time had passed, the participants were asked to answer a questionnaire.

The questionnaire consisted of four 5-point Likert scale questions, as listed in Table 9.1. In the first two questions, participants were asked to rate their perception of the distant object, both in terms of their feeling of the object and the object reacting to their input (hand movements). We ask these questions to find evidence of whether the participants can connect the haptic stimulus to the object at a distance and feel that the stimulus is changing in relation to their movement, which is important for Principle 2. In the last two questions, participants were asked to rate the degree to which they felt the pseudo-magnetic properties of the stimulus. These questions relate to the perception of pseudo-magnetism and give a first indicator of whether the stimuli can be perceived as feeling attractive, repulsive, or both.

9.4.5. Procedure

Participants were welcomed and seated at a desk with all haptic devices visible. The participants were introduced to the purpose of the study, emphasising that they should be aware of the haptic interaction between them and the virtual object present in the task, but without explicitly mentioning magnetism-related terms (e.g., attraction, repulsion, pull, push). This approach was taken to help the participants focus on understanding the intention behind the designed stimuli, allowing them to answer the questionnaire with the haptic stimulus in mind. After this, participants filled out an informed consent form and a demographics questionnaire. Participants entered the virtual environment and were introduced to a haptic device by trying a sample stimulus before trying the device. The sample stimulus was not from the set of designed stimuli but rather a haptic stimulus with maximal intensity on the palm of the hand. Participants could control for how long they would feel the sample stimulus. Each time the task was completed on a device, the participant could remove the virtual reality display so as to see (and equip themselves with) the next haptic device. After

Table 9.1. Questionnaire used to assess the qualities of the haptic stimuli.

Question	5-point Likert scale answer options				
I felt the object at a distance	Never	Rarely	Sometimes	Often	Always
The object reacted to my movement	Never	Rarely	Sometimes	Often	Always
The object was pushing my hand away	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
The object was pulling my hand towards it	Strongly disagree	Disagree	Neutral	Agree	Strongly agree

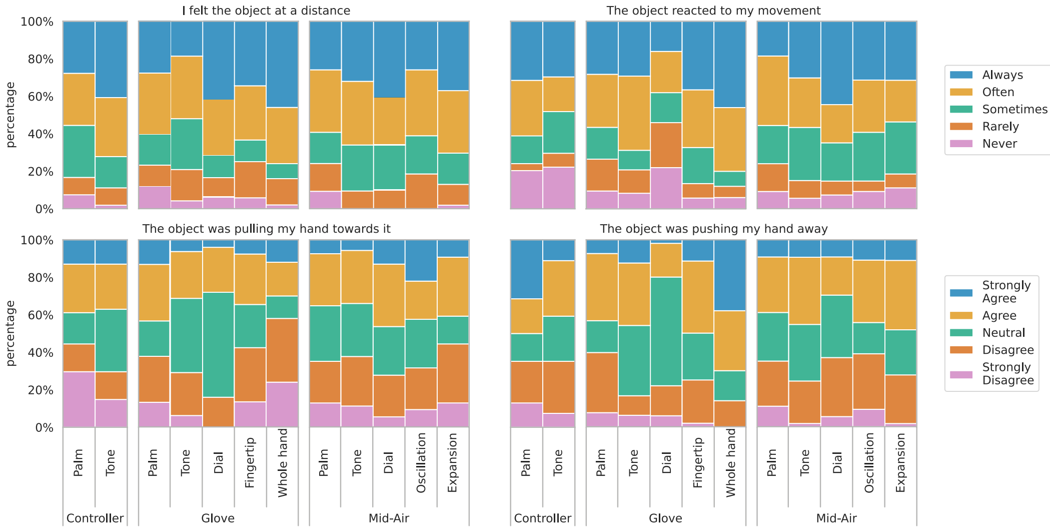

Figure 9.5. The frequencies of the ratings for each of the four questions on their respective 5-point scales across the 12 stimuli. Ratings were obtained from 18 participants.

all trials were completed, participants were informed about the intention of Haptic Magnetism and could ask questions and leave comments to the experimenter.

9.4.6. *Data Processing*

We started the data analysis by removing outliers. We considered as outliers those participants whose ratings varied extremely little across stimuli. These ratings could be different among the questions but consistent across the stimuli for each question (e.g., always strongly agreeing to feeling an object at a distance and always disagreeing to feeling a pull). With three repetitions to each stimulus and 12 stimuli, such consistency was strikingly visible among individual plots of the ratings. To confirm this perception, we marked participants as outliers if the mean standard deviation of their rating fell below the threshold of one-third. There were three such outliers.

9.4.7. *Results*

In this section, we report the results of Study 1. First, we explain our method for data processing and analysis. Then, to investigate which stimuli are best suited to provide a sense of Haptic Magnetism, we analyse the ratings for the four questions. We analyse how participants rated the 12 stimuli using the four questions, and what may the interactions between the ratings imply about the Haptic Magnetism of the stimuli. To investigate the interactions among the stimulus ratings we use a repeated measures ANOVA to find significant differences. Where we find significance, Tukey's post hoc test is used to test for individual differences. The data is available at osf.io/62pyj [69].

9.4.7.1. Feeling a virtual object. Figure 9.5, top row, presents the distributions of the ratings for each stimulus in the first two questions about feeling a virtual object. Here, we analyse these ratings and their frequencies.

The frequencies of the ratings show that the participants experienced feeling the object at a distance in most of the stimulations. They answered the question *"I felt the object at a distance"* (Figure 9.5, top left) with "Often" or "Always" on average 64.60% (std: 7.03) of the stimulations. Out of the 12 stimuli, the [Glove, Whole Hand] stimulus was felt most frequently (76% of the stimulations) at a distance. However, Tukey's post hoc test showed no significant differences among the 12 stimuli.

Similarly often, the participants experienced the feeling that the object reacted to their movement (Figure 9.5, top right). They answered the question *"The object reacted to my movement"* with "Often" or "Always" on average 59.15% (std: 10.67) of the stimulations. Again, the [Glove, Whole Hand] stimulus was felt most frequently (80% of the stimulations) to react to their movement. The ANOVA revealed a significant difference in absolute value of ratings (on the 5-point scale from "Never" to "Always") for this question ($F(11, 618) = [2.99]$, $p < .01, \eta^2 = 0.02$). The post hoc test showed significantly lower ratings for the [Glove, Dial] stimulus compared to the [Mid-Air, Dial] ($p < .01, 95\%\ C.I. = [0.17, 1.85]$) the [Glove, Finger] ($p < .01, 95\%\ C.I. = [0.14, 1.83]$) and the [Glove, Whole Hand] ($p < .01, 95\%\ C.I. = [0.36, 2.08]$) stimulus.

9.4.7.2. Feeling a push and a pull. Figure 9.5, bottom row, presents the distributions of the ratings for each stimulus in the two questions about feeling the virtual object pull or push.

The frequencies of the ratings show, that the participants experienced feeling a push or a pull less in than half of the stimulations. The participants answered the question *"The object was pulling my hand towards it"* (Figure 9.5, bottom left) with "Agree" or "Strongly agree" on average 36.83% (std: 5.7) of the stimulations, and the question (*"The object was pushing my hand away"*) on average 43.86% (std: 12.02) of the stimulations.

There are no significant differences among the 12 stimuli in the absolute values of ratings (on the 5-point scale from "Strongly Agree" to "Strongly Disagree") of feeling a pull. The ratings for push, however, showed a significant effect ($F(11, 618) = [3.12]$, $p < .01$, $\eta^2 = 0.02$) higher for the [Glove, Whole Hand] stimulus than the [Mid-Air, Dial] ($p < .01, 95\%\ C.I. = [0.26, 1.69]$), [Mid-Air, Oscillation] ($p < .01, 95\%\ C.I. = [0.15, 1.58]$), [Mid-Air, Palm] ($p < .01, 95\%\ C.I. = [0.21, 1.64]$), [Glove, Palm] ($p < .01, 95\%\ C.I. = [0.18, 1.62]$), [Glove, Dial] ($p < .01, 95\%\ C.I. = [0.27, 1.73]$), and [Controller, Tone] ($p < .01, 95\%\ C.I. = [0.13, 1.56]$) stimuli.

The frequency distributions for pulling and pushing do not seem consistent across stimuli: the participants often rated pull and push equally high, or the ratings varied between the trials within the same stimulations. Many participants commented in the experiment, that for some stimuli they found it hard to judge whether they felt a pull towards or a push away from the object. This is also reflected in the high mean standard deviations for the ratings (1.18 for pulling and 1.10 for pushing).

9.4.7.3. Feeling Magnetism. Next, we determine what the ratings of push and pull may imply about experiences of magnetism with the 12 stimuli. Figure 9.6 presents four types of interactions between the frequencies of ratings of "Agree" or "Strongly Agree" to the feeling of push or pull.

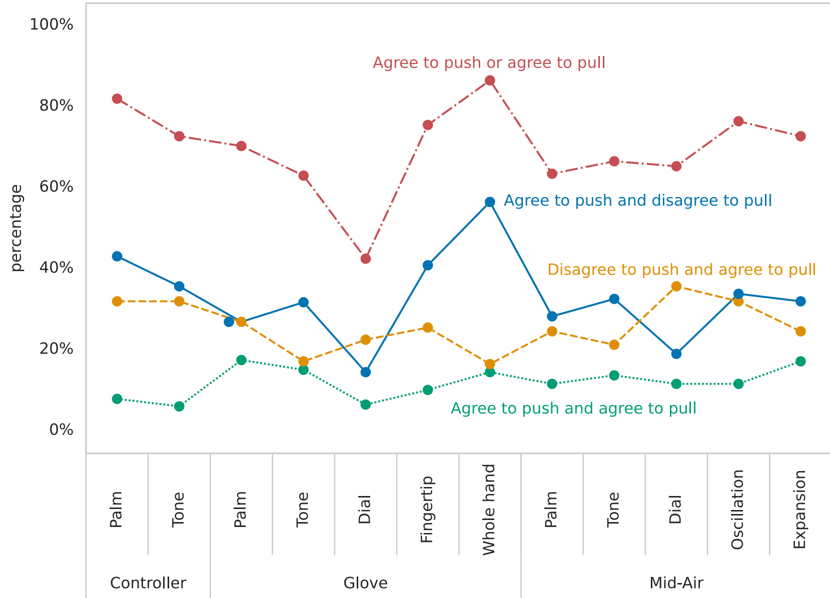

Figure 9.6. Frequency of answer combinations for each stimulus. For instance, the green line ······ shows the frequency of participants disagreeing to both feeling a pulling and a pushing sensation. Ratings were obtained from 18 participants.

Overall, all but [Glove, Dial] stimulus are most often (over 50 of the stimulations) rated to convey sensations of a pull or a push. The red line -·- shows those frequencies of rating either pull or push high ("Agree" or "Strongly Agree"). Therefore, the peaks on this line indicate that the stimulus in question most frequently conveys experiences of magnetism in some direction (pull or push). Similarly, the peaks on the green line ······, which shows the frequency of the participants rating both pull and push high, indicate that those stimuli most frequently convey experiences of magnetism but do that in both directions. The frequencies here are lower as it is less common to agree on both the sensations of pull and push.

The highest point for the controller on both the red -·- and the green ······ lines is the [Controller, Palm] stimulus. In addition, the [Controller, Palm] stimulus seems to also convey a clear sense of the direction of magnetism, because the difference between the frequencies of the experiences of pull and push are also larger than in the [Controller, Tone] stimulus. This can be seen with the yellow line - - which shows the frequency of the participants rating pull high but push low, and the blue line — which shows the frequency of the participants rating push high but pull low. The [Controller, Palm] stimulus frequently conveys an experience of push.

The highest point on the red line -·- for the haptic glove is the [Glove, Whole Hand] stimulus, indicating that it most frequently conveys a sense of magnetism in some direction. The third highest point on the red line -·-, [Glove, Palm], is more frequently experienced to provide a sense of magnetism to both directions as indicated by the green line ······. Yet, the clearest sense of the direction of magnetism is provided by the [Glove, Whole Hand] stimulus, as the blue line — shows, conveying an experience of push.

The highest point on the red line -·- for the mid-air haptic device is the [Mid-Air, Oscillation] stimulus. However, the [Mid-Air, Expansion], which is the second highest point on the red line -·-, most frequently provides a sense of magnetism to both directions as indicated by the green line ·····. The [Mid-Air, Expansion] also conveys a clearer sense of push (the difference between the blue — and the yellow - - lines) than the [Mid-Air, Oscillation] stimulus.

We further explored the interactions between the ratings through correlations. Ratings about the pull and push sensations are weakly to moderately negatively correlated (mean: –0.30, std: 0.19). Both [Glove, Whole Hand] and [Controller, Palm] are moderatly negatively correlated, with correlation coefficients of –0.54 and –0.56 respectively. This shows that participants often treat the questions as being opposed, for instance by agreeing to feeling a pull and disagreeing to feeling a push.

9.4.7.4. Summary. This study aimed to show that participants can gain a sense of distant objects through a set of haptic stimuli. Since participants are agreeing to the statements *"I felt the object at a distance"* and *"The object reacted to my movement"* for many stimuli, we show that participants feel objects at a distance through most of the designed stimuli. Thus, we show that it is possible to design stimuli that induce a sensation of distant objects, providing evidence for Principles 1 and 2. We also show that participants can gain a sensation of pseudo-magnetism, as agreement towards feeling a pulling or a pushing experience is high, but participants are not in agreement on the mode. It is thus unclear still, whether Principle 3 holds. We have shown the aim of the study, but have also identified a need to investigate how to induce pseudo-magnetic experiences.

9.5. Study 2: Validating Pseudo-Magnetic Experiences

The goal of the second study is to find how pseudo-magnetic experiences can enable interactions with distant objects (Principle 3). We chose three stimuli to induce pseudo-magnetic experiences, which in the first study were rated to provide the strongest magnetic sensations of objects at a distance. A novel set of participants perform two interactive tasks that represent the use cases of Haptic Magnetism: (1) selecting which of two objects magnetically attracts (Figure 9.1c-d), and (2) locating the source of magnetic attraction on a plane (Figure 9.1a-b).

9.5.1. Participants

We invited 15 participants to complete the two tasks in the study. The participants were aged between 24 and 35 (mean: 27.47, std: 3.40). Seven participants self-reported being female and eight being male. The experiment took 43 minutes on average to complete. All participants were rewarded with a gift valued at $25.

9.5.2. Study Design

The second study followed a within-subject design with the two tasks and the stimulus as an independent variable. In the first task, the participants chose which of the two visually identical objects felt attractive to them. The objects emitted either attractive, repulsive, or neutral versions of one of the three stimuli. The neutral means no haptic stimulation is provided. The attractive and repulsive are opposites for each stimulus. For example, in the case of the [Controller, Palm] stimulus, the attractive cue is a weak intensity when close to the object and strong when far away, and the repulsive cue is the opposite. As the object's location on the left and right may also influence the choice, we posed six conditions for each of the three stimuli (two objects and three versions of the stimulus): neutral-attractive, attractive-neutral, neutral-repulsive, repulsive-neutral, attractive-repulsive, repulsive-attractive. We repeat these conditions three times for a total of 18 trials with each stimulus. The order of the three stimuli is counterbalanced so that the tasks are performed with one device at a time, and the order of the 18 trials within the stimuli was always fully randomised.

In the second task, the participants received only the attractive cue from each of the three stimuli and were asked to locate the source of the stimuli on a plane. This task was always performed last because getting to know only the attractive cue here could have primed the participants to always choose that in the selection task. The task of locating the stimulus on the plane was performed 15 times for each of the three stimuli. The source of the stimulus on the plane was fully randomised.

9.5.3. Selection of Stimuli

We selected one stimulus for each device based on their ratings in the first study. For the controller, we chose the [Controller, Palm] and for the haptic glove the [Glove, Whole Hand] stimulus, as they most frequently provided the sense of magnetism to either direction and also the clearest sense of direction (pushing away from the object). For the mid-air haptic device, we chose the [Mid-Air, Expansion] stimulus, as it most frequently provided the sense of magnetism to both directions, and here as well more frequently toward pushing away.

As all of the three selected stimuli are rated more frequently to provide a pushing sensation, we use those as the repulsive versions of the stimuli. To induce an experience of attraction, we reversed them. Thereby, in the attractive versions, the intensities of the [Controller, Palm] and the [Glove, Whole Hand] stimuli are decreasing and the diameter of the circular pattern in the [Mid-Air, Expansion] stimulus is expanding, when moving closer to the object.

9.5.4. Tasks

The purpose of the first task is to investigate whether attraction can be distinguished from repulsive and neutral variations of the stimuli and thereby used as a sole source of information in decision making. Additionally, the results of this task should reveal whether a stimulus can be reversed and thus be used for both attraction and repulsion. In the task, the participants were asked to select which virtual object among two objects 30 cm apart felt attractive to them (Figure 9.7). The selection is made by taking the dominant (virtual) hand close to an object, and when it highlights as an indication of closeness, pressing a button on a controller in the non-dominant hand to confirm the selection. For each trial, we log the selection and measure the completion time from starting the trial to selecting one of the spheres.

The purpose of the second task is to find how accurately the origin of an attractive stimulus can be located and thereby used as a sole source of information for locating objects. In the task, the participants were asked to point out a location on a white 30×30 cm plane at which they believed the stimulus had its source (Figure 9.8). The selection was made by placing a small cursor that moved on the plane below the centre of the participant's (virtual) palm on the desired location and confirming the selection by pressing a button on the controller in the non-dominant hand. For each trial, we log the location of the selection and calculate the selection error as a distance to the actual origin of the stimulus and the completion time from starting the trial to selecting the location.

9.5.5. Procedure

The experimenter welcomed the participants and they filled out an informed consent form and a demographics questionnaire. Participants were introduced to Haptic Magnetism as a concept and were explained how the haptic stimuli would be rendered on their dominant hand. Then, the participants entered the virtual environment and were introduced to a haptic device by trying a sample stimulus, similar as in the first study. Again, the sample stimulus was not from the set of designed stimuli, but rather a haptic stimulus with maximal intensity on the palm of the hand. Each task was introduced shortly before the start of the task. For the first task, the experimenter emphasised that the participant should pick the attractive stimulus and that they should go after their intuition. For the second task, the experimenter emphasised that the precision of the selection was important for the task. Each time a set of trials was completed on a device, the participant could remove the virtual reality display, as to see (and equip themselves with) the next haptic device. After all trials were completed, participants could ask questions and leave comments to the experimenter.

9.5.6. Data Processing

There were no outliers detected in the data collected in the second study.

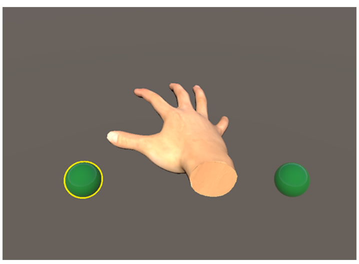

Figure 9.7. The virtual reality used in the first task of the second study. A participant is moving their hand toward one of two virtual objects. The yellow highlight shows the object closest to the hand.

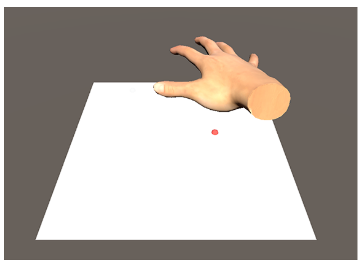

Figure 9.8. The virtual reality used in the second task of the second study. A participant is moving their hand to locate a magnetic stimulus.

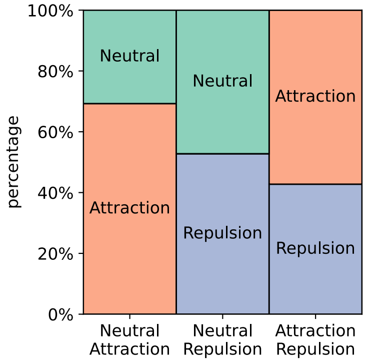

Figure 9.9. Frequency distribution of selected stimuli in the first task.

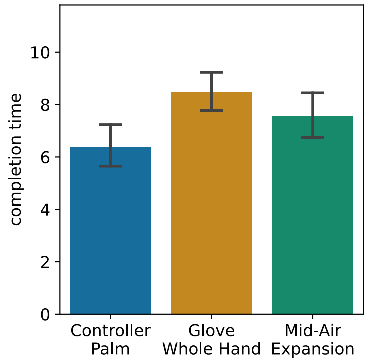

Figure 9.10. Time in seconds used to select a stimulus in the first task. Error bars show 95% CI.

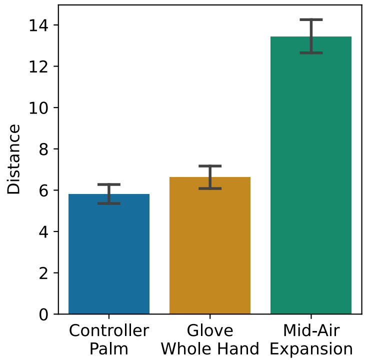

Figure 9.11. Distance in centimetres between stimulus source and selected location in the second task. Error bars show 95% CI.

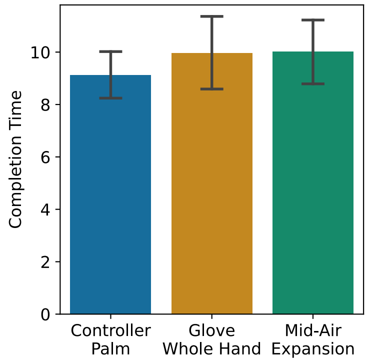

Figure 9.12. Time in seconds used to locate a stimulus in the second task. Error bars show 95% CI.

9.5.7. Results

To investigate whether attraction can be distinguished from repulsive and neutral variations of the stimuli, we first analyse the results from the selection tasks. We then analyse how accurately the origin of an attractive stimulus could be located in the second task. The data is available at osf.io/62pyj [69].

9.5.7.1. Selection task. Figure 9.9 shows the frequency distribution of whether participants selected an attracting over a neutral stimulus, a repulsing over a neutral stimulus, and an attracting over a repulsing stimulus. These frequencies show that the participants selected the attracting stimulus over the neutral stimulus in (69.26%) of the trials and an attracting over a repulsing stimulus in (57.25%) of the trials. This suggests that attraction can be distinguished from repulsion and neutral in a forced-choice task, although in the ratings of Study 1 the distinction was often less clear. Participants also tend to pick haptic stimulation over no haptic stimulation (attraction 69.26% and repulsion 52.77% over neutral). This suggests that to induce experiences of magnetism, the reverse

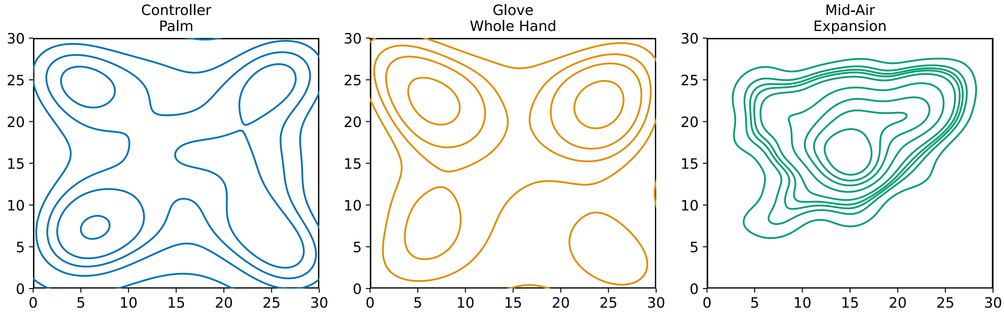

Figure 9.13. Distribution of selected stimulus location, grouped per stimulus. The locations are plotted as a kernel density estimation, showing the likelihood of where participants supposed the source of the stimuli. The box around the distribution shows the 30 × 30 cm boundary in which the participants could select locations.

stimuli among these three tested ones would work better than no stimuli at all. We found no significant differences with an ANOVA in the time participants used to choose a stimulus (Figure 9.10).

9.5.7.2. Precision task. Figure 9.11 shows the distances between the selected location and the true source of the attractive stimuli. These distances show, that the participants were able to locate an object based on their experience of an attractive stimulus. Both the [Glove, Whole Hand] stimulus and the [Controller, Palm] stimulus perform well with an average error of 6.64 cm (std: 4.08) and 5.91 cm (std: 3.49), respectively, in locating the source of the attractive stimulus. However, the [Mid-Air, Expansion] stimulus provided little or no help for locating the source, having a 13.50 cm (std: 5.79) error on the 30 x 30 cm plane with targets spun randomly across it.

Figure 9.13 shows the distribution of the selected locations on the plane for each stimulus. Here we see that participants generally estimated the [Mid-Air, Expansion] stimulus to be in the centre of the boundary. This suggests that participants, as also seen in Figure 9.11, find it difficult to locate the source of the [Mid-Air, Expansion] stimulus, and usually select a rather central location, perhaps reflecting the insecurity in detecting the source. In contrast, the estimated sources of [Glove, Whole Hand] and the [Controller, Palm] stimuli are distributed more evenly across the boundary, although showing that participants generally estimated the source to be in one of the four quadrants of the plane. We found no significant differences with an ANOVA in the time participants used to choose a stimulus (Figure 9.12), suggesting that participants are equally thorough in performing the task with all stimuli. The time spent on this task is slightly higher than in the previous task, reflecting the instruction that participants should focus on the precision of their estimation.

9.5.7.3. Summary. The aim of Study 2 was to show that pseudo-magnetic experiences can enable interactions with distant objects, to show that Principle 3 holds. We find that participants can distinguish pseudo-magnetic modes when prompted, showing that participants gain an experience of pseudo-magnetism. As a result of the second task, we show that participants can estimate the location of a pseudo-magnetic stimulus accurately, implying how these experiences can enable interactions with distant objects. With these two findings, we gain evidence for Principle 3.

9.6. Discussion

We have conceptualised Haptic Magnetism, which enables users to gain a sense of objects at a distance. Here, we first discuss the feasibility of Haptic Magnetism, which we investigated in two studies. We then discuss how to design pseudo-magnetic stimuli to extend the presented designs. Finally, we discuss the kinds of applications seen in previous work which, if altered to use pseudo-magnetism, could benefit from Haptic Magnetism.

9.6.1. The Feasibility of Haptic Magnetism

Haptic Magnetism is an interaction modality that extends a user's sense of touch to enable interactions with objects at a distance. The modality operates by three principles:

1. Haptic Magnetism relies on providing tactile stimuli to the haptic sense.
2. Haptic Magnetism delivers sensations of objects at a distance.
3. Haptic Magnetism enables interactions through experiences of pseudo-magnetic attraction and repulsion.

As discussed earlier, these three principles are the foundation of Haptic Magnetism, guiding the design of pseudo-magnetic stimuli. Thus, if we show these three principles to be feasible, we show that Haptic Magnetism is feasible. The designs presented and evaluated as part of the first study show the feasibility of Principle 1. We show that it is possible to design tactile stimuli that do not rely on force or kinesthetic feedback but still deliver sensations and experiences as sought for by Principles 2 and 3. We have shown that there exist haptic stimuli, that can deliver a sense of attraction and repulsion at a distance. An instance of this is the [Glove, Whole Hand] stimulus.

Participants gain a sense of the object at a distance through tactile stimulation and feel that the object interacts with them as they move their hands in the first study. By extension, we show Principle 2. In the first study, participants felt sensations of being pulled towards or pushed away from an object.

The notion of attraction and repulsion is confirmed in the first task of the second study by a different set of participants. We also show that participants can extract information from the haptic stimulus in the second task, allowing them to locate objects without audiovisual feedback. Together this shows that Principle 3 holds, as interactions can be enabled through the information, rendered haptically as a pseudo-magnetic attraction or repulsion, gathered from the environment.

With our approach to evaluating the perceptual qualities of Haptic Magnetism, we study the basic feeling of pseudo-magnetism. This feeling is solely induced through the sense of touch. In that way, we have shown that foundational aspects of the concept hold.

9.6.2. Designing Stimuli for Haptic Magnetism

Haptic interactions are getting integrated into audiovisual computer systems allowing for richer user experiences. Often these haptic interactions are associated with proximity and intimacy [298], as well as mimicing realism [206, 275]. For the concept of Haptic Magnetism, we have drawn inspiration from the works of Sadeghian and Hassenzahl [329] and Willett et al. [412], who in turn are inspired by comics of superheroes and their superpowers to enhance visual interactions in virtual reality and visualisations. Engaging with works of fiction can help designers start a creative process also when designing non-realistic haptic stimuli. Users of these non-realistic stimuli have shown to accept and engage with them in the two works on visual feedback, but also when asked about their experience of mid-air haptic stimuli [63]. Therefore, while designing non-realistic stimuli is not trivial, they carry a promise of new experiences.

Based on our two studies, we recommend designers consider three factors when designing pseudo-magnetic stimuli:

(1) *We recommend considering the relationship function that modulates the value of stimuli parameters.* The function describes a relationship between the user and the object, such as distance or direction. The relationship should be relevant to the interaction. Possible parameters to modulate include intensity, size of a haptic shape, or stimulus location.

We created the 12 stimuli presented in Study 1 for Haptic Magnetism. The stimuli are designed to convey a sense of the distance between hand and object through different haptic patterns and modulations. As the studies show, some stimuli induced a sense of object at a distance and of magnetic properties. Thus, while we seem to be on the right track, there might be designs that more strongly induce pseudo-magnetic sensations.

Our designs are based on a linear function describing the distance relationship between the user's hand and a virtual object. That is, all stimuli are implemented with at least one distance-dependent design parameter. For instance, the drawing speed of a circle is dependent on the distance between hand and object in the [Mid-Air, Dial] stimulus. This approach proved promising in the first study, but alternative functions that could produce a stronger sense of magnetism remain future work. For example, the design of the relationship function could be non-linear or be dependent on another relation (e.g., direction) or a combination thereof. If the function were exponential, designers could archive a sudden strong magnetic sensation, similar to when two physical magnets get close and "snap" together.

(2) *We recommend considering the haptic device used for the pseudo-magnetic stimulus.* As haptic devices have different modes of stimulation and intended functionality, we suggest implementing Haptic Magnetism on devices used for other interactions in the created application. In virtual reality, controllers are often used to interact with the virtual environment, so it is apparent to use such devices for pseudo-magnetic effects. Our studies show that a standard controller is a promising device for inducing pseudo-magnetism. In augmented reality or the real world, a mid-air haptic device is an option, as it is less intrusive than the other presented haptic devices. However, the imprecision of the [Mid-Air, Expansion] stimulus should be considered.

In our 12 designs, the haptic stimuli depend on the capabilities of the device, although some characteristics and parameters are translatable between devices. The stimuli are limited in design by the device inducing the haptic sensation. The controller can only vibrate its whole casing, simulating the whole hand at once, while the haptic glove can stimulate the fingertips and palm, but only in specific areas. The ultrasound mid-air haptic device can stimulate anywhere on the hand, although with limited concurrency, intensity, and interaction space. But, even with these limitations, the devices were shown to be feasible for Haptic Magnetism. Introducing Haptic Magnetism to less generic devices can increase the performance of the modality but with decreased device versatility. Such devices could employ asymmetric vibrations, similar to those of Culbertson et al. [61], or kinesthetic feedback, to shear the skin and thereby guide users as implemented in the Haptic Revolver [411], to induce a sense of magnetism.

(3) *We recommend considering the spatial span of the pseudo-magnetic effect.* This span relates to the distance at which the relationship function reaches its maximal and minimal values. We suggest adjusting the span to the modulated parameter since subtle changes in intensity are hard to perceive for users. Generally, a small span should be used only to deliver precise information.

In the second study, we were limited by the interaction space of the mid-air haptic device, which is an approximately 50 × 50 × 50 cm large imagined box 15 cm above the device, where a lot of intensity is lost at the edges of this boundary. Thus we sought to create two tasks that could be implemented using the mid-air haptic device. As a result, the first task was limited to two objects, as they needed appropriate spacing such that participants could feel the distinct magnetic stimulus over a distance. The interaction space of these stationary devices can be extended by using systems like PUMAH [167], but as we used off-the-shelf devices, this work is limited to standard use.

It is not immediately obvious how to generalise a specific stimulus design to a new device, as stimulus and device are confounded. We see an indication of a correlation between the area of skin stimulated and the perceived strength of pseudo-magnetism in the results of Study 1. Although this hypothesis needs further investigation, such a correlation can help designers start their process of designing stimuli. During the studies, participants generally stated that the mid-air haptic feedback felt less clear and intense. They cited this as a reason for their difficulty locating the source of the pseudo-magnetic stimuli in the second task of Study 2. Although only anecdotal evidence from participants' statements, this could be part of the reason for worse performance in the same task. Thus, when designing for Haptic Magnetism, designers should design clear and intense stimuli to induce magnetic sensations.

9.6.3. Designing Interactions with Haptic Magnetism

We envision Haptic Magnetism to become an extension of and alternative to existing interaction modalities. Additionally, Haptic Magnetism allows for novel interactions previously restricted by the limits of other sensory modalities. Haptic Magnetism has flexible uses, as seen in the examples of applications we presented earlier (for instance, in Figure 9.1). We see the use of the modality within guidance, navigation, nudging, and discovering affordances or feedforward interactions. This is likely an incomplete list, but we hope that Haptic Magnetism can act as a framework for designers to create new haptic experiences through pseudo-magnetic stimulation. We provide the following ideas for future work:

(1) *Using Haptic Magnetism in with other interaction modalities.* Our approach to investigating the perception of the stimuli, contrary to showing their practical use, helps to consolidate a strong foundation for the concept on which future designs of stimuli and applications can stand. We investigated

the perception of pseudo-magnetic haptic stimuli and thereby showed that the concept of Haptic Magnetism is feasible. Haptic Magnetism only relies on the haptic sense and is thus usable outside of common audiovisual interfaces, such as augmented or virtual reality devices and smartphone or desktop interfaces. The concept can, however, be used in conjunction with these interfaces. Exploring how Haptic Magnetism could, combined with other interaction modalities, allow for richer experiences remains future work.

(2) *Providing an intuitive and clear sense of attraction and repulsion.* Through our studies, we show that users can feel haptic stimuli to be magnetic when prompted. They seem to build an intuition of which stimuli they find attracting or repulsing, although they might not always be certain on the mode. As a part of the results of the first study, we see that participants are not consistent in their rating of feeling a stimulus to attract or repulse them towards an object. This could be due to the purposely limited instructions given and the freedom to rate the stimuli simultaneously on both scales of pulling and pushing. The second study already suggested a clearer sense of attraction when the participants encountered a forced-choice task between the two options. The clarity of attraction could be further increased by providing a reference by letting participants try out a real-world magnet before the study. However, such extensive instruction would defeat the idea of Haptic Magnetism not mimicking reality and yet being intuitive. Yet, other types of instructions or prompts for learning the meaning of the stimulations could enhance the clarity of sensations. This too remains future work. We thus hypothesise that users may gain a greater sense of magnetic stimuli when receiving specific instructions on which stimulus is attracting or repulsing, for instance, through an application tutorial.

(3) *Testing the concept of Haptic Magnetism in new applications and tasks.* We have suggested multiple application areas for Haptic Magnetism. The studies do not address all possible application areas we discuss, as the concept is novel and flexible in its use-cases. Replicating tasks and studies by other researchers working on these areas would help validate our suggestions. For instance, replicating the tasks developed by Lopes et al. [240], designed to evaluate "Affordance++", with Haptic Magnetism instead of electronic muscle stimulation is an option to show the usefulness in the discovery of affordances, using a more subtle form of feedback. The feelSpace belt [278] could be extended to also repulse from navigating in the wrong direction to show the usefulness of Haptic Magnetism in larger environments, such as the real world. Haptic Magnetism could also be implemented in a scene with many magnetic objects. Lilija et al. [233] investigated interactions in occluded areas by creating a view of the area in augmented reality. Replicating the task on this work while using pseudo-magnetic stimuli instead of visual stimuli, or using them in combination, could show the usefulness of Haptic Magnetism in occluded interactions and for multi-modal interactions. Tasks here include placing, dragging, and rotating objects, which also are interesting use cases for Haptic Magnetism. Thus, while this concept passed a hard feasibility test as a sole interaction modality, its application in combination with other modalities and in specific tasks and application areas remains future work.

9.7. Conclusion

Haptic technologies allow us to feel virtual objects, mimicking the experience of contact with a surface of a physical object. In this paper, we break open a design space for abstract haptic stimuli previously under-explored by the haptics community. We present *Haptic Magnetism*, an interaction modality allowing users to interact with distant objects through experiences of pseudo-magnetic attraction and repulsion. We show that Haptic Magnetism enables novel interactions solely through haptic stimuli and finds applications also outside audiovisual interfaces.

Acknowledgements

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9.8. Supplemental Material

9.8.1. *Haptic Devices*

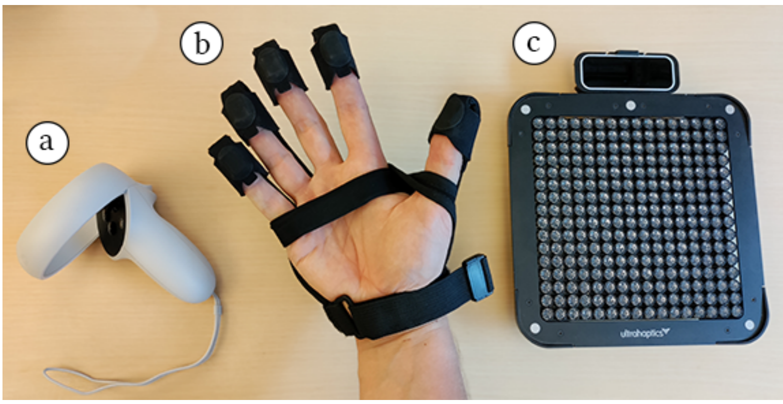

Figure 9.14. The three devices used in the study: (a) a virtual reality controller, (b) a haptic glove, and (c) a mid-air haptic device.

We used three different devices, controller, glove, and mid-air since each of them has a different level of versatility in producing skin vibrations on the hand. The first device was a hand-held *controller* with a vibration motor, representing the most common haptic feedback device, as found in mobile phones and game controllers. The second was a haptic *glove* with multiple vibration motors meant for use in augmented and virtual reality. The third was a *mid-air* haptic device, which induces skin vibrations through ultrasonic sound waves anywhere on the hand. When using the *controller* device, participants held the Meta Touch 2 Controller by Meta[11] (Figure 9.14a), a virtual reality controller equipped with one vibration motor in its casing. When using the haptic *glove* device, participants wore the Forte Data Gloves by BeBop Sensors[12] (Figure 9.14b), a haptic glove capable of

[11] https://store.facebook.com/quest/products/quest-2/, accessed 01.12.22
[12] https://bebopsensors.com/arvr/, accessed 01.12.22

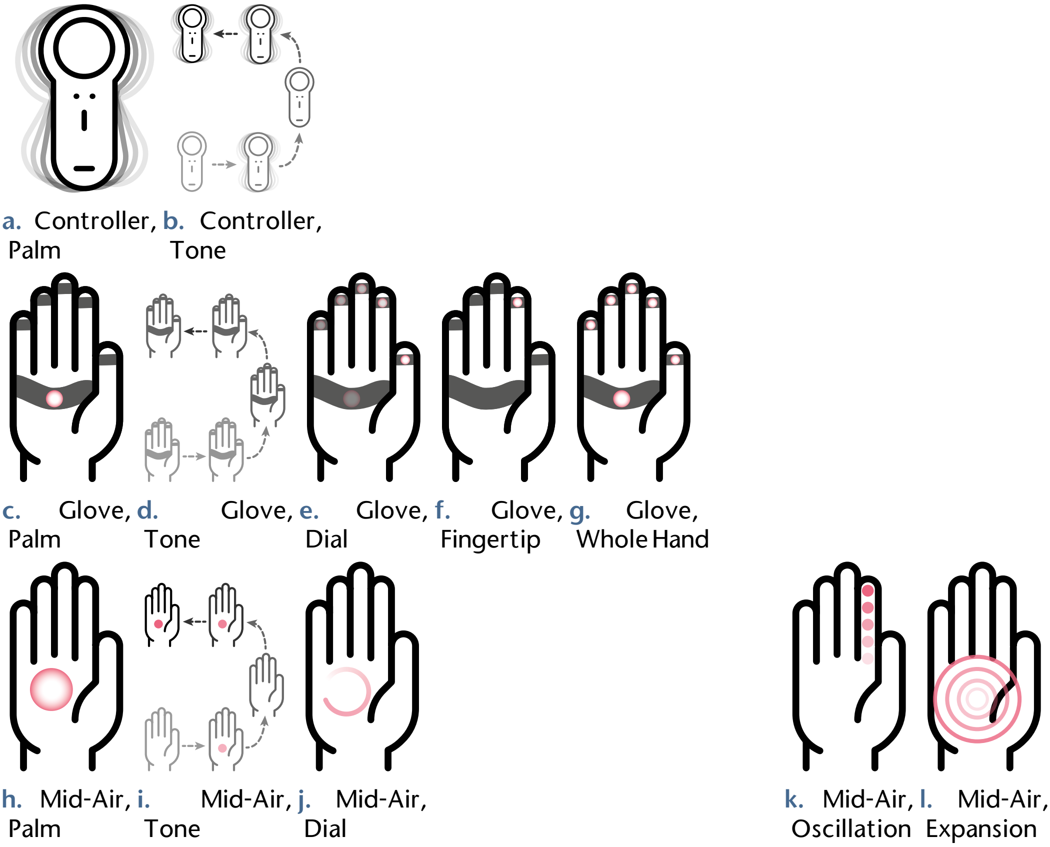

Figure 9.15. The 12 candidate designs for pseudo-magnetic haptic stimuli. Rows indicate the haptic device used to induce the stimulus, and columns indicate the comparable haptic stimuli across devices.

stimulating all fingertips and the palm with vibrotactile actuators. These actuators have a frequency range of 100 Hz to 2kHz. When using the *mid-air* haptic device, participants were stimulated with the STRATOS Explore by Ultraleap[13] while tracked with a LeapMotion by Ultraleap[14] (Figure 9.14c). This device can stimulate the human hand at any given position using ultrasound to vibrate the user's skin, and we can stimulate the full frequency range of tactile receptors in the human skin (approx. 1 Hz-1kHz; [59, 110]). All haptic feedback was rendered on the participant's dominant hand. The study was conducted in virtual reality, using a Meta Quest 2 by Meta head-mounted display[15]. The virtual coordinate space was aligned with the coordinate space of the mid-air haptic device by aligning the output of the Meta Quest's built-in hand tracking and the LeapMotion's hand tracking.

[13] https://www.ultraleap.com/product/stratos-explore/, accessed 01.12.22
[14] https://www.ultraleap.com/product/leap-motion-controller/, accessed 01.12.22
[15] See footnote 11.

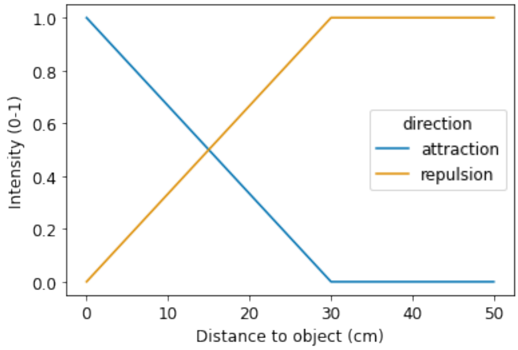

Figure 9.16. Intensity modulation of the stimuli shown in Figure 9.15a, Figure 9.15c, and Figure 9.15h.

9.8.2. Haptic Stimuli

For the study, we designed 12 haptic stimuli for the three devices. The stimuli are visualised for reference in Figure 9.15. In this section, we will describe the details of the implementation.

All stimuli have a similar structure in that we modulate design parameters based on the distance between the user's hand and the surface of an object. We use a linear modulation function, where the modulation to produce "attraction" stimuli are inverted from "repulsion" stimuli.

$$f(x) = (x - b_{min})/(b_{max} - b_{min}) \tag{9.1}$$

$$r(x) = \begin{cases} v_{min} & x < b_{min} \\ v_{max} & x > b_{max} \\ f(x) & \text{otherwise} \end{cases} \tag{9.2}$$

$$a(x) = \begin{cases} v_{min} & x > b_{max} \\ v_{max} & x < b_{min} \\ f(x) & \text{otherwise} \end{cases} \tag{9.3}$$

where x is the distance, b_{min} and b_{max} are the distance boundaries of the haptic feedback, and v_{min} and v_{max} are the min and max value of the modulation (e.g., for intensity the values are between 0 and 1). Equation (9.2) describes the modulation for repulsion, while Equation (9.3) describes modulation for attraction. In the first study, we used $b_{min} = 20$ and $b_{max} = 60$ (in centimeter) for all stimuli, as the target was 70 cm away from the participant. In the second study, we used $b_{min} = 0$ and $b_{max} = 40$ (in centimeter) for all stimuli. In our implementation, the distance measure was computed at 120 Hz.

Where nothing else is stated, the controller intensity and frequency are set to max. What that means is unclear, as the manufacturer does not share details about the vibration motors built into the controller. The glove The mid-air stimuli, by default, use a small circle with a diameter of 1 cm, and we render patterns using spatio-temporal modulation (STM) [106]. The circle is rendered with a drawing frequency of 64 Hz.

For the three stimuli centred on the palm ([Controller, Palm] (Figure 9.15a), [Glove, Palm] (Figure 9.15c), and [Mid-Air, Palm] (Figure 9.15h)) the intensity is modulated based on the distance to the object. In essence, the intensity will increase linearly when the haptic device is moved closer to the object. Here we use Equation (9.2) and Equation (9.3), with $v_{min} = 0$ and $v_{max} = 1$, where 0 denotes no haptic feedback, while 1 is maximal vibrotactile intensity. The plot in Figure 9.16 shows the function for intensity modulation.

For the three stimuli with changing periodical beat ([Controller, Tone] (Figure 9.15b), [Glove, Tone] (Figure 9.15d), and [Mid-Air, Tone] (Figure 9.15i)), we modulate the frequency of the stimulus based on the distance to the object. The frequency is also computed using the linear functions Equation (9.2) and Equation (9.3) with $v_{min} = 0$ and $v_{max} = 150$.

We modulate the rendering speed of a circular stimulus to create the [Glove, Dial] (Figure 9.15e) and [Mid-Air, Dial] (Figure 9.15l) stimuli. For both, we use Equation (9.2) and Equation (9.3), with $v_{min} = 0$ and $v_{max} = 5$, where the value denotes the number of seconds used to complete the circular pattern (i.e., the drawing frequency in seconds). As the glove has six vibration motors (one on each finger and one on the palm), we start the circle at the thumb, move to the index finger, then the middle finger, the ring finger, the pinky, the palm, and then start the loop again. Each location is stimulated for $\frac{1}{r(x)}$ seconds (or $\frac{1}{a(x)}$ seconds for attraction), where x is the current distance to the object. The mid-air haptic device can stimulate continuously in a circular pattern, where the rendering speed is determined by the aforementioned Equation (9.2) and Equation (9.3).

When stimulating with the [Glove, Fingertip] (Figure 9.15f) and [Glove, Whole Hand] (Figure 9.15c) stimuli, the intensity is modulated using Equation (9.2) and Equation (9.3) with $v_{min} = 0$ and $v_{max} = 1$. The difference is that the [Glove, Fingertip] stimulus stimulates only the index fingertip, while the [Glove, Whole Hand] stimulus stimulates using all six vibration motors.

The [Mid-Air, Oscillation] (Figure 9.15k) modulates the position of the mid-air haptic focal point based on the distance to the object. We use a LeapMotion controller to track the hand and measure the finger length. The focal point is then moved using Equation (9.2) and Equation (9.3), with $v_{min} = 0$ and $v_{max} = l$, where l is the length of the finger. Here 0 corresponds to the base of the finger, approximately at the knuckels.

At last, the [Mid-Air, Expansion] (Figure 9.15l) stimulus modulates the size of a circular pattern. For this we use Equation (9.2) and Equation (9.3), with with $v_{min} = 1$ and $v_{max} = 6$ (diameter in centimeter). A diameter smaller than 1 is not possible due to the technical limitations of the used device.

10. Beyond Representations of Touch

Haptic technology is capable of mimicking physical touch sensations. Kappers and Bergmann Tiest's [200] and Lederman and Klatzky's [226] taxonomies of touch representations are useful for such aims, as they go in great detail of the properties perceivable through touch. However, the potential of haptic technology is its capacity to mediate and modulate touch stimulation. The concept of Haptic Magnetism, harnesses this potential through the mediation of haptic sensations *only* perceivable through haptic technology, just as research on sensory augmentation through haptic feedback (e.g., [278, 431]; overview by Macpherson [249]) and haptic redirection (e.g., [8, 61, 358]) has done in the past. In this chapter, I will discuss the potential of these unrealistic haptic sensations, revisiting Hollan and Stornetta's ideas of creating tools that go "*beyond being there*" [159].

To discuss the potential of unrealistic haptic sensations, I will try to narrow down what the meaning of 'unrealistic' is. Let us start by considering what it is not. Unrealistic does not mean *not occurring in the natural environment*, as that, by any definition of the word 'natural', would label any tool created by humans unrealistic, which is not true as tools exist. Unrealistic does not mean *impossible*, as that would mean imagining and dreaming of the future would be meaningless – an unrealistic future is not impossible, but rather improbable. Unrealistic, thus, is about the *abstract*, *speculative*, and *hypothetical*. A culture, a society, or an individual determines what is considered realistic or unrealistic. As such, what is unrealistic develops over time. Take, for instance, the case of distant interpersonal communication. Throughout the Industrial Revolution and up to the present, interpersonal communication has developed from mail coaches to real-time video calls. At each stage, between sending letters, telegraphs, telephones, instant messages, and video calls, humans must have found the next steps unrealistic. Yet, they are achievable – they are possible.

The potential for touch mediation has been uncovered with the advances in haptic technology. A current example is social touch: Not too many years ago, touching at a distance was unrealistic. Yet, through the ongoing work of Huisman and colleagues [172, 173, 174, 175], Price et al. [308], and many others (e.g., [127, 258, 395]), communicating through touch at a distance does seem within arms reach. A second example that utilises sensory augmentation and a representation of touch only perceivable through haptic technology is haptic redirection. Research on this topic is in an earlier conceptual stage than social touch; most redirection techniques require the perceiving human to adapt their behaviour consciously. The concept of Haptic Magnetism *Haptic Magnetism* [68] is one such technique, asymmetric vibration [8, 61] another, magnetic redirection [223] a third. These techniques require the perceiving human to be driven by some motivation to move before haptic stimulation – the techniques 'just' guide and alter the path taken. Candidates for techniques in which the perceiving human is guided actively by the stimulation include tendon vibration, in which the receptors around the muscles are stimulated to cause the muscles to contract [95], and the technique described by Moscatelli et al. [273], in which a moving finger directed over a surface by parallel ridges on the surface.

This last technique by Moscatelli et al. was the point of departure for the project that later became Haptic Magnetism. In a pilot study, I reproduced Moscatelli et al.'s setup (shown in Figure 10.1)

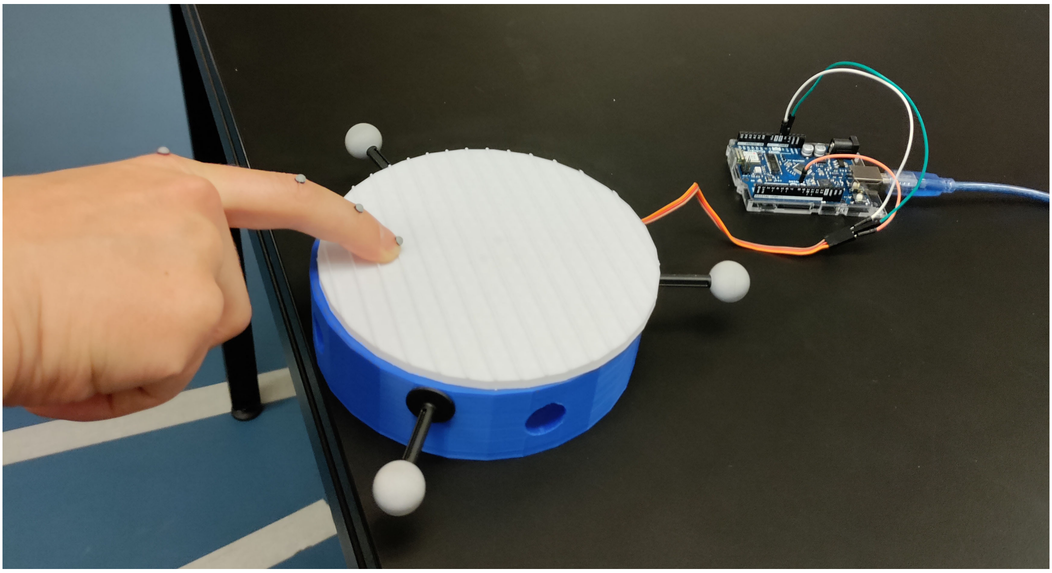

Figure 10.1. A reproduced experimental setup from Moscatelli et al. [273]. Participants were asked to slide their fingers over the ridged surface in a straight line away from their bodies. The finger would systematically deviate in accordance with the angle of the ridges on the surface.

and had similar findings: The participants would be unconsciously guided towards a direction depending on the angle of the ridged surface. However, the project came to a halt as there is no current haptic device capable of rendering the 1 mm wide ridges onto the fingertip. Mid-air haptic devices, for instance, have a resolution of around 1 cm – too large to yield a satisfying result. Expanding the area of stimulation to cover the whole palm does not help, as the current mid-air haptic devices can not render edges sharp enough to be perceived distinctly. Thus, dissatisfied with the state of technology, I turned to an abstraction, a physical metaphor, that became the concept of Haptic Magnetism.

Metaphors are powerful tools for designing haptic sensations, yet they do not always work, as humans must learn to understand their components. Using metaphors to extend the possible representations of touch can be useful for designing haptic interactions.

Part V

Haptic Experience

There is nothing that we know more
intimately than conscious experience,
but there is nothing that is harder to explain.
– David J. Chalmers

haptic experience The conscious perception arising from a (multi-)sensory configuration that includes a haptic stimulus at an abstract, conceptual level.

Experience is implicitly understood as 'the experience of something' in human-computer interaction. Typically, that something is 'use', 'interaction', or other activities are supported by technology. This is evident from the various approaches to the term user experience, whether as a design practice or as the search for what 'good' interaction is like [84, 146, 265]. This understanding is neither wrong nor surprising; much work in human-computer interaction is concerned with 'good' design. The Inference-Design Model for Haptic Experience elucidates the potential of investigating inference and design as a two-way process, allowing for exploratory research investigating the sensations and experiences that can be elicited by haptic stimuli, as we show in the journal paper *A User-Derived Mapping for Mid-Air Haptic Experiences* [63].

Experience, nevertheless, remains an elusive concept. Philosopher David J. Chalmers fittingly wrote, "there is nothing that we know more intimately than conscious experience, but there is nothing that is harder to explain" [47, p. 1]. The elusive nature of experience has profound consequences for the design of experiences. Scott and Waddell argued that "the designed experience is not determined, but rather enabled" [340, p. 11]. Frauenberger goes further:

> We are not designing computers, nor can we design interactions. What we seem to be doing is creating configurations that enact certain phenomena. These configurations and phenomena are situated and fluid, but not random. In fact, they are causally linked–the entirety of a configuration determines the phenomena. [105, p. 2:12]

This suggests a critical difference between designing experiences and designing *for* experiences. Frauenberger's and Scott and Waddell's statements imply that experience designers should design not only proximal stimuli but also surrounding sensory environment and social context (a 'configuration') as much as possible to enable particular experiences. Throughout this part, I will explore this notion of experiences and its consequences for haptic experience design.

The term 'haptic experience' implies that experiences are separable and categorizable based on the sensory modality that elicits them. I have previously argued that all experiences are multi-sensory, making such discrete categorisation implausible. I explore this in Chapter 11 and relate the multi-sensory nature to the phenomenal character of haptic experiences. Putting the phenomenal character in the context of user experience research, I present the manuscript *A Unified Model for Haptic Experience* [71] in Chapter 12. The Unified Model provides a holistic way of engaging with the design of haptic experiences. I provide more insights around the notion of 'context' and around ethics in Chapter 13. The practice of haptic design is typically attributed to designers with expert knowledge of the perception of touch [206, 245, 334]; however, with the democratisation novices gain more access to haptic technologies [336, 341]. In Chapter 14, I describe how novices engage with novel mid-air haptic technology in a reprint of the short paper *A Touch of the Future: The TOUCHLESS Hackathon 2022* [67]. Using the resulting prototypes as an example, I propose a novel approach to haptic experience design, *narrative haptic design*, in Chapter 15. I discuss the challenges of designing for haptic experiences with haptic technology.

11. The Phenomenal Character of Touch

The phenomenological characterisation of touch is inevitably connected with the experience of the body. In Husserlian phenomenology, tactile experiences have been of special interest, and what it is like to be touching has sparked a lot of discussion [255]. Edmund Husserl argued that experiences of touch are *double experiences*: touch allows for the experience of the object touched *and* the experience of the perceiving human's body through touching [176, pp. 152–157]. This sets the phenomenal character of touch apart from that of other senses, primarily because touch requires direct contact with the object to be touched. Mattens explains the Husserlian view, "in touching, and only in touching, does the body gain its peculiar character as a lived body and become my body" [255, p. 99]. In this understanding, touch is the most basic of all senses, allowing for self-awareness and physicality [282]. O'Shiel argued that touch, by allowing for an experience of the body, facilitates important aspects of movement, such as standing up and navigating the body through "any kind of external world, real or imaginary" [282, p. 197].

With the importance of touch asserted, it is easy to see the appeal of designing experiences of touch. Indeed, much of modern technology is controlled with the fingers [93]; touchscreens, keyboards, and mid-air gestures are common interaction modalities in existing and emerging technologies. However, the haptic feedback these technologies provide is mundane; these touches do not often facilitate hedonic or eudaimonic haptic experiences. Elo puts it drastically, "the finger has been handed the status of a switch" [93, p. 2] in the digital world. Haptic technology has the potential to elevate the status of the digital finger, possibly the whole hand and the whole body even, to become the sensing and feeling body it is in the physical world. However, the importance of mundane experiences should not be understated, as that understates their frequent occurrence [88, 199].

Humans use experiences of touch to make sense of the world around them. The double experience of touch facilitates exactly that: perceiving the characteristics of the world while also perceiving the characteristics of the body. However, as Wright et al. argue, "people do not simply engage in experiences as ready-made, they actively construct them through a process of sense making" [416, p. 324]. Humans bring themselves, their past experiences and their body, into the experience. The human, the subject, interacts with the other, the object. This subject-object relation is necessary for the formation of experiences as a sense-making device; there is no experience without subject or object.

Following the ontology of philosophers, such as David J. Chalmers [47], John Dewey [81], and many others, experiences are irreducible, fundamental. Experiences in human-computer interaction have been confused with activity, social practice, and knowledge [416]; however, experience is much more than that. Experiences are interwoven threads of sensing, thinking, feeling, and acting that expose meaning to the perceiving human [81, 416]. Wright et al. [416], as mentioned before, proposed a language of talking about the user experience with emerging technologies, suggesting that experiences consist of four threads: the compositional thread, the sensual thread, the emotional thread, and the spatio-temporal thread. In short, the compositional thread relates to the narrative structure of the experience, the sensual thread to the 'look and feel' of the object, the emotional thread to the emotional qualities, such as joy, satisfaction, and the like, of an experience, and the spatio-temporal thread to the time and space of the experience. There are many examples of haptic research, studying these threads of experience and, in particular, how to design for them. While the threads are interwoven, haptic research tends to focus on individual threads — only a collective overview of haptic research allows a broader understanding of the threads of haptic experience. Affective haptics [92, 245], for instance, investigates primarily the emotional thread. Research on multisensory integration often relates to the spatio-temporal thread (e.g., [247, 396, 399]). In the following chapter, I will present a model for designing haptic experiences that takes departure point in user experience and haptic experience research. Through the Inference-Design Model, I attempt to bind together the threads of haptic experience.

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12. A Unified Model for Haptic Experience

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Abstract. Designed haptic feedback—technology-mediated touch feedback—has the potential to mediate positive and meaningful experiences in the human mind. However, these experiences are rich and complex in nature and thus challenging to design. Established user experience (UX) and haptic experience (HX) models describe the design of experiences; however, they are too general and evaluation-focused to inform haptic experience design. We review 104 publications designing haptic experiences and analyse how researchers consider pragmatic, hedonic, and eudaimonic qualities of haptic experience. Our findings show that researchers mainly engage with the pragmatic qualities of the experience. We thus propose a unified HX model for understanding the design of haptic experiences, combining key elements of UX and HX research to give haptic designers a tool for thinking about the rich and complex haptic experiences elicited by their designs. This raises open questions for haptic experience research, as designing mediated touch experiences through haptic technology remains challenging.

Keywords. haptic experience, user experience

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12.1. Introduction

The haptic senses co-create experiences in the human mind. Receptors of the haptic senses are distributed across all parts of the skin, requiring physical stimulation [245], thus making this sensory modality uniquely challenging to mediate through technology. Successfully designing haptic experiences, however, bears great potential, as the haptic senses are important for forming interpersonal relations [107], communicating emotions and affect [92, 151], exploring and manipulating the world around [272], and revealing affordances of objects [68, 240].

Tackling these challenges of mediation requires technological innovation and models for haptic experience. The design of haptic experiences has earlier been addressed through methods and models of User Experience (UX) [206, 334] and affective computing [92, 305], considering the usability of a product, system, or service [281]. Haptic Experience (HX) is a relatively new subfield of UX that formulates the specific design-related challenges of haptics. Kim and Schneider's HX model [206], similar to Hassenzahl's model for UX [140], puts the design of positive experiences at the centre of research. UX research classically distinguishes between pragmatic [140, 142] and hedonic [19, 84] experiences, with the latter valuing pleasurable and enjoyable experiences highly. Influenced by positive psychology (e.g., [177, 179, 326]), more recent work has introduced the notion of eudaimonic experiences to UX (e.g., [79, 265, 266]) – experiences of meaning and elevation. UX is conceptualised agnostic to the technology in use and thus acts as an umbrella term for understanding and evaluating any technology, including haptics (e.g., [213, 252, 355]). However, it is unclear if and when the generalisations of UX break in relation to haptic experiences, in particular, because the haptic senses are 'always on' and distributed across the body [23][16], and because of the stunning variety and complexity of haptic actuation technologies, limited language to describe touch, and individual differences [334].

Kim and Schneider's HX model [206] provides a haptics-focused model for UX and defines constructs imperative to hapticians[17]. The model takes the haptician's perspective, emphasising the constructs important for the design process and evaluation of a haptic experience. However, this focuses on the system as having inherent qualities rather than the user as the subject of the design process. Important facets of the user's positive experience are not included in the model, not considering the fulfilment of psychological needs [143] and the experience of meaning [265, 266].

The contribution of this paper is twofold. First, we analyse practices employed by authors researching haptic experiences and engaging with the constructs, methods, and measures of UX to understand and evaluate haptic experiences. Our analysis reveals the limits of established UX and HX models in relation to haptic experiences. We analyse 104 recent publications through the lenses of pragmatic, hedonic, and eudaimonic qualities to investigate how the existing models of UX, HX, and meaning capture the experiences designed by HX researchers. We employ the ISO 9241-11 definition of usability, Kim and Schneider's HX model [206], and Mekler and Hornbæk's Framework for the Experience of Meaning [266] to reflect upon the designed haptic experiences in the sampled publications.

Second, informed through identified practices and limits, wepropose a unified model for HX. This model synthesizes existing models and other common concepts in haptics, describing the relationships between haptic design, experiential qualities, and perceived consequences. The unified HX model provides opportunities for further research, as it can be used to understand haptic experiences mediated through haptic technology and generate novel questions about the relationship between haptic stimulus and experience. We discuss how HX research can benefit from seeking out established theories and methodologies inside and outside the field of human-computer interaction.

12.2. Background

The concept of 'experience' has a rich history and meaning. Within human-computer interaction, the term has been used in many variations and interpretations [144]. In the following, we outline our view on experiences in general and haptic experiences in particular. Other interpretations exist; however, we aim to clarify the context of this paper through our outline. We provide background

[16] Barrow and Haggard [23] discussed the ethical challenges of haptic design, citing the fact that the haptic senses are 'always on' as an ethical challenge for haptic designers to consider; sensory autonomy and sensory consent are major concerns.
[17] A haptician is one "who is skilled at making haptic sensations, technology, or experiences." [334, p. 6]

through the current state of research within UX and HX; in particular, we discuss notions of pleasure and meaning in technology-mediated contexts.

12.2.1. Experiences

The human mind constructs experiences based on the collective perceptions of sensory stimuli in the moment and past experiences [20], making sense of the world through bodily sensations. In this constructionist view, experiences are inherently multisensory [254, pp. 41–42], a moment-to-moment interpretation of the world around the human. Hassenzahl [141] describes experiences as a collection of "sights and sounds, feelings and thoughts, motives and actions [...] closely knitted together, stored in memory, labeled, relived and communicated to others." [p. 8] Thus, we suggest that a haptic experience is such a collection related to the technology-mediated stimulation of the sense of touch. The relation is formed by a mental process of sense-making, informed by the bodily and environmental state. Sensing never halts, continuously allowing the mind to infer the world around the human, constructing subjective experiences. These are thus ever-present and ever-changing [259, pp. 49–51].

Hassenzahl et al. suggested that "two experiences may never be alike, we may nevertheless be able to categorize them" [143, p. 354], and showed that experiences, at the core, can be categorised by the basic human needs fulfilled by the experience. In addition, Hassenzahl et al. showed that need satisfaction relates to positive experiences. Huta [177] similarly states that experiences reflecting need satisfaction are associated with low negative affect. Experiences are at the core of this paper and thus are the many aspects influencing human experience, such as context, needs, and motivation, important to our later discussions. Within haptics, aspects of experience have been considered in different degrees – Peck and Childers [301] developed the Need For Touch Scale measuring, among others, the motivation for touch, while MacLean [245] argued for differences in situatedness within touch, as for instance social context and a functional context differs. In this paper, we discuss current practices in HX research in relation to these aspects and attempt to build a model capturing them in the context of haptic experience design.

12.2.2. Positive Experiences

Research in UX has for a long time concerned itself with designing positive experiences using interactive technology [146, 259, 281], for instance, by designing mobile applications for meditation or by controlling the sensory environment through Extended Reality (XR). McCarthy and Wright [259] argued that developing an account of the experience with interactive technology is challenging, as these experiences are simultaneously rich and illusive – so illusive, in fact, that they are gone in the moment of description. Hassenzahl et al. critiqued this view, arguing that "although two experiences may never be alike, we may nevertheless be able to categorize them" [143, p. 354]. The challenge of capturing these rich and illusive experiences has led to research practices in UX focusing on pragmatic qualities of interactive technology, such as utility and usability, in particular efficiency, effectiveness, and satisfaction [84, 142, 163]. Hassenzahl et al. [142] argued that usability and UX are distinct in goals, focus, and ideals, but that UX researchers often understand UX as usability and preference. The third wave of human-computer interaction has since the early 2000s brought with it an increased focus on positive experiences [32, 135], for instance, through affective computing [305]. The increased focus on the *'human'* in human-computer interaction was facilitated by the introduction of new methods and theories to the field, such as the introduction of phenomenology to human-computer interaction [85], resulting in the use of for instance micro-phenomenological interviews [309] and Self-Determination Theory [325]. Thereby, third-wave research has shown that interactive technology can facilitate experiences beyond the pragmatic.

Questions of 'what constitutes a good interaction' have become the leading motivation to UX research [142, 266]. The notion of 'good' in this context refers to *hedonic* and *eudaimonic* qualities of an experience [79, 142, 266]. While pragmatic qualities are related to behavioural goals of use (e.g., ease-of-use, precision) [140], hedonic qualities are broadly related to momentary psychological well-being (e.g., pleasure, enjoyment) [84, 181] and eudaimonic qualities to long-term psychological well-being (e.g., growth, meaning) [79, 177, 265]. Huta shows that meaning acts as a good proxy for eudaimonia [177].

The term 'meaning', however, is ambiguous. Within haptics, the term is often used in a notion of understanding or sense-making of a haptic stimulus [34, 94, 308, 355]. Enriquez and MacLean [94] investigated the learnability of tactile icons, asking users to recall the conceptual meaning of these icons. Yoo et al. [422] extended this work by using users to attach affective meaning to haptic icons. Brave and Dahley [34], in their seminal work, introduced interpersonal communication facilitated through hapic technology. This line of work has continued ever since; Price et al. [308] asked a pair of users to convey tactile messages through a haptic device and interpret the social meaning of these messages. In this work, we focus on the long-term aspects that go beyond understanding and sense-making. Both hedonic and eudaimonic experiences can be elicited in users of interactive technology [265]. While we have observed instances of hedonic experiences mediated through haptic technology, it remains unclear whether eudaimonic experiences also manifest in the context of haptic technology.

Eudaimonia is often contrasted to hedonia[18], however Desmet and Hassenzahl [79] argued that the distinction is artificial: experiences of meaning can be pleasurable. It is, nevertheless, useful to consider these as distinct as a starting point for design [79]. In line with this, Mekler and Hornbæk [265] found experiences including interactive technology distinctly hedonic or eudaimonic, but also experiences both hedonic and eudaimonic, aligning with Huta's findings [177].

There have been many calls to design for moments of meaning within UX [142, 144, 265, 266], often criticising exactly the UX-typical focus on the design of pragmatic experiences. Hassenzahl et al. [143] and Yoon et al. [423] proposed that understanding the underlying needs of users is crucial to being able to design purposeful and positive emotional experiences. We aim to investigate how recent work on haptic experiences engages with hedonic haptic experiences and haptic experiences of meaning. Through this, we show how HX research has and has not addressed positive experiences in haptics and identify open research questions about why haptic experiences are perceived as they are.

[18] See, for instance, Desmet and Hassenzahl [79], Huta [177], and Huta and Waterman [181], and Mekler and Hornbæk [265] for discussions of the contrast.

12.2.3. Haptic Experience and Haptic Experiences

As a subfield of UX, HX has evolved similarly, shifting focus from the purely pragmatic to the experiential, however, on a later timeline. In particular, work on affective haptics has researched methods to elicit positive emotions through haptic experiences [92, 245]. While affective haptics concerns itself with recognising, processing, and eliciting emotional states in humans through the sense of touch [92], research in HX considers usability requirements and experiential factors more generally [206, 334] – similar to the distinction between affective computing and UX [305]. In particular, Maggioni et al. [252] showed that the addition of haptic feedback can increase the perceived pleasantness and overall liking of an audio-visual experience. Similarly, Singhal and Schneider [355] showed that vibrotactile feedback increases the appeal and immersion of a smartphone game. Price et al. [308], on the other hand, showed that vibrotactile stimulation is not well suited for social touch applications, as these stimuli are perceived as unpleasant and unnatural. These haptic experiences show the broad potential for interactive haptic feedback; however, they also show that it is unclear which combinations of haptic modalities, contexts, and interactions are suitable to enhance an experience using haptic technology. Attempts to solve this challenge have led to a plethora of haptic research focusing on the pragmatic qualities of a haptic system, for instance, seeking insights into mimicry of textures and human skin (e.g., [126, 169]), often evaluating whether a haptic system works as the designer intended rather than evaluating the felt haptic experience, as Strohmeier et al. [360] pointed out.

Research within HX and affective haptics has shown that haptic experiences are rich, nuanced, and personal [63, 214, 284, 360], but work on questionnaire development shows how difficult it is to capture the qualities of these experiences [12, 330]. The focus on the pragmatic qualities of the experience is thus understandable but, in our view, not sustainable. Work in haptics is often driven by the availability of technology rather than the desire to enhance human cognition through technology. This is unfortunate, as the sense of touch has much potential for positive and interactive experiences of pleasure and meaning.

Kim and Schneider [206] defined the term 'Haptic Experience', providing a model for haptic experiences from the designers' and users' perspectives. The HX model encapsulates design parameters, technical requirements, and factors important to the pragmatic and hedonic aspects of the haptic experience. Kim and Schneider propose utility, causality, consistency, and saliency as pragmatic qualities of a positive haptic experience and expressivity, harmony, involvement, realism, and autotelic as hedonic qualities of a positive haptic experience. In the following, we will clarify our understanding of these qualities. We argue that expressivity, harmony, involvement, and realism are not positive or negative experiences per se; they are defined by the designed environment in which the experience takes place and thus are not purely hedonic qualities. Expressivity, the richness of haptic feedback, is a feature of the functionality of the chosen haptic application, modality, and device – it enables designers to provide diverse haptic feedback. Involvement[19], defined as the degree of engagement and connection, is related to established notions of immersion, presence, and

[19] Anwar et al. [12] replaced Kim and Schneider's [206] 'immersion' with 'involvement' to reflect a user's active engagement with a haptic system.

agency. It captures the user's sense of 'being part' of the experience. Harmony and realism have a pragmatic counterpart that enables the environment to be perceived as harmonious and realistic. Harmony requires haptic stimuli to integrate well with other sensory stimuli, allowing users to perceive them congruently. Hoggan et al. [157] define haptic congruence as the intuitive match between different modalities. We argue that congruency is the pragmatic quality related to harmony, as congruency relates to the features of the designed system, while harmony is the user's perception of congruency. Realism, the degree of verisimilitude, similarly has a related pragmatic quality: fidelity. Fidelity relates to the ability of a haptic system to convey the broad range of a user's neurophysical haptic perception [35]. Realism and involvement might not always be desirable or required traits in haptic interactions [68] (e.g., when designing for navigation [61, 278], guidance [125], and other sensory substitutions [249]). Nonetheless, these factors contribute to the perception of the experience. Autotelics is described as the pleasantness of the haptic stimulus in and of itself. The importance of autotelic factor was put into question, as Anwar et al. [12] and Sathiyamurthy et al. [330] found diverging importance of this factor in the search for a standard questionnaire to measure HX. As autotelics is the sole pure hedonic factor in the HX model, the HX model lacks both breadth and depth to capture available models of hedonia [84, 286, 423]. The model is useful as a starting point for HX but has yet to experience the iterative process UX has gone through in the past decades.

Our intention is thus to iterate on Kim and Schneider's HX model [206]. We seek insights from UX research, in particular from Hassenzahl's model for UX [140], and practices of HX researchers to extend the reach of the HX model. Contrary to the Hassenzahl's model, the experiential factors of HX are not clearly divided into constructs of the designers' intended experience and the experience apparent to the user. In addition, we discuss how HX can benefit from the adoption of other UX constructs and theories.

12.3. Method of Review

We review research discussing and measuring haptic experiences to gain insights into how pragmatic, hedonic, and eudaimonic qualities are presented in recent literature. This review aims to explore how authors engage with haptic experiences, allowing us to get an overview of current practices in HX research. We followed an analytical approach to using a representative sample of published work through the lenses of pragmatic, hedonic, and eudaimonic aspects of the experience. The analysis allows us to inform our model iteration based on existing research within HX and contemplate open questions of how designers of haptic experiences investigate the different aspects of the experiences. The sample is extracted from five databases storing publications spanning multiple disciplines and academic traditions. Figure 12.1 shows the PRISMA flow diagram [293] reporting our selection procedure.

12.3.1. Protocol and Search

In our search query development, we followed a similar approach to Bargas-Avila and Hornbæk [19]. We used the exact query "haptic experience". The term 'haptic experience' has gained more

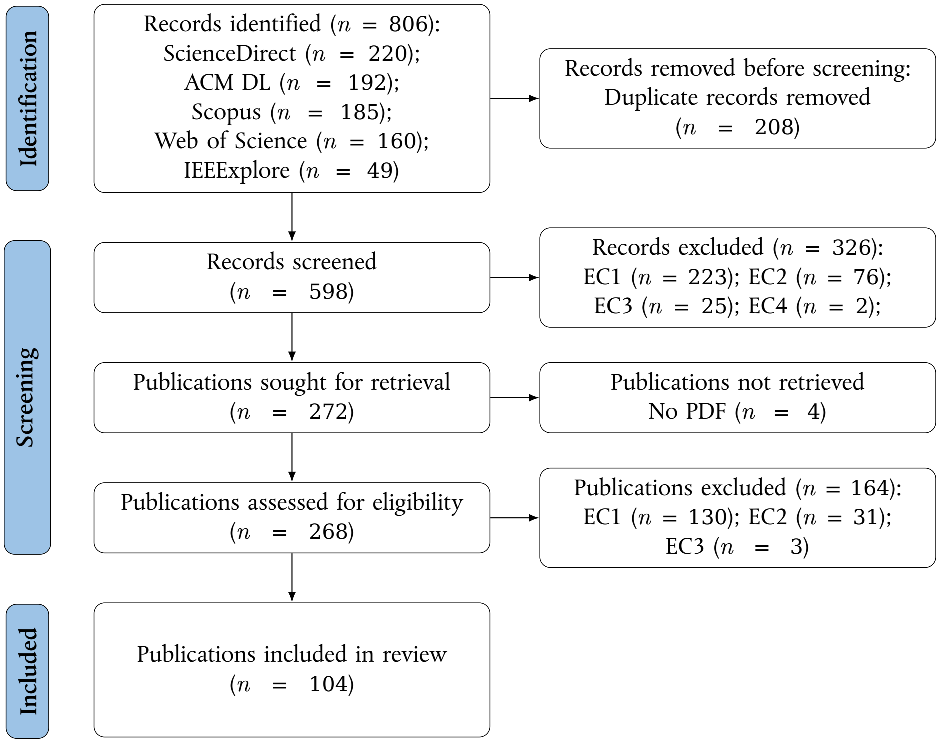

Figure 12.1. The PRISMA flow diagram [293] for papers included in our analysis.

popularity recently through the introduction of Haptic Experience Design [334] in 2017 and the development of the HX model [206] in 2020 and related work [12, 330] in later years. The practice of designing haptic stimuli to elicit experiences, however, is older (e.g., Maclean and Enriquez's seminal work on 'Perceptual Design of Haptic Icons' was published in 2003 [246]). While the query does not capture all relevant publications throughout the past ten years, it captures one of the main constructs within experiential haptics research.

To find relevant publications to include in our analysis, we identified five scientific repositories for suitable for our search. The ACM Digital Library and the IEEExplore digital library, as these index conferences and journals most relevant to the field of haptics (e.g., CHI, Transactions on Haptics, UIST, World Haptics Conference). In addition, we searched ScienceDirect, Scopus, and Web of Science, as these span multiple research fields with great potential for haptic stimulation (e.g., learning and accessibility applications). We restrict the search to full papers written in English and to the publishing dates spanning 2013-2023 as much as database filters allow. The search was conducted on the 5th of July, 2023, and yielded 806 candidate publications. The number was substantially reduced as the indices of the databases overlap, leading to 208 entries being marked as duplicates based on identical metadata. The full queries for all databases are available in the supplemental material. The first author conducted the screening and extraction.

Table 12.1. Summary of the codes used for data extraction.

Research Aspect	Stimulus	Technology	Usability	HX model [206]	Framework for the Experience of Meaning [266]
			Intended and Apparent Character [140]		
Motivation	Description	Haptic device	Effectiveness	Autotelics	Connectedness
Measure	Purpose	Device details	Efficiency	Expressivity	Purpose
Methodology		Body parts	Satisfaction	Harmony	Coherence
Method				Involvement	Resonance
Questionnaire				Realism	Significance

12.3.1.1. Limitations. We see several implications to our approach. First, we acknowledge that the search term is not exhaustive, in particular does it not cover all ways different fields engaging with the design of haptic experiences (e.g., the medical domain). We deem this acceptable, as we are interested in instances of haptic experience, rather than covering the full range of applications – we are aware of the many uses of haptic feedback, but are interested in the design and evaluation of it. Second, we miss publications that cover topics and design experiences relevant to HX but do not use the term 'haptic experience'. However, this is acceptable, as our main goal includes analysing the purposefully designed haptic experiences. Third, the term is ambiguous, as it both refers to those experiences that are afforded by interactive haptic technology, as well as those design principles and definitions surrounding the HX model [206] and Haptic Experience Design [334]. The ambiguity of the term usage in publications was resolved in a screening phase involving a set of inclusion and exclusion criteria.

12.3.2. Screening Phase

We adopted a two-phase screening process. In the first phase, we screened the publications based on title and abstract. We included papers generously for the second screening to allow a more thorough look where required. Publications included in the second phase were screened for inclusion based on the full text. Publications were included if the following inclusion criteria applied:

- IC1 *Purposefully designed haptic experience:* Papers that describe one or more haptic experiences designed to change a human's bodily perception using interactive technology were included.

On the other hand, publications were excluded if any of the following exclusion criteria applied:

- EC1 *No designed haptic experience*: Papers that do not present a haptic experience designed for humans were excluded.
- EC2 *Publication Type:* Adjuncts, posters, extended abstracts, companion proceedings, short papers, workshop proposals, position papers, demos, and editorials were excluded.
- EC3 *Survey or literature review:* Surveys, literature reviews, and opinion pieces were excluded.
- EC4 *Language:* Non-English papers were excluded.

Our exclusion criteria were informed by the work of Hirzle et al. [154] and Rogers et al. [316]. After both phases, we included 104 publications for further data extraction.

Table 12.2. Methods employed to capture data.

Collection method	n	%*	Examples
Questionnaire	85	81.7	Affect measured with SAM questionnaire [3]; Assessment of perceived enjoyment [130], presence [208], and realism [374]; Haptic Experience (HX) questionnaire [296]
Semi-structured interview	13	12.5	Reflections of the (haptic) experience of personal data [311]; Understanding participants' experiences of the tactile messaging experience [308]; Description and perception of mid-air haptic feedback in an art gallery [399]
Task performance	9	8.7	Discrimination of patterns [1]; Task completion time [13]; Accurate placement of objects [83]
Psychophysiological measures	9	8.7	Just notable difference (JND) measure of force magnitude [115], contact size [171], or stiffness perception [417] of a haptic stimulus; Electromyography (EMG) and heart rate measure during stiffness perception [427]
Open interview	5	4.8	Descriptions of any notable differences between physical properties of objects [338]; Open-ended interview to understand free-hand drawing [406]
Micro-phenomenological interview	4	3.8	Descriptions of experiences elicited through mid-air haptic feedback [63], electric muscle stimulation [214], and motion-coupled, non-grounded vibrotactile feedback [360]
Think-aloud	1	1.0	Verbalize thought processes during a learning task [251]

Note. $n = 104$ publications that collected data. *Data does not sum to 100%, as some publications use multiple collection methods.

12.3.3. Data Extraction

Table 12.1 shows the summary of the codebook used to extract data from the 104 included publications. We coded different experiential aspects of the publications for further analysis. In broad terms, we are interested in details of the designed haptic stimulus, the haptic technology used to induce a haptic experience, and details of the measurements obtained through stimuli and technologies in human subject studies. In addition, we organise the measurements and qualitative participant statements quoted in the publications by their relation to usability requirements of the designs [142, 186], the experiential factors described in the HX model [206], and components identified in the Framework for the Experience of Meaning [266]. Hassenzahl's model [140] describes UX as a negotiation between a designer's *intent* and a user's *apparent* perception of products and technology. We thus code the aspects of experiences as described by the different frameworks and models for their intended and apparent characters.

An inductive and deductive process developed the codebook. We started with a set of codes devised from the mentioned models and frameworks, common codes found in related reviews (e.g., [19, 84, 163]), as well as traits of academic tradition within haptics. After coding ten randomly selected publications (~10%), we revised the suitability of the codes. We adapted the codes based on these and ended up with 22 codes, six with a predefined set of options and 16 open codes. The full codebook can be found in the supplemental materials.

Table 12.3. Questionnaires used to evaluate haptic experiences.

Questionnaire	n	%*
Self-developed (items listed in the paper)	37	43.5
Self-developed (items unknown)	27	31.8
Presence Questionnaire (PQ) [413]**	7	8.2
Self-Assessment Mannequin (SAM) [33]	6	7.1
igroup presence questionnaire (IPQ) [339]	5	5.9
Avatar Embodiment [302]	4	4.7
Haptic Experience (HX) [12, 206, 330]	4	4.7
Simulator Sickness Questionnaire (SSQ) [203]	4	4.7
Other surveys (e.g., AttrakDiff [139])***	10	11.8

Note. $n = 85$ publications that used questionnaires. *Data does not sum to 100%, as some publications use multiple questionnaires. **Also known as Witmer-Singer Presence Questionnaire (WSPQ). ***Full list shown in supplemental material.

12.4. Current practices in Haptic Experience Research

In the following, we report the methodologies used to measure the different aspects of the haptic experience and how authors and their participants engage with the different factors and components influential to haptic experiences.

12.4.1. Evaluation of Haptic Experiences

To a large degree, the presented sample of publications employed quantitative methods to collect data ($n = 85$, 81.7%). Only 10 (9.6%) publications use qualitative methods, while 9 (8.7%) use both methodological approaches to collect data. Bargas-Avila and Hornbæk [19] analysed empirical studies of UX, finding a similarly increased use of quantitative methods, although the overall distribution in our sample is heavily shifted towards quantitative methods. Bargas-Avila and Hornbæk found that 33% of the studies used qualitative methods, whereas about 50% used quantitative methods (the rest used both methodologies). This comparison is to be taken with a grain of salt, as the publication dates of analysed publications do not overlap, and empirical traditions differ in UX and HX. However, it shows that work within haptics disproportionally uses quantitative methods to evaluate systems, devices, experiences, and interactions.

Questionnaires are the most often used method for assessing a haptic experience. Only few questionnaires collected qualitative data ($n = 2$, 2.4% of questionnaires); however, all papers that use a mixed methodology use a questionnaire in combination with a semi-structured or open interview (e.g., [72, 351, 406]). Other sources of quantitative data are task performance and psychophysical measures. Table 12.2 shows a breakdown of the methods used to collect data in the sampled publications.

Table 12.3 lists the types of questionnaires used in the sample of publications. The list shows that most empirical work involving haptic experiences is assessed by self-developed questionnaires ($n = 64$, 75.3% of publications using questionnaires). However, publications differ in how well-documented the employed questionnaires are. Most use self-developed questionnaire items and report the items within the publication; for instance, Turchet et al. [386] designed a wearable to augment a musical experience with haptic feedback and listed all experiential qualities measured, the corresponding question, and the used rating scale: “Participants were asked to evaluate on a visual analog scale (VAS) the following questions: *Irritating.* I found the vibrations irritating while listening to the music; *Enjoyed.* I enjoyed the music with the vibrations; [...]” [386, p. 762] (other examples include [36, 111, 126, 419]). A high number of publications using self-developed questionnaires do not provide any items administered through the questionnaire. Often, authors only report the high-level dimension of the question, such as realism, preference, or engagement, but do not provide additional information on the phrasing of the question. For instance, Liu et al. [237] augmented a VR headset to provide directional cues using directed air and listed only the overall qualities to be measured: “Participants were then asked to rate realism, immersion, and enjoyment using 7-point Likert scales” [237, p. 84:8] (other examples include [50, 130, 190, 374]). The finding that many authors use unvalidated, self-developed questionnaires without providing the items is not new in HCI and UX research [19, 163]. We can only echo the statement of Bargas-Avila and Hornbæk: “In terms of transparent study reporting, authors as well as reviewers should aim at changing this in the future” [19, p. 2694]. Publications that employ questionnaires use standardised questions or reference a source for the questionnaires, often evaluate the sense of embodiment [116], simulator sickness (SSQ [203]), and the sense of presence (IPQ [339], PQ [413]). Within our sample, it is common to measure these constructs in a virtual environment, studying whether adding haptic feedback changes the subjective perception of the constructs. Fewer publications use questionnaires measuring hedonic qualities, such as the SAM questionnaire [33], questionnaires influenced by the HX model [206] or developments by Anwar et al. [12] and Sathiyamurthy et al. [330], and the AttrakDiff questionnaire [139] ($n = 13$, 15.3% of publications using questionnaires).

Interviews were almost always used to collect qualitative descriptions of haptic experiences (Table 12.2). Generally, these interviews yielded detailed insights into the haptic experiences, hard to capture with quantitative data. For instance, Vi et al. [399] augmented the experience of artworks in a gallery with ultrasonic haptic feedback. They conducted a semi-structured interview and reported on the participant’s changed perception of the artwork: “The sound really brought some of the pictures alive, the [artwork], if I’d have walked through the gallery and looked at that, I would have just gone past it, whereas because I was there with the sound, I found myself looking at different parts of the picture.” [399, p. 11]. Wagener et al. [404] captured the complexity of a multi-faceted experience relating the sense of touch to the perception of one’s body when interviewing participants using a VR application for well-being: “And I think that’s why I found it so pleasant to really caress this grass with my hands because it helped me to focus a bit on myself and my body.” [404, p. 563]. These examples show that haptic experiences are rich and detailed and that participants can express the richness when prompted. This is particularly evident in the reports of the publications that use micro-phenomenological interviews [309] – a method particularly useful to dive deep into the multi-dimensional, ever-present, and ever-changing nature of experiences. Dalsgaard et al. [63], for instance, reported a participant relating a haptic experience to the feeling of happiness, safety, and fun, as well as an intimate social relation: “Yes, well, it was a lot...it was really funny, this feeling. It made me happy, that is. [...] it could also be a feeling, where my partner is running their hand down over my hand, or like..., it was very much like safe or fun, or something, that feeling...” [63, p. 8]. These interview methods are a great resource for assessing users' perceived experience while using haptic technology; authors within HX could, however, consider how other qualitative methods could unpack the perceived experience of these technologies.

12.4.2. *Aspects of Haptic Experiences*

Publications in the sample almost always describe confirmatory research (n = 96, 92.3%); a haptic experience is designed for a particular intent, for instance, to increase immersion in an e-book [6] or altering the perceived softness of rigid objects [369]. The publications that do not have a particular intent are exploratory in nature, i.e., they design a haptic stimulus and ask “what does this feel like?” [63] or “how would you use this?” [414]. Forty publications (38.5%) report the haptic design's appearance, often through participant statements. It is, however, difficult to use the statements in our analysis, as often only selected, positive statements are reported (e.g., “It was really fun!” [190, p. 771], “'fun', 'interactive', and 'playful'” [55, p. 508]). We will thus focus on the design intent but augment with appearance where appropriate. We distinguish between intended and apparent character by investigating who is articulating a statement: the researcher or the participant[20]. Table 12.4 shows an overview of how and how often authors engage with the different aspects important to positive experiences as listed by the presented models and frameworks [140, 206, 266].

12.4.2.1. User Experience Aspects. Authors often measure or discuss usability aspects of their haptic designs (n = 67, 64.4%). This trend indicates that authors see a need to assess their haptic designs' intended functionality. This is true for both publications that present custom devices (n = 44, 71.0% of custom devices presented) and those that employ commercial devices (n = 24, 75.0% of commercial devices uses) or proxies (n = 6, 60.0% of proxies presented), suggesting that ensuring the functionality of haptic designs is still at the core of research, no matter the means of stimulation. Measures of functionallity often revolve around effectiveness, for instance Breitschaft et al. [36] measured the perceived quality of haptic feedback on a tactile screen for an automotive application, as well as visual distractions, perceived task difficulty, and precision.

Measures of *effectiveness* are used to assess how properties of the haptic design, such as stiffness or roughness, are perceived or that the design positively influences task performance. Examples of these are the works by Wang et al. [406], which assessed the perception of hardness, roughness, and friction of an actuated pen, and Auda et al. [13], which assessed task completion time while using a haptic input device for drone control. *Efficiency* is often assessed to argue for the quality of the haptic design. For instance, Kovacs et al. presented a device enabling users to grasp a wrist-worn proxy, claiming its haptic design to “greatly reduces the user's effort to engage, disengage, and re-engage with virtual objects; and frees the user's hand when the device is not in use.” [220, p. 1047] This argument is typical for devices introducing a custom device capable of stimulating multiple

[20] One could argue that a participant articulates a statement through subjective measurement devices (e.g., questionnaires), evaluating and reporting their perception of a haptic system. We, however, differentiate here, as we see the measurement device as a tool employed by the researcher to validate an assumption or hypothesis about the haptic design thought to be important by the researcher. This is also where questionnaire and interview methodologies differ – the participant has many more opportunities to articulate their perception within an interview compared to a questionnaire.

Table 12.4. Aspects of haptic experiences mediated through technology. *(continued)*

	Aspect	Persp.*	n	%**	Examples
Usability	Effectiveness	Design	40	38.5	Performance evaluation [14, 418]; Physiological measures [52, 171]; Simulation of texture properties [169, 261, 362]; The ability of participants to perceive the design intention of haptic stimulus (e.g., recognition, distinction) [261, 386, 407]
		Use	11	10.6	Perceiving texture properties [55, 360];
	Efficiency	Design	25	24.0	Improving interaction (through decreased task completion time, increased presence, etc.) [30, 91, 406]; Comparison of system with and without haptic feedback [253, 385]
		Use	6	5.8	Ability to learn the design intention of haptic stimulus [83, 243]
	Satisfaction	Design	26	25.0	The ease of use of a novel haptic system [277, 297, 359, 419]; SUS questionnaire to measure usability [13, 46]
		Use	6	5.8	Suggestions for extensions of evaluated haptic feedback [5]; The ease of use of a novel haptic system [9, 13]
Haptic Experience Model	Expressivity	Design	18	17.4	The ability of participants to perceive the design intention of haptic stimulus: emotional (e.g., tactile message) [243, 277, 308] and functional (e.g., pattern recognition) [351, 362, 366, 406]; Perceive haptic intensity [401];
		Use	12	11.6	Differentiating haptic stimuli [1, 383]; Perceiving haptic intensity [6, 382]; Ability to learn the design intention of haptic stimulus [405]
	Harmony	Design	14	13.5	Audiohaptic correspondence [5, 385]; Visuohaptic correspondence [162, 411]; Matching texture properties to virtual object [162]
		Use	9	8.7	Perceived sensory correspondance [126]; Haptic feedback matching overall experience [190, 351]
	Realism	Design	39	37.5	Purposefully unrealistic haptic feedback [54]; Perceived realism [220, 366, 369]; Mimicry of a touch stimulus with haptic technology [401, 428]
		Use	14	13.5	Perceived as unrealistic [63, 126, 327]; Perceived as realistic [126, 327, 383]; "I have felt this before" [360]
	Involvement	Design	27	26.0	Questionnaire for presence [13, 421], immersion [111, 355, 374, 383], or embodiment [116, 364]; Engagement in the overall experience [385]
		Use	10	9.7	Agency and control [251, 418]; Focus on self and body [404]
	Autotelics	Design	41	39.5	Assessing pleasantness [63, 126, 230], enjoyment [130, 327, 374, 383, 405], fun [190, 421], satisfaction [201, 355, 385], or comfort [383]; Eliciting emotions [243, 386, 399, 428]
		Use	17	16.4	Joy [6, 399]; Perceiving comfort, relaxation through haptic properties [308, 404]; Perceiving empowerment through haptic feedback [351]

Note. $n = 104$ publications. **Perspective*. The examples relate to either the designer's intention or the user's apparent perception of the design. This distinction illustrates the differences in how the designers and users engage with haptic technology. **Data does not sum to 100%, as some publications discuss multiple aspects.

Table 12.4 cont: Aspects of haptic experiences mediated through technology.

	Aspect	Persp.*	n	%**	Examples
Framework for the Experience of Meaning	Connectedness	Design	3	2.9	Connectedness to a person responsible for the haptic stimulus [308, 385]; Perceived meaningfulness assessed through questionnaire [355, 399]
		Use	6	5.8	The feeling of "something is missing" [360]; Seeking relationships "between music and vibrations" [385]
	Purpose	Design	4	3.8	Motivation, interest, and engagement [91]; Engagement in learning [432]
		Use	2	2.0	Seeing purpose in the experience of personal data [311]
	Coherence	Design	5	4.8	The overall experience aligns with the participant's goals [386]
		Use	5	4.8	Feeling emotional closeness [9]; Perceived intent of other in social touch (emotion, meaning associations) [308, 414]
	Resonance	Design	5	4.8	Evoking real-world phenomena and eliciting emotional responses [243]
		Use	3	2.9	A haptic pattern perceived as a touch of a significant other [63, 308]; A haptically augmented musical piece was perceived as meaningful [385]
	Significance	Design	2	2.0	The impact of an experience [311]
		Use	2	2.0	Receiving a touch from a significant other [63, 308]

Note. n = 104 publications. **Perspective*. The examples relate to either the designer's intention or the user's apparent perception of the design. This distinction illustrates the differences in how the designers and users engage with haptic technology. **Data does not sum to 100%, as some publications discuss multiple aspects.

haptic or sensory modalities (e.g., [338, 378, 411, 427]). The *satisfaction* aspect of user experience is measured through common UX constructs; for instance, ease of use (e.g., [277, 297, 359, 366, 419]), preference (e.g., [250, 354, 385]), and quality of the feedback (e.g., [130, 418]). Most of these reports were collected using quantitative measures (n = 24, 92.3% of publications measuring satisfaction), while five were collected using qualitative methods (19.3% of publications measuring satisfaction) – three through both methodologies. The satisfaction reports and ratings were used to assess the suitability of the haptic design; when the design is preferable or easy to use, the haptic system was deemed valuable (e.g., [250, 366, 418]).

12.4.2.2. Haptic Experience Aspects. The authors evaluate their haptic design's internal distinguishability (*expressivity*) and how it integrated with other senses (*harmony*). Günther et al.'s work [126] stands exemplary for such an assessment: The publication investigates how roughness perception is affected within VR. Expressivity was assessed by asking participants to 'rate the roughness of the haptic stimulus', while harmony was assessed through questions of whether the 'virtual environment seems consistent with your real-world experiences' and whether a visual and a haptic stimulus matched. Together, these ratings inform how effectively and efficiently a user can distinguish the roughness of a texture in VR.

Increasing *involvement* and *realism* is one of the main motivations for eliciting haptic experiences. Wagener et al., for instance, hypothesise "that when multimodal cues differ between VR and reality, especially when visual and auditory cues in VR mismatch from haptic sensations and auditory cues in reality, it might break presence and disturb mindfulness practice." [404, p. 559] Measures of involvement are typically related to the effect of haptic feedback on the senses of presence, immersion, or embodiment inside a virtual environment ($n = 23$, 85.2% of publications discussing involvement). Publications employing haptic technology into the context of XR often are motivated by increasing immersion in a virtual environment [40, 111, 208, 237, 361], while others measure it as a quality criterion next to usability [366, 383, 421]. Simulating weight [220], stiffness [354], sheer [411] or other haptic properties are typical approaches to facilitate the increase. Involvement is often assessed through questionnaires such as Peck and Gonzalez-Franco's Avatar Embodiment Questionnaire [302], the igroup presence questionnaire (IPQ) [339], Witmer and Singer's Presence Questionnaire [413], and various self-developed questions such as "How immersed were you in the Virtual Reality Environment experience?" [124, p. 235].

Involvement and realism are often seen as dependent on each other: statements such as "presence is increased through high realism" [404, p. 559] and "participants [...] rated a VR experience as more realistic and engaging using our device" [374, p. 2] are common motivations. Authors engage with the perceived realism of a designed haptic stimulus or a (virtual) environment incorporating a haptic stimulus. For instance, Kovacs et al. [220] assessed the perceived realism of the haptic experience provided by a novel device, whereas Je et al. [191] assessed the perceived realism of the overall experience of a shape-changing terrain in VR. How deeply authors engage with constructs of involvement and realism remains questionable. Publications do concerningly often ($n = 15$, 29.4% of publications engaging with involvement, realism, or both) state that they asked participants to 'rate immersion and realism using 7-point Likert scales' often without stating the actual items displayed to the participants (e.g., [130, 191, 327, 354, 366, 369]).

The *autotelics* factor of the HX model [206] captures the experiential motivations of haptic designs. Autotelics is generally discussed in terms of capturing user satisfaction [163]. In our sample of publications, 53 (51.0%) include discussions and measures of hedonia. Particularly often, the constructs enjoyment, pleasure, fun, comfort, liking, satisfaction, and preference are used to engage with the measurement of this factor ($n = 31$, 75.6% of publications discussing autotelics). Engagements of this kind are often rather superficial and of the form: "How fun was your experience?" [50, 277, 401, 421]. However, the work by Cingel and Piper [55] is an example of the contrary. They assessed the shared hedonic experience of parent and child while reading a haptically augmented e-book together, engaging with both the parent's and child's experience of joy and motivation. We found only two instances of explicitly using a validated questionnaire to assess the hedonic qualities of a haptic experience: Auda et al. [13] and Ceccacci et al. [46] used the AttrakDiff questionnaire [140].

Furthermore, seven publications (17.1% of publications discussing autotelics) measure discuss emotion elicitation through haptic feedback. These often employ the SAM and Valence-Arousal questionnaires, assessing general emotional intensity and positivity (e.g., "How was your emotional experience during the video clip?" [201, p. 29:15]). Turchet et al. [385] measured arousal of a haptically augmented musical instrument and found that participants perceived the experience to be more exciting when using vibrotactile feedback. Zhou et al. [428] more deeply engages with eliciting emotions through haptic feedback, investigating how users perceive emotional robotic touch.

12.4.2.3. Aspects of Meaning. Mekler and Hornbæk [266] outlined five components of meaning in interaction: connectedness, purpose, coherence, resonance, and significance. In our sample, 11 publications (10.6%) discuss or measure the perceived experience of meaning. The discussion in these publications is often shallow, as only a few publications actively engage with the components of the experience of meaning. None, however, engage with all the components as described by Mekler and Hornbæk – which does not mean that they are less useful or valuable, but shows that engagement with experiences of meaning has not been in focus. The experience of meaning was discussed as a guidance for a haptic design (e.g., [9, 308, 399]) or as a quality of interaction (e.g., [355, 385, 386]). Authors often employ an interview method to investigate the experience of meaning, thereby allowing a deeper understanding of the underlying connection between haptic stimuli and the experience of meaning.

Meaning does not emerge from a vacuum, implying that a haptic experience of meaning is dependent on a broader experienced context. *Connectedness* in our sample often relates to a contextual haptic stimulus that requires users to interpret the perceived sensation. Price et al. [308] presented haptic gloves that, as a set of two, are capable of sending haptic messages to each other. Participants were grouped in pairs; one would design and send a haptic message, while the other would receive and decode the message. Price et al. found that haptic feedback is capable of eliciting the feeling of togetherness but that the perception of a social touch is dependent on the relation between sender and receiver, as well as the context in which the touch happens.

Not many publications discuss their work in terms of *purpose*, the sense of direction and striving towards a clear end. Both Edwards et al. [91] and Zohar and Levy [432] used haptics to enhance a learning experience by measuring motivation to learn and engagement with the material. Both found that participants perceived increased motivation and engagement through these virtual learning experiences, from which we can infer that participants found purpose in learning.

Publications in this small set discuss meaning in terms of *coherence*, the extent to which an experience makes sense, especially when engaging with social touch. An et al. [9] enhanced emoticons with vibrotactile feedback, discussing the emotional dimension of receiving a tactile message. The authors explain how pairs build a shared understanding of emoticons in a four-week study and gain a sense of "mental closeness". As a non-social example, Je et al. [190] quoted a participant saying, "[the haptic] feedback was appropriate" [190, p. 771], leading us to connect the sense of coherence with the senses of harmony and realism as a foundational element.

The notion of *resonance*, denoting the immediate, unreflected experience of something making sense in relation to life as a whole, is also addressed within the sample. The haptic sensation is understood as causation to the experience of meaning; one of Wagener et al.'s participants exclaimed, "I think that's why I found it so pleasant to really caress this grass with my hands because it helped me to focus a bit on myself and my body" [404, p. 563], suggesting that a pleasant experience resonated with the participant's heightened self.

Significance, "the sense that our experiences and actions at a given moment feel important and worthwhile" [266, p. 6], is rarely discussed within the sampled publications. Rajko et al. made personal data tangible by vibrating a smartphone while data was sent through a network and asked participants, "What part of this experience was the most impactful for you?" [311, p. 6]. While participants reported being concerned about how much data was made tangible, the haptic experience seemed not significant enough to prompt a behaviour change.

Mekler and Hornbæk [266] applied their framework by conducting an analysis of how CHI authors write about meaning. We see a few differences between our haptics-focused and Mekler and Hornbæk's general application of the Framework for the Experience of Meaning. In our sample, most instances of the experience of meaning are related to social interactions. A feeling of 'togetherness' is cited in technology-mediated human touch, often relating to the notion of resonance (e.g., [9, 63, 243, 308]). The works by Turchet et al. [385, 386] describe an interesting experience of connectedness and coherence when audiences perceive more connected to musicians through haptic feedback. We observe more instances of social interactions being perceived as meaningful than Mekler and Hornbæk, which reflects that a common goal within haptics is facilitating social touch. Our sample contains few mentions of 'meaning', but some works revolve around meaning-making, sense-making, and understanding. This is often related to whether a user can recognise or decipher a haptic design (e.g., [156, 311]). Vi et al. [399], on the other hand, asked participants 'Was it meaningful to you?' after perceiving a haptic stimulus in conjunction with an artwork in a gallery and Singhal and Schneider [355] used the PXI questionnaire [2] to collect subjective ratings on 'Playing this game was valuable to me.' Overall, users perceive haptic experiences of meaning. However, since most research in the sample is focused on pragmatic qualities, there are only few insights into how, why, and when haptic experiences of meaning occur.

12.5. The State of Haptic Experience Research

Our review shows the state of research involving purposefully designed haptic experiences. We have detailed and criticised practices within that research and found many simplifications of complex experiences; the reductionistic approach is prevalent in HX research. In the following, we will discuss the positioning of HX as a subfield of UX and draw parallels between HX and UX. This allows us to reveal implications for the theories used in HX and argue for changing the approach to designing haptic experiences by proposing a paradigm shift to a model-centric approach to research instead of a results-centric approach. We propose a second iteration of the HX model to facilitate this shift. We also call for a change in the use of methodology in HX, which, in our view, would strengthen the reliability and reproducibility of studies within the domain.

We uncover patterns of reductionistic research in the approach to HX similar to those described by Bargas-Avila and Hornbæk [19] ten years ago in UX research. HX researchers employ predominantly quantitative, self-developed questionnaires to understand and evaluate haptic experiences. We discuss these quantitative approaches and their limitations; while we acknowledge the value of quantitative approaches, we criticise the lack of qualitative reports on the use of haptic technology. Gathering diverse data describing haptic experiences allows for the design of better haptic systems.

12.5.1. Usability Plus X

The methodology used to investigate haptic experiences is similar to those used in various aspects of UX research. Haptic researchers often follow an analytical, confirmatory approach, using primarily quantitative questionnaires focusing on insights into the pragmatic qualities of the experience. Where hedonic or eudaimonic qualities are considered, descriptions and insights are shallow, as unvalidated and unreliable instruments are used to measure qualities. Within these patterns have also been observed and criticised for the past twenty years [19, 39, 84, 141, 142, 390, 423]; researchers evaluating haptic (and user) experiences nonetheless continue to employ questionable practices that provide little epistemic value.

Hassenzahl et al. [142] in particular criticised the misunderstanding of user experience as 'usability plus x'—usability plus fun, plus presence, plus something—after Väänänen-Vainio-Mattila et al. [390] found that publications within ubiquitous computing often focus on usability issues. Väänänen-Vainio-Mattila et al. argued that, "such findings do not reveal insights to actual subjective experiences" [390, p. 395]. We see a very similar pattern within research on haptic experiences. We are equally surprised how few researchers engage with the elicitation experience of haptic experiences rather than just the induction of haptic stimuli. Hassenzahl et al. [143] argued that pragmatic qualities are a 'hygiene factor'; it ensures that a haptic system, in principle, *can* elicit certain haptic experiences. Pragmatic qualities, however, do not inform about *why* certain haptic experiences are experienced.

The reason why researchers do not engage more deeply with haptic experiences is not immediately clear. Schneider et al. [334] argue that the root of the challenge of designing a 'good haptic interaction' in practice is many-fold: access and availability of high-fidelity haptic technology are limited, the effect of haptic stimuli on the user's state of mind is not well understood, perception and context vary between people and applications, and effective evaluation methods are scarce. As we see in our sample, this leads to research focused on building a 'novel' haptic device that has some hypothesised capability of creating a new or enhancing an existing haptic experience and, following the 'usability plus x' pattern, evaluating the utility of the device and the perceived fun, enjoyment, realism, immersion, presence, preference, and the like. However, we have gained only a few generalizable insights through this bottom-up, brute-forcing approach. The capturing of users' perceptions of touch and technology-mediated touch is, contrary to the building 'novel' device, not in focus, although such captures promise rich accounts of haptic experiences. We argue that the human experience and the context around the human are at least equally important to the development of HX research.

12.5.2. Biases in Haptic Experience Research

To a large degree, researchers employ quantitative questionnaires to asses haptic experiences. Most commonly, these questionnaires are self-developed and unvalidated – too often, the items of the questionnaire are not listed. This has a plethora of implications revolving around transparency, replicability, reproducibility, comparability, generalizability, and validity. As readers of such a publication, we can not know which constructs are actually measured when authors claim they measure 'enjoyment, realism, and immersion' through 7-point Likert scales. It leaves a lot of room for interpretation for the reader: Did the questionnaire item read just 'realism'? Did the scales have endpoints? Was 'enjoyment' measured through one or more items? Neither is it clear which nuance of the experience a participant is rating: Is it the haptic sensation, the virtual environment, or specific aspects of their virtual avatar? Nor are the instructions for the participants clear: Do the participants share the researcher's understanding of the 'immersion' construct when asked, *"How immersive was the experience?"*? Is the participant aware of what 'user experience' entails when asked, *"Does the haptic feedback enhance user experience?"*? All these questions have a profound impact on the conclusions we are able to make based on the ratings, and this method of engagement with complex constructs has many downsides. First, unvalidated and simplified questionnaires can not capture the nuances of the experience. Next, the data collected might be subject to biases, particularly since we, as researchers, can not expect participants to share a common understanding of the word 'immersion' or even 'realism'. Neither do these data points reflect which nuance of the experience a user is rating: Is it the haptic sensation, the virtual environment, or specific aspects of their virtual avatar? Lastly, involvement and realism are treated as quality criteria, only surfacing the underlying mechanisms of why a haptic experience could be perceived as realistic or engaging.

Researchers within HX are exposed to biases when focusing research on the intended characteristics of their haptic system rather than the perceived experience. When researchers pose questions of 'fun' or 'immersion', participants will answer these questions, possibly assigning these constructs post hoc to an experience. It is imperative that researchers guard themselves against biases in their research. One way of doing so is to use validated, readily available scales. Tisza and Markopoulos [377] provided a list of validated measurement instruments for preference, engagement, and experienced fun. Bargas-Avila and Hornbæk [19] mentioned the works by Huang [170] and van der Heijden [394] providing validated instruments with 3-4 items measuring enjoyment Presence questionnaires are already popular in the community (e.g., [302, 339, 413]). Huta and Ryan [180] presented a questionnaire for assessing the hedonic and eudaimonic motivations behind an activity. For haptic feedback specifically, Peck and Childers [301] developed the Need for Touch (NFT) Scale to measure individual differences in preference for haptic feedback, and Anwar et al. [12] and Sathiyamurthy et al. [330] have worked on scale development of a questionnaire for a subset of the HX model [206]. Another way is to use diverse methodologies to capture user experiences, for instance, by interviewing participants post hoc engaging with a haptic system. Researchers thereby give participants space and opportunity to articulate experiences in their own words. That is not to put qualitative above quantitative measures; it is merely a call for more diverse data assessing haptic experiences – yielding valuable insights into how humans perceive haptic experiences.

12.5.3. Approach to Experience

Experiences are often misunderstood as simple input-output models under the assumption that 'haptics feedback leads to x' – enjoyment, immersion, realism, pleasantness – input a bit of haptic feedback on one side, and voilà, fun is ensured to appear on the other side. This positivist view is evident in the way the HX research community values result-centric science [80]: Researchers have created a collection of dichotomised fact-like results proving the presence or absence of a, in the researcher's view, positive effect when inducing haptic stimuli. However, these fact-like results stand on their own and are hard to generalize. A common way for evaluating haptic experience is to generate a hypothesis using the formula:

$$(\text{Baseline} + \text{Haptics})_{\text{Positive effect}} - \text{Baseline}_{\text{Positive effect}} = \text{Haptics}_{\text{Positive effect}}$$

Take, for instance, the most common motivation in the sampled publication: increasing immersion in XR through haptic feedback; here, XR is the baseline, while immersion is the positive effect. Following the formula, a common approach is to measure immersion in XR with haptic feedback and immersion in XR without haptic feedback to be able to claim that haptic feedback increases immersion. This approach not only reduces haptic feedback to a binary factor rather than a designed system feature, but it also rests on the assumption that an experience is static and repeatable, an assumption that has been argued against by Hassenzahl et al. [143] and McCarthy and Wright [259] and disproven through experience sampling (e.g., [63, 214, 360]). The positivist input-output model approach does not hold, and we thus argue for a paradigm shift in the approach to research in haptic experiences.

We see experiences as such: the human mind is running an internal model that, based on past experiences, constructs a prediction of the sensory environment around the human [20, 21, 254]. The prediction informs the mind of the next best action and the consequences of that action. If the prediction is erroneous, the mind learns and adapts. Once the prediction error is minimized, a prediction becomes an experience, ready to be stored in memory [20]. These experiences are thus subjective constructs of the individual situated in a specific context.

With this view comes a paradigm shift from result-centric to model-centric science. Devezer and Buzbas argue that such a result-centric approach, while accumulating facts, promotes only questions of "Are these effects true for other populations, contexts, tasks, measures?" [80, p. 109]. However, such questions allow for little epistemic progress, as they create a positive feedback loop in which truth is evaluated through self-reflection. Research in HX is often driven by motivations of increasing a consequence of haptic feedback, might that be perceived realism, immersion, roughness, stiffness, enjoyment, preference, engagement, satisfaction, fun, or another positively connotated noun. Gathering 'truth' based on unvalidated questionnaires raises concerns about rigour, credibility, and generalizability. We propose conducting research that considers factors influencing the prediction of the human mind to build models for understanding how haptic experiences are made rather than generating islands of knowledge.

12.5.4. Open Questions in Haptic Experience Research

We have identified a set of open questions in HX research related to the current state of haptic research. We have already raised questions about the approach to the notion of an experience within the community, particularly how we, the HX community, conduct our research. Here, we open a few additional questions. A significant challenge is the generalisability of our haptic experience studies; many results stand isolated and are hard to interpret in relation to each other. Collecting these accumulated fact-like results into a generalisable model remains challenging, as employed methodologies often differ too much for comparison. More work is needed to create a robust mapping between haptic stimuli and haptic experience. Strohmeier and colleagues [361, 362] have, as mentioned earlier, proposed that parametrisation and defining a syntax for haptic feedback. Such an approach is still valuable for future work.

Another question is how hedonic and eudaimonic experiences manifest and what characterises these experiences while using haptic technology. We have seen instances of these manifestations, both within haptics (e.g., [308, 386, 404]) and beyond [84, 265]. Hedonic and eudaimonic qualities are found to be important for positive haptic experiences; however, developing an operationalization and practices for these qualities remains valuable for future work. Such work should offset in existing work, such as Mekler and Hornbæk's Framework for the Experience of Meaning [266] and work on psychological needs [143, 177].

Lastly, within the sampled publications, we have seen a few instances of ongoing use of haptic technology (studies lasting more than 60 minutes; e.g., [9, 311]). However, there are many open questions related to the long-term effects of haptics as the experience changes over time. For instance, vibrotactile feedback might become dull after prolonged or repeated use. Or, users might opt out of using a haptic device after an initial phase of excitement. Other times, vibrotactile feedback might lead to heightened learning retention due to higher engagement in a language-learning application. Understanding these factors are important for the adoption of haptic technology in the everyday life of users.

12.6. Haptic Experience

Through our review, we have shown that haptic stimuli can elicit pragmatic, hedonic, and eudaimonic experiences. However, we have also argued that the current result-centric approach to HX research is leading to disconnected gatherings of 'truth'. To bridge these islands of knowledge, we constructed a model for understanding haptic experiences.

12.6.1. The Unified Haptic Experience Model

We have established a need for iterating and unifying the established theories relevant to HX research. We thus propose a unified model for HX (Figure 12.2), based on Kim and Schneider's HX model [206] and influenced by UX theories [140, 143, 266], constructs from haptics research [35, 157], and positive psychology [177, 325, 387]. HX is, by definition, a subfield of UX [206, 334], implying that core UX principles also apply to HX. This manifests, for instance, in the methodologies used in the reviewed publications; both UX and HX research primarily use questionnaires and interviews to assess their designs and research findings are interpreted using similar methods [19]. In addition, pragmatic, hedonic, and eudaimonic qualities are equally important to UX and HX [142, 206, 266].

We introduce the constructs from psychological needs and eudaimonic experiences to the HX model, as these constructs have been shown to be important to the design of positive experiences. A haptic system has certain *features* curated by a designer that shape the *intended* system character. The features include the haptic content (i.e., haptic stimuli) and the presentation of this content (e.g.,

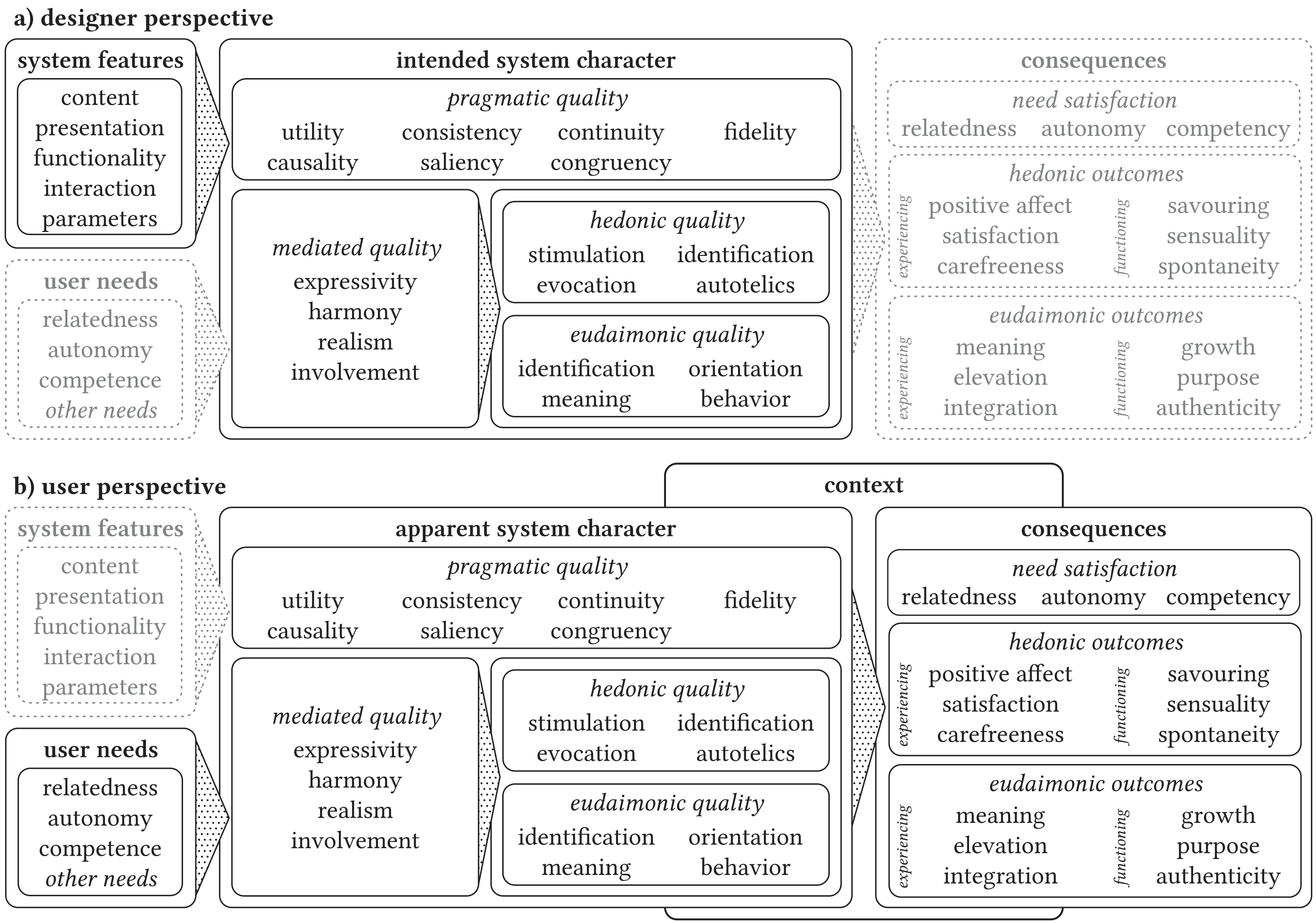

Figure 12.2. Key elements of the unified model of Haptic Experience (HX) from a) a designer's perspective and b) a user's perspective. Iterated from Kim and Schneider's HX model [206], informed by Hassenzahl's model for UX [140].

haptic devices, virtual environments). Hassenzahl [140] defines the character as a summary of the system's qualities (e.g., exciting, useful, interesting) while its function is to provide an intuition of use. The user perceives the system through its features and their psychological *needs*, shaping the *apparent* system character – an individual perception of the system. This perception is shaped by instances of *pragmatic*, *mediated*, *hedonic*, and *eudaimonic* qualities. Lastly, the perception leads to *consequences* of use: needs are satisfied, and connections to long-term well-being are formed. Consequences are, however, not formed in a vacuum – the context of use influences them.

On a high level, this model is equal to Hassenzahl's model for UX [140], with adaptations to reflect recent research on need fulfilment [84, 143, 177], the distinction between hedonic and eudaimonic experiences [139, 177, 181], and applications of eudaimonia in UX [266]. More concretely, the model was adapted towards haptics through our findings and the constructs and factors present in Kim and Schneider's HX model [206], as well as the congruency [157] and fidelity [35] constructs, often discussed on haptic experience research (e.g., [63, 245]). Next to these, we introduce more nuances on the consequences, based on the work by Huta and colleagues [177, 178, 181] within positive psychology, as well the factor of motivation through need satisfaction [143, 387].

Next, we outline the presented model and key adaptations; however, we emphasise that Hassenzahl's considerations on the model for UX (e.g., manipulation, stimulation, identification, and evocation) still hold [140] and integrate with Kim and Schneider's pragmatic qualities and the autotelics factor [206]. The supplemental material shows a breakdown of the many works that influence this model[21].

12.6.2. System Features

A designer can choose and combine a set of *system features* to design their haptic system. In the context of haptic experience design, these features include the modality of a haptic stimulation, the parameters of a haptic pattern, and the multisensory context in which it is presented. The designer controls the features by creating content or implementing particular functionality, aiming to fulfil a user's need or elicit an emotional state within the user. Kim and Schneider [206] define the design parameters for haptic stimuli as timeliness, density, intensity, and timbre for haptic patterns.A haptic example for designed haptic content and interaction is the work on haptic guidance and navigation (e.g., [61, 68, 173, 278]). Much work in the field of haptics is dedicated to identifying novel methods of stimulation and creating novel devices, thus focusing on designing system features. Our analysis of the sampled publications shows that the system character often seems to be an afterthought. Although the designer is in control of the system features, they can choose to allow users to customize their experience [206]. While this might influence the displayed content or change the values of parameters, the designer still chooses which and how much control is given to the user. How much and which kind of customization to allow for remains a challenge to solve.

[21] We encourage readers to seek out the works by Hassenzahl [140], Huta [177], Kim and Schneider [206], and Mekler and Hornbæk [266] as they describe concepts and terminology to depth.

12.6.3. User Needs

The first adaptation is related to the influence of *psychological needs* on the apparent system character. Hassenzahl and colleagues [141, 143] argued that the designers should consider users' needs, as the fulfilment of these promises positive experiences while using interactive technology. Huta [177] relates psychological needs to hedonic and eudaimonic qualities of well-being. Both list relatedness, autonomy, and competence as basic human needs related to intrinsic motivation on the basis of Self-Determination Theory [325]. Within haptics, these needs can be addressed, for instance, within social touch designs, allowing for remote communication through haptic feedback (e.g., [9, 308, 364]). Designers engage with the user's needs when designing the intended system character to inform system features – addressing the user's needs gives the system its purpose. While the user's needs influence the design, designers do not influence the user's needs; they only fulfil them through their designs.

12.6.4. System Character

The next adaptation is related to the increasing interest of eudaimonia to UX [265, 266] and the repeated calls to design for meaningful experiences [142, 144]. We thus split the qualities into four groups from Hassenzahl's two groups [140]: pragmatic, mediated, hedonic, and eudaimonic.

Pragmatic qualities relate to the functionality of a haptic system, addressing the user's functional needs. Hassenzahl's model for UX [140] lists 'manipulation' as the primary pragmatic quality – users require relevant functionality (i.e., utility) and ways to access this functionality (i.e., usability). We argue that manipulation, within the context of haptic systems, can be broken down into six requirements for functionality and access. Users of haptic technology require relevant functionality (i.e., utility), ways of identifying the cause of the feedback (i.e., causality), the feedback to be consistent across identical system inputs (i.e., consistency), and the feedback to be noticeable when displayed (i.e., saliency) – these are proposed by Kim and Schneider's HX model [206]. We earlier argued that the harmony and realism factors of the HX model can be broken down into a pragmatic and a 'mediated' quality (more about mediated qualities later). Thus, we add the quality of continuity, the instrumental requirement of a system to integrate multi-sensory feedback coherently, as the pragmatic quality of harmony. Congruence allows users to act on sensory feedback and understand the design intent [157]. A system's fidelity, the sensory and functional resemblance to the real world, enables users to acquire intuition and understanding of use [35]. Pragmatic haptic systems are purely instrumental; They allow users to act on their "externally given or internally generated behavioural goals" [140, p. 4]. An example of a highly pragmatic haptic system is a surgery robot – it must convey convincing haptic feedback at the right time and for the right reason. Operating a surgery robot might be perceived as hedonic and eudaimonic by users, it is, however, not necessarily the system character the designer intends or needs to design.

The mediated, hedonic, and eudaimonic qualities are co-related as constructs of positive haptic experience. *Mediated qualities* arise from the environment defined by the haptic system; they are composed of percepts of the (virtual) environment, the user, and the system. The designer has control over the mediated quality as part of the multisensory system they design (e.g., a visouhaptic environment in XR, an audiohaptic experience in a museum). These qualities can be subdivided into the involvement, realism, harmony, and expressivity factors of the HX model [206]. For instance, a user can feel present or immersed in a virtual environment that is augmented with haptic feedback. These qualities are not positive or negative per se; however, they influence the context of the experience, and thus, they contribute to the valence of an experience. For instance, users of a shape-changing floor perceived a strong, negative experience due to the realistic feeling of the haptic feedback; "I was extremely horrified when I moved closer to the cliff edge." [191, p. 9] On the other hand, an artificial grass proxy increased the pleasantness of a mindfulness application in VR due to increased engagement in the environment [404].

We differentiate between the conceptual sets of continuity and harmony and fidelity and realism, as continuity and fidelity refer to the underlying system design, while harmony and realism refer to the users' felt experience of the pragmatic qualities. This distinction is important as, for instance, realism traditionally refers to both the system's degree of verisimilitude (i.e., recording and playing back a vibrotactile pattern produced by moving a finger over texture) and the user's perception of 'this feels realistic to me' (i.e., the perceived feedback matches the user's expectation of a realistic sensory input) [356]. These two notions, however, are important to distinguish within haptics, as verisimilitude often is a design goal (e.g., for designing texture resemblances), while the user might not perceive it as 'realistic'.

The *hedonic and eudaimonic qualities* relate to well-being [177] and are the primary drivers of need fulfilment [84, 144]. We keep this classical divide of hedonic and eudaimonic qualities [79], we do, however, note that experiences can be any combination of hedonic and eudaimonic (and pragmatic, for that matter) at the same time [177, 265]. Like other systems, haptic systems need to be stimulating, evoke memories, and communicate identity to be perceived as hedonic, according to Hassenzahl [140]. Prevalent is the need for stimulation (i.e., providing new impressions, opportunities, and insights) to keep a user engaged in the system, as compelling stimulation can compensate for a lack of motivation through novel, interesting, or exciting feedback. The need for stimulation relates to the autotelics factor of the HX model [206] – haptic feedback feeling good in and of itself is influential on the system being perceived as compelling. Haptic systems can provoke memories important to past events, relationships, or thoughts important to the individual [140]. In the constructivist view, these memories are essential to forming the experience, often influencing the perceived valence of an experience [20]. In other words, designers will aim to evoke pleasant memories to provoke hedonic experiences. For instance, Dalsgaard et al. [63] found memory to haptic stimuli relations by asking users to recall experiences of which the haptic stimuli reminded them. Users reported experiences of affective touch and haptic massages, while the haptic stimulus was described as pleasant. Important for both hedonic and eudaimonic qualities is the need for the user to be able to identify themselves with the system as they express their self through it. This self-expression is entirely social [140] and thus relates to the user's need for relatedness and the feeling of connectedness to their surroundings [177, 266]. That is also the reason why it is important to the fulfilment of both hedonic and eudaimonic motives of the user.

Meaning is another eudaimonic quality. Mekler and Hornbæk's Framework for the Experience of Meaning [266] describes five components of meaning. Through the design towards these components, designers can evoke experiences of meaning. The framework serves as an important foundation for the eudaimonic qualities, as "meaning alone can serve as a good proxy for eudaimonic experience" [177, p. 22]. We have shown manifestations of haptic experiences of meaning; for instance, Turchet et al. created a haptic system providing vibrotactile feedback synchronised with a musical performance – "Vibrations added a new level and I found myself searching for relationships between music and vibrations" [385, p. 5]. Lastly, we add orientation and behaviour to the eudaimonic qualities. Similar to how identification describes the need for external self-expression, orientation describes the need for internal self-actualisation, driven by the values, motives, ideals, and goals that guide a user [177]. Relatedly, the behaviour quality represents users' activities to achieve self-actualisation [177]. Thus, a system needs to support different ways of living and design for different motives of engaging with the system. As an example, An et al. [9] designed a haptic system in which users could customize haptic patterns displayed along with emoticons. Through this system, users could express their motives and ideals to others and engage with remote communication, allowing them to actualize their motives. What sets haptic systems apart from other systems in the context of eudaimonia is unclear and subject to future work.

12.6.5. Consequences

As a last adaptation, we expanded the *consequences* of the system character to reflect the renewed focus on well-being and the additional considerations for needs satisfaction. Need satisfaction arises from the use of the system if it supports the motivational goal of the user [143, 387]. We understand the consequences of a system character as two-fold in nature: as a subjective feeling (i.e., experiencing) and as an advancement of the user's abilities, habits, or accomplishments (i.e., functioning) [177]. Huta [177] gives a comprehensive overview of the contents of experiencing and functioning; we list just a subset in the depicted model. Both experiencing and functioning can be related to hedonic and eudaimonic motivations; some consequences might, however, be more or less closely tied to either of the two motivations. For instance, positive affect is primarily related to hedonic experiencing but also contributes positively to eudaimonic experiences. Similarly, personal growth is primarily a eudaimonic functioning but contributes positively to hedonic experiences [177]. As a rule of thumb, we can say that hedonic consequences refer to momentary feelings, while eudaimonic consequences describe long-term accomplishments (there are exceptions, e.g., the 'resonance' component of meaning as presented by Mekler and Hornbæk [266]). Hassenzahl [140] states that emotional consequences are a major design goal in UX research, particularly design for satisfaction and pleasure. We see as much in our sample of publications, we nonetheless propose to broaden this scope to also include meaningful consequences, based on Mekler and Hornbæk's work [265, 266].

12.6.6. Context

Consequences are invoked in *context*. Hassenzahl [140] distinguishes between two usage modes in context; goal mode and action mode. Users in goal mode are motivated by completing a specific task or goal as they try to be efficient and effective. An example is the feelSpace belt [278], a belt vibrating in the direction of travel for navigational purposes – the goal is to navigate to a specific location. The hedonic qualities, such as pleasure or satisfaction, are in the back, whereas the pragmatic qualities of finding the way, such as effectiveness or efficiency, are in the fore. Conversely, when in action mode, users determine goals during use; using the system can be an 'end in itself'. An example of the user in action mode is the use of haptic embellishments, a concept in which haptic feedback reinforces information already provided through other means [355] – actions are driven through enjoyment and appeal. Hassenzahl [140] emphasises that a system can and will be used in either mode: embellished games can be played solely to beat a particular high score, while the feelSpace belt can be used to explore a city without a particular goal. Both modes can elicit positive experiences and need satisfaction.

We expand on this notion of context as we see the importance of multi-modal sensory information influencing haptic experiences. Haptic experiences are constructed in the context of use and in the context of internal and external influence. The internal influence describes the state of the user, their state of mind and their previous experiences. Dalsgaard et al. [63] found that haptic stimuli can prompt users to describe complex and non-haptic previous experiences. However, this is only one example of the internal state influencing the experience – social relations, motivation, needs, and mood all influence the haptic experience. Similarly complex and varied are external influences. These range from the classical distinction between passive and active touch [227] to the social situation of the haptic stimulation [308] and whether the experience is multisensory [396]. Maggioni et al. [252], for instance, showed the added value of haptic feedback in multimedia content. The context thus influences haptic feedback; however, context is influenced by haptic feedback.

12.6.7. Using the Unified Haptic Experience Model

We view the uses of the unified HX model as being three-fold: It allows for deductive, abductive, and counterfactual reasoning [291]. The model unifies theories and models relevant to hapticians, giving an overview of the key components of haptic design. This allows for deductive reasoning through understanding the relation between components and predicting the consequences of a haptic design. The model similarly allows for abductive reasoning by offering an explanation for observed consequences. Most importantly, however, the model allows for counterfactual reasoning [291]; it allows for constrained thought experiments around a haptic design. Hapticians can thus use the model to reason about *possible* worlds with a haptic design in it. Thus, the model carries constructive power[22], as it consists of factors important to user and haptic experiences. Although our assumption is that these factors are related, as they appear in UX and HX contexts, the strength of their relationship is not mapped out extensively.

12.6.8. Iterating the Unified Haptic Experience Model

We see iterating the unified HX model as *the* essential next step for HX research. Based on previous work, we have drawn a picture of the haptic design process. However, we do not claim sovereignty

[22] Oulasvirta and Hornbæk [291] defined constructive power of a theory as its ability to "inform decisions that yield desirable outcomes to end-users" and the expressive strength of factors in the theory [pp. 82–83].

of interpretation and invite iterations to this unified HX model. There are multiple pathways for such future research.

A first pathway is to iterate on the constructs listed in the model. We do not show the relation between the constructs; we merely theorize how they are related based on established theories and current practices. Establishing clearer boundaries between constructs would allow for more precise reasoning and, thus, for a more robust model. As an example, whether the concepts of consistency and congruency are correlated or orthogonal is not clear. Or which system features have the most profound impact on need satisfaction. Questions such as these should be asked and answered.

The model does not address the ethical implications of technology-mediated touch, although these are underlying the haptic design process. A second pathway to iterating the model is thus relating ethical implications to the constructs in the model. Barrow and Haggard [23] presented a number of ethical considerations for designers of haptic systems, in particular, considerations of sensory autonomy and consent, transparency of affective and interpersonal touch, and of ethical design. We see the impact of such consideration on the unified model for HX as profound and particularly important to hapticians. Ethical considerations need to permeate the work of the hapticians using the model. The model, however, does not guide hapticians in these considerations. How the integration of Barrow and Haggard's work can be shaped remains future work.

As a third pathway, future research could investigate the diversity of haptic technology users. Both the psychophysical and psychological states of the users influence the perception of haptic technology. With age, sensitivity to touch does decrease [59]. Within and across individuals does the perception of touch differ [301] and individuals make sense of haptic sensations in their own ways [342]. Thus, there have been calls for personalisation within haptic research [206, 342]. The model, however, does not guide the designers towards personalisation. Such considerations are important to address individual differences between users as well as accessibility needs by users.

These and other pathways form the future direction of the unified HX model. Each step on a possible pathway will change and strengthen the model.

12.7. Conclusion

To conclude, we argue that an extension of the methodological and theoretical framework used in Haptic Experience (HX) research is necessary. We present a unified model based on User Experience (UX) methods and theories as one way forward, acknowledging that many more avenues have to be explored to iterate the presented model. The model is an effort to facilitate a paradigm shift from result-centric to model-centric research in HX.

We critically present current practices in HX research, not to question these practices and results but rather to open a forum for discussion of future practices. These current practices find themselves in a predicament; neither do they satisfy the aspirations of rigour and generalisability of empirical positivists nor situatedness and embodiment important to the interpretivist stance. Untangling this predicament is a grand challenge in HX research, in which it is important to engage with truth-seeking empirical evidence and holistic descriptions of human experience – but not confuse one for the other. The need for a methodological and theoretical grounding of HX arises from current practice. We show the unification of HX with UX as one pathway enabling inductive, abductive, and counterfactual reasoning.

The unified model serves multiple purposes: it enables hapticians to reason about their designs, it directs attention towards human experience, and it facilitates a discussion about the constructs relevant to HX, opening the space for future iterations of this model. The last point, in particular, is an important future step. The unified model for HX needs to be iterated, for instance, by showing the relation between the concepts, arguing for the adaption of the concepts, and alterations to the structure. The model addresses the functional relation between haptic design, experiential qualities and perceived consequences.

We sketch a possible future for HX research by unifying the relatively novel HX with established concepts from UX. However, we also explain that this is the first step in a series of iterations towards an HX model that describes how haptic experiences are made. That is the drive of developing an HX model; as Hassenzahl et al. explained: "Rest assured that no matter whether we want to focus on experience or not, technology will always create some. Consequently, it seems wise to actually put experiences at the center of our design efforts." [142, p. 209]

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12.8. Supplemental Material

12.8.1. Litterature review

12.8.1.1. Search Queries.

Table 12.5. The search queries used to search papers. The search was conducted on the 5th of July, 2023.

Repository	Query	Url	N
ScienceDirect	*Query:* "haptic experience" *Year(s):* 2013-2023	Link	220
ACM DigitalLibrary	*Query:* "haptic experience" *Publication Date:* Jan 2013 - Jul 2023	Link	192
Scopus	*Query:* `TITLE-ABS-KEY("haptic experience") AND PUBYEAR > 2012 AND PUBYEAR < 2024 AND (LIMIT-TO(DOCTYPE, "cp") OR LIMIT-TO(DOCTYPE, "ar")) AND (LIMIT-TO(LANGUAGE, "English")) AND (LIMIT-TO(SRCTYPE, "p") OR LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO(PUBSTAGE, "final"))`	Link	185
Web of Science	*Query:* ALL=("haptic experience") *Publication Date:* 2013-01-01 to 2024-01-01	Link	160
IEEExplore	*Query:* ("All Metadata":"haptic experience") *Filters applied:* IEEE, Conferences, Journals, 2013 - 2023	Link	49

12.8.1.2. Code Book. *(see following page)*

Table 12.6. ❑ stands for one selection only; ❍ stands for multiple selections; [...] stands for copied text.

Category	Code
Research Aspect	
Motivation	❑ Assess perception of feedback; ❑ Designed purpose of haptic feedback; ❑ Facilitate non-XR interaction; ❑ Facilitate social interaction; ❑ Increase immersion in XR; ❑ Investigate psychophysical properties; ❑ Learning, education, or training; ❑ Sensory Augmentation
Measure	[...]
Methodology	❑ Qualitative; ❑ Quantitative
Method	❑ Explicitation interview; ❑ Group interview; ❑ Micro-phenomenological interview; ❑ Open interview; ❑ Psychophysiological measures; ❑ Questionnaire; ❑ Semi-structured interview; ❑ Structured interview; ❑ Task performance; ❑ Other methods
Questionnaire	❑ AttrakDiff [139]; ❑ Discrete Emotions Questionnaire (DEQ) [133]; ❑ Avatar Embodiment [302]; ❑ Haptic Experience model [12, 206, 330]; ❑ igroup presence questionnaire (IPQ) [339]; ❑ Liking Scale; ❑ NASA-TLX [136]; ❑ Networked Minds Measure of Social Presence (NMMSP) [134]; ❑ Perceived Stress Scale (PSS) [56]; ❑ Player Experience Inventory (PXI) [2]; ❑ Presence Questionnaire (PQ) [413]; ❑ Quality of Experience (QoE) [205]; ❑ Self-Assessment Maniquin (SAM) [33]; ❑ Self-developed (items listed in the paper); ❑ Self-developed (items partly known); ❑ Self-developed (items unknown); ❑ Simulator Sickness Questionnaire (SSQ) [203] ; ❑ State Mindfulness Scale (SMS) [368]; ❑ System Usability Scale (SUS) [37]
Stimulus	
Descripton	[...]
Purpose	[...]
Technology	
Haptic Device	❑ Commercial Device; ❑ Custom Device; ❑ Proxy
Device Details	[...]
Bodypart	❑ Arm; ❑ Back; ❑ Feet; ❑ Freely placed by participant; ❑ Head; ❑ Index finger; ❑ Legs; ❑ Lips; ❑ Middle finger; ❑ Palm; ❑ Pinky; ❑ Ring finger; ❑ Thumb; ❑ Torso; ❑ Whole Body; ❑ Whole Hand
Usability [142]	
– *Intended and Apparent Character* [140]	
Usability	[...]
Utility	[...]
Haptic Experience (HX) model [206]	
– *Intended and Apparent Character* [140]	
Autotelics	[...]
Expressivity	[...]
Harmony	[...]
Involvement	[...]
Realism	[...]
Framework for the Experience of Meaning [266]	
– *Intended and Apparent Character* [140]	
Connectedness	[...]
Purpose	[...]
Coherence	[...]
Resonance	[...]
Significance	[...]

12.8.2. *Current Practice in Haptic Experience Research*

In the following, we report the methodologies used to measure the different aspects of the haptic experience and how authors and their participants engage with the different factors and components influential to haptic experiences.

Table 12.7. The primary purpose of designed haptic feedback.

Designed purpose of haptic feedback	n	%
Increase immersion in XR	41	39.4
Assess perception of feedback	23	22.1
Facilitate non-XR interaction	13	12.5
Learning, education, or training	12	11.5
Facilitate social interaction	6	5.8
Investigate psychophysical properties	5	4.8
Sensory Augmentation	4	3.8

Note. N = 104 publications.

12.8.2.1. Purpose of Stimulation. Research in haptics is motivated by a number of concrete use cases and to study the psychophysical properties of touch. Table 12.7 shows an overview of the design intend of haptic stimulation. Most of the 104 publications in our sample seek to heighten the interaction in XR applications ($n = 41$, 39.4%; e.g., through increase presence and immersion). This is archived, for instance, through building a custom controller to simulate weight [220], stiffness [354], shear [411], and other haptic properties. A set of 23 (22.1%) of sampled publications aims to assess the perception of haptic stimuli, for instance, the perception of physical textures [169, 261] and their properties (e.g., slipperiness [60], friction [362], stiffness [417]). While some publications in this set might use XR as a tool for study, perception of a haptic stimulus is in focus (e.g., [52, 126]). Further, 13 (12.5%) publications are concerned with designing interactions outside XR augmented with haptic feedback. These allow for tangible interactions in data visualizations [30], "intuitive, eyes-free, and tactually rich interactions" in automotive interfaces [36], forearm actuation using smartwatches [115, 171], and "excessive positive haptic feedback" to increase enjoyment of a smartphone game [355]. A nearly equal amount of publications ($n = 12$, 11.5%) use haptic feedback for applications within learning, education, and training. In these cases, the aim is to provide realistic haptic feedback for skill learning (e.g., surgery [114], dentistry [315], human-robot interaction [297]), provide tangibility to intangible objects (e.g., molecules [91, 432]), or augment a story to deepen understanding and to provide interactivity [6, 46, 55].

The aim of six (5.8%) publications is to study affective social touch facilitated through haptic technology. All publications design haptic systems allowing participants to customise a tactile pattern before sending it to another person. The studies differ in the relationship between sender and receiver; some pairs held a romantic relationship [308, 328], some pairs had another established social relationship [9, 308], and some pairs consisted of a participant and a author [364]. Five (4.8%) publications studied psychophysical properties of touch using haptic technology, measuring texture discrimination thresholds [1], Just-Noticeable Difference (JND) of haptic stimuli [49], and "detection thresholds between physical and virtual object sizes" [29]. Lastly, four (3.8%) publications

Table 12.8. Haptic devices and methods used to stimulate study participants.

Device	n	%
Custom built device	62	59.6
Haptic proxy	10	9.6
Phantom Omni	8	7.7
Ultraleap Stratos Explore	6	5.8
Mobile device	5	4.8
XR controller	4	3.8
Linear Resonant Actuator	2	1.9
Electrical Muscle Stimulation	1	1.0
C-2 tactor	1	1.0
MimoVue TanvasTouch	1	1.0
Omaga 6	1	1.0
Woojer	1	1.0
TPad Haptic Surface	1	1.0
Butterfly Haptics	1	1.0

Note. N = 104 publications.

investigate different forms of sensory augmentation [249], augmenting artworks [399], movies [3] and music [385, 386] with haptic feedback.

12.8.2.2. Means of Stimulation. Publications either use a novel, custom-built haptic device ($n = 62$, 59.6%), a commercially available device ($n = 32$, 30.8%), or haptic proxies ($n = 10$, 9.6%). Custom-built devices are designed to provide feedback using one or more haptic modalities: Kinesthetic ($n = 43$, 69.4% of custom devices), tactile ($n = 28$, 45.1% of custom devices), and thermal ($n = 5$, 8.1% of custom devices). Often these devices are handheld or -mounted, attached to a finger, the arm, or, in rare cases, to the feet or the torso. The aim is often to develop a device capable of providing feedback on a range of haptic perceptions (e.g., temperature [40, 131, 308], roughness [126, 362], shear forces [207, 411], stiffness [359, 369, 409, 427]). Other aims include studying a particular phenomenon such as social touch [308, 328] or interpersonal interaction [54]. The Phantom Omni ($n = 8$, 7.7%) and the Ultraleap Stratos Explore ($n = 6$, 5.8%) are common choices when using commercially available haptic devices. These two devices provide feedback on different haptic modalities, kinesthetic and vibrotactile, respectively. Other commercial devices include vibration motors and surface haptic devices. Publications involving commercial devices aim to assess pleasure and enjoyment [3, 355], the ability to elicit emotions [9, 277, 344], and qualities of designed interactions [46, 406, 432]. Haptic proxies are commonly used in XR, as it is easy to mask the physical appearance of the proxy in the virtual world. The size of a proxy ranges from a 3 cm cuboid [29] to moveable walls [50, 421]. The functionality and design intent of the proxies is diverse. Wagener et al. [404] find that sitting in artificial grass while in VR can increase well-being, Auda et al. [13] attached 3D printed objects to a drone, mimicking buttons, sliders, and other interactables, and Yang and Weng [419] used physical puzzle pieces to consolidate a leaning objective in VR.

12.8.2.3. Location of Stimulation. Table 12.9 shows the distribution of body parts described to be stimulated as part of sampled publications. Overall, the sample presents devices capable of pro-

Table 12.9. Body parts stimulated using haptic technology.

Body part	n	%*	Body part	n	%*
Hand	**84**	**80.8**	**Lower body**	**7**	**6.7**
Whole hand	60	71.4	Feet	5	71.4
Index finger	19	22.6	Legs	2	28.6
Thumb	4	4.8	**Head**	**4**	**3.8**
Middle	1	1.2	Mouth	2	50.0
Upper body	**19**	**18.3**	Head	2	50.0
Arm	13	68.4	**Whole body**	**3**	**2.9**
Torso	4	21.1	Whole body	2	66.7
Back	2	10.5	Freely placed	1	33.3

Note. N = 104 publications. *Percentages in roman are within the group. Data between groups do not sum to 100%, as some publications stimulate multiple body parts.

viding haptic feedback on all body parts, although the hands and fingers are clearly in focus. The fact that hands are the sensitive body parts to haptics (next to the lips) [59] and that the hands are the primary mode of touching proxemic objects and people [299] explains this focus on subjecting the hands to haptic stimuli. While most publications describe stimulating the whole hand through XR controllers (e.g., [72, 116]) or custom devices (e.g., [220, 308, 360]), others describe stimulating one or more fingers in particular (e.g., [83, 366, 409]). The rest of the body is subjected to stimulation far less, partly due to the lower sensitivity to touch and partly due to the need for the creation of custom devices or proxies for stimulation on other parts of the body. Such devices are often impractical, requiring users to wear the haptic device on their bodies. This limitation has been overcome by attaching the haptic actuator to an already worn accessory or device; for instance, a smartwatch [115], a VR headset [351], or sewn into a piece of clothing [6, 201]. An observed exception is the work by Wittchen et al. [414], who allowed participants to place vibration motors on their bodies. Another notable exception would have been commercial haptic vests or jackets; we have not observed instances of this technology used in our sample.

Table 12.10. Questionnaires used to evaluate haptic experiences.

Questionnaire	n	%*
Self-developed (items listed in the paper)	37	43.5
Self-developed (items unknown)	27	31.8
Presence Questionnaire (PQ) [413]**	7	8.2
Self-Assessment Maniquin (SAM) [33]	6	7.1
igroup presence questionnaire (IPQ) [339]	5	5.9
Avatar Embodiment [302]	4	4.7
Haptic Experience model [12, 206, 330]	4	4.7
Simulator Sickness Questionnaire (SSQ) [203]	4	4.7
System Usability Scale (SUS) [37]	3	3.5
AttrakDiff [139]	2	2.4
Quality of Experience (QoE) [205]	2	2.4
Discrete Emotions Questionnaire (DEQ)	1	1.2
Liking Scale	1	1.2
NASA-TLX [136]	1	1.2
Networked Minds Measure of Social Presence (NMMSP) [134]	1	1.2
Player Experience Inventory (PXI) [2]	1	1.2
State Mindfulness Scale (SMS) [368]	1	1.2
Perceived Stress Scale (PSS) [56]	1	1.2

Note. N = 85 publications that used questionnaires. *Data does not sum to 100%, as some publications use multiple questionnaires. **Also known as Witmer-Singer Presence Questionnaire (WSPQ).

12.8.2.4. Evaluation of Haptic Experiences. Table 12.10 shows all questionnaires used in the sampled publications. Note that the '*other surveys*'-row in the full paper lists 10 publications using 'other surveys', whereas Table 12.10 shows 17 individual uses of 'other surveys', implying that 10 publications used at least 17 different questionnaires.

12.8.3. Sources for our model

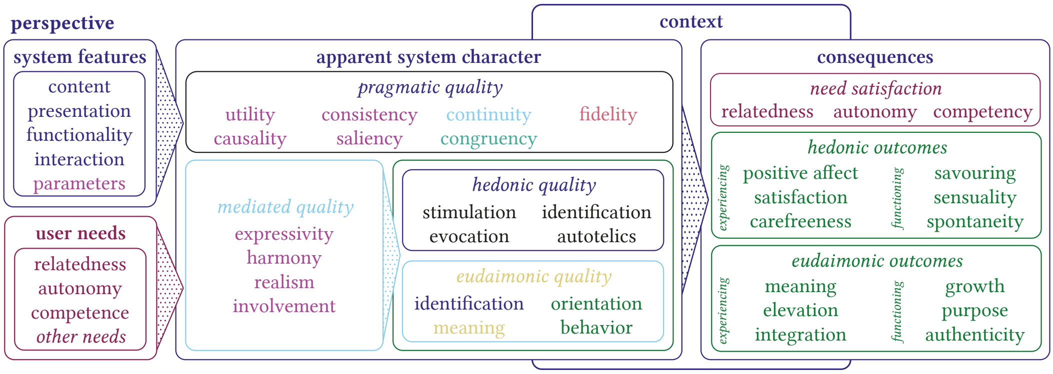

Figure 12.3. The presented model, coloured by source:
- Breitschaft et al.'s Haptic Fidelity Framework [35];
- Hassenzahl's UX model [140];
- User needs [143, 177];
- Hoggan et al.'s 'congruence' [157];
- Huta's Overview of Hedonic and Eudaimonic Wellbeing Concepts [177];
- Kim and Schneider's HX model [206];
- Mekler and Hornbæk's Framework for the Experience of Meaning [266];
- Newly introduced in our model.

13. Extending the Unified Model for Haptic Experience

The development of the Unified Model for Haptic Experience is not complete. In the paper, we call for iteration and specification of the concepts mentioned in the model. This is the aim of this chapter; I expand on the concept of context and discuss the ethics of digital touch. The Unified Model and the Inference-Design Model gain more depth through this.

13.1. The Context of Touch

Interaction happens in context – haptic experiences are made within it. What constitutes context is illusive and, according to Dourish [86], often misunderstood. Interest in the context of interaction initially arose from the idea of context-aware computing, in which designers consider the context of technology use in their designs. Dey defined context as such:

> Context is any information that can be used to characterise the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and applications themselves. [82, p. 5]

In such a context definition, context is an encoded representation of a space and the objects within it. Dourish argued to the contrary; context arises from the activity and is dynamically changing according to the activity, "context is an occasional property, relevant to particular settings, particular instances of action and particular parties to that action" [86, p. 22]. As such, context is not an encoding of a setting but something people do – context is relational.

No matter whether one follows the path of Dourish or the path of Dey, the question for haptic designers remains, 'What influence does the context have on haptic experiences?'. The answer to that is complex, as contexts are diverse and inseparable from activity, in Dourish's view. Schneider et al. [334] has previously argued that complex contexts hinder haptic designers' attempts to design consistent experiences, particularly as these experiences are multisensory. As an example, consider Wagener et al.'s application of passive haptic feedback in the form of artificial grass [404]. In a virtual reality nature experience, the haptic feedback contributed to presence and mindfulness. However, it remains questionable whether mindfulness would have occurred outside of the virtual context[23]. The artificial grass gets its 'mindfulness value' through the action of sitting on it, touching it. Together, I get the sense that much research is needed to find those aspects of a context that influence the perception of haptic feedback the most. Dourish [85, 86, 87] has long argued for the introduction of interpretivistic methods to human-computer interaction; this call does not seem to have reached haptic research yet. However, it is not too late nor too early to start; the presented journal paper *A User-Derived Mapping for Mid-Air Haptic Experiences* [63] might serve as an example.

13.2. Ethics of Technology-Mediated Touch

An emerging topic in haptic research is related to the ethical questions of technology-mediated touch [23, 57, 192]. In a recent episode of the Haptics Club podcast[24], David Parisi speculated that

[23] This is not a criticism; the authors were motivated differently.

[24] Ashley Huffman (Host). (2024, May 9). Special Guest David Parisi on Technohaptics (No. 54) [Audio podcast episode]. In *Haptics Club*. https://thehapticsclub.com/episodes/too6wf4b9d4szg70ozqgu7fcl4newv

the concerns for ethics within haptic research are emerging, due to recent technological advancements – the fidelity and availability of haptic technologies are increasing. The Unified Model is not explicit about ethics, and we suggest considering ethical aspects of haptic stimulation in a future iteration of the model. Similarly, the Inference-Design Model does explicate ethics, yet it is underlying the design processes. Haptic stimulation is inevitably linked to the senses of touch, which are, by definition, close to the body and the embodied experience. Thus, I discuss the ethical aspects of digital touch to explicitly consider the implications of using haptic technologies. To begin with, I acknowledge my limited overview of the discussion around different forms of ethics. However, I find it important to mention and engage with ethics in haptic research, particularly for the designers of haptic experiences. For further discussion, I take offset in the work of Barrow and Haggard [23] and Jewitt et al. [192], who, more expertly than I can, engaged with ethics surrounding digital touch. In addition, I point to the work of Cornelio et al. [57] for considerations about responsible research and innovation in the realm of haptic technology.

The question of what ethical touch is is fluent and develops over time and with social norms. Barrow and Haggard argues that "the ethical concerns surrounding touch are more strongly related to being touched, than to touching" [23, p. 4] and suggest *sensory autonomy* and *sensory consent* as the main ethical concerns in physical, non-mediated touch. Sensory autonomy refers to the human's self-determination over their body, particularly their senses of touch. As stated before, touch is special – sensing of touch never halts and is not easily suppressed. Due to this and the variety of senses that make up touch (mechanical, nociceptive, and thermal), it is difficult to maintain full conscious self-determination over the body. Ethically, however, there is a difference in whether the self is responsible for stimulating the senses versus the other [23]. This leads to sensory consent: The general principle of consent involves the self allowing or disallowing the other to perform an action over which the self has authority. Through sensory consent, sensory autonomy is maintained.

In technology-mediated touch, these concerns are amplified; autonomy and consent are even more difficult to maintain, and issues of trust, control, and privacy are introduced [23, 192]. A haptic device that can deliver stimulation across the body can quickly violate sensory autonomy, particularly when they are hard to turn off or difficult to remove, as current form factors of haptic devices are (e.g., haptic gloves, haptic vests). Similarly, the distant other can abuse a haptic communication system by administering unwanted sensations of touch to the self. As such, an ethical haptic device needs an easily available switch-off button, as Barrow and Haggard [23] suggested. In addition, Jewitt et al. [192] raised concerns of trust and privacy: On one side, there is the issue of trust between interacting people and on the other; on the other, there is the issue of trust between the human and the machine. Haptic technology allows touch interactions across time and space, which raises questions about who the self is touching through the technology – a consenting other or an adversarial agent who hacked into the system. Lastly, Jewitt et al. brings up the concern of control by asking who is in control of the encoded touch communication and who decides whom to share the encoded touches with. "Will the touch of one's child – e.g. a baby's first kiss – become a tangible, sharable artefact and, if so, how might digital-mechanical reproduction disguise or attribute the uniqueness of the baby's touch? If someone engages in and records inappropriate or illegal touch, what stops them from sharing these touches with others?" [192, p. 117]. Haptic system providers may take commercial advantage of such recorded touches without ethical haptic practices.

And thus, we see the landscape of digital touch ethics; it is vast and largely unexplored. As haptic designers, we need to consider the ethics of touch, particularly as technology advances. While this section is drifting from the main point of the Inference-Design Model for Haptic Experience, it is important to me to highlight the ethics of digital touch, as they are often not considered in haptics research.

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14. A Touch of the Future: The TOUCHLESS Hackathon 2022

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Abstract. Ultrasound haptics allows us to experience the sense of touch without contact with any physical surface. This novel "touchless" feedback can be used for various use cases but is not widely adopted nor incorporated in everyday products. The 2022 TOUCHLESS Hackathon aimed to enable novel practitioners to learn about touchless technology, generate new ideas, and implement prototypes. We invited participants to a 3-day hackathon in Copenhagen, Denmark, where we introduced touchless technology and provided novel touchless devices for prototyping use cases. Participants were joined by experts on ultrasound haptics, who helped them achieve their prototyping goals. Coming from various educational and national backgrounds, the participants approached the task in different ways and created four unique interactive prototypes. This event report introduces the TOUCHLESS Hackathon and reflects on the lessons learned.

Keywords. mid-air haptics, tactile experience, hackathon

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14.1. Introduction

In the field of Human-Computer Interaction (HCI), novel computing devices are prototyped, and the interactions they enable are evaluated. Less common are the adoptions of these novel devices into our everyday life. One reason for the lack of adoption is the lack of access to the research prototypes, especially since a significant time and monetary investment is connected to acquiring, reproducing and implementing them into projects. Thus, it is important to give developers and designers access to novel technologies.

Hackathons have already shown their potential in facilitating the collaboration between technology creators and adopters. A hackathon is a themed, time-limited event (typically ranging from a few hours to a few days) where a group of people intensively collaborates to create a prototype that solves a problem within a particular theme [280, 370]. Initially thought as a way of bringing together coders and developers with designers and project managers [7], hackathons have developed into a tool for community engagement in biodiversity, future cities, and schools and more [280]. Such events have the potential to generate excitement and enthusiasm around technological possibilities [371], which makes them ideal venues to introduce novel technologies. They create a context for toying around with technology which makes it easier for people to understand and think about potential use cases [202], as well as builds a bridge between technology creators and adopters.

One such technology is ultrasound vibrotactile haptics. These devices emit ultrasound waves with force strong enough to vibrate the human skin and thereby stimulate the mechanoreceptors situated in the skin. This type of haptics, or virtual stimulation of the sense of touch, is a relatively novel technology that is yet to be integrated into consumer products. For the scope of this paper, we will refer to this technology as "touchless" technology, as it allows for touch sensations in mid-air. The technology has extensive possibilities for research. It can be used to study the receptors in our skin [44], improve everyday interactions [257], and help us understand the experience of touch [63].

In April 2022, we organised the TOUCHLESS Hackathon 2022 in Copenhagen under the theme "A Touch of the Future"[25]. The goal of the hackathon was to introduce touchless technology to a mix of interested people, such as developers, designers, and researchers, to generate ideas and potential use cases. For this, we set the following learning goals for the participants:

- Learn about touchless technology
- Generate new ideas on how to design and apply touchless interaction
- Build, draw and test touchless prototypes in groups

To facilitate these goals, we structured a program consisting of learning opportunities (i.e., expert talks and workshops), feedback sessions (i.e., participant presentations and expert assistance), and plenty of time to explore the technology. In this work, we provide an overview of the activities and reflect upon whether they supported the learning goals.

14.2. Organisation

The hackathon was hosted at the University of Copenhagen. We invited participants from six universities located in or near Copenhagen (Denmark), London (UK), Krakow (Poland), and Navarre (Spain). In total, 26 participants signed up for the hackathon and were divided into four groups on the first day. The division was made based on their background, such that each group would have two or three people confident in coding in C++ or Unity (C#). Their backgrounds ranged from designers and musicians to computer scientists and engineers. Additionally, we invited eight academic and industrial experts to guide and assist the participants throughout the weekend. The experts were part of the EU-FET project TOUCHLESS, sponsoring this event.

During the hackathon, the participants were provided with the Ultrahaptics Evaluation Kit (UHEV1), a touchless haptic device. Virtual Reality glasses and 3D printers were also made available in case some project ideas could involve their use. To inspire the participants on the kind of haptic experiences they could create, a box full of materials with different haptic properties was provided. The box contained fabrics, toys made of various materials, compact discs, cassettes, rubber bands, and further items with different haptic properties.

We assumed that the participants would not have in-depth knowledge about the technology at the beginning of the hackathon. Thus, when structuring the program, we gradually built a common

[25] https://www.touchlessai.eu/hackathon

understanding of the technology over the weekend. This was facilitated through a mix of research talks, workshops, and independent hacking. We aimed to leave the most time for hacking, as that is what we thought participants would get the most out of. As a means of setting milestones for the participants throughout the event, we asked the groups to present their work during the event, where they received constructive feedback from both experts and other groups.

Food for each meal and snacks were provided throughout the hackathon. We chose to serve vegetarian food for all dinners. Eating together served as a natural point of sharing ideas and progress.

In the following, we will provide a detailed overview of the hackathon. It started Friday mid-day and lasted until Sunday afternoon.

14.2.1. Friday: introduction and getting started

We planned Friday afternoon to be all about getting started with touchless technology. For this purpose, we organised a 25-minute talk motivating the use of touchless technology in everyday life, for instance, for social communication and interaction in automobiles. The talk was meant to inspire and give a high-level overview.

The opening talk was followed by a demonstration session, where the participants had the opportunity to feel the haptic feedback produced by the touchless technology on their own bodies. During this time, the participants asked questions and discussed their first ideas.

Next on the program was a session where participants could freely pick between two workshops. We recommended that the groups split their group members between the workshops, so knowledge from both sessions could inform the hacking process. The workshops ran simultaneously in different rooms.

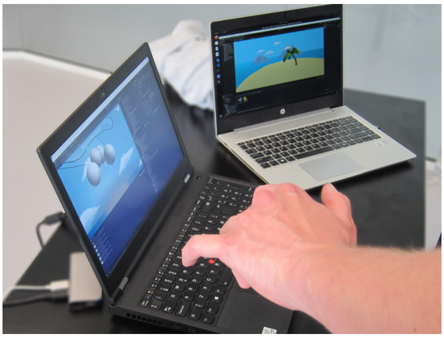
The first workshop was called "How to Code in Mid-Air". It taught the participants how to do the technical setup of the touchless device and how to write code for it. The participants were provided with examples in C++ and Unity (C#), specifically made for the hackathon. This workshop session was meant for participants adept in coding.

The second workshop was called "The Hedonistic Value of Mid-Air Haptics" and was focused on the design of touchless haptic experiences. The workshop included a design session, where participants were encouraged to come up with pleasurable designs for these experiences. This workshop session was meant for participants wanting to focus on interaction design.

The rest of the day was reserved for a group session, in which we encouraged the groups to explore and brainstorm about the prototype they wished to create.

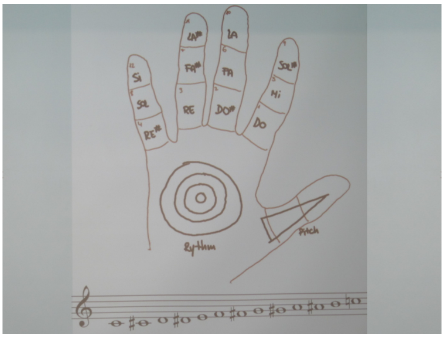
14.2.2. Saturday: hacking and inspiration

The focus of Saturday was on hacking and group work. Therefore, the only expert presentation of the day was a short 20-minute talk about the design of touchless devices. We had set a milestone for the participants at lunch, where they gave a five-minute talk about their project to receive feedback.



a. Diddle Engine: Social interaction at a distance.

b. Hapticolor: Mapping colour perception to the sense of touch.



c. Mutics: Mapping musical notes to sections of the hand.

d. String: Touchless guitar plucking.

Figure 14.1. The four prototypes created at the hackathon.

During this session, both experts and other participants could engage in the discussion about the prototypes. Afterwards, the participants continued to hack away on their prototypes.

Throughout the day, participants had the option to participate in a user study for a research project using touchless technology.

14.2.3. *Sunday: final hacking and conclusion*

On Sunday, the final day, participants hacked away and put the final touches on their prototypes. At mid-day, they presented their prototypes to the experts and the other participants in a five-minute talk. After all talks were completed, groups would exhibit their prototype and show how they worked. In the afternoon, all participants received a prize they could take home. The prizes were inspired by haptic interactions, such as a wooden human statue or a fidget toy.

14.3. Prototypes

During the hackathon, the four groups each created a prototype. All the prototypes used the UHEV1 device to induce touchless haptics. We here present the four prototypes:

14.3.1. Diddle Engine

We can communicate online through text, video and audio. But what about online touch communication? One group addressed this topic, known as Mediated Social Touch [127], by implementing the "Diddle Engine". The group was inspired by an article on our university's website, presenting a vision of being able to hug friends and family at a distance using touchless technology. The article was included as introductory material for all participants. However, as the intensity and interaction space of the touchless device is limited, the group scoped out other forms of greetings such as hugs, high-fives and handshakes. They eventually settled on the lesser-known greeting - diddling. Diddling is a greeting between two people holding out their hand, one above the other, palms facing, and fingertips touching. The group implemented a prototype in which one person could diddle a virtual version of themselves. They used the touchless device, LeapMotion for tracking and implemented it using Unity. Additionally, they considered combining it with Virtual Reality, but could not complete that due to time limitations. The Diddle Engine prototype is depicted in Figure 14.1a.

14.3.2. Hapticolor

The aim of the Hapticolor project was to be able to differentiate colours using the sense of touch. This would allow users to experience colour in a way and could potentially give people with muted colour perception, due to colour vision deficiency or a visual impairment, a novel way of interacting with colours. The group mapped the colour range to the frequency of a haptic stimulus. For their demo, they implemented a virtual flower with coloured petals, that users could interact with. They tracked the hand of the UHEV1 using a LeapMotion device and implemented it in Unity. The Hapticolor prototype is depicted in Figure 14.1b, where users can be seen interacting with the virtual flower above the touchless device.

14.3.3. Mutics

The Mutics project aimed to create a music experience with haptics. Through the sense of touch, deaf people and people with other hearing impairments could experience music on their hands. Musical notes, pitch, and rhythm were mapped to different sections of the hand. The index, middle, ring, and pinky fingers were divided into three sections, each representing a different note, where haptic sensations were induced. The thumb represented the pitch on a continuous scale, while the palm was used to give a sense of the rhythm by rendering a haptic circle with varying intensity and size. Mutics could also be used as an additional sense to augment the experience of music listening. The hand was tracked by a LeapMotion device. The mapping design is depicted in Figure 14.1c.

14.3.4. String

Another music-inspired project, the String project, aimed to allow guitar plucking in mid-air. The group created a virtual musical string instrument, where the touchless haptic device provides feedback upon plucking a virtual string. When plucked, the sound was generated through physical sound models, simulating realistic instruments. The sound model was imported as a plugin in Unity, and a LeapMotion tracked users' hands.

These prototypes show possible application areas of touchless haptics, addressing social, accessibility, and technical issues. There are similarities between projects, as both the Hapticolor and Mutics projects worked with the idea of sensory augmentation [249], augmenting the sense of touch to deliver information about colour and music. Both projects aimed to make colour and music accessible to a broader population and augment the user's experience with these two concepts. The projects were commonly inspired by the participants' free-time activities, such as surfing (Diddle Engine) and music (Mutics and String).

14.4. Reflections

In this section, we reflect upon the learnings of creating a hackathon based on a novel technology. We discuss the different initiatives we took to facilitate the learning goals of the event and what were the lessons we learned.

14.4.1. Learn about touchless technology

Our focus on devoting as much time as possible to hacking enabled **learning by doing**, rather than frontal lectures on technology. Instead of spending too much time in a classroom setting or studying the technology on their own, participants could get their hands dirty immediately as they always had experts in touchless technology at their disposal if they had questions or felt stuck.

Having **multiple parallel workshops**, which participants could choose between, allowed them to focus on their interests and learn from their teammates. It also saved time for hacking as we could transfer a lot of knowledge simultaneously to different members of the teams.

Participating in user studies allowed participants to **try out expert demos** that showcased the technology and inspired them about different domains it could be applied to.

14.4.2. Generate new ideas

The event had a strong focus on **collaboration rather than competition** to facilitate the sharing of ideas. Instead of declaring a "winner" of the hackathon and handing a 1st prize to that group, we gave all participants a participation gift. This allowed the event to have an atmosphere of working together, with participants openly discussing their ideas across groups and helping each other with minor technical issues. **Splitting teams for the workshops** and bringing different members together helped increase opportunities for cross-team discussions. Doing different activities together, listening to talks, coding programs for the touchless haptic device, brainstorming applications, and eating dinner together helped the participants exchange ideas and get creative. While this worked well for the event's goals, a drawback of this approach was that recruitment was more challenging without advertising a 1st prize. We believe more participants could have been recruited with a more desirable prize.

Along with communication amongst participants, we also facilitated **interactions between experts and participants** to inspire new ideas and discussions. This was done by creating opportunities to interact with them, such as participating in user studies, getting feedback on milestones and eating cake together. We believe that small events, such as our hackathon, require the organizers (experts) to be reachable by the participants and engaged with the projects. Engagement does not mean taking over the project, as the participants should remain the driving force, but rather that the organizer should **help out when needed** and inspire where they can. This ensures that the participants are motivated and feel that their work is valued. This helped participant engagement and their desire to create a prototype. It also enabled the organizers to track progress to see where participants excel or struggle when building touchless haptic prototypes.

An idea that did not work for inspiring participants was to provide a box full of materials with different haptic properties. We hoped participants would touch and play with items in the boxes to try to recreate or enhance the sensations they felt. However, very few participants came up to the box and none of the projects directly used the provided items. We imagine this could be because we needed a more **diverse set of participants** as most were from a computer science background and focused on exploring the technology rather than how it related to the real world.

14.4.3. Build, draw, and test touchless prototypes in groups

While planning the event, we set milestones for the groups. These were meant to help the participants organise their time and have continuous progress. We did not set specific goals for each milestone, rather we set headlines such as “Presentation of the main idea” or “Exhibition of prototype”, **leaving it to the groups how they would achieve the milestone**. Thereby, we hoped to keep the presentations relaxed and informal while still making sure that the groups were on track.

At the end of the hackathon, we organised an exhibition of the prototypes, where participants could discuss their designs with other participants, the experts, and guests from a research lab in Copenhagen. These discussions served as **an inspiration for further designs** for further research projects. The participants expressed cited this exhibition as **a good final mark on the hackathon**.

14.5. Conclusion

We believe in the potential of hackathons to give users access to novel technologies that have not yet found their way to consumer products. With a mix of talks, multiple workshops, and set milestones, our hackathon structure allowed novel users to engage with touchless technologies and produce meaningful prototypes. We also believe that we, as researchers within touchless haptics, learned a lot about the technology by seeing the novices engage with the technology. Thus, we encourage academia and industry to organise more hackathons in which they present their novel prototypes.

Acknowledgements

We thank Ultraleap for letting us borrow their devices and providing their expertise during the hackathon. This work was supported by the European Union’s Horizon 2020 research and innovation programme [grant number 101017746, TOUCHLESS].

15. Narratives of Touch

The short paper *A Touch of the Future: The TOUCHLESS Hackathon 2022* [67] presented a number of findings related to the practical organisation of the hackathon; however, from a haptic experience design perspective, the paper presents something much more interesting – the prototypes. From them, I have learned some of the challenges haptic designers face while creating haptic experiences, yet also how the designers find ways around these challenges. Consider the *Diddle Engine*. It allows for remote communication by mediating the sensation of two humans touching their fingertips. As we write in the short paper, the haptic device's technological limitations hindered the design process. The designers aimed to allow for hugs and handshakes, but it settled on fingertip-touching; undeterred by the headwind, the designers found a way of communicating their design's meaning and usefulness – they told a story. Apparently, diddling is used by surfers on the beaches of California to greet each other and complement each other on their wave-riding skills[26]. The Diddle Engine emphasised this relation to surfing culture by placing a beach and a palm tree next to the visual representation of the hands diddling. This story helped the perceiving human contextualise the perceived haptic feedback. In this chapter, I explore the power of narratives to tell the story around the touch as a practical way of designing the intended haptic experiences.

The strategy of storytelling and creating a narrative around a design has the potential to increase engagement in the haptic system [340, pp. 28–47]. Creating a compelling narrative and, thereby, context shapes the experience [86]. As such, designers can design a haptic stimulus that fits into their designed narrative, in which haptic experiences can occur [295, 340, 416]. In short, designers do not design haptic experiences; they design *for* haptic experiences.

Designing for haptic experiences requires designing the narrative just as much as designing the haptic stimulus. The story can be complex and elaborate or straightforward and mundane, just as the stimulus can be – important is the interplay. I will not equate this narrative approach with multisensory design; they can work in conjunction and support, but telling a story to induce a feeling in a human is different from stimulating multiple senses in more or less congruence. The narrative approach has proven effective in designing for experiences [340, pp. 114–129]. Introducing the narrative approach is an attempt to broaden the toolkit of haptic designers; they do not need to subscribe to the methods of affective haptics nor any particular collection of methods, as the narrative approach to design has the potential to elicit affective, hedonic, eudaimonic, pragmatic, and other types of experiences. MacLean argues, on the contrary, to specify the scope towards affective haptics:

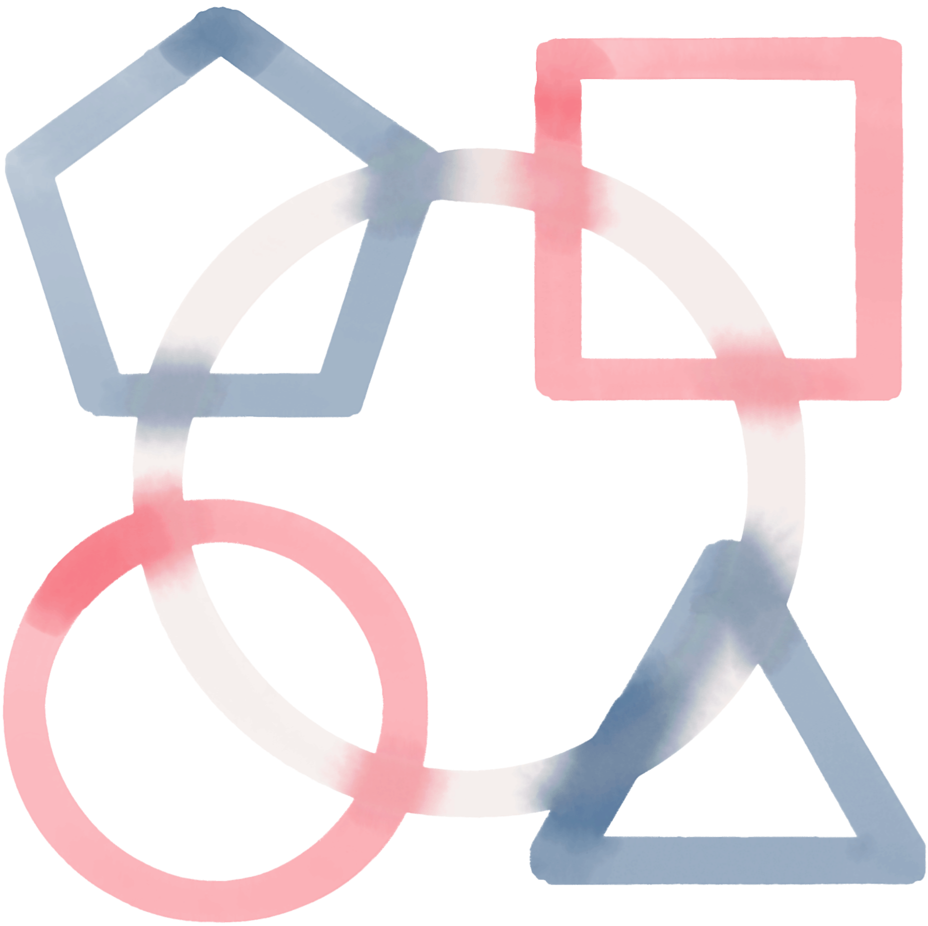
> An affective lens may be a good, perhaps the best, design approach generally because of its centrality to how humans process physical experience. [245, p. 2]

However, not all experience is affective—quite the way to sensory and emotional overload, if that were the case—humans also need *mundane experiences* [88]. These are the ones we have the most of in everyday life. Technologies are introduced to fulfil the functions of everyday tasks and the workplace; however mundane they might seem, these experiences are also designed. Consider the

[26] It later turned out that the story is not based on fact; surfers do not diddle to greet, and the word 'diddle' has a generally negative connotation.

example of haptic feedback that a smartphone provides while typing. The feedback is simple, mundane even, but serves as reassurance to the typing human that a keystroke was registered. Affective haptic technologies are important to research due to their potential impact on perceiving humans, but framing them as the 'best' approach might be a stretch. The narrative approach can also be used to design shared experiences amongst a pair, a group, or a society of humans. One such shared experience is related to mediated social touch [395]. Take, for instance, the example of the Tactile Emoticon prototype, presented by Price et al. [308]: Humans are paired to share a sensation of touch. The experience here is facilitated through the designed haptic stimulus and the story of the relationship between the pairs.

Both the model presented in the manuscript *A Unified Model for Haptic Experience* [71] and the Inference-Design Model benefit from a narrative approach. A narrative approach lets designers influence the context in which an experience occurs and, thereby, the consequences outlined in the Unified Model. Similarly, a narrative approach is a practical guide to the experience design process, described in the Inference-Design Model for Haptic Experience.



Part VI

Discussion and Conclusion

With the knowledge comes the thinking.
– Alexander von Humboldt

The Inference-Design Model for Haptic Experience frames this thesis; it serves as an aid to the search of an Inference-Design Theory for Haptic Experience. As we have seen in previous chapters, haptic experiences are not simply made. As examples serve the subjective reports of haptic experiences gathered for the journal paper *A User-Derived Mapping for Mid-Air Haptic Experiences* [63], suggesting that previous experience and imagination play a vital role in the inference process of haptic stimuli, our argument in the manuscript *A Unified Model for Haptic Experience* [71], claiming that human psychological needs, motivation, and the situated context are of critical importance when designing haptic experiences, and the proposed narrative design approach to haptic experiences.

This thesis is titled *How Haptic Experiences Are Made*. The title can be read in two ways: either emphasis is put on the psychophysical question of *how* haptic experiences are made, or on the designerly question of how haptic experiences are *made*. Both the psychophysical and the designerly aspects are captured in the Inference-Design Model, and the work presented in this thesis reflects upon the answers to these questions. Take, for instance, the work presented in the manuscript *Ultrasound can deliver chemical stimulants to the skin and modulate their perception* [65], which relates to questions of the psychophysical perception of chemical stimulants and feeds back into questions of possible haptic designs. In essence, the psychophysical question explores the path from the perceived stimulus to the apparent experience, while the designerly question returns to the path to go from the intended experience back to an actuated stimulus.

In this last part of my thesis, I will conclude with speculations around an Inference-Design Theory for Haptic Experience. I reflect back on the title to consider whether the distinction between psychophysics and design is useful for designing haptic systems or if a more blended and exploratory approach would yield more insight. Each component of the Inference-Design Model has been discussed in relation to the work I have conducted to explore them; here, however, I will discuss them in relation to each other and beyond. The part is split in three: first, Chapter 16 explains the theoretical reasoning for the model and discusses its place in the current research context; next, Chapter 17 discusses the implications for haptic designs and practices in haptic research; and last, Chapter 18 suggests future directions in haptic experience research.

16. Theoretical Reflections

The Inference-Design Model was derived from empirical findings but has been influenced by theories of conscious experience. As the name suggests, the model is a model and not a theory; in this chapter, I explain why. I discuss the theoretical and empirical underpinnings of the model, first by deriving learnings from my own work that has formed the Inference-Design Model for Haptic Experience, then by drawing upon established theories within philosophy, neuroscience, and human-computer interaction to explain the implications of the model to haptics research.

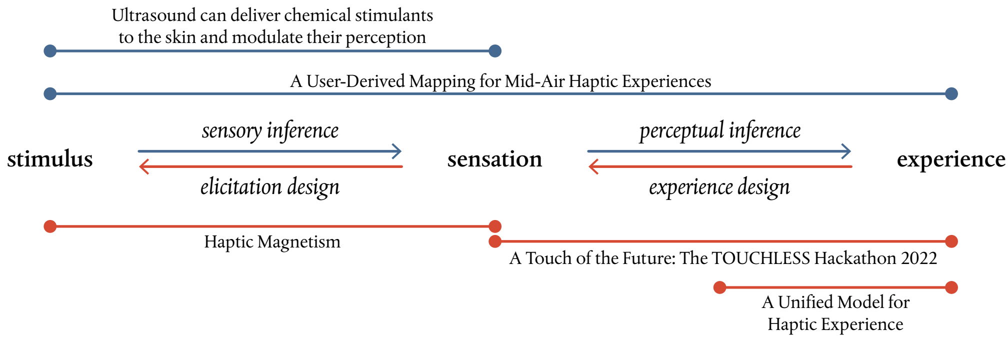


Figure 16.1. The Inference-Design Model for Haptic Experience and the work presented as part of this thesis. The works span multiple components and overlap; nevertheless, they describe very different research. For instance, the overlapping works *A Touch of the Future: The TOUCHLESS Hackathon 2022* [67] and *A Unified Model for Haptic Experience* [71] – very different in research paradigm but similar in that they discuss the experience and experience design components.

16.1. The Inference-Design Model for Haptic Experience

The Inference-Design Model for Haptic Experience provides a holistic understanding of how haptic experiences are made. It expresses my understanding of the inference and design processes required to have and make these haptic experiences. The model is derived from the projects and papers described throughout this thesis and influenced by other works inside and outside haptics research. Yet, some reflections are to be had: how did it come to be, and where are its limitations?

16.1.1. Early Model Iterations

The Inference-Design Model reflects the journey of my PhD studies through its connections to the presented papers and manuscripts. The current iteration has been developed over time, and thus, I can place the conducted work in correspondence to the model as shown in Figure 16.1.

At first, the journal paper *A User-Derived Mapping for Mid-Air Haptic Experiences* [63] established the distinction and connection between stimuli, sensations, and experiences. While the interview data showed that there is a distinction, boundaries were not clear, and connections were established, the data did not show how the connections are made. Nevertheless, the participants could articulate rich and detailed descriptions of their experiences. As such, the paper investigated how a stimulus is perceived, rather than how it can be designed, in line with work on haptic libraries (e.g., [137, 347]) and cognitive models (e.g., [234]). With the reading of Barrett's *How emotions are made* [21], I was introduced to the concept of perceptual inference, *simulation* as it is called in the book, which put in motion thoughts of how stimuli, sensation, and experiences are connected and related. While simulation covers the whole sense-making process from stimulus to perception, it seemed to me that there must be a difference between low-level perceptions (sensations) and high-level perceptions (experiences). Thus, I split the simulation process into sensory and perceptual inference. But again, the boundaries are not as clear as they need to be.

The manuscript *Ultrasound can deliver chemical stimulants to the skin and modulate their perception* [65] expanded on my notion of stimulation; it outlines a novel use for acoustic levitation as a haptic device and studies the elicited sensation from chemical stimulants. The ability to place chemical stimulants anywhere on the body carries many implications for design, yet it relates mostly to how different stimuli are perceived on the skin. But again, while we show the chemical stimulants to be perceivable, it is not certain how robust and reliable the sensory inference of the studied stimulants is.

Interesting is how haptic stimulation is perceived differently across humans, although the fundamental parameters of the vibration are accounted for. Another factor, outside the haptic factors, must play a role in the perception of the stimulation. I observed this in the studies conducted for the journal paper *Haptic Magnetism* [68]. From the given studies, it is difficult to say whether that might be previous experience, context, or some other factor. However, the most interesting contribution of this work is the insights gained towards elicitation design. We show the feasibility of providing actionable information through haptic sensations, showing that sensations carry information. Elicitation design can be used to design informative applications – humans can imagine and infer meaning from these haptic sensations, but the question of how remains.

Lastly, experience design was introduced through two projects: the short paper *A Touch of the Future: The TOUCHLESS Hackathon 2022* [67] and the manuscript *A Unified Model for Haptic Experience* [71]. I find both projects very interesting in their own right. One has given me practical insights into how designers create haptic designs, while the other has given me theoretical insights. Both discuss how haptic experiences do not occur in a vacuum – experiences happen in context and as a part of a narrative. The design process is hard and requires many considerations [245, 334]. The Unified Model, presented in *A Unified Model for Haptic Experience* [71], discusses the design process holistically, giving designers tools and considerations for the experience design process.

Together with much other work, the presented papers and manuscripts informed the creation of the Inference-Design Model. They provide the empirical basis for the model, yet much iteration is still to be done, and more evidence is to be gathered to claim the model to be more than a thinking tool: an Inference-Design Theory for Haptic Experience.

16.1.2. The Current Iteration

The presented papers and manuscripts inform the current iteration of the Inference-Design Model. The model is simple in structure yet complex in meaning and implication. It creates clear and concise language around haptic experiences and helps practitioners and researchers to express aspects of their work. The most important aspect of the model is the distinction between sensations and experiences, which previously have been mixed together or have had different names. Additionally, the model serves as a thinking tool and clarifies what needs to be designed to create haptic experiences: the stimulus and the narrative. Throughout this thesis, I have discussed the details of the different components of the model; let us consider it holistically. As such, two questions emerge: **(1)** why it is the Inference-Design Model for Haptic Experience rather than the Inference-Design Model for Sensoric Experience?; and **(2)** why do haptic designers need this model?

I have previously stated that the sense of touch is special because it is distributed throughout the body and not easily suppressed. Yet, why this special status merits a specialized model may be unclear. Consider visual stimuli – they can be described through the model in the same way as haptic stimuli; they have a sensory organ within the eye, elicit sensations of brightness and colour, and facilitate visual experiences of, say, trees and flowers. I do not believe there is much difference in the construction of an Inference-Design Model for Visual Experience, or Sensoric Experience for that matter, yet I do not have a full overview of research in (multi-)sensory experiences. There are, however, some differences in the details; for instance, Schneider et al. [334] put forward haptic designers' reliability on prototyping, MacLean [245] argued for expanding the haptic designers' horizon to neuroscience and psychology, and the lack of the 'ultimate' haptic display is cited as a challenge throughout (e.g., [295, 299, 334]). In the end, the generalisation of the model requires more thought and an overview of how multisensory experiences are made. A starting point to this journey could be Velasco and Obrist's ethical considerations for multisensory experiences [396, p. 72–82]: follow the principle of 'do no harm', create inclusive designs, and be transparent about the purpose and creator of the design.

The motivation for creating the Inference-Design Model was a practical one at first; I needed a way of describing the experiences participants reported in the journal paper *A User-Derived Mapping for Mid-Air Haptic Experiences* [63] in a structured manner. Then, it became theoretical, as I began wondering what goes on between perceiving and experiencing haptic stimulation. The model became more of a thinking tool, as mentioned above. To formalize these considerations, consider Höök and Löwgren's [161] strong concepts: concepts derived from instances of the concept that have the potential to be used by designers and researchers. The Inference-Design Model is not a strong concept; it is a model, after all. However, it consists of strong concepts, concepts that are derived from the presented papers and more, concepts that guide design. Together, the concepts form the model, a first step towards making the model a theory [26]. Through the concepts and the structure, the model carries generative power [26, 291] – it acts as a stimulant for new ideas and designs, as it did for the development of the Haptic Magnetism concept [68]. The generative power of the model also allows for counterfactual reasoning about *possible* haptic designs. The model tells that a stimulus is followed by a sensation followed by an experience, allowing the designer to reason about the sensations and experiences that follow from their designs.

16.2. Related Models and Theories

A number of models and theories of how experiences emerge and how they should be designed exist. Each theory comes with a set of commitments, which are more or less acceptable depending on the individual's ontology. In this section, I hold the Inference-Design Model up against a set of theories and ideas from philosophical phenomenology, cognitive neuroscience, and user experience research. A common theme emerges: something is missing.

16.2.1. The Search for a Theory of the Conscious Mind

The question of what it is like to be human has driven many philosophical debates around the kitchen tables of various homes and in literature. Literature, such as Heidegger's *Being and Time* [149] and Merleau-Ponty's *Phenomenology of perception* [268], shaped phenomenology—the philosophy of experience—giving future generations an ontology to discuss being and consciousness in depth around said kitchen tables. In the mid-1990s, Chalmers [47, 48] coined the differentiation between the 'easy' and the 'hard' problems of consciousness. In general terms, Chalmers refers to problems related to conscious behaviour, or awareness, as the easy problems, not because they are easy to solve in the ordinary sense, but because standard methods in cognitive science, in principle, are able to solve them. On the other hand, hard problems relate to the phenomena of experience, more concretely, the question of why conscious experiences accompany the performance of cognitive functions. "What makes the hard problem hard and almost unique is that it goes beyond problems about the performance of functions" [47, p. 5]. The standard methods of cognitive science seem to lack what Chalmers called an *extra ingredient* to account for these conscious experiences – something that makes up for the difference in the performance of cognitive functions and the phenomena of experience. Thus motivated, Chalmers set out to search for a theory of consciousness in which experience is taken as fundamental, as irreducible.

Chalmers continues to explain the constraints under which such a theory of consciousness would exist and the commitments necessary to accept a theory of consciousness. The search and speculation of how experiences are made have sparked a lot of discussion and controversy; Dennett [77] called Chalmers' hard problem a "theoretical illusion" [77, p. 4] and a "chimera" [77, p. 6]. Dennett's main question was: "once some item or content 'enters consciousness', what does this cause or enable or modify?" [77, p. 1], which Chalmers fails to ask and answer. I will not go too deep into this particular discussion; my intention is to draw attention to the fundamental problem of defining human experience. The point is not to put Gestaltianism [197, pp. 404–405], a computational approach [254, p. 43], Chalmers [48] or Dennett [77], constructionism [20], or any other view on experiences on a pedestal, but rather establish links between the Inference-Design Model and some of these views, to see how my empirical findings hold up against the grand philosophical thoughts of the time.

I describe two conscious processes in the Inference-Design Model, sensory and perceptual inference. Sensory inference is a problem within psychophysics and relates to "the ability to discriminate, categorize and react to environmental stimuli" [48, p. 1] – implying that sensory inference is an easy problem. And indeed, much research within haptics has succeeded in describing the psychophysical properties of touch. For example, studies on spatial acuity [115, 171, 417], weight [52], textures [60, 261], stiffness [378, 409, 427], thermal [40, 287], and other psychophysical properties are not rare. In the manuscript *Ultrasound can deliver chemical stimulants to the skin and modulate their perception* [65], we describe to what degree and how our participants perceive chemical stimulants and speculate on the inference process between stimulation and perception. With this, we gather insights into the process of sensory inference, showing, on the one hand, the elicitation of sensations through the chemical stimuli and, on the other hand, that there must be an interplay between the different receptors in the skin, given that chemical stimulation alone compared to chemical and vibrotactile stimulation yield different sensations.

Conversely, perceptual inference is a problem relating to the process that yields an experience from the performance of cognitive functions. If we think about perceptual inference as a hard prob-

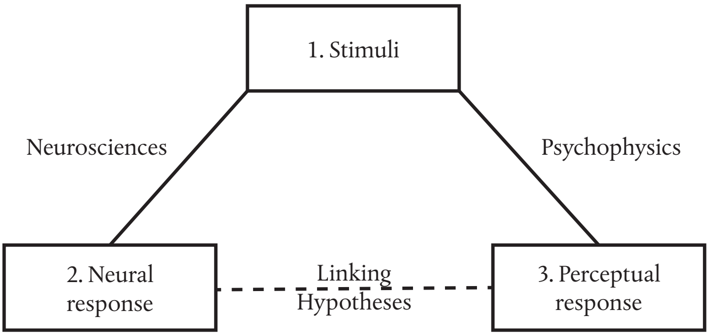


Figure 16.2. The three key elements of perception: (1) sensory stimuli (light, sound, etc.); (2) neural responses to stimulation; (3) perceptual experiences, which correlate with neural responses. Neuroscience studies the relation between stimuli and neural responses; psychophysics studies the relation between stimuli and perceptual experiences. Psychophysical linking hypotheses bridge the gap between neural activity and perception.
Reproduced, with permission, from Mather [254]. © 2023 Informa UK Limited, obtained through PLSclear.

lem (in Chalmers' sense), it becomes apparent that designing haptic experiences is a hard problem. In the manuscript *A Unified Model for Haptic Experience* [71], we suggest psychological needs, physical context, and previous experience as proxies for the *extra ingredient* – a proxy because these are experiences in themselves, meaning they are influencing the inference processes rather than a fundamental process for the emergence of experiences. Barrett [20] cited context and previous experience as factors in the emergence of emotions, showing that these factors are somehow underlying the perceptual inference process. Experiences have been studied in haptics research also, experiences such as presence (e.g., [383, 404]), realism (e.g., [201, 374, 418]), emotions (e.g., [242, 285, 386]), and the more complex phenomena of social touch (e.g., [172, 308]) and affective haptics (e.g., [92, 174, 245]); these, however, fall short of answering why these occur from the cognitive functioning elicited by the haptic stimulation. This is not to be held against these studies, as they have different aims. Finding the answer to that question is just plain hard. However, haptics research is conducted with an underlying assumption that we can answer the question.

Overall, the Inference-Design Model is useful as a thinking device to understand where the difficulty of designing haptic experiences lies. From Chalmers' distinction between the easy and the hard problems, we can derive an understanding of what makes sensations easier to design than experiences. According to the Inference-Design Model, an experience follows from a sensation that, in turn, follows from a stimulus. A haptic designer has control over the stimulus, has an understanding of the resulting sensation, and hopes that these elicit a particular experience. Through my work, in particular through *A Unified Model for Haptic Experience* [71] and this thesis, I argue for psychological needs, physical context, and previous experience as proxies for that extra ingredient that makes up the connection between cognitive function and experience. Thus, designing *for* haptic experiences through the proxies is a solvable task in the current paradigm for haptic design, while designing haptic experiences still remains hard.

16.2.2. The Key Elements of Perception

Methods, models, and theories from psychophysics inform and constrain the design of haptic feedback and technology. Similarly, insights from neuroscience form the foundation of what haptic stimuli are theoretically perceivable. Haptic research concerning the construction of novel haptic technology, in particular, uses the Just-Noticeable-Difference or Two-Point-Discrimination methodologies to evaluate its designs [295, pp. 99–150], in addition to less structured perceptual measures [71]. More generally, insights within neuroscience and psychophysics create opportunities for haptic designs: take, for instance, the chemical stimulation proposed in the manuscript *Ultrasound can deliver chemical stimulants to the skin and modulate their perception* [65], where the insights gathered through psychophysical research informed our research within haptics (e.g., [118, 121, 158]). The neural scientific approaches to experience by, for instance, Mather [254] and Kandel et al. [197], resemble much more scientific theories than the Inference-Design Model does; however, they recognise that there is something about the sensory perception, a 'linking hypothesis' [254, pp. 5, 29] or a 'top-down learning mechanism' [197, pp. 404–405], that is in need of an explanation still.

Figure 16.2 shows Mather's key elements of perception: Stimulus, neural response, and perceptual response. The key elements in Mather's representation roughly equivalent to components in the Inference-Design Model: while stimuli appear in both representations, are sensation and experiences grouped to be a perceptual response and Mather's neural response component is part of the sensory and perceptual inference process components. But most interesting are linking hypotheses; the proposal of how sensations and experiences are made relies on "hypotheses about how [sensory signals] are linked to neural activity" [254, p. 29]. Linking hypotheses are often characterised by an underlying belief that the link between sensory signals and perceptual response is deterministic—"if two sensory inputs to the brain cause different sensations, then they must have different effects on the brain." [271, p. 197]

Much controversy surrounds the search for a neuroscientific theory for consciousness and how experiences arise. Tononi proposed a mathematical model for consciousness, the integrated information theory, as a candidate for explaining consciousness [380, 381].

> Integrated information theory [states] that one cannot infer the existence of consciousness starting from physical systems ("from matter, never mind"). Instead, [integrated information theory] takes the opposite approach: it starts from experience itself, by identifying its essential properties (*axioms*), and then infers what kind of properties physical systems must have to account for its essential properties (*postulates*). Then [integrated information theory] employs the postulates to derive, for any particular system of elements in a state, whether it has consciousness, how much, and of which kind. [381]

This theory, however, has been criticised for being "pseudoscience" [183], as the theory ascribes consciousness to systems that can not be scientifically tested, such as organs developed in petri dishes or plants. As a rivalling theory stands the global neuronal workspace theory [73, 74], which, loosely formulated, states that sensory information arrives inscribed on a 'blackboard', that is broadcast to the relevant regions of the brain [217]. Whatever information is written on the blackboard becomes conscious. Indeed, these differences in approach have sparked an "adversarial collaboration" between proponents of each theory, in which both theories were independently tested and compared [103][27].

My head is spinning from trying to make sense of these competing theories, yet I have made one observation and am left with one question. The *observation*: The question of why sensory signals give rise to experiences remains unanswered, yet it seems scientific advances are undertaking significant steps towards a Theory for Conscious Experience, as called for by Chalmers [47]. This prompts the *question*: How can haptic research contribute to these advances? In my view, haptics research has rich opportunities to feed knowledge back to neuroscientific research. I have argued before that haptic designers have precise control over the delivery of haptic stimuli, which enables the practical application of neuroscientific theories and models. MacLean [245] argued that haptic designers must consider many different lenses of experience, might that be the core science lense, the design lense, the technology lense, or the application lense, but that precisely this enables "a unique bridging quality"; haptic research can bridge the differences between these lenses to evaluate the haptics-related theories in the respective field. In the journal paper *A User-Derived Mapping for Mid-Air Haptic Experiences* [63], I have shown the potential of haptic feedback to elicit rich and detailed experiences, yielding a potential for further study of the determinism of haptic experiences between and across humans. Considering the results presented, it seems plausible that sensory inference can be deterministic; however, the reason for any margin of error is unclear. I have continuously presented candidates for the margin of error, previous experience, context, and so on; however, that is subject to additional research. On the other hand, it is unclear whether perceptual inference is deterministic. Individual experiences vary widely, which is not surprising given the individual nature of previous experience. This example shows the potential of haptics research to contribute to developments in other fields, particularly neuroscience.

16.2.3. *Experiencing Technology*

Books have been written, studies have been conducted, research fields have emerged, and theories have been constructed: figuring out what experiencing with technology is like has been a back-and-forth since the emergence of human-computer interaction. Hence, capturing the discussion in a short section is no easy feat. Often, the mentioned work falls under user experience research, with the aim to create 'good' experiences (e.g., [84, 139, 144, 165, 259, 265, 423]). What is considered 'good' is less than defined; experiences are often designed to be pleasant, aesthetic, or fulfil a user's needs. With reference to positive psychology and their differentiation between hedonic (related to experiences of pleasure) and eudaimonic (related to experiences of meaning) experiences in mind [177, 181], user experience research argues for nonutilitarian use of technology [140]. These notions also apply to haptic experience research as a subfield to user experience research, as we argue in the manuscript *A Unified Model for Haptic Experience* [71].

McCarthy and Wright's *Technology as Experience* [259] forms a central piece for the understanding of technology as an experience in human-computer interaction. In it, McCarthy and Wright argue

[27] The following publicity of this collaboration gave rise to the mentioned criticism by the IIT-Concerned et al. [183].

that the experience of technology is shaped not only by direct interaction with it and the usability of it but also driven by the overarching context of use. As such, "experience of technology refers to something other than usability or one of its dimensions, such as satisfaction or attitude." [259, p. 6] Again, there is that ominous 'something' that defines experience; McCarthy and Wright explain experiences to be dependent on "needs, desires, and values at [a] particular time" [259, p. 86], but fail to explain the what this dependency entails. In this view, experiences are situated in a context such that they are inseparable from it and may never reoccur. Hassenzahl et al. [143] critiqued and extends this notion by arguing that while a technology-mediated experience might not reoccur, at least an experience must be prone to categorisation—Hassenzahl et al. suggest "categorizing experiences on the basis of the psychological needs they fulfil" [143, p. 354]. And thus, we find ourselves in the midst of a discussion again. The notion of experience in human-computer interaction is very useful to develop on the Inference-Design Model, in particular the design processes, as both McCarthy and Wright, Hassenzahl et al., and many others (e.g., [32, 87, 105, 160, 165]) concern themselves with the question of how to design for technology-mediated experiences.

Haptic Experience research has been developing more recently as a branch of haptic research analogue to User Experience research in broader human-computer interaction. As discussed in Chapter 5, Schneider et al. [334] defined Haptic Experience Design:

> [Haptic Experience Design is] the design (planning, development, and evaluation) of user experiences deliberately connecting interactive technology to one or more perceived senses of touch, possibly as part of a *multisensory experience*. [334, p. 5].

In that discussion, I criticised the vagueness of the word 'connecting' and the broad scope of design. Later, Kim and Schneider [206] defined Haptic Experience based on Sharp et al.'s writing on User Experience [349]:

> [Haptic Experience 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. [206, p. 2]

With this definition Kim and Schneider distinguished between lowercase haptic experience, the experience elicited by haptic technology, and uppercase Haptic Experience, the criteria under which humans assess haptic technology. Within the Inference-Design Model, haptic experience relates to the inference processes, while Haptic Experience relates to the design processes. Underlying both Kim and Schneider's and Schneider et al.'s definitions is the separability of experiences and sensory information, suggesting a focus on 'pure' haptic experience. I find this notion difficult as pure haptic experiences are not the norm in the experiencing human; rather, they are the exception compared to multisensory experiences. In my view, this promotes the idea that haptic feedback elicits a particular experience, say, emotion, affect, or joy, without consideration for the context in which the experience happens. Experience designers can control the tactile aspects of an experience, but what the experience feels like is individual to the perceiving human.

17. Practical Reflections

The Inference-Design Model for Haptic Experience allows for a number of practical reflections, particularly related to the statement that designers do not design haptic experiences but rather design *for* haptic experiences. The theoretical aspects of the model imply a number of assumptions and implications relevant to practice and design. These are the ones I reflect on in this chapter. First, I reflect on what to design *for* when designing haptic experiences based on the notion of narrative haptic design. Second, I reflect on the implications of the model for the research methodologies used to study haptic experiences. I close the chapter by reflecting on the model as a thinking tool and discussing how the theoretical underpinnings of generative power and counterfactual reasoning relate to research and practice. From theory follows practice. Or was it the other way around?

17.1. Designing for Haptic Experience

Strategies for designing for haptic experiences are spread thin. According to MacLean [245] and Schneider et al. [334] haptic designers need help. Help from other fields, particularly psychology and neuroscience. Indeed, it is difficult to design haptic feedback. This has been a theme throughout the presented papers and manuscripts – the sole motivation of the first study presented in the journal paper *A User-Derived Mapping for Mid-Air Haptic Experiences* [63] was to establish boundaries in a design space for mid-air haptic stimuli. To find approaches to design that make the design process less difficult, it is important to not close oneself to alternative approaches that might fall outside one's ontology. The presented papers and projects, for instance, range between deeply quantitative and highly qualitative research, a balancing act that gave a lot of useful insights. My suggestion to help haptic designers: integrate haptic feedback into a narrative.

Narrative analysis has for a long time been in the repertoire of psychologists [41], social scientists [62], and economists [318]. Within human-computer interaction, narratives are classically related to games studies (e.g., [218, 320]), framing narratives not only suitable for analysis but also design; Koenitz [218] suggested the creation of a research discipline concerning digital narratives. While I won't go that far, I still suggest that designing a narrative to shape haptic experiences has great potential. I hypothesize that narratives can tell a story around haptic feedback without requiring high-fidelity haptic feedback, as narratives and stories fill the logic gaps in experience – "[narratives deal] not in the truthful, but rather in the believable, and is how our experience of others is given meaning through story" [340, p. 31]. In the narrative approach, haptic designers create believable and plausible stories alongside haptic stimuli, working in harmony. Thus, when creating a narrative haptic design, designers engage with two design tasks, **(1)** the narrative and **(2)** the haptic stimulus.

Through developing the Inference-Design Model and writing the manuscript *A Unified Model for Haptic Experience* [71], I have learned about the complexities of designing consistent haptic experiences. Designing a narrative gives designers better—not total—control over the factors influencing perceptual inference. A narrative can adapt the context in which the perceiving human finds themselves closer to the designer's intentions. Similarly, a narrative can appeal to the perceiving human's previous experiences, for instance, an individual experience, a collective experience, or a pop-cultural experience. Narratives are powerful [340], and thus carry additional ethical responsibilities for the designers of transparency: the perceiving human should stay in control of their sensory autonomy and be able to give consent on an informed basis [23, 192]. Yet, narratives promise great flexibility; a romantic narrative can elicit an affective haptic experience, an entertaining narrative can elicit enjoyment and excitement, and a functional narrative can elicit mundane experiences. Narrative haptic design, in addition, allows for touching *untouchable objects*—objects that do not have a physical representation—through a science-fiction or fantasy narrative. The rumble of a video game controller might convince a perceiving human that they are creating healing magic through the narrative created around their virtual character.

Designing haptic narratives is an iterative process in which stories and stimuli are adapted to match. Research involving the design of haptic stimuli often cites congruence between sensory modalities as important to achieve as a way of ensuring multisensory integration (e.g., [96, 157, 206, 208, 384]; overview by Velasco and Obrist [396]). However, I suggest elevating the term within narrative haptic design: Haptic stimuli should match the story, independent of other sensory modalities, in *narrative congruence*. Haptic libraries can be helpful in the design process, as they give an overview of sensations related to the stimuli, yet more research is needed. An example of a narrative haptic design is the *PiloNape* by Iriarte et al. [187]; a haptic system that electrostatically raises the hairs of the skin to increase the arousal of emotional experiences. The system's effect was shown experimentally: PiloNape increased the perceived scariness of a movie. The haptic sensation adds to the already intense experience, enhancing the narrative.

Designing for haptic experiences is challenging; narrative haptic design offers a way of thinking about the design process. The Inference-Design Model supports the narrative approach by clarifying the difference between inference and design, similar to Hassenzahl's distinction between the intended and apparent character of an interactive system [140]. Using the narrative approach gives a practical starting point for haptic design: the narrative in which the haptic stimuli play a role.

17.2. Studying Haptic Experiences

The current research paradigm of haptics is reductionistic in approach to experiences; this I argue in the manuscript *A Unified Model for Haptic Experience* [71]. Complex hedonic and eudaimonic experiences are reduced to questions of presence, realism, preference, engagement, and other constructs with positive connotations. In this paradigm, answers on a scale are aggregated, answering the question, '*What is the average haptic experience of this stimulus?*', which statistically is valid, less so if we think about the complexities of human perception. The Inference-Design Model illustrates this point, making clear that the sensory and perceptual inference processes have a non-trivial effect on the haptic experience. Thus, the approach to studying haptic experiences must be diversified; reductionistic measures do not generalise beyond the individual. I have argued earlier that design is difficult due to the influence of context and previous experience on the perceived haptic experience. This has implications for the methodologies used to study the components of the model. This means that we can use ratings and scales to study sensory inference and sensations. In contrast, the study of perceptual inference and experiences requires methodologies that can be tailored to the experiencing individual. Exemplary to this approach is my work on the experiences elicited by mid-air haptic technology, described in the journal paper *A User-Derived Mapping for Mid-Air Haptic Experiences* [63], which employs a semantic differential rating scale to determine the sensory qualia of particular haptic stimuli and a micro-phenomenological approach to explore the experiences elicited by the haptic stimuli.

There are many approaches to studying human experiences qualitatively. We present a micro-phenomenological approach in the journal paper *A User-Derived Mapping for Mid-Air Haptic Experiences* [63], inspired by the use of the same technique by Obrist et al. [284]; Dourish [86] suggested ethnomethodology to study the phenomenal character of technology use; Frauenberger [105] suggested posthumanist approach to technology; and focus groups, workshops, hackathons, and the like have a strong tradition in haptics already (e.g., [206, 333, 334, 336, 343]). Such approaches promise rich and detailed descriptions of experiencing or designing with haptic technology, yielding insights for the Inference-Design Model. I am not suggesting that quantitative data has no value, the opposite rather. A well-placed, validated questionnaire or physiological measures can be indicators for subjective experience. Yet, handling the data correctly and understanding what they mean is imperative to good research practice. Consider the common example of using a Likert scale to measure realism. Measuring a construct like realism in a single question is questionable, as we argue in the manuscript *A Unified Model for Haptic Experience* [71]. To begin with, the sense of realism is a complex structure, influencing the perception of self, others, and the world [282, pp. 188–194]; reducing this structure to one question seems thoughtless. However, I suspect the question asked in papers that say they measure 'realism' without providing exact wording is 'Does the haptic feedback feel realistic?'. Yet, there is a conjecture in such a question, as highly realistic does not imply perceived realism – at the very least, it is only one factor in the perception of realism. Next, the statistical analysis and interpretation of the resulting Likert data need to be dissected more carefully than often is the case. As argued above, realism, like other phenomena, is a subjective experience that is difficult to generalise beyond the individual, and thus, it is questionable how to operationalise such research results in haptic designs at scale. A qualitative approach seems to yield more diverse insights into overarching phenomena like realism, fun, presence, or embodiment, whereas quantitative approaches are useful for judging performance with haptic designs.

Studying the phenomenal character of haptic technology should not be taken lightly; reductionistic approaches may confuse more than they inform. There is no one-size-fits-all methodology; rather, it should be fitted to the situation and research context.

17.3. The Inference-Design Model as a Thinking Tool

The Inference-Design Model for Haptic Experience carries generative power and allows for counterfactual reasoning. Yet, practical applicability is not a given; arguing for it as a thinking tool is pending. There are three benefits for practice: **(1)** The model explains how haptic experiences are made in a framework of inference and design, drawing a distinction between the experience intended by the designer and the experience apparent to the perceiving human, **(2)** the model yields a language for haptic experience design that clearly distinguishes between sensation and experience and thus

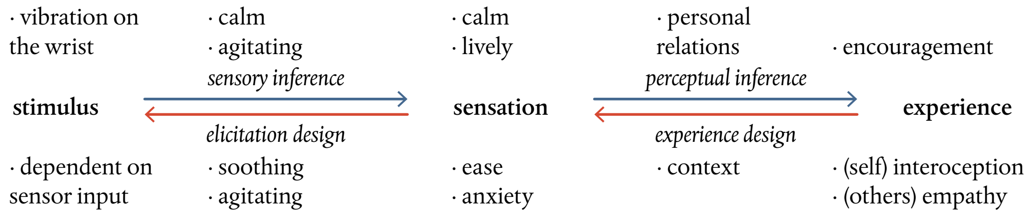


Figure 17.1. A practical use-case of planning and analysing the implementation of *Flow*, a hypothetical haptic device.

allows researchers and practitioners alike to describe their work coherently, and (3) the model can act as an analysis tool for designing for haptic experiences.

To illustrate these benefits, suppose a haptic designer and a hypothetical haptic device.

> *Flow*, the hypothetical device, displays the ease or anxiety of members of a conversation based on data from a range of sensors, including spatial, auditory, biometric and other measures. It feeds back that information to the group through its interface (i.e., how the conversation flows) as well as to individual peers through actuators, such as vibration motors in bracelets. Possible application areas include smart offices or more informal spaces such as bars or cafés. [105, p. 2:12][28]

The haptic designer starts by dissecting the design requirements of *Flow*, writing notes underneath the Inference-Design Model, as shown in Figure 17.1. The design is conceptually clear from the description – the stimulation depends on the sensor input to display a sensation that conveys either ease or anxiety. However, the design's purpose is unclear from the description, but let us suppose it follows some form of care ethics. The designer realises that the human using *Flow* does not need to be induced with ease or anxiety; rather, the designer needs to find a way of representing the feelings of partners in the conversation. Thus, the designer wants to facilitate self-reflection through interoception and provide an empathic understanding of how the other feels. As such, the analysis of stimulus, sensation, and experience forms the frame in which the design exists; the purpose of elicitation and experience design is to construct the frame. To start the elicitation design, the designer orients themselves in the vibrotactile space using existing haptic libraries, specifically, the aforementioned VibViz project [347]. In the library, the designer searches for soothing and agitating stimuli to represent ease and anxiety. They quickly find an agitating stimulus, as that is a category for filtering the library. However, for a soothing stimulus, the designer has to choose a proxy, as soothing is not a category in VibViz, and thus, the designer settles for a calm stimulation. Lastly, the designer considers the context in which the interaction happens to find opportunities for presenting a narrative that fits the experience the designer intends to convey. The designer tones down the stimulus, making it subtle enough not to distract from a conversation, and creates materials—leaflets, videos, and the like—to convey the intended use of the haptic device to the human using *Flow* before the conversation.

[28] Frauenberger [105] used this example to argue about the relation between the individuals using such technology. I will use it to argue about the technology and perception of the individuals.

How exactly humans interact with the device and perceive their experience is not knowable without further study. Especially those humans in conversation with a human using *Flow*, while not wearing one themselves, are interesting to study. Yet, the designer can speculate; the Inference-Design Model offers a framework for that – the designer can write notes above the Inference-Design Model, as shown in Figure 17.1. The perceiving human is embedded in the context created by the conversation, the location, and the narrative of the designer, yet starts with perceiving a vibration on their wrist. According to the data provided by the VibViz library, the stimulus representing ease is perceived as being calm, while the stimulus representing anxiety is perceived as being lively. In this setting, the designer speculates, based on VibViz and their personal experience with similar contexts, that the human might feel encouraged to keep the conversation at ease or attempt to resolve the anxiety-inducing situation. Overall, the designer gained insights into the factors that influence the perception of their haptic design, allowing them to iteratively adjust the design to counteract unintended or even unethical experiences.

Designing for haptic experiences is not an exact science, at least not until we find Chalmers's *extra ingredient* [47]. Yet, designers can engage with tools like the Inference-Design Model to speculate about their designs. While designing for haptic experiences remains challenging, the model marks a starting point for the design process through the listed benefits. The model supports designers in facing some of the challenges of designing for haptic experiences mentioned by Schneider et al. [334]: a shared language aids collaboration, sketching initial iterations on a conceptual level is facilitated through the model as a framework, and the evaluation of designs can be outlined by the model.

18. Reflections on the Future

The future of haptic experiences is bright, dystopian or somewhere in-between, depending on who is asked. Most empirical haptic research is motivated by the short-term bright future of interacting haptically at a distance. Following Parisi [295, pp. 323–333], this motivation might be naive due to the ethical aspects of technology-mediated touch. Sutherland's vision of the 'Ultimate Display' [363] is sometimes seen as the desirable future for interactive technology, despite the fact that it involves creating technology potentially fatal to the human using it. Dystopian and not desirable, in my view. Yet, this begs the question of what the future of haptic experiences could be instead.

Haptic feedback has shown to be a great, sometimes necessary, addition to technology. Surgeons using surgical robots benefit from haptic feedback; social interaction at a distance is facilitated through haptic technology; assistive haptic technology can benefit those with and without a need for support. Developing these and other use cases seems valuable. In this chapter, I explore the pathways for developing the Inference-Design Model for Haptic Experience to an Inference-Design Theory for Haptic Experience, with the aim of supporting the development of existing and future haptic technology.

18.1. Limitations of the Current Iteration

The current iteration of the Inference-Design Model is compact, which helps conciseness and consistency; however, it hides many complex relations and considerations when designing for haptic experiences. Moving from left to right in the model, the complexities become more and more profound. The *experience* component carries much epistemological weight and is subject to much philosophical discussion. For designers, this means more guesswork for how their designs might be perceived.

I have previously argued that ethics should be embedded in the design for haptic experience, yet I have not found a way of doing so in the model. A possible way could be to embed Barrow and Haggard's considerations of sensory autonomy and sensory consent [23] into the components, for instance, through more emphasis on the individual humans needs and the ability for them to customise their experience, as suggested by, among others, Kim and Schneider [206] and Schneider et al. [334].

Another consideration is how haptic illusions fit in the model and their relationship to the components of the model. I suspect that different kinds of illusions exist at different levels of the model. For instance, the thermal grill illusion, in which interlaced warm and cool stimuli produce a burning hot sensation, is related to the *sensory inference* and *sensation* components, while the rubber hand illusion, in which a human assumes body ownership over a rubber hand, relates to the *perceptual inference* and *experience* components. According to Kappers and Bergmann Tiest's taxonomy [200], illusions are a form of representation that touch produces – a notion that I mostly agree with, yet believe that illusions can go beyond such representations.

Overall, the Inference-Design Model needs to be strengthened through more empirical data, quantitative and qualitative. Establishing a stronger link between sensation and experience, in particular, is helpful for haptic designers. However, studying the link systematically in a laboratory setting is difficult – haptic research needs to move into the wild.

18.2. An Inference-Design Theory for Haptic Experience

I have situated the Inference-Design Model for Haptic Experience in the current research context. Given the situation, I will not claim the model to be a theory, at least in the sense of Whetten's framework of what constitutes a theory [410], as the critical question of 'why' haptic experiences are made is yet to be answered. As it stands right now, I believe in an empirical answer found through quantitative and qualitative methods – both the psychophysical and phenomenological aspects of experiencing need to be studied further. The components of the Inference-Design Model need to be given more substance to be considered a Inference-Design Theory for Haptic Experience. I have outlined the fundamentals based on Macpherson's taxonomy of senses, discussing the haptic *proximal stimulus* and *sense organ* in Part II, haptic *representation* in Part IV, and the *phenomenal character* of haptic experiences in Part V. In addition, I discuss how the components are connected from a psychophysical and a design perspective in Part III. I have also gone beyond the fundamentals through the papers presented in this thesis; yet is this beyond not sufficient to fully chart out the constructs of a Inference-Design Theory for Haptic Experience. Archiving such a feat requires finding a solution to Chalmers' hard problem [47] (we're back to the slippery fish [340]). But that is not to say we should not try.

The way towards an actual, robust theory is through an iterative process. In the manuscript *A Unified Model for Haptic Experience* [71], I call for such a model-centric approach to haptic research [80]. Human-computer interaction research, and thereby haptic research, is a clear beneficiary of Chalmers' Theory of the Conscious Mind (or, at least, will be once it has been constructed). Thus, a central question is how haptics research can contribute to the construction of the Theory of the Conscious Mind. Iterating the Inference-Design Model can act as a proxy for the search for a Inference-Design Theory for Haptic Experience, as it consists of the basic components of what constitutes haptic experiences. However, the model is not complete; some unclarities exist. In the following, I thus suggest pathways to reduce the number of unclarities.

The stimulus, sensation, and experience components are relatively well-defined; the inference between them is less so. Investigating the inference process is a first pathway to develop the model. The sensory and perceptual inference processes are essential in the emergence of haptic experiences, both related to the *something* or *extra ingredient* that seems to be missing. However, current scientific knowledge does not sufficiently explain how emergence occurs. Chalmers argued that inference is deterministic, as the same configuration of the environment will yield qualitatively identical experiences [47, p. 20]. Such a statement seems promising for haptic designers; however, as I have argued before, in practice, it is more complex than it seems due to contextual influence. Understanding the kinds of contextual influence relevant to haptic experiences is imperative to deploying haptic research at scale. I have suggested the sensory environment, social context, and previous experiences as candidates, yet I am sure there are others. Following Dourish [86], ethnography as a methodological approach can help to scope the problem; what is it humans do and experience when interacting with haptic technologies? Once the candidates are clear, a more quantitative approach could yield insights into the importance of the individual factors.

Humans are continuously perceiving and feeling – an instance of experience is realised when brought to consciousness and described to others. Experiences are thus bound in time and space; one experience follows after the other. Considering the experiences before the current is a second pathway to form an Inference-Design Theory for Haptic Experience. I have argued before that an experience is influenced by the previous, giving the perceiving human a basis on which to infer the next experience. The brain makes predictions about the future through past experiences [20, 21], novel experiences allow the perceiving human to learn and develop. Take, for instance, sensory substitution and augmentation: adapting to a novel sense of magnetic north requires learning and developing the sense through past experiences [278]. Quickly, previously novel experiences become normal, seemingly mundane even, yet incredibly useful for the brain to predict the future. The plasticity of the brain adapts by experiencing. In the journal paper *A User-Derived Mapping for Mid-Air Haptic Experiences* [63], we saw this prediction of novel stimuli in action: Participants related experiences of interacting with a hairdryer or hearing a firetruck drive by. This shows potential, yet how to harness it is unclear.

As a last pathway, I acknowledge that designing for haptic experiences is difficult. MacLean [245] argued that this difficulty stems from the many perspectives of haptic design a designer needs to be aware of: neuroscientific principles, interaction design, technological advances, and identification design requirements. These are broad problems that require much work to solve. For one, the barrier to accessing haptic technology needs to be lowered; currently, no general-purpose haptic device exists in a form-factor deployable to a wide range of designers. Similarly, current technology is not able to simulate the range of haptic sensations perceivable – the work presented in the manuscript *Ultrasound can deliver chemical stimulants to the skin and modulate their perception* [65] is a possible way forward. In essence, haptic technologies lack a layer of abstraction that virtual reality headsets offer for the visual sense. Recent advances in generative AI can inform the creation of such abstraction, might that be in the form of parameterisation, as suggested by Strohmeier et al. [361], or cognitive modelling, as suggested by Lim and Park [234].

In the end, the search for an Inference-Design Theory for Haptic Experience requires advancement in all epistemological layers of haptic research – novel devices, neuroscientific insights, and phenomenological understanding are all necessary to understand how haptic experiences are made.

19. Conclusion

The authorial audacity continues; at first calling this thesis *How Haptic Experiences Are Made* and then proposing a Inference-Design Model for Haptic Experience without a proper account of the physical and mental processes of consciousness. Well, what can you do...[29]

Yet, the model explains the questions posed by the title: designers can use the Inference-Design Model to overview how haptic experiences are *made* by the designers and to reason about *how* haptic experiences are made in perceiving humans. Thus, the model poses the main contribution of this thesis. The Inference-Design Model consists of the stimulus, sensation, and experience components and the inference and design processes forming the relation between components. The five presented papers and manuscripts are at the foundation of the model's structure, and this thesis aligns the model with models and theories of phenomenology, neural sciences, and human-computer interaction.

Throughout the thesis, I discuss the components individually based on the presented papers and established knowledge. The stimulus component relates to the different forms of stimulation that haptic designers control to elicit haptic sensations. In the manuscript *Ultrasound can deliver chemical stimulants to the skin and modulate their perception* [65], we present a set of chemical stimulants that can be perceived on the human skin. Such a form of stimulation can be considered unconventional – more traditional is vibrotactile or kinesthetic stimulation. Yet, we show the breadth of possible haptic stimuli through chemical stimulation. Haptic stimulation yields haptic sensation—an immediate interpretation of the sensory environment. We show that haptic sensations can convey information, specifically, information of direction through the concept of the same name presented in the journal paper *Haptic Magnetism* [68]. From haptic sensation arises haptic experience—a considerate interpretation of the sensory environment and the context in which haptic stimulation occurs. Haptic experiences are relational; they happen in a context and vary across humans, as we argue in the manuscript *A Unified Model for Haptic Experience* [71]. Yet, it is possible to design for haptic experiences, as shown through the prototypes presented in the short paper *A Touch of the Future: The TOUCHLESS Hackathon 2022* [67]. The processes of inference and design form the connection between the components; they facilitate the inferred perception of a haptic stimulus and describe the process of designing for haptic experiences. The journal paper *A User-Derived Mapping for Mid-Air Haptic Experiences* [63] serves as the empirical foundation for these concepts; however, it only forms the initial iteration of the Inference-Design Model. The model is in need of more empirical evidence to evolve into an Inference-Design Theory for Haptic Experience.

I use the insights gathered in the development of the Inference-Design Model to argue that designers do not design haptic experiences; rather, they design *for* haptic experiences. These two approaches are fundamentally different. Experiences are shaped and coloured by the embodied knowledge the perceiving human brings into the situation at hand. When designing *for* haptic experience, designers acknowledge this and thus design the context in which a haptic stimulus is administered rather than assuming knowledge about how physical stimulation is lifted to consciousness.

[29] I'm still not sorry.

However, designing the context of use is challenging, as this often is beyond the designer's control. As such, I propose a narrative design approach in which a haptic stimulus is integrated into a story that conveys the intended experience to be elicited.

Designing for haptic experiences is not easy; experiences are relational. They are a compound of what the experiencing human brings to the situation *and* the stimulation a haptic device provides. Focusing on creating haptic stimulation to elicit haptic experiences without considering the humans perceiving them seems shortsighted. The Inference-Design Model provides a language for thinking and talking about haptic experiences and a high-level analysis tool allowing designers to reason about their designs. That is why this thesis is titled *How Haptic Experiences Are Made*.

Bibliography

[1] Fasihah Haji Abd Samad, Suziah Sulaiman, Dayang Rohaya Awang Rambli, and Halabi Hasbullah. 2018. Capturing haptic experience through users' visual sketches. In *Recent Trends in Information and Communication Technology* (Lecture notes on data engineering and communications technologies). Faisal Saeed, Nadhmi Gazem, Srikanta Patnaik, Ali Saleh Saed Balaid, and Fathey Mohammed, (Eds.) Univ Teknologi Malaysia, Informat Serv Syst & Innovat Res Grp; Yemeni Scientists Res Grp, Malaysia. DOI: 10.1007/978-3-319-59427-9_44.

[2] Vero Vanden Abeele, Katta Spiel, Lennart Nacke, Daniel Johnson, and Kathrin Gerling. 2020. Development and validation of the player experience inventory: A scale to measure player experiences at the level of functional and psychosocial consequences. *International Journal of Human-Computer Studies*. DOI: 10.1016/j.ijhcs.2019.102370.

[3] Damien Ablart, Carlos Velasco, and Marianna Obrist. 2017. Integrating mid-air haptics into movie experiences. In *Proceedings of the 2017 ACM international conference on interactive experiences for TV and online video* (TVX '17). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3077548.3077551.

[4] Ramzi Abou Chahine, Dongjae Kwon, Chungman Lim, Gunhyuk Park, and Hasti Seifi. 2022. Vibrotactile Similarity Perception in Crowdsourced and Lab Studies. In *Haptics: Science, Technology, Applications*. Hasti Seifi, Astrid M. L. Kappers, Oliver Schneider, Knut Drewing, Claudio Pacchierotti, Alireza Abbasimoshaei, Gijs Huisman, and Thorsten A. Kern, (Eds.) Springer International Publishing, Cham. DOI: 10.1007/978-3-031-06249-0_29.

[5] Alexander Achberger, Fabian Aust, Daniel Pohlandt, Kresimir Vidackovic, and Michael Sedlmair. 2021. STRIVE: String-based force feedback for automotive engineering. In *The 34th annual ACM symposium on user interface software and technology* (UIST '21). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3472749.3474790.

[6] Kazi Masudul Alam, Abu Saleh Md Mahfujur Rahman, and Abdulmotaleb El Saddik. 2013. Mobile haptic E-book system to support 3D immersive reading in ubiquitous environments. *ACM Trans. Multimedia Comput. Commun. Appl.* DOI: 10.1145/2501643.2501649.

[7] Breno Alencar and Kiev Gama. 2018. Global Gov Jam: Motivational Aspects of Participants. In *Proceedings of the International Conference on Game Jams, Hackathons, and Game Creation Events*. ACM, San Francisco CA USA. DOI: 10.1145/3196697.3196701.

[8] Tomohiro Amemiya and Hiroaki Gomi. 2014. Distinct Pseudo-Attraction Force Sensation by a Thumb-Sized Vibrator that Oscillates Asymmetrically. In *Haptics: Neuroscience, Devices, Modeling, and Applications; EuroHaptics 2014* (Lecture Notes in Computer Science). Malika Auvray and Christian Duriez, (Eds.) Springer, Versailles, France. DOI: 10.1007/978-3-662-44196-1_12.

[9] Pengcheng An, Ziqi Zhou, Qing Liu, Yifei Yin, Linghao Du, Da-Yuan Huang, and Jian Zhao. 2022. VibEmoji: Exploring user-authoring multi-modal emoticons in social communication. In *Proceedings of the 2022 CHI conference on human factors in computing systems* (CHI '22). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3491102.3501940.

[10] Annarita Ghosh Andersen, Laila Rahmoui, Tor-Salve Dalsgaard, Morten Bo Søndergaard Svendsen, Paul Frost Clementsen, Lars Konge, and Flemming Bjerrum. 2023. Preparing for Reality: A Randomized Trial on Immersive Virtual Reality for Bronchoscopy Training. *Respiration*. DOI: 10.1159/000528319.

[11] Marco A. B. Andrade, Asier Marzo, and Júlio Cezar Adamowski. 2020. Acoustic levitation in mid-air: Recent advances, challenges, and future perspectives. *Applied Physics Letters*. DOI: 10.1063/5.0012660.

[12] Ahmed Anwar, Tianzheng Shi, and Oliver Schneider. 2023. Factors of Haptic Experience across Multiple Haptic Modalities. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (CHI '23). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3544548.3581514.

[13] Jonas Auda, Nils Verheyen, Sven Mayer, and Stefan Schneegass. 2021. Flyables: Haptic input devices for virtual reality using quadcopters. In *Proceedings of the 27th ACM symposium on virtual reality software and technology* (VRST '21). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3489849.3489855.

[14] Mirjam Augstein, Thomas Neumayr, and Thomas Burger. 2017. The role of haptics in user input for people with motor and cognitive impairments. In *Harnessing the Power of Technology to Improve Lives*. Studies in health technology and informatics. P Cudd and L De-Witte, (Eds.) Assoc Advancement Assist Technol Europe, Amsterdam, The Netherlands. ISBN: 978-1-61499-798-6.

[15] B. Averbeck, F. Rucker, Rüdiger P. Laubender, Richard W. Carr, and Richard W. Carr. 2013. Thermal grill-evoked sensations of heat correlate with cold pain threshold and are enhanced by menthol and cinnamaldehyde. *European Journal of Pain*. DOI: 10.1002/j.1532-2149.2012.00239.x.

[16] 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). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2858036.2858226.

[17] Paul Bach-Y-Rita, Carter C. Collins, Frank A. Saunders, Benjamin White, and Lawrence Scadden. 1969. Vision Substitution by Tactile Image Projection. *Nature*. DOI: 10.1038/221963a0.

[18] Stephanie Balters, Matthew L. Mauriello, So Yeon Park, James A. Landay, and Pablo E. Paredes. 2020. Calm commute: Guided slow breathing for daily stress management in drivers. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* DOI: 10.1145/3380998.

[19] Javier A. Bargas-Avila and Kasper Hornbæk. 2011. Old wine in new bottles or novel challenges: a critical analysis of empirical studies of user experience. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '11). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/1978942.1979336.

[20] Lisa Feldman Barrett. 2016. The theory of constructed emotion: an active inference account of interoception and categorization. *Social Cognitive and Affective Neuroscience*. DOI: 10.1093/scan/nsw154.

[21] Lisa Feldman Barrett. 2017. *How emotions are made: the secret life of the brain*. (Paperback ed.). PAN Books, London. ISBN: 978-1-5098-3752-6.

[22] Lisa Feldman Barrett, Ralph Adolphs, Stacy Marsella, Aleix M. Martinez, and Seth D. Pollak. 2019. Emotional Expressions Reconsidered: Challenges to Inferring Emotion From Human Facial Movements. *Psychological Science in the Public Interest*. DOI: 10.1177/1529100619832930.

[23] Nicholas Barrow and Patrick Haggard. 2023. The Ethics of Digital Touch. *PhilArchive [Preprint]*. URL: philpapers.org/rec/BARTEO-111.

[24] Cagatay Basdogan, Frederic Giraud, Vincent Levesque, and Seungmoon Choi. 2020. A Review of Surface Haptics: Enabling Tactile Effects on Touch Surfaces. *IEEE Transactions on Haptics*. DOI: 10.1109/TOH.2020.2990712.

[25] Patricia J. Bauer. 2023. Generalizations: The grail and the gremlins. *Journal of Applied Research in Memory and Cognition*. DOI: 10.1037/mac0000106.

[26] Michel Beaudouin-Lafon, Susanne Bødker, and Wendy E. Mackay. 2021. Generative Theories of Interaction. *ACM Transactions on Computer-Human Interaction*. DOI: 10.1145/3468505.

[27] 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. *Acta Psychologica*. DOI: 10.1016/j.actpsy.2005.04.005.

[28] Joanna Bergström, Tor-Salve Dalsgaard, Jason Alexander, and Kasper Hornbæk. 2021. How to Evaluate Object Selection and Manipulation in VR? Guidelines from 20 Years of Studies. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (CHI '21). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3411764.3445193.

[29] 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). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3332165.3347939.

[30] Ayush Bhardwaj, Junghoon Chae, Richard Huynh Noeske, and Jin Ryong Kim. 2021. TangibleData: Interactive Data Visualization with Mid-Air Haptics. In *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology* (VRST '21). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3489849.3489890.

[31] Matteo Bianchi, Alessandro Moscatelli, Simone Ciotti, Gemma Carolina Bettelani, Federica Fioretti, Francesco Lacquaniti, and Antonio Bicchi. 2017. Tactile slip and hand displacement: Bending hand motion with tactile illusions. In *2017 IEEE World Haptics Conference (WHC)*. DOI: 10.1109/WHC.2017.7989883.

[32] Susanne Bødker. 2015. Third-wave HCI, 10 years later—participation and sharing. *Interactions*. DOI: 10.1145/2804405.

[33] Margaret M. Bradley and Peter J. Lang. 1994. Measuring emotion: The self-assessment manikin and the semantic differential. *Journal of Behavior Therapy and Experimental Psychiatry*. DOI: 10.1016/0005-7916(94)90063-9.

[34] Scott Brave and Andrew Dahley. 1997. inTouch: a medium for haptic interpersonal communication. In *CHI '97 Extended Abstracts on Human Factors in Computing Systems* (CHI EA '97). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/1120212.1120435.

[35] Stefan Josef Breitschaft, Stella Clarke, and Claus-Christian Carbon. 2019. A Theoretical Framework of Haptic Processing in Automotive User Interfaces and Its Implications on Design and Engineering. *Frontiers in Psychology*. DOI: 10.3389/fpsyg.2019.01470.

[36] Stefan Josef Breitschaft, Alexander Pastukhov, and Claus-Christian Carbon. 2022. Where's my button? Evaluating the user experience of surface haptics in featureless automotive user interfaces. *IEEE Transactions on Haptics*. DOI: 10.1109/TOH.2021.3131058.

[37] John Brooke. 1996. SUS: A 'Quick and Dirty' Usability Scale. In *Usability Evaluation In Industry*. CRC Press, Boca Raton, Florida, United States. ISBN: 978-0-429-15701-1.

[38] Roger W. Brown. 1957. Linguistic determinism and the part of speech. *The Journal of Abnormal and Social Psychology*. DOI: 10.1037/h0041199.

[39] Michael Burmester, Marc Hassenzahl, and Franz Koller. 2002. Usability ist nicht alles – Wege zu attraktiven Produkten (Beyond Usability – Appeal of interactive Products). *i-com*. DOI: 10.1524/icom.2002.1.1.032.

[40] Shaoyu Cai, Pingchuan Ke, Takuji Narumi, and Kening Zhu. 2020. ThermAirGlove: A Pneumatic Glove for Thermal Perception and Material Identification in Virtual Reality. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces*. IEEE; IEEE Comp Soc, Atlanta, GA, USA. DOI: 10.1109/VR46266.2020.00044.

[41] James Carney, Rafael Wlodarski, and Robin Dunbar. 2014. Inference or Enaction? The Impact of Genre on the Narrative Processing of Other Minds. *PLOS ONE*. DOI: 10.1371/journal.pone.0114172.

[42] Juan Pablo Carrascal and Roel Vertegaal. 2017. Effects of tactile feedback on the perception of virtual shapes on non-planar DisplayObjects. In *Proceedings of the 2017 CHI conference on human factors in computing systems* (CHI '17). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3025453.3025488.

[43] Cristiano Carvalheiro, Rui Nóbrega, Hugo da Silva, and Rui Rodrigues. 2016. User Redirection and Direct Haptics in Virtual Environments. In *Proceedings of the 24th ACM international conference on Multimedia* (MM '16). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2964284.2964293.

[44] Antonio Cataldo, William Frier, and Patrick Haggard. 2023. The Limits of Touch: Spatial acuity for frequency-resolved air-borne ultrasound vibrotactile stimuli. DOI: 10.1101/2023.02.08.527028.

[45] Antonio Cataldo, Nobuhiro Hagura, Yousef Hyder, and Patrick Haggard. 2021. Touch inhibits touch: sanshool-induced paradoxical tingling reveals perceptual interaction between somatosensory submodalities. *Proceedings of the Royal Society B: Biological Sciences*. DOI: 10.1098/rspb.2020.2914.

[46] Silvia Ceccacci, Andrea Generosi, Alma Leopardi, Maura Mengoni, and Ferruccio Mandorli. 2021. The role of haptic feedback and gamification in virtual museum systems. *Journal on Computing and Cultural Heritage*. DOI: 10.1145/3453074.

[47] David J. Chalmers. 1995. Facing Up to the Problem of Consciousness. *Journal of Consciousness Studies*. URL: philpapers.org/rec/CHAFUT.

[48] David J. Chalmers. 1996. *The conscious mind: in search of a fundamental theory*. (1st ed.). *Philosophy of mind series*. Oxford University Press, New York. ISBN: 978-0-19-511789-9.

[49] Lung-Pan Cheng, Eyal Ofek, Christian Holz, Hrvoje Benko, and Andrew D. Wilson. 2017. Sparse haptic proxy: Touch feedback in virtual environments using a general passive prop. In *Proceedings of the 2017 CHI conference on human factors in computing systems* (CHI '17). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3025453.3025753.

[50] 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). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2807442.2807463.

[51] Sean Chew, Tor-Salve Dalsgaard, Martin Maunsbach, Hasti Seifi, Joanna Bergström, Kasper Hornbæk, Josu Irisarri, Iñigo Ezcurdia, Naroa Iriarte, Asier Marzo, William Frier, Orestis Georgiou, Anna Sheremetieva, Kamil Kwarciak, Maciej Stroinski, Daria Joanna Hemmerling, Mykola Maksymenko, Antonio Cataldo, Marianna Obrist, Patrick Haggard, and Sriram Subramanian. 2023. TOUCHLESS: Demonstrations of Contactless Haptics for Affective Touch. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems* (CHI EA '23). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3544549.3583913.

[52] 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* (UIST '17). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3126594.3126599.

[53] 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)*. IEEE, Daejeon, Korea (South). DOI: 10.1109/IROS.2016.7759169.

[54] Jean Ho Chu, Paul Clifton, Hank Blumenthal, Abhishek Nandakumar, Balasubramanium Ganapathi, Janet Murray, and Ali Mazalek. 2015. Universal threshold object: Designing haptic interaction for televised interactive narratives. In *Proceedings of the ninth international conference on tangible, embedded, and embodied interaction* (TEI '15). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2677199.2680563.

[55] Drew Cingel and Anne Marie Piper. 2017. How parents engage children in tablet-based reading experiences: An exploration of haptic feedback. In *Proceedings of the 2017 ACM conference on computer supported cooperative work and social computing* (CSCW '17). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2998181.2998240.

[56] Sheldon Cohen, Tom Kamarck, and Robin Mermelstein. 1983. A Global Measure of Perceived Stress. *Journal of Health and Social Behavior*. DOI: 10.2307/2136404.

[57] Patricia Cornelio, Stephen Hughes, Orestis Georgiou, William Frier, Martin Maunsbach, Madhan Kumar Vasudevan, and Marianna Obrist. 2023. Responsible Innovation of Touchless Haptics: A Prospective Design Exploration in Social Interaction. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. ACM, Hamburg Germany. DOI: 10.1145/3544548.3581228.

[58] Patricia Cornelio, Carlos Velasco, and Marianna Obrist. 2021. Multisensory Integration as per Technological Advances: A Review. *Frontiers in Neuroscience*. DOI: 10.3389/fnins.2021.652611.

[59] Giulia Corniani and Hannes P. Saal. 2020. Tactile innervation densities across the whole body. *Journal of Neurophysiology*. DOI: 10.1152/jn.00313.2020.

[60] Heather Culbertson and Katherine J. Kuchenbecker. 2017. Importance of matching physical friction, hardness, and texture in creating realistic haptic virtual surfaces. *IEEE Transactions on Haptics*. DOI: 10.1109/TOH.2016.2598751.

[61] Heather Culbertson, Julie M. Walker, Michael Raitor, and Allison M. Okamura. 2017. WAVES: A Wearable Asymmetric Vibration Excitation System for Presenting Three-Dimensional Translation and Rotation Cues. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, Denver Colorado USA. DOI: 10.1145/3025453.3025741.

[62] Barbara Czarniawska. 2009. *Narratives in social science research*. (Repr ed.). *Introducing qualitative methods*. SAGE, Los Angeles. ISBN: 978-0-7619-4195-8.

[63] Tor-Salve Dalsgaard, Joanna Bergström, Marianna Obrist, and Kasper Hornbæk. 2022. A User-Derived Mapping for Mid-Air Haptic Experiences. *International Journal of Human-Computer Studies*. DOI: 10.1016/j.ijhcs.2022.102920.

[64] Tor-Salve Dalsgaard, Joanna Bergström, Marianna Obrist, and Kasper Hornbæk. 2022. A User-Derived Mapping for Mid-Air Haptic Experiences - Dataset. DOI: 10.17894/ucph.57bf8bb1-98ac-4e5b-b3ec-47b3575815b8.

[65] Tor-Salve Dalsgaard, Arpit Bhatia, Lei Gao, Ryuji Hirayama, Sriram Subramanian, Joanna Bergström, and Kasper Hornbæk. [n. d.] Ultrasound can deliver chemical stimulants to the skin and modulate their perception. *In Progress*.

[66] Tor-Salve Dalsgaard, Arpit Bhatia, Lei Gao, Ryuji Hirayama, Sriram Subramanian, Joanna Bergström, and Kasper Hornbæk. [n. d.] Ultrasound can deliver chemical stimulants to the skin and modulate their perception - Preregistration & dataset.

[67] Tor-Salve Dalsgaard, Arpit Bhatia, and Martin Maunsbach. 2023. A Touch of the Future: The TOUCHLESS Hackathon 2022. In *Proceedings of the 7th International Conference on Game Jams, Hackathons and Game Creation Events* (ICGJ '23). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3610602.3610607.

[68] Tor-Salve Dalsgaard, Kasper Hornbæk, and Joanna Bergström. 2023. Haptic Magnetism. *IEEE Transactions on Haptics*. DOI: 10.1109/TOH.2023.3299528.

[69] Tor-Salve Dalsgaard, Kasper Hornbæk, and Joanna Bergström. 2023. Haptic Magnetism - Dataset. DOI: 10.17605/OSF.IO/62PYJ.

[70] Tor-Salve Dalsgaard, Jarrod Knibbe, and Joanna Bergström. 2021. Modeling Pointing for 3D Target Selection in VR. In *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology*. Association for Computing Machinery. DOI: 10.1145/3489849.3489853.

[71] Tor-Salve Dalsgaard and Oliver Schneider. [n. d.] A Unified Model for Haptic Experience. *Under Review*.

[72] Donald Degraen, Bruno Fruchard, Frederik Smolders, Emmanouil Potetsianakis, Seref Güngör, Antonio Krüger, and Jürgen Steimle. 2021. 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). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3472749.3474797.

[73] Stanislas Dehaene, Jean-Pierre Changeux, and Lionel Naccache. 2011. The Global Neuronal Workspace Model of Conscious Access: From Neuronal Architectures to Clinical Applications. In *Characterizing Consciousness: From Cognition to the Clinic?* Stanislas Dehaene and Yves Christen, (Eds.) Springer, Berlin, Heidelberg. DOI: 10.1007/978-3-642-18015-6_4.

[74] Stanislas Dehaene, Michel Kerszberg, and Jean-Pierre Changeux. 1998. A neuronal model of a global workspace in effortful cognitive tasks. *Proceedings of the National Academy of Sciences*. DOI: 10.1073/pnas.95.24.14529.

[75] Daniel C. Dennett. 1991. *Consciousness explained*. (1st ed ed.). Little, Brown and Co, Boston. ISBN: 978-0-316-18065-8.

[76] Daniel C. Dennett. 2001. The Zombic Hunch: Extinction of an Intuition? *Royal Institute of Philosophy Supplement*. DOI: 10.1017/S1358246100010687.

[77] Daniel C. Dennett. 2018. Facing up to the hard question of consciousness. *Philosophical Transactions of the Royal Society B: Biological Sciences*. DOI: 10.1098/rstb.2017.0342.

[78] Alexandra Dépeault, El-Mehdi Meftah, and C. Elaine Chapman. 2009. Tactile perception of roughness: raised-dot spacing, density and disposition. *Experimental Brain Research*. DOI: 10.1007/s00221-009-1907-1.

[79] Pieter Desmet and Marc Hassenzahl. 2012. Towards Happiness: Possibility-Driven Design. In *Human-Computer Interaction: The Agency Perspective*. Studies in Computational Intelligence. Marielba Zacarias and José Valente de Oliveira, (Eds.) Springer, Berlin, Heidelberg. DOI: 10.1007/978-3-642-25691-2_1.

[80] Berna Devezer and Erkan O. Buzbas. 2023. Rigorous exploration in a model-centric science via epistemic iteration. *Journal of Applied Research in Memory and Cognition*. DOI: 10.1037/mac0000121.

[81] John Dewey. 1925. *Experience and nature.* (unabr. and unalt. republ. of the 2. ed.). Dover Publ, New York. ISBN: 978-0-486-20471-0.

[82] Anind K. Dey. 2001. Understanding and Using Context. *Personal and Ubiquitous Computing*. DOI: 10.1007/s007790170019.

[83] Carlos Diaz and Shahram Payandeh. 2014. Toward haptic perception of objects in a visual and depth guided navigation. In *2014 IEEE international conference on systems, man, and cybernetics (SMC)*. IEEE, San Diego, CA, USA. DOI: 10.1109/SMC.2014.6974466.

[84] Sarah Diefenbach, Nina Kolb, and Marc Hassenzahl. 2014. The 'hedonic' in human-computer interaction: history, contributions, and future research directions. In *Proceedings of the 2014 conference on Designing interactive systems* (DIS '14). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2598510.2598549.

[85] Paul Dourish. 2001. *Where the Action Is: The Foundations of Embodied Interaction*. (1. MIT Press paperback ed ed.). MIT Press, Cambridge, MA. DOI: 10.7551/mitpress/7221.001.0001.

[86] Paul Dourish. 2004. What we talk about when we talk about context. *Personal and Ubiquitous Computing*. DOI: 10.1007/s00779-003-0253-8.

[87] Paul Dourish. 2006. Implications for design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '06). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/1124772.1124855.

[88] Paul Dourish, Connor Graham, Dave Randall, and Mark Rouncefield. 2010. Theme issue on social interaction and mundane technologies. *Personal and Ubiquitous Computing*. DOI: 10.1007/s00779-010-0281-0.

[89] R Eccles. 1994. Menthol and Related Cooling Compounds. *Journal of Pharmacy and Pharmacology*. DOI: 10.1111/j.2042-7158.1994.tb03871.x.

[90] Judith Eck, Amanda L. Kaas, Joost L. J. Mulders, and Rainer Goebel. 2013. Roughness perception of unfamiliar dot pattern textures. *Acta Psychologica*. DOI: 10.1016/j.actpsy.2013.02.002.

[91] Bosede Iyiade Edwards, Kevin S. Bielawski, Rui Prada, and Adrian David Cheok. 2019. Haptic virtual reality and immersive learning for enhanced organic chemistry instruction. *VIRTUAL REALITY*. DOI: 10.1007/s10055-018-0345-4.

[92] Mohamad A. Eid and Hussein Al Osman. 2016. Affective Haptics: Current Research and Future Directions. *IEEE Access*. DOI: 10.1109/ACCESS.2015.2497316.

[93] Mika Elo. 2012. Digital finger: beyond phenomenological figures of touch. *Journal of Aesthetics & Culture*. DOI: 10.3402/jac.v4i0.14982.

[94] Mario Enriquez and Karon MacLean. 2008. The Role of Choice in Longitudinal Recall of Meaningful Tactile Signals. In *2008 Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. IEEE, Reno, Nevada, USA. DOI: 10.1109/HAPTICS.2008.4479913.

[95] Gregg Eschelmuller, Annika Szarka, Braelyn Gandossi, J. Timothy Inglis, and Romeo Chua. 2024. The effects of periodic and noisy tendon vibration on a kinesthetic targeting task. *Experimental Brain Research*. DOI: 10.1007/s00221-023-06727-1.

[96] George Evangelou, Orestis Georgiou, and James Moore. 2023. Using Virtual Objects With Hand-Tracking: The Effects of Visual Congruence and Mid-Air Haptics on Sense of Agency. *IEEE Transactions on Haptics*. DOI: 10.1109/TOH.2023.3274304.

[97] Stephen Everson. 1995. Proper Sensibles and Causes. *Phronesis*. URL: jstor.org/stable/4182505.

[98] 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). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3313831.3376470.

[99] Aleksey Fedoseev, Akerke Tleugazy, Luiza Labazanova, and Dzmitry Tsetserukou. 2020. TeslaMirror: Multistimulus encounter-type haptic display for shape and texture rendering in VR. In *ACM SIGGRAPH 2020 emerging technologies* (SIGGRAPH '20). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3388534.3407300.

[100] Sari Goldstein Ferber, Ruth Feldman, and Imad R. Makhoul. 2008. The development of maternal touch across the first year of life. *Early Human Development*. DOI: 10.1016/j.earlhumdev.2007.09.019.

[101] Tiffany Field. 2010. Touch for socioemotional and physical well-being: A review. *Developmental Review*. DOI: 10.1016/j.dr.2011.01.001.

[102] Renée-Pier Filiou, Franco Lepore, Bruce Bryant, Johan N. Lundstrom, and Johannes Frasnelli. 2015. Perception of Trigeminal Mixtures. *Chemical Senses*. DOI: 10.1093/chemse/bju064.

[103] Elizabeth Finkel. 2023. Consciousness hunt yields results but not clarity. *Science*. DOI: 10.1126/science.adj4498.

[104] Daniele Foresti, Majid Nabavi, Mirko Klingauf, Aldo Ferrari, and Dimos Poulikakos. 2013. Acoustophoretic contactless transport and handling of matter in air. *Proceedings of the National Academy of Sciences*. DOI: 10.1073/pnas.1301860110.

[105] Christopher Frauenberger. 2019. Entanglement HCI The Next Wave? *ACM Transactions on Computer-Human Interaction*. DOI: 10.1145/3364998.

[106] William Frier, Dario Pittera, Damien Ablart, Marianna Obrist, and Sriram Subramanian. 2019. Sampling Strategy for Ultrasonic Mid-Air Haptics. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (CHI'19). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3290605.3300351.

[107] Alberto Gallace and Charles Spence. 2010. The science of interpersonal touch: An overview. *Neuroscience & Biobehavioral Reviews*. Touch, Temperature, Pain/Itch and Pleasure. DOI: 10.1016/j.neubiorev.2008.10.004.

[108] Lei Gao, Giorgos Christopoulos, Prateek Mittal, Ryuji Hirayama, and Sriram Subramanian. 2024. StableLev: Data-Driven Stability Enhancement for Multi-Particle Acoustic Levitation. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (CHI '24). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3613904.3642286.

[109] Lei Gao, Pourang Irani, Sriram Subramanian, Gowdham Prabhakar, Diego Martinez Plasencia, and Ryuji Hirayama. 2023. DataLev: Mid-air Data Physicalisation Using Acoustic Levitation. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (CHI '23). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3544548.3581016.

[110] George A. Gescheider, Stanley J. Bolanowski, and Kathleen R. Hardick. 2001. The frequency selectivity of information-processing channels in the tactile sensory system. *Somatosensory & Motor Research*. DOI: 10.1080/01421590120072187.

[111] Janet K. Gibbs, Marco Gillies, and Xueni Pan. 2022. A comparison of the effects of haptic and visual feedback on presence in virtual reality. *International Journal of Human-Computer Studies*. DOI: https://doi.org/10.1016/j.ijhcs.2021.102717.

[112] James J. Gibson. 1962. Observations on active touch. *Psychological Review*. DOI: 10.1037/h0046962.

[113] Gerd Gigerenzer. 2018. Statistical Rituals: The Replication Delusion and How We Got There. *Advances in Methods and Practices in Psychological Science*. DOI: 10.1177/2515245918771329.

[114] Matthias Gmeiner, Johannes Dirnberger, Wolfgang Fenz, Maria Gollwitzer, Gabriele Wurm, Johannes Trenkler, and Andreas Gruber. 2018. Virtual cerebral aneurysm clipping with real-time haptic force feedback in neurosurgical education. *World Neurosurgery*. DOI: https://doi.org/10.1016/j.wneu.2018.01.042.

[115] Jun Gong, Da-Yuan Huang, Teddy Seyed, Te Lin, Tao Hou, Xin Liu, Molin Yang, Boyu Yang, Yuhan Zhang, and Xing-Dong Yang. 2018. Jetto: Using lateral force feedback for smartwatch interactions. In *Proceedings of the 2018 CHI conference on human factors in computing systems* (CHI '18). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3173574.3174000.

[116] Mar Gonzalez-Franco and Christopher C. Berger. 2019. Avatar embodiment enhances haptic confidence on the out-of-body touch illusion. *IEEE Transactions on Haptics*. DOI: 10.1109/TOH.2019.2925038.

[117] Mar Gonzalez-Franco, Eyal Ofek, Christian Holz, Anthony Steed, Jaron Lanier, Bill Buxton, Ken Hinckley, and Mike Sinclair. 2022. Taxonomy of Hand-Object Haptics for Virtual Reality. preprint. DOI: 10.36227/techrxiv.20182229.v1.

[118] B. G. Green. 1986. Menthol inhibits the perception of warmth. *Physiology & Behavior*. DOI: 10.1016/0031-9384(86)90050-8.

[119] Barry G. Green. 1977. The effect of skin temperature on vibrotactile sensitivity. *Perception & Psychophysics*. DOI: 10.3758/BF03214234.

[120] Barry G. Green. 1992. The Sensory Effects of l-Menthol on Human Skin. *Somatosensory & Motor Research*. DOI: 10.3109/08990229209144774.

[121] Barry G. Green and Linda J. Flammer. 1988. Capsaicin as a cutaneous stimulus: sensitivity and sensory qualities on hairy skin. *Chemical Senses*. DOI: 10.1093/chemse/13.3.367.

[122] Barry G. Green and Linda J. Flammer. 1989. Methyl Salicylate as a Cutaneous Stimulus: A Psychophysical Analysis. *Somatosensory & Motor Research*. DOI: 10.3109/08990228909144676.

[123] Erik Grönvall, Jonas Fritsch, and Anna Vallgårda. 2016. FeltRadio: Sensing and Making Sense of Wireless Traffic. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems* (DIS '16). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2901790.2901818.

[124] Sebastian Günther, Mohit Makhija, Florian Müller, Dominik Schön, Max Mühlhäuser, and Markus Funk. 2019. PneumAct: Pneumatic kinesthetic actuation of body joints in virtual reality environments. In *Proceedings of the 2019 on designing interactive systems conference* (DIS '19). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3322276.3322302.

[125] Sebastian Günther, Florian Müller, Markus Funk, Jan Kirchner, Niloofar Dezfuli, and Max Mühlhäuser. 2018. TactileGlove: Assistive Spatial Guidance in 3D Space through Vibrotactile Navigation. In *Proceedings of the 11th PErvasive Technologies Related to Assistive Environments Conference* (PETRA '18). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3197768.3197785.

[126] Sebastian Günther, Julian Rasch, Dominik Schön, Florian Müller, Martin Schmitz, Jan Riemann, Andrii Matviienko, and Max Mühlhäuser. 2022. Smooth as Steel Wool: Effects of Visual Stimuli on the Haptic Perception of Roughness in Virtual Reality. In

CHI Conference on Human Factors in Computing Systems (CHI '22). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3491102.3517454.

[127] Antal Haans and Wijnand IJsselsteijn. 2006. Mediated social touch: a review of current research and future directions. *Virtual Reality*. DOI: 10.1007/s10055-005-0014-2.

[128] Daniel Hajas, Dario Pittera, Antony Nasce, Orestis Georgiou, and Marianna Obrist. 2020. Mid-Air Haptic Rendering of 2D Geometric Shapes With a Dynamic Tactile Pointer. *IEEE transactions on haptics*. DOI: 10.1109/TOH.2020.2966445.

[129] Takumi Hamazaki, Taiki Takami, Keigo Ushiyama, Izumi Mizoguchi, and Hiroyuki Kajimoto. 2024. ALCool: Utilizing alcohol's evaporative cooling for ubiquitous cold sensation feedback. In *Proceedings of the CHI conference on human factors in computing systems* (Chi '24). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3613904.3642113.

[130] Ping-Hsuan Han, Yang-Sheng Chen, Kong-Chang Lee, Hao-Cheng Wang, Chiao-En Hsieh, Jui-Chun Hsiao, Chien-Hsing Chou, and Yi-Ping Hung. 2018. Haptic around: Multiple tactile sensations for immersive environment and interaction in virtual reality. In *Proceedings of the 24th ACM symposium on virtual reality software and technology* (VRST '18). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3281505.3281507.

[131] Teng Han, Fraser Anderson, Pourang Irani, and Tovi Grossman. 2018. HydroRing: Supporting mixed reality haptics using liquid flow. In *Proceedings of the 31st annual ACM symposium on user interface software and technology* (UIST '18). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3242587.3242667.

[132] Annie Handler and David D. Ginty. 2021. The Mechanosensory Neurons of Touch and their Mechanisms of Activation. *Nature reviews. Neuroscience*. DOI: 10.1038/s41583-021-00489-x.

[133] Cindy Harmon-Jones, Brock Bastian, and Eddie Harmon-Jones. 2016. The Discrete Emotions Questionnaire: A New Tool for Measuring State Self-Reported Emotions. *PLOS ONE*. DOI: 10.1371/journal.pone.0159915.

[134] Chad Harms and F. Biocca. 2006. Internal Consistency and Reliability of the Networked Minds Social Presence Measure. In *Seventh Annual International Workshop: Presence 2004*. Universidad Politecnica de Valencia, Valencia. URL: cogprints.org/7026/.

[135] Steve Harrison, Phoebe Sengers, and Deborah Tatar. 2007. The Three Paradigms of HCI. In *CHI EA '07: Extended Abstracts of the 2007 CHI Conference on Human Factors in Computing Systems*. ACM, San Jose California USA. URL: people.cs.vt.edu/srh/Downloads/TheThreeParadigmsofHCI.pdf.

[136] Sandra G. Hart and Lowell E. Staveland. 1988. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In *Advances in Psychology*. Human Mental Workload. Peter A. Hancock and Najmedin Meshkati, (Eds.) North-Holland, Amsterdam. DOI: 10.1016/S0166-4115(08)62386-9.

[137] Waseem Hassan, Arsen Abdulali, Muhammad Abdullah, Sang Chul Ahn, and Seokhee Jeon. 2018. Towards Universal Haptic Library: Library-Based Haptic Texture Assignment Using Image Texture and Perceptual Space. *IEEE Transactions on Haptics*. DOI: 10.1109/TOH.2017.2782279.

[138] Waseem Hassan, Asier Marzo, and Kasper Hornbæk. 2024. Using Low-frequency Sound to Create Non-contact Sensations On and In the Body. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (CHI '24). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3613904.3642311.

[139] Marc Hassenzahl. 2004. The Interplay of Beauty, Goodness, and Usability in Interactive Products. *Human–Computer Interaction*. DOI: 10.1207/s15327051hci1904_2.

[140] Marc Hassenzahl. 2004. The thing and I: Understanding the relationship between user and product. In *Funology: From usability to enjoyment*. Mark A. Blythe, Kees Overbeeke, Andrew F. Monk, and Peter C. Wright, (Eds.) Springer Netherlands, Dordrecht. DOI: 10.1007/1-4020-2967-5_4.

[141] Marc Hassenzahl. 2010. *Experience Design: Technology for All the Right Reasons*. *Synthesis Lectures on Human-Centered Informatics*. Springer International Publishing, Cham. DOI: 10.1007/978-3-031-02191-6.

[142] Marc Hassenzahl, Michael Burmester, and Franz Koller. 2021. User Experience Is All There Is: Twenty Years of Designing Positive Experiences and Meaningful Technology. *i-com*. DOI: 10.1515/icom-2021-0034.

[143] Marc Hassenzahl, Sarah Diefenbach, and Anja Göritz. 2010. Needs, affect, and interactive products – Facets of user experience. *Interacting with Computers*. DOI: 10.1016/j.intcom.2010.04.002.

[144] Marc Hassenzahl, Kai Eckoldt, Sarah Diefenbach, Matthias Laschke, Eva Lenz, and Joonhwan Kim. 2013. Designing Moments of Meaning and Pleasure. Experience Design and Happiness. *International Journal of Design*. URL: ijdesign.org/index.php/IJDesign/article/view/1480/589.

[145] Marc Hassenzahl, Stephanie Heidecker, Kai Eckoldt, Sarah Diefenbach, and Uwe Hillmann. 2012. All You Need is Love: Current Strategies of Mediating Intimate Relationships through Technology. *ACM Transactions on Computer-Human Interaction*. DOI: 10.1145/2395131.2395137.

[146] Marc Hassenzahl and Noam Tractinsky. 2006. User experience - a research agenda. *Behaviour & Information Technology*. DOI: 10.1080/01449290500330331.

[147] Lukáš Havrlant and Vladik Kreinovich. 2017. A simple probabilistic explanation of term frequency-inverse document frequency (tf-idf) heuristic (and variations motivated by this explanation). *International Journal of General Systems*. DOI: 10.1080/03081079.2017.1291635.

[148] Martin Heidegger. 1927. *Sein und Zeit*. (19. Aufl., unveränd. Nachdr. d. 15. Aufl ed.). Niemeyer, Tübingen. ISBN: 978-3-484-70153-3.

[149] Martin Heidegger, Joan Stambaugh, and Dennis J. Schmidt. 2010. *Being and Time*. *SUNY series in contemporary continental philosophy*. State University of New York Press, Albany. ISBN: 978-1-4384-3276-2.

[150] David R. Heise. 1987. Affect Control Theory: Concepts and Model. *Journal of Mathematical Sociology*. DOI: 10.1080/0022250X.1987.9990025.

[151] Matthew J. Hertenstein, Rachel Holmes, Margaret McCullough, and Dacher Keltner. 2009. The communication of emotion via touch. *Emotion*. DOI: 10.1037/a0016108.

[152] Ryuji Hirayama, Giorgos Christopoulos, Diego Martinez Plasencia, and Sriram Subramanian. 2022. High-speed acoustic holography with arbitrary scattering objects. *Science Advances*. DOI: 10.1126/sciadv.abn7614.

[153] Ryuji Hirayama, Diego Martinez Plasencia, Nobuyuki Masuda, and Sriram Subramanian. 2019. A volumetric display for visual, tactile and audio presentation using acoustic trapping. *Nature*.

[154] Teresa Hirzle, Florian Müller, Fiona Draxler, Martin Schmitz, Pascal Knierim, and Kasper Hornbæk. 2023. When XR and AI Meet - A Scoping Review on Extended Reality and Artificial Intelligence. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. ACM, Hamburg Germany. DOI: 10.1145/3544548.3581072.

[155] Trevor Hogan, Uta Hinrichs, and Eva Hornecker. 2016. The Elicitation Interview Technique: Capturing People's Experiences of Data Representations. *IEEE Transactions on Visualization and Computer Graphics*. DOI: 10.1109/TVCG.2015.2511718.

[156] Trevor Hogan, Uta Hinrichs, and Eva Hornecker. 2017. The Visual and Beyond: Characterizing Experiences with Auditory, Haptic and Visual Data Representations. In *Proceedings of the 2017 Conference on Designing Interactive Systems* (DIS '17). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3064663.3064702.

[157] Eve Hoggan, Topi Kaaresoja, Pauli Laitinen, and Stephen Brewster. 2008. Crossmodal congruence: the look, feel and sound of touchscreen widgets. In *Proceedings of the 10th international conference on Multimodal interfaces*. ACM, Chania Crete Greece. DOI: 10.1145/1452392.1452423.

[158] Chris R Højland, Hjalte H Andersen, Jeppe N Poulsen, Lars Arendt-Nielsen, and Parisa Gazerani. 2015. A Human Surrogate Model of Itch Utilizing the TRPA1 Agonist Transcinnamaldehyde. *Acta Derm Venereol*. DOI: 10.2340/00015555-2103.

[159] Jim Hollan and Scott Stornetta. 1992. Beyond being there. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '92). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/142750.142769.

[160] Kristina Höök, Sara Eriksson, Marie Louise Juul Søndergaard, Marianela Ciolfi Felice, Nadia Campo Woytuk, Ozgun Kilic Afsar, Vasiliki Tsaknaki, and Anna Ståhl. 2019. Soma Design and Politics of the Body. In *Proceedings of the Halfway to the Future Symposium 2019*. ACM, Nottingham United Kingdom. DOI: 10.1145/3363384.3363385.

[161] Kristina Höök and Jonas Löwgren. 2012. Strong concepts: Intermediate-level knowledge in interaction design research. *ACM Transactions on Computer-Human Interaction*. DOI: 10.1145/2362364.2362371.

[162] Matthias Hoppe, Pascal Knierim, Thomas Kosch, Markus Funk, Lauren Futami, Stefan Schneegass, Niels Henze, Albrecht Schmidt, and Tonja Machulla. 2018. VRHapticDrones: Providing haptics in virtual reality through quadcopters. In *Proceedings of the 17th international conference on mobile and ubiquitous multimedia* (MUM '18). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3282894.3282898.

[163] Kasper Hornbæk. 2006. Current practice in measuring usability: Challenges to usability studies and research. *International Journal of Human-Computer Studies*. DOI: 10.1016/j.ijhcs.2005.06.002.

[164] Kasper Hornbæk. 2015. We must be more wrong in HCI research. *Interactions*. DOI: 10.1145/2833093.

[165] Kasper Hornbæk and Antti Oulasvirta. 2017. What Is Interaction? In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, Denver Colorado USA. DOI: 10.1145/3025453.3025765.

[166] Takayuki Hoshi, Masafumi Takahashi, Takayuki Iwamoto, and Hiroyuki Shinoda. 2010. Noncontact Tactile Display Based on Radiation Pressure of Airborne Ultrasound. *IEEE Transactions on Haptics*. DOI: 10.1109/TOH.2010.4.

[167] Thomas Howard, Maud Marchal, Anatole Lecuyer, and Claudio Pacchierotti. 2020. PUMAH: Pan-Tilt Ultrasound Mid-Air Haptics for Larger Interaction Workspace in Virtual Reality. *IEEE Transactions on Haptics*. DOI: 10.1109/TOH.2019.2963028.

[168] Xinyue Hu, Tor-Salve Dalsgaard, and Kasper Hornbæk. [n. d.] "A False Reality"? A Microphenomenology of Avatars in VR. *Under Review*.

[169] Yuhan Hu and Guy Hoffman. 2019. Using Skin Texture Change to Design Emotion Expression in Social Robots. In *2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. ACM/IEEE, Daegu, Korea (South). DOI: 10.1109/HRI.2019.8673012.

[170] Ming-Hui Huang. 2005. Web performance scale. *Information & Management*. DOI: 10.1016/j.im.2004.06.003.

[171] Da-Yuan Huang, Ruizhen Guo, Jun Gong, Jingxian Wang, John Graham, De-Nian Yang, and Xing-Dong Yang. 2017. RetroShape: Leveraging rear-surface shape displays for 2.5D interaction on smartwatches. In *Proceedings of the 30th annual ACM symposium on user interface software and technology* (UIST '17). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3126594.3126610.

[172] Gijs Huisman. 2017. Social Touch Technology: A Survey of Haptic Technology for Social Touch. *IEEE Transactions on Haptics*. DOI: 10.1109/TOH.2017.2650221.

[173] Gijs Huisman, Aduén Darriba Frederiks, Betsy Van Dijk, Dirk Hevlen, and Ben Kröse. 2013. The TaSSt: Tactile sleeve for social touch. In *2013 World Haptics Conference (WHC)*. IEEE, Daejeon, Korea (South). DOI: 10.1109/WHC.2013.6548410.

[174] Gijs Huisman, Aduén Darriba Frederiks, and Dirk Heylen. 2013. Affective Touch at a Distance. In *2013 Humaine Association Conference on Affective Computing and Intelligent Interaction*. IEEE, Geneva, Switzerland. DOI: 10.1109/ACII.2013.122.

[175] Gijs Huisman, Aduén Darriba Frederiks, Jan B. F. van Erp, and Dirk K. J. Heylen. 2016. Simulating Affective Touch: Using a Vibrotactile Array to Generate Pleasant Stroking Sensations. In *Haptics: Perception, Devices, Control, and Applications* (Lecture Notes in Computer Science). Fernando Bello, Hiroyuki Kajimoto, and Yon Visell, (Eds.) Springer International Publishing, Cham. DOI: 10.1007/978-3-319-42324-1_24.

[176] Edmund Husserl. 1989. *Ideas Pertaining to a Pure Phenomenology and to a Phenomenological Philosophy*. Kluwer Academic Publishers, London. ISBN: 0-7923-0713-5.

[177] Veronika Huta. 2016. An Overview of Hedonic and Eudaimonic Well-being Concepts. In *The Routledge handbook of media use and well-being*. (1st Edition ed.). Leonard Reinecke and Mary Beth Oliver, (Eds.) Routledge, New York ; London. ISBN: 978-1-315-71475-2.

[178] Veronika Huta. 2016. Eudaimonic and Hedonic Orientations: Theoretical Considerations and Research Findings. In *Handbook of Eudaimonic Well-Being*. Joar Vittersø, (Ed.) Springer International Publishing, Cham. DOI: 10.1007/978-3-319-42445-3_15.

[179] Veronika Huta. 2017. Meaning as a Subjective Experience. *Journal of Constructivist Psychology*. DOI: 10.1080/10720537.2015.1119088.

[180] Veronika Huta and Richard M. Ryan. 2010. Pursuing Pleasure or Virtue: The Differential and Overlapping Well-Being Benefits of Hedonic and Eudaimonic Motives. *Journal of Happiness Studies*. DOI: 10.1007/s10902-009-9171-4.

[181] Veronika Huta and Alan S. Waterman. 2014. Eudaimonia and Its Distinction from Hedonia: Developing a Classification and Terminology for Understanding Conceptual and Operational Definitions. *Journal of Happiness Studies*. DOI: 10.1007/s10902-013-9485-0.

[182] Inwook Hwang, Karon E. MacLean, Matthew Brehmer, Jeff Hendy, Andreas Sotirakopoulos, and Seungmoon Choi. 2011. The haptic crayola effect: Exploring the role of naming in learning haptic stimuli. In *2011 IEEE World Haptics Conference*. IEEE, Istanbul, Turkey. DOI: 10.1109/WHC.2011.5945517.

[183] IIT-Concerned, Stephen M Fleming, Chris D. Frith, Mel Goodale, Hakwan Lau, Joseph E LeDoux, Alan L. F. Lee, Matthias Michel, Adrian M Owen, Megan A. K. Peters, and Heleen A Slagter. 2023. The Integrated Infor-

mation Theory of Consciousness as Pseudoscience. DOI: 10.31234/osf.io/zsr78.

[184] Wijnand IJsselsteijn. 2002. Elements of a multi-level theory of presence: Phenomenology, mental processing and neural correlates. *Proceedings of PRESENCE 2002*.

[185] Seki Inoue, Yasutoshi Makino, and Hiroyuki Shinoda. 2015. Active touch perception produced by airborne ultrasonic haptic hologram. In *2015 IEEE World Haptics Conference (WHC)*. DOI: 10.1109/WHC.2015.7177739.

[186] International Organization for Standardization. 2018. *Ergonomics of Human-system Interaction. International standard*. ISO 9241-11:2018, Geneva, Switzerland. URL: iso.org/standard/63500.html.

[187] Naroa Iriarte, Iñigo Ezcurdia, Sonia Elizondo, Josu Irisarri, Daria Hemmerling, Amalia Ortiz, and Asier Marzo. 2023. Contactless Electrostatic Piloerection for Haptic Sensations. *IEEE Transactions on Haptics*. DOI: 10.1109/TOH.2023.3269885.

[188] Hiroshi Ishii and Brygg Ullmer. 1997. Tangible bits: towards seamless interfaces between people, bits and atoms. In *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems* (CHI '97). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/258549.258715.

[189] Takayuki Iwamoto, Mari Tatezono, and Hiroyuki Shinoda. 2008. Non-contact Method for Producing Tactile Sensation Using Airborne Ultrasound. In *Haptics: Perception, Devices and Scenarios*. Manuel Ferre, (Ed.) Springer, Berlin, Heidelberg. DOI: 10.1007/978-3-540-69057-3_64.

[190] Seungwoo Je, Myung Jin Kim, Woojin Lee, Byungjoo Lee, Xing-Dong Yang, Pedro Lopes, and Andrea Bianchi. 2019. Aero-plane: A handheld force-feedback device that renders weight motion illusion on a virtual 2D plane. In *Proceedings of the 32nd annual ACM symposium on user interface software and technology* (UIST '19). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3332165.3347926.

[191] Seungwoo Je, Hyunseung Lim, Kongpyung Moon, Shan-Yuan Teng, Jas Brooks, Pedro Lopes, and Andrea Bianchi. 2021. Elevate: A walkable pin-array for large shape-changing terrains. In *Proceedings of the 2021 CHI conference on human factors in computing systems* (CHI '21). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3411764.3445454.

[192] Carey Jewitt, Sara Price, Kerstin Leder Mackley, Nikoleta Yiannoutsou, and Douglas Atkinson. 2020. Digital Touch Ethics and Values. In *Interdisciplinary Insights for Digital Touch Communication*. Carey Jewitt, Sara Price, Kerstin Leder Mackley, Nikoleta Yiannoutsou, and Douglas Atkinson, (Eds.) Springer International Publishing, Cham. DOI: 10.1007/978-3-030-24564-1_7.

[193] Kevin John, Yinan Li, and Hasti Seifi. 2024. AdapTics: A Toolkit for Creative Design and Integration of Real-Time Adaptive Mid-Air Ultrasound Tactons. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (CHI '24). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3613904.3642090.

[194] Lise A. Johnson and Charles M. Higgins. 2006. A Navigation Aid for the Blind Using Tactile-Visual Sensory Substitution. In *2006 International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE, New York, NY, USA. DOI: 10.1109/IEMBS.2006.259473.

[195] Mirela Kahrimanovic, Wouter M. Bergmann Tiest, and Astrid M. L. Kappers. 2009. Context effects in haptic perception of roughness. *Experimental Brain Research*. DOI: 10.1007/s00221-008-1697-x.

[196] Dietrich Kammer, Mathias Müller, Jan Wojdziak, and Ingmar S. Franke. 2018. New impressions in interaction design: a task taxon-

omy for elastic displays. *i-com*. DOI: 10.1515/icom-2018-0021.

[197] Eric R. Kandel, John D. Koester, Sarah H. Mack, and Steven A. Siegelbaum, (Eds.) 2021. *Principles of neural science*. (6th ed.). McGraw-Hill, New York. ISBN: 978-1-259-64223-4.

[198] Eric R. Kandel, James H. Schwartz, and Thomas M. Jessell, (Eds.) 2013. *Principles of neural science*. (5th ed.). McGraw-Hill, New York. ISBN: 978-0-07-139011-8.

[199] Marije Kanis and Willem-Paul Brinkman. 2010. Making mundane pleasures visible: mediating daily likings with lightweight technology. *Personal and Ubiquitous Computing*. DOI: 10.1007/s00779-009-0256-1.

[200] Astrid M. L. Kappers and Wouter M. Bergmann Tiest. 2013. Haptic perception. *WIREs Cognitive Science*. DOI: 10.1002/wcs.1238.

[201] Georgios Karafotias, Akiko Teranishi, Georgios Korres, Friederike Eyssel, Scandar Copti, and Mohamad Eid. 2017. Intensifying emotional reactions via tactile gestures in immersive films. *ACM Trans. Multimedia Comput. Commun. Appl.* DOI: 10.1145/3092840.

[202] Arafeh Karimi, Peter Worthy, Paul McInnes, Marie Bodén, Ben Matthews, and Stephen Viller. 2017. The community garden hack: participatory experiments in facilitating primary school teacher's appropriation of technology. In *Proceedings of the 29th Australian Conference on Computer-Human Interaction*. ACM, Brisbane Queensland Australia. DOI: 10.1145/3152771.3152787.

[203] Robert S. Kennedy, Norman E. Lane, Kevin S. Berbaum, and Michael G. Lilienthal. 1993. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology*. DOI: 10.1207/s15327108ijap0303_3.

[204] Hooman Khosravi, Katayoon Etemad, and Faramarz F. Samavati. 2022. Mass simulation in VR using vibrotactile feedback and a co-located physically-based virtual hand. *Computers & Graphics*. DOI: https://doi.org/10.1016/j.cag.2021.12.002.

[205] Kalevi Kilkki. 2008. Quality of Experience in Communications Ecosystem. *J. UCS*. URL: jucs.org/jucs_14_5/quality_of_experience_in/jucs_14_05_0615_0624_kilkki.pdf.

[206] 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*. ACM, Honolulu HI USA. DOI: 10.1145/3313831.3376280.

[207] Lawrence H. Kim, Pablo Castillo, Sean Follmer, and Ali Israr. 2019. VPS tactile display: Tactile information transfer of vibration, pressure, and shear. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* DOI: 10.1145/3328922.

[208] Myung Jin Kim, Neung Ryu, Wooje Chang, Michel Pahud, Mike Sinclair, and Andrea Bianchi. 2022. SpinOcchio: Understanding haptic-visual congruency of skin-slip in VR with a dynamic grip controller. In *Proceedings of the 2022 CHI conference on human factors in computing systems* (CHI '22). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3491102.3517724.

[209] Roberta L. Klatzky and Susan J. Lederman. 1992. Stages of manual exploration in haptic object identification. *Perception & Psychophysics*. DOI: 10.3758/BF03211702.

[210] Roberta L. Klatzky and Susan J. Lederman. 1995. Identifying objects from a haptic glance. *Perception & Psychophysics*. DOI: 10.3758/BF03208368.

[211] Roberta L. Klatzky, Susan J. Lederman, and Victoria A. Metzger. 1985. Identifying objects

by touch: An "expert system". *Perception & Psychophysics*. DOI: 10.3758/BF03211351.

[212] 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. *Journal of Experimental Psychology: General*. DOI: 10.1037/0096-3445.116.4.356.

[213] Roberta L. Klatzky and Joann Peck. 2012. Please Touch: Object Properties that Invite Touch. *IEEE Transactions on Haptics*. DOI: 10.1109/TOH.2011.54.

[214] Jarrod Knibbe, Adrian Alsmith, and Kasper Hornbæk. 2018. Experiencing Electrical Muscle Stimulation. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*. DOI: 10.1145/3264928.

[215] Jarrod Knibbe, Jonas Schjerlund, Mathias Petraeus, and Kasper Hornbæk. 2018. The Dream is Collapsing: The Experience of Exiting VR. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3173574.3174057.

[216] Marie Høxbro Knudsen, Niklas Breindahl, Tor-Salve Dalsgaard, Dan Isbye, Anne Grethe Mølbak, Gerhard Tiwald, Morten Bo Søndergaard Svendsen, Lars Konge, Joanna Bergström, and Tobias Todsen. 2023. Using Virtual Reality Head-Mounted Displays to Assess Skills in Emergency Medicine: Validity Study. *Journal of Medical Internet Research*. DOI: 10.2196/45210.

[217] Christof Koch. 2018. What Is Consciousness? *Nature*. DOI: 10.1038/d41586-018-05097-x.

[218] Hartmut Koenitz. 2018. Thoughts on a Discipline for the Study of Interactive Digital Narratives. In *Interactive Storytelling*. Rebecca Rouse, Hartmut Koenitz, and Mads Haahr, (Eds.) Springer International Publishing, Cham. DOI: 10.1007/978-3-030-04028-4_3.

[219] Georgios Korres and Mohamad Eid. 2016. Haptogram: Ultrasonic Point-Cloud Tactile Stimulation. *IEEE Access*. DOI: 10.1109/ACCESS.2016.2608835.

[220] 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). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3379337.3415854.

[221] Yosuke Kurihara, Seiya Takei, Yuriko Nakai, Taku Hachisu, Katherine J. Kuchenbecker, and Hiroyuki Kajimoto. 2014. Haptic robotization of the human body by data-driven vibrotactile feedback. *Entertainment Computing*. DOI: https://doi.org/10.1016/j.entcom.2014.08.010.

[222] Dongjae Kwon, Ramzi Abou Chahine, Chungman Lim, Hasti Seifi, and Gunhyuk Park. 2023. Can we crowdsource Tacton similarity perception and metaphor ratings? In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (CHI '23). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3544548.3581120.

[223] Thomas Langerak, Juan José Zárate, Velko Vechev, David Lindlbauer, Daniele Panozzo, and Otmar Hilliges. 2020. Optimal Control for Electromagnetic Haptic Guidance Systems. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. Association for Computing Machinery, New York, NY, USA. ISBN: 978-1-4503-7514-6.

[224] R. Lasanen, P. Julkunen, O. Airaksinen, and J. Töyräs. 2016. Menthol concentration in topical cold gel does not have significant effect on skin cooling. *Skin Research and Technology*. DOI: 10.1111/srt.12226.

[225] Susan J Lederman and Roberta L Klatzky. 1987. Hand movements: A window into haptic object recognition. *Cognitive Psychology*. DOI: 10.1016/0010-0285(87)90008-9.

[226] Susan J. Lederman and Roberta L. Klatzky. 1993. Extracting object properties through haptic exploration. *Acta Psychologica*. Tactile Pattern Recognition. DOI: 10.1016/0001-6918(93)90070-8.

[227] Susan J. Lederman and Roberta L. Klatzky. 2009. Haptic perception: A tutorial. *Attention, Perception & Psychophysics*. DOI: 10.3758/APP.71.7.1439.

[228] 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). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2148131.2148157.

[229] 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). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3290605.3300301.

[230] Ye-Seul Lee, Isac Sehlstedt, Håkan Olausson, Won-Mo Jung, Christian Wallraven, and Younbyoung Chae. 2018. Visual and physical affective touch delivered by a rotary tactile stimulation device: A human psychophysical study. *Physiology & Behavior*. DOI: 10.1016/j.physbeh.2017.12.022.

[231] R. C. Lennertz, M. Tsunozaki, D. M. Bautista, and C. L. Stucky. 2010. Physiological Basis of Tingling Paresthesia Evokedby Hydroxy- -Sanshool. *Journal of Neuroscience*. DOI: 10.1523/JNEUROSCI.4666-09.2010.

[232] Sihui Li, Raagini Rameshwar, Ann Marie Votta, and Cagdas D. Onal. 2019. Intuitive Control of a Robotic Arm and Hand System With Pneumatic Haptic Feedback. *IEEE Robotics and Automation Letters*. DOI: 10.1109/LRA.2019.2937483.

[233] Klemen Lilija, Henning Pohl, Sebastian Boring, and Kasper Hornbæk. 2019. Augmented Reality Views for Occluded Interaction. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (CHI '19). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3290605.3300676.

[234] Chungman Lim and Gunhyuk Park. 2023. Can a Computer Tell Differences between Vibrations?: Physiology-Based Computational Model for Perceptual Dissimilarity Prediction. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (CHI '23). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3544548.3580686.

[235] Chungman Lim, Gunhyuk Park, and Hasti Seifi. 2024. Designing Distinguishable Mid-Air Ultrasound Tactons with Temporal Parameters. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (CHI '24). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3613904.3642522.

[236] Chungman Lim, Hasti Seifi, and Gunhyuk Park. 2024. An Interactive Tool for Simulating Mid-Air Ultrasound Tactons on the Skin. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems* (CHI EA '24). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3613905.3650981.

[237] Shi-Hong Liu, Pai-Chien Yen, Yi-Hsuan Mao, Yu-Hsin Lin, Erick Chandra, and Mike Y. Chen. 2020. HeadBlaster: A wearable approach to simulating motion perception using head-mounted air propulsion jets. *ACM Trans. Graph.* DOI: 10.1145/3386569.3392482.

[238] Y.-H. Liu and H. J. H. MacFie. 1990. Methods for averaging time – intensity curves. *Chemical Senses*. DOI: 10.1093/chemse/15.4.471.

[239] Benjamin Long, Sue Ann Seah, Tom Carter, and Sriram Subramanian. 2014. Rendering

volumetric haptic shapes in mid-air using ultrasound. *ACM Transactions on Graphics*. DOI: 10.1145/2661229.2661257.

[240] Pedro Lopes, Patrik Jonell, and Patrick Baudisch. 2015. Affordance++: Allowing Objects to Communicate Dynamic Use. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (CHI '15). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2702123.2702128.

[241] Jasmine Lu, Ziwei Liu, Jas Brooks, and Pedro Lopes. 2021. Chemical Haptics: Rendering Haptic Sensations via Topical Stimulants. In *The 34th Annual ACM Symposium on User Interface Software and Technology* (UIST '21). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3472749.3474747.

[242] Shaun Alexander Macdonald, Euan Freeman, Stephen Brewster, and Frank Pollick. 2021. User preferences for calming affective haptic stimuli in social settings. In *Proceedings of the 2021 international conference on multimodal interaction* (ICMI '21). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3462244.3479903.

[243] Shaun Alexander Macdonald, Frank Pollick, and Stephen Anthony Brewster. 2022. The impact of thermal cues on affective responses to emotionally resonant vibrations. In *Proceedings of the 2022 international conference on multimodal interaction* (ICMI '22). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3536221.3556572.

[244] Karon E. MacLean. 2000. Designing with haptic feedback. In *Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No.00CH37065)*. DOI: 10.1109/ROBOT.2000.844146.

[245] Karon E. MacLean. 2022. Designing affective haptic experience for wellness and social communication: where designers need affective neuroscience and psychology. *Current Opinion in Behavioral Sciences*. DOI: 10.1016/j.cobeha.2022.101113.

[246] Karon E. Maclean and Mario J. Enriquez. 2003. Perceptual Design of Haptic Icons. In *EuroHaptics 2003*. University of British Columbia, CA, Dublin, UK. URL: cs.ubc.ca/labs/lci/papers/docs2003/EH03-hapticIcon-reprint.pdf.

[247] 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*. Association for Computing Machinery and Morgan & Claypool. ISBN: 978-1-970001-67-9.

[248] Fiona Macpherson. 2011. Taxonomising the senses. *Philosophical Studies*. DOI: 10.1007/s11098-010-9643-8.

[249] Fiona Macpherson, (Ed.) 2018. *Sensory substitution and augmentation*. (First edition ed.). *Proceedings of the British Academy*. Published for the British Academy by Oxford University Press, Oxford. ISBN: 978-0-19-726644-1.

[250] Tomosuke Maeda, Shigeo Yoshida, Takaki Murakami, Kenroh Matsuda, Tomohiro Tanikawa, and Hiroyuki Sakai. 2022. Fingeret: A wearable fingerpad-free haptic device for mixed reality. In *Proceedings of the 2022 ACM symposium on spatial user interaction* (SUI '22). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3565970.3567703.

[251] Alejandra J. Magana and Sadhana Balachandran. 2017. Unpacking students' conceptualizations through haptic feedback. *Journal of Computer Assisted Learning*. DOI: 10.1111/jcal.12198.

[252] Emanuela Maggioni, Erika Agostinelli, and Marianna Obrist. 2017. Measuring the added value of haptic feedback. In *2017 Ninth International Conference on Quality of Multimedia Ex-

perience (QoMEX). IEEE, Erfurt, Germany. DOI: 10.1109/QoMEX.2017.7965670.

[253] Lawrence Makin, Gareth Barnaby, and Anne Roudaut. 2019. Tactile and kinesthetic feedbacks improve distance perception in virtual reality. In *Proceedings of the 31st conference on l'Interaction homme-machine* (IHM '19). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3366550.3372248.

[254] George Mather. 2023. *Foundations of sensation and perception*. (4th ed.). Routledge, Milton Park, Abingdon, Oxon. ISBN: 978-1-00-333548-1.

[255] Filip Mattens. 2009. Perception, Body, and the Sense of Touch: Phenomenology and Philosophy of Mind. *Husserl Studies*. DOI: 10.1007/s10743-009-9054-x.

[256] Martin Maunsbach, William Frier, and Kasper Hornbæk. 2024. MAMMOTH: Mid-Air Mesh-based Modulation Optimization Toolkit for Haptics. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems* (CHI EA '24). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3613905.3651060.

[257] Martin Maunsbach, Kasper Hornbæk, and Hasti Seifi. 2022. Whole-Hand Haptics for Mid-air Buttons. In *Haptics: Science, Technology, Applications; EuroHaptics 2022* (Lecture Notes in Computer Science). Springer International Publishing, Cham. DOI: 10.1007/978-3-031-06249-0_33.

[258] Martin Maunsbach, Kasper Hornbæk, and Hasti Seifi. 2023. Mediated Social Touching: Haptic Feedback Affects Social Experience of Touch Initiators. In *2023 IEEE World Haptics Conference (WHC)*. DOI: 10.1109/WHC56415.2023.10224506.

[259] John McCarthy and Peter Wright. 2004. *Technology as Experience*. (1st paperback ed.). MIT Press, Cambridge, Mass. ISBN: 978-0-262-63355-0.

[260] Shane T. McDonald, David Bolliet, and John Hayes. 2016. *Chemesthesis: chemical touch in food and eating*. (1. ed.). John Wiley & Sons, Inc, Chichester, West Sussex. ISBN: 978-1-118-95173-6.

[261] Conor McGinn and Dylan Dooley. 2020. What should robots feel like? In *Proceedings of the 2020 ACM/IEEE international conference on human-robot interaction* (HRI '20). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3319502.3374835.

[262] Jess McIntosh, Paul Strohmeier, Jarrod Knibbe, Sebastian Boring, and Kasper Hornbæk. 2019. Magnetips: Combining fingertip tracking and haptic feedback for around-device interaction. In *Proceedings of the 2019 CHI conference on human factors in computing systems* (CHI '19). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3290605.3300638.

[263] Gary J. McKeown and Ian Sneddon. 2014. Modeling continuous self-report measures of perceived emotion using generalized additive mixed models. *Psychological Methods*. DOI: 10.1037/a0034282.

[264] Albert Mehrabian. 1996. Pleasure-arousal-dominance: A general framework for describing and measuring individual differences in Temperament. *Current Psychology*. DOI: 10.1007/BF02686918.

[265] Elisa D. Mekler and Kasper Hornbæk. 2016. Momentary Pleasure or Lasting Meaning?: Distinguishing Eudaimonic and Hedonic User Experiences. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, San Jose California USA. DOI: 10.1145/2858036.2858225.

[266] Elisa D. Mekler and Kasper Hornbæk. 2019. A Framework for the Experience of Meaning in Human-Computer Interaction. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, Glasgow Scotland Uk. DOI: 10.1145/3290605.3300455.

[267] Maurice Merleau-Ponty. 1945. *Phénoménologie de la perception*. *Tel*. Gallimard, Paris. ISBN: 978-2-07-029337-7.

[268] Maurice Merleau-Ponty and Donald A. Landes. 2012. *Phenomenology of perception*. Routledge, Milton Park, Abingdon, Oxon. ISBN: 978-0-415-83433-9.

[269] Roberto Montano-Murillo, Ryuji Hirayama, and Diego Martinez Plasencia. 2023. OpenMPD: A low-level presentation engine for Multimodal Particle-based Displays. *ACM Transactions on Graphics*. DOI: 10.1145/3572896.

[270] Tony Morelli, John Foley, and Eelke Folmer. 2010. Vi-bowling: a tactile spatial exergame for individuals with visual impairments. In *Proceedings of the 12th international ACM SIGACCESS conference on Computers and accessibility* (ASSETS '10). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/1878803.1878836.

[271] M. J. Morgan, D. Melmoth, and J. A. Solomon. 2013. Linking hypotheses underlying Class A and Class B methods. *Visual Neuroscience*. DOI: 10.1017/S095252381300045X.

[272] India Morrison. 2023. Touching to connect, explore, and explain: how the human brain makes social touch meaningful. *The Senses and Society*. DOI: 10.1080/17458927.2023.2200065.

[273] A. Moscatelli, M. Bianchi, S. Ciotti, G. C. Bettelani, C. V. Parise, F. Lacquaniti, and A. Bicchi. 2019. Touch as an auxiliary proprioceptive cue for movement control. *Science Advances*. DOI: 10.1126/sciadv.aaw3121.

[274] M. Reza Motamedi, Jean-Baptiste Chossat, Jean-Philippe Roberge, and Vincent Duchaine. 2016. Haptic feedback for improved robotic arm control during simple grasp, slippage, and contact detection tasks. In *2016 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, Stockholm. DOI: 10.1109/ICRA.2016.7487694.

[275] Thomas Muender, Michael Bonfert, Anke Verena Reinschluessel, Rainer Malaka, and Tanja Döring. 2022. Haptic Fidelity Framework: Defining the Factors of Realistic Haptic Feedback for Virtual Reality. In *CHI Conference on Human Factors in Computing Systems*. ACM, New Orleans LA USA. DOI: 10.1145/3491102.3501953.

[276] James Mullen, Josh Mosier, Sounak Chakrabarti, Anqi Chen, Tyler White, and Dylan Losey. 2021. Communicating Inferred Goals With Passive Augmented Reality and Active Haptic Feedback. *IEEE Robotics and Automation Letters*. DOI: 10.1109/LRA.2021.3111055.

[277] Joe Mullenbach, Craig Shultz, J. Edward Colgate, and Anne Marie Piper. 2014. Exploring affective communication through variable-friction surface haptics. In *Proceedings of the SIGCHI conference on human factors in computing systems* (CHI '14). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2556288.2557343.

[278] Saskia K. Nagel, Christine Carl, Tobias Kringe, Robert Märtin, and Peter König. 2005. Beyond sensory substitution—learning the sixth sense. *Journal of Neural Engineering*. DOI: 10.1088/1741-2560/2/4/R02.

[279] Barbara Namer, Frank Seifert, Hermann Otto Handwerker, and Christian Maihöfner. 2005. TRPA1 and TRPM8 activation in humans: effects of cinnamaldehyde and menthol. *NeuroReport*. DOI: 10.1097/00001756-200506210-00015.

[280] Alexander Nolte, Ei Pa Pa Pe-Than, Abasiamefon Obot Affia, Chalalai Chaihirunkarn, Anna Filippova, Arun Kalyanasundaram, Maria Angelica Medina Angarita, Erik Trainer, and James D. Herbsleb. 2020. How to organize a hackathon – A planning kit. *arXiv:2008.08025 [cs]*. URL: arxiv.org/abs/2008.08025.

[281] Donald A. Norman. 2002. *The design of everyday things*. (1st Basic paperback ed.). Basic Books, New York. ISBN: 978-0-465-06710-7.

[282] Daniel O'Shiel. 2022. *The Phenomenology of Virtual Technology*. Bloomsbury Publishing. ISBN: 978-1-350-24554-9.

[283] Marianna Obrist, Rob Comber, Sriram Subramanian, Betina Piqueras-Fiszman, Carlos Velasco, and Charles Spence. 2014. Temporal, affective, and embodied characteristics of taste experiences: a framework for design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '14). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2556288.2557007.

[284] 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*. Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2470654.2466220.

[285] Marianna Obrist, Sriram Subramanian, Elia Gatti, Benjamin Long, and Thomas Carter. 2015. Emotions Mediated Through Mid-Air Haptics. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (CHI '15). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2702123.2702361.

[286] Mary Beth Oliver and Arthur A. Raney. 2011. Entertainment as Pleasurable and Meaningful: Identifying Hedonic and Eudaimonic Motivations for Entertainment Consumption. *Journal of Communication*. DOI: 10.1111/j.1460-2466.2011.01585.x.

[287] Simone Ooms, Minha Lee, Pablo Cesar, and Abdallah El Ali. 2023. FeelTheNews: Augmenting affective perceptions of news videos with thermal and vibrotactile stimulation. In *Extended abstracts of the 2023 CHI conference on human factors in computing systems* (CHI EA '23). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3544549.3585638.

[288] Charles Egerton Osgood. 1962. Studies on the generality of affective meaning systems. *American Psychologist*. DOI: 10.1037/h0045146.

[289] Charles Egerton Osgood, George J. Suci, and Percy H. Tannenbaum. 1978. *The measurement of meaning*. University of Illinois Press, Urbana-Champaign. ISBN: 978-0-252-74539-3.

[290] Antti Oulasvirta and Kasper Hornbæk. 2016. HCI Research as Problem-Solving. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2858036.2858283.

[291] Antti Oulasvirta and Kasper Hornbæk. 2022. Counterfactual Thinking: What Theories Do in Design. *International Journal of Human–Computer Interaction*. DOI: 10.1080/10447318.2021.1925436.

[292] Joseph Owens. 1982. Aristotle on Common Sensibles and Incidental Perception. *Phoenix*. DOI: 10.2307/1087890.

[293] Matthew J. Page, Joanne E. McKenzie, Patrick M. Bossuyt, Isabelle Boutron, Tammy C. Hoffmann, Cynthia D. Mulrow, Larissa Shamseer, Jennifer M. Tetzlaff, Elie A. Akl, Sue E. Brennan, Roger Chou, Julie Glanville, Jeremy M. Grimshaw, Asbjørn Hróbjartsson, Manoj M. Lalu, Tianjing Li, Elizabeth W. Loder, Evan Mayo-Wilson, Steve McDonald, Luke A. McGuinness, Lesley A. Stewart, James Thomas, Andrea C. Tricco, Vivian A. Welch, Penny Whiting, and David Moher. 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*. DOI: 10.1136/bmj.n71.

[294] Stefano Papetti, Hanna Järveläinen, Bruno L. Giordano, Sébastien Schiesser, and Martin Fröhlich. 2017. Vibrotactile Sensitivity in Active Touch: Effect of Pressing Force. *IEEE Transactions on Haptics*. DOI: 10.1109/TOH.2016.2582485.

[295] David Parisi. 2018. *Archaeologies of Touch: Interfacing with Haptics from Electricity to Computing*. University of Minnesota press, Minneapolis, [Minnesota] London. ISBN: 978-1-5179-0059-5.

[296] Chaeyong Park, Jeongwoo Kim, and Seungmoon Choi. 2023. Visuo-haptic crossmodal shape perception model for shape-changing handheld controllers bridged by inertial tensor. In *Proceedings of the 2023 CHI conference on human factors in computing systems* (CHI '23). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3544548.3580724.

[297] Chung Hyuk Park, Eun-Seok Ryu, and Ayanna M. Howard. 2015. Telerobotic haptic exploration in art galleries and museums for individuals with visual impairments. *IEEE Transactions on Haptics*. DOI: 10.1109/TOH.2015.2460253.

[298] Mark Paterson. 2006. Feel the Presence: Technologies of Touch and Distance. *Environment and Planning D: Society and Space*. DOI: 10.1068/d394t.

[299] Mark Paterson. 2007. *The Senses of Touch: haptics, affects, and technologies*. Berg, Oxford ; New York. ISBN: 978-1-84520-478-5.

[300] Ralph Pawling, Peter R. Cannon, Francis P. McGlone, and Susannah C. Walker. 2017. C-tactile afferent stimulating touch carries a positive affective value. *PLoS ONE*. DOI: 10.1371/journal.pone.0173457.

[301] Joann Peck and Terry L. Childers. 2003. Individual Differences in Haptic Information Processing: The "Need for Touch" Scale. *Journal of Consumer Research*. DOI: 10.1086/378619.

[302] Tabitha C. Peck and Mar Gonzalez-Franco. 2021. Avatar Embodiment. A Standardized Questionnaire. *Frontiers in Virtual Reality*. DOI: 10.3389/frvir.2020.575943.

[303] Claire Petitmengin. 2006. Describing one's subjective experience in the second person: An interview method for the science of consciousness. *Phenomenology and the Cognitive Sciences*. DOI: 10.1007/s11097-006-9022-2.

[304] Claire Petitmengin, Anne Remillieux, and Camila Valenzuela-Moguillansky. 2018. Discovering the structures of lived experience. *Phenomenology and the Cognitive Sciences*. DOI: 10.1007/s11097-018-9597-4.

[305] Rosalind W. Picard. 2000. *Affective computing*. (1. paperback ed ed.). MIT Press, Cambridge, Mass. ISBN: 978-0-262-66115-7.

[306] Dario Pittera, Marianna Obrist, and Ali Israr. 2017. Hand-to-hand: An intermanual illusion of movement. In *Proceedings of the 19th ACM international conference on multimodal interaction* (ICMI '17). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3136755.3136777.

[307] Ingrid Maria Pohl and Lian Loke. 2014. Touch toolkit: A method to convey touch-based design knowledge and skills. In *Proceedings of the 8th international conference on tangible, embedded and embodied interaction* (TEI '14). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2540930.2540957.

[308] Sara Price, Nadia Bianchi-Berthouze, Carey Jewitt, Nikoleta Yiannoutsou, Katerina Fotopoulou, Svetlana Dajic, Juspreet Virdee, Yixin Zhao, Douglas Atkinson, and Frederik Brudy. 2022. The Making of Meaning through Dyadic Haptic Affective Touch. *ACM Transactions on Computer-Human Interaction*. DOI: 10.1145/3490494.

[309] Mirjana Prpa, Sarah Fdili-Alaoui, Thecla Schiphorst, and Philippe Pasquier. 2020. Articulating Experience: Reflections from Experts Applying Micro-Phenomenology to Design Research in HCI. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (CHI '20). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3313831.3376664.

[310] Roope Raisamo, Katri Salminen, Jussi Rantala, Ahmed Farooq, and Mounia Ziat. 2022. Interpersonal Haptic Communication: Review and Directions for the Future. *International Journal of Human-Computer Studies*. DOI: 10.1016/j.ijhcs.2022.102881.

[311] Jessica Rajko, Michael Krzyzaniak, Jacqueline Wernimont, Eileen Standley, and Stjepan Rajko. 2016. Touching data through personal devices: Engaging somatic practice and haptic design in felt experiences of personal data. In *Proceedings of the 3rd international symposium on movement and computing* (MOCO '16). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2948910.2948937.

[312] Ismo Rakkolainen, Euan Freeman, Antti Sand, Roope Raisamo, and Stephen Brewster. 2020. A Survey of Mid-Air Ultrasound Haptics and Its Applications. *IEEE Transactions on Haptics*. DOI: 10.1109/TOH.2020.3018754.

[313] Juan Ramos. 2003. Using TF-IDF to Determine Word Relevance in Document Queries. In *Proceedings of the first instructional conference on machine learning*. Rutgers University, Piscataway, NJ.

[314] Gabriel Robles-De-La-Torre and Vincent Hayward. 2001. Force can overcome object geometry in the perception of shape through active touch. *Nature*. DOI: 10.1038/35086588.

[315] Pedro Rodrigues, Artur Esteves, João Botelho, Vanessa Machado, Carlos Zagalo, Ezequiel Roberto Zorzal, José João Mendes, and Daniel Simões Lopes. 2022. Usability, acceptance, and educational usefulness study of a new haptic operative dentistry virtual reality simulator. *Computer Methods and Programs in Biomedicine*. DOI: https://doi.org/10.1016/j.cmpb.2022.106831.

[316] Katja Rogers, Sukran Karaosmanoglu, Maximilian Altmeyer, Ally Suarez, and Lennart E. Nacke. 2022. Much Realistic, Such Wow! A Systematic Literature Review of Realism in Digital Games. In *CHI Conference on Human Factors in Computing Systems*. ACM, New Orleans LA USA. DOI: 10.1145/3491102.3501875.

[317] Yvonne Rogers. 2004. New theoretical approaches for human-computer interaction. *Annual Review of Information Science and Technology*. DOI: 10.1002/aris.1440380103.

[318] Michael Roos and Matthias Reccius. 2024. Narratives in economics. *Journal of Economic Surveys*. DOI: 10.1111/joes.12576.

[319] James Robert Rossman and Matthew D. Duerden. 2019. *Designing experiences. Columbia Business School publishing*. Columbia university press, New York. ISBN: 978-0-231-54951-6.

[320] Christian Roth and Hartmut Koenitz. 2016. Evaluating the User Experience of Interactive Digital Narrative. In *Proceedings of the 1st International Workshop on Multimedia Alternate Realities* (AltMM '16). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2983298.2983302.

[321] Joseph Rufo, Feiyan Cai, James Friend, Martin Wiklund, and Tony Jun Huang. 2022. Acoustofluidics for biomedical applications. *Nature Reviews Methods Primers*. DOI: 10.1038/s43586-022-00109-7.

[322] James A. Russell. 1980. A circumplex model of affect. *Journal of Personality and Social Psychology*. DOI: 10.1037/h0077714.

[323] 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). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3290607.3313004.

[324] Isa Rutten and David Geerts. 2020. Better Because It's New: The Impact of Perceived Novelty on the Added Value of Mid-Air Haptic Feedback. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA. ISBN: 978-1-4503-6708-0.

[325] Richard M. Ryan and Edward L. Deci. 2000. Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *American Psychologist*. DOI: 10.1037/0003-066X.55.1.68.

[326] Richard M. Ryan and Edward L. Deci. 2001. On Happiness and Human Potentials: A Review of Research on Hedonic and Eudaimonic Well-Being. *Annual Review of Psychology*. DOI: 10.1146/annurev.psych.52.1.141.

[327] Neung Ryu, Woojin Lee, Myung Jin Kim, and Andrea Bianchi. 2020. ElaStick: A handheld variable stiffness display for rendering dynamic haptic response of flexible object. In *Proceedings of the 33rd annual ACM symposium on user interface software and technology* (UIST '20). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3379337.3415862.

[328] Elham Saadatian, Hooman Samani, Rahul Parsani, Anshul Vikram Pandey, Jinhui Li, Lenis Tejada, Adrian David Cheok, and Ryohei Nakatsu. 2014. Mediating intimacy in long-distance relationships using kiss messaging. *International Journal of Human-Computer Studies*. DOI: 10.1016/j.ijhcs.2014.05.004.

[329] Shadan Sadeghian and Marc Hassenzahl. 2021. From Limitations to "Superpowers": A Design Approach to Better Focus on the Possibilities of Virtual Reality to Augment Human Capabilities. In *Designing Interactive Systems Conference 2021*. Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3461778.3462111.

[330] Suji Sathiyamurthy, Melody Lui, Erin Kim, and Oliver Schneider. 2021. Measuring Haptic Experience: Elaborating the HX model with scale development. In *2021 IEEE World Haptics Conference (WHC)*. IEEE, Montreal, Canada. DOI: 10.1109/WHC49131.2021.9517220.

[331] Michael N Sawka, C Bruce Wenger, Andrew J Young, and Kent B Pandolf. 1993. Physiological responses to exercise in the heat. *Nutritional needs in hot environments: applications for military personnel in field operations*.

[332] Annett Schirmer, Ilona Croy, and Rochelle Ackerley. 2023. What are C-tactile afferents and how do they relate to "affective touch"? *Neuroscience & Biobehavioral Reviews*. DOI: 10.1016/j.neubiorev.2023.105236.

[333] 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 *Extended abstracts of the 2022 CHI conference on human factors in computing systems* (CHI EA '22). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3491101.3503734.

[334] Oliver Schneider, Karon MacLean, Colin Swindells, and Kellogg Booth. 2017. Haptic experience design: What hapticians do and where they need help. *International Journal of Human-Computer Studies*. Multisensory Human-Computer Interaction. DOI: 10.1016/j.ijhcs.2017.04.004.

[335] Oliver S. Schneider and Karon E. MacLean. 2014. Improvising design with a Haptic Instrument. In *2014 IEEE Haptics Symposium (HAPTICS)*. DOI: 10.1109/HAPTICS.2014.6775476.

[336] 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)*. DOI: 10.1109/HAPTICS.2016.7463155.

[337] Oliver S. Schneider, Hasti Seifi, Salma Kashani, Matthew Chun, and Karon E. MacLean. 2016. HapTurk: Crowdsourcing Affective Ratings of Vibrotactile Icons. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (CHI '16). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2858036.2858279.

[338] 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). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3025453.3025744.

[339] Thomas W. Schubert. 2003. The sense of presence in virtual environments: A three-component scale measuring spatial presence, involvement, and realness. *Zeitschrift für Medienpsychologie*. DOI: 10.1026//1617-6383.15.2.69.

[340] Adam Scott and Dave Waddell. 2023. *The Experience Book: for designers, thinkers & makers*. Black Dog Press, London, United Kingdom. ISBN: 978-1-912165-38-4.

[341] H. Seifi, M. Chun, C. Gallacher, O. Schneider, and K. E. MacLean. 2020. How Do Novice Hapticians Design? A Case Study in Creating Haptic Learning Environments. *IEEE Transactions on Haptics*. DOI: 10.1109/TOH.2020.2968903.

[342] Hasti Seifi. 2019. *Personalizing Haptics: From Individuals' Sense-Making Schemas to End-User Haptic Tools*. *Springer Series on Touch and Haptic Systems*. Springer International Publishing, Cham. DOI: 10.1007/978-3-030-11379-7.

[343] Hasti Seifi, Sean Chew, Antony James Nascè, William Edward Lowther, William Frier, and Kasper Hornbæk. 2023. Feellustrator: A design tool for ultrasound mid-air haptics. In *Proceedings of the 2023 CHI conference on human factors in computing systems* (CHI '23). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3544548.3580728.

[344] Hasti Seifi, Mattew Chun, and Karon E. Maclean. 2018. Toward affective handles for tuning vibrations. *ACM Transactions on Applied Perception*. DOI: 10.1145/3230645.

[345] 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 *CHI Conference on Human Factors in Computing Systems*. Assoc Comp Machinery; ACM SIGCHI. DOI: 10.1145/3290605.3300788.

[346] Hasti Seifi, Michael Oppermann, Julia Bullard, Karon E. MacLean, and Katherine J. Kuchenbecker. 2020. 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* (CHI '20). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3313831.3376395.

[347] Hasti Seifi, Kailun Zhang, and Karon E. MacLean. 2015. VibViz: Organizing, visualizing and navigating vibration libraries. In *2015 IEEE World Haptics Conference (WHC)*. IEEE, Evanston, IL. DOI: 10.1109/WHC.2015.7177722.

[348] C. E. Shannon. 1948. A Mathematical Theory of Communication. *Bell System Technical Journal*. DOI: 10.1002/j.1538-7305.1948.tb01338.x.

[349] Helen Sharp, Jenny Preece, and Yvonne Rogers. 2019. *Interaction design: beyond human-computer interaction*. (Fifth edition ed.). Wiley, Indianapolis, IN. ISBN: 978-1-119-54735-8.

[350] Donald Sharpe. 2019. Chi-Square Test is Statistically Significant: Now What? *Practical Assessment, Research, and Evaluation*. DOI: https://doi.org/10.7275/tbfa-x148.

[351] Vivian Shen, Craig Shultz, and Chris Harrison. 2022. Mouth Haptics in VR using a Headset Ultrasound Phased Array. In *CHI Conference on Human Factors in Computing Systems* (CHI '22). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3491102.3501960.

[352] Smitha Sheshadri, Shengdong Zhao, Yang Chen, and Morten Fjeld. 2020. Learn with haptics: Improving vocabulary recall with free-form digital annotation on touchscreen mobiles. In *Proceedings of the 2020 CHI conference on human factors in computing systems* (CHI '20). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3313831.3376272.

[353] Cristina Simões Franklin, Teresa Aisling Whitaker, and Fiona N. Newell. 2010. Active and passive touch differentially activate somatosensory cortex in texture perception. *Human Brain Mapping*. DOI: 10.1002/hbm.21091.

[354] 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). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3332165.3347891.

[355] Tanay Singhal and Oliver Schneider. 2021. Juicy Haptic Design: Vibrotactile Embellishments Can Improve Player Experience in Games. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3411764.3445463.

[356] Mel Slater, Domna Banakou, Alejandro Beacco, Jaime Gallego, Francisco Macia-Varela, and Ramon Oliva. 2022. A Separate Reality: An Update on Place Illusion and Plausibility in Virtual Reality. *Frontiers in Virtual Reality*. DOI: 10.3389/frvir.2022.914392.

[357] Mel Slater, Anthony Steed, John McCarthy, and Francesco Maringelli. 1998. The Influence of Body Movement on Subjective Presence in Virtual Environments. *Human Factors*. DOI: 10.1518/001872098779591368.

[358] Frank Steinicke, Gerd Bruder, Luv Kohli, Jason Jerald, and Klaus Hinrichs. 2008. Taxonomy and Implementation of Redirection Techniques for Ubiquitous Passive Haptic Feedback. In *2008 International Conference on Cyberworlds*. DOI: 10.1109/CW.2008.53.

[359] Evan Strasnick, Christian Holz, Eyal Ofek, Mike Sinclair, and Hrvoje Benko. 2018. Haptic links: Bimanual haptics for virtual reality using variable stiffness actuation. In *Proceedings of the 2018 CHI conference on human factors in computing systems* (CHI '18). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3173574.3174218.

[360] 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* (CHI '18). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3173574.3173639.

[361] 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). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3379337.3415828.

[362] 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* (CHI '17). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3025453.3025812.

[363] Ivan E. Sutherland. 1965. The Ultimate Display. *Proceedings of the IFIPS Congress*. URL: my.eng.utah.edu/~cs6360/Readings/UltimateDisplay.pdf.

[364] Philipp Sykownik and Maic Masuch. 2020. The experience of social touch in multi-user virtual reality. In *Proceedings of the 26th ACM

symposium on virtual reality software and technology (VRST '20). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3385956.3418944.

[365] Ryoko Takahashi, Keisuke Hasegawa, and Hiroyuki Shinoda. 2018. Lateral Modulation of Midair Ultrasound Focus for Intensified Vibrotactile Stimuli. In *Haptics: Science, Technology, and Applications* (Lecture Notes in Computer Science). Domenico Prattichizzo, Hiroyuki Shinoda, Hong Z. Tan, Emanuele Ruffaldi, and Antonio Frisoli, (Eds.) Springer International Publishing, Cham. DOI: 10.1007/978-3-319-93399-3_25.

[366] Aishwari Talhan, Sanjeet Kumar, Hwangil Kim, Waseem Hassan, and Seokhee Jeon. 2022. Multi-mode soft haptic thimble for haptic augmented reality based application of texture overlaying. *Displays*. DOI: https://doi.org/10.1016/j.displa.2022.102272.

[367] Yudai Tanaka, Jacob Serfaty, and Pedro Lopes. 2024. Haptic Source-Effector: Full-Body Haptics via Non-Invasive Brain Stimulation. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (CHI '24). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3613904.3642483.

[368] Galia Tanay and Amit Bernstein. 2013. State Mindfulness Scale (SMS): development and initial validation. *Psychological Assessment*. DOI: 10.1037/a0034044.

[369] Yujie Tao, Shan-Yuan Teng, and Pedro Lopes. 2021. Altering perceived softness of real rigid objects by restricting fingerpad deformation. In *The 34th annual ACM symposium on user interface software and technology* (UIST '21). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3472749.3474800.

[370] Nick Taylor and Loraine Clarke. 2018. Everybody's Hacking: Participation and the Mainstreaming of Hackathons. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA. ISBN: 978-1-4503-5620-6.

[371] Nick Taylor, Loraine Clarke, Martin Skelly, and Sara Nevay. 2018. Strategies for Engaging Communities in Creating Physical Civic Technologies. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3173574.3174081.

[372] 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* (CHI '21). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3411764.3445099.

[373] 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). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3332165.3347958.

[374] Shan-Yuan Teng, K.D. Wu, Jacqueline Chen, and Pedro Lopes. 2022. Prolonging VR haptic experiences by harvesting kinetic energy from the user. In *UIST 2022 - Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology* (UIST 2022 - Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3526113.3545635.

[375] David Ternes and Karon E. MacLean. 2008. Designing Large Sets of Haptic Icons with Rhythm. In *Haptics: Perception, Devices and Scenarios* (Lecture Notes in Computer Science). Manuel Ferre, (Ed.) Springer, Berlin, Heidelberg. DOI: 10.1007/978-3-540-69057-3_24.

[376] Karthikan Theivendran, Andy Wu, William Frier, and Oliver Schneider. 2023. RecHap: An Interactive Recommender System For Navigating a Large Number of Mid-Air Haptic Designs. *IEEE Transactions on Haptics*. DOI: 10.1109/TOH.2023.3276812.

[377] Gabriella Tisza and Panos Markopoulos. 2023. FunQ: Measuring the fun experience of a learning activity with adolescents. *Current Psychology*. DOI: 10.1007/s12144-021-01484-2.

[378] Qianqian Tong, Zhiyong Yuan, Mianlun Zheng, Weixu Zhu, Guian Zhang, and Xiangyun Liao. 2016. A novel magnetic levitation haptic device for augmentation of tissue stiffness perception. In *Proceedings of the 22nd ACM conference on virtual reality software and technology* (VRST '16). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2993369.2993377.

[379] Giulio Tononi. 2004. An information integration theory of consciousness. *BMC Neuroscience*. DOI: 10.1186/1471-2202-5-42.

[380] Giulio Tononi. 2012. Integrated information theory of consciousness: an updated account. *Archives Italiennes de Biologie*.

[381] Giulio Tononi. 2015. Integrated Information Theory. *Scholarpedia*. DOI: 10.4249/scholarpedia.4164.

[382] Ching-Yi Tsai, I-Lun Tsai, Chao-Jung Lai, Derrek Chow, Lauren Wei, Lung-Pan Cheng, and Mike Y. Chen. 2022. AirRacket: Perceptual design of ungrounded, directional force feedback to improve virtual racket sports experiences. In *Proceedings of the 2022 CHI conference on human factors in computing systems* (CHI '22). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3491102.3502034.

[383] Chun-Miao Tseng, Po-Yu Chen, Shih Chin Lin, Yu-Wei Wang, Yu-Hsin Lin, Mu-An Kuo, Neng-Hao Yu, and Mike Y. Chen. 2022. HeadWind: Enhancing teleportation experience in VR by simulating air drag during rapid motion. In *Proceedings of the 2022 CHI conference on human factors in computing systems* (CHI '22). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3491102.3501890.

[384] Luca Turchet and Stefania Serafin. 2014. Semantic congruence in audio–haptic simulation of footsteps. *Applied Acoustics*. DOI: 10.1016/j.apacoust.2013.06.016.

[385] Luca Turchet, Travis West, and Marcelo M. Wanderley. 2019. Smart mandolin and musical haptic gilet: Effects of vibro-tactile stimuli during live music performance. In *Proceedings of the 14th international audio mostly conference: A journey in sound* (AM'19). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3356590.3356616.

[386] Luca Turchet, Travis West, and Marcelo M. Wanderley. 2021. Touching the audience: musical haptic wearables for augmented and participatory live music performances. *Personal and Ubiquitous Computing*. DOI: 10.1007/s00779-020-01395-2.

[387] April Tyack and Elisa D. Mekler. 2020. Self-Determination Theory in HCI Games Research: Current Uses and Open Questions. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (CHI '20). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3313831.3376723.

[388] Michael Tye. 2021. Qualia. In *The Stanford encyclopedia of philosophy*. (Fall 2021 ed.). Edward N. Zalta, (Ed.) Metaphysics Research Lab, Stanford University. URL: plato.stanford.edu/archives/fall2021/entries/qualia/.

[389] Yusuke Ujitoko and Yuki Ban. 2023. Toward Designing Haptic Displays for Desired Touch Targets: A Study of User Expectation for Haptic Properties via Crowdsourcing. *IEEE Transactions on Haptics*. DOI: 10.1109/TOH.2023.3310662.

[390] Kaisa Väänänen-Vainio-Mattila, Thomas Olsson, and Jonna Häkkilä. 2015. Towards Deeper Understanding of User Experience with Ubiquitous Computing Systems: Systematic Literature Review and Design Framework. In *Human-Computer Interaction – INTERACT 2015* (Lecture Notes in Computer Science). Julio Abascal, Simone Barbosa, Mirko Fetter, Tom Gross, Philippe Palanque, and Marco Winckler, (Eds.) Springer International Publishing, Cham. DOI: 10.1007/978-3-319-22698-9_26.

[391] Åke Vallbo and Roland Johansson. 1984. Properties of cutaneous mechanoreceptors in the human hand related to touch sensation. *Human neurobiology*. URL: pubmed.ncbi.nlm.nih.gov/6330008/.

[392] Åke Vallbo, Håkan Olausson, Johan Wessberg, and Ulf Norrsell. 1993. A system of unmyelinated afferents for innocuous mechanoreception in the human skin. *Brain Research*. DOI: 10.1016/0006-8993(93)90968-S.

[393] Lawrence Van den Bogaert and David Geerts. 2020. User-Defined Mid-Air Haptic Sensations for Interacting with an AR Menu Environment. In *Haptics: Science, Technology, Applications* (Lecture Notes in Computer Science). Ilana Nisky, Jess Hartcher-O'Brien, Michaël Wiertlewski, and Jeroen Smeets, (Eds.) Springer International Publishing, Cham. DOI: 10.1007/978-3-030-58147-3_3.

[394] Hans van der Heijden. 2004. User Acceptance of Hedonic Information Systems. *MIS Quarterly*. DOI: 10.2307/25148660.

[395] Jan B. F. van Erp and Alexander Toet. 2015. Social Touch in Human–Computer Interaction. *Frontiers in Digital Humanities*. URL: frontiersin.org/articles/10.3389/fdigh.2015.00002.

[396] Carlos Velasco and Marianna Obrist. 2020. *Multisensory Experiences: Where the Senses Meet Technology*. (1st ed.). Oxford University Press, Oxford. ISBN: 978-0-19-884962-9.

[397] Pierre Vermersch. 1994. *L'entretien d'explicitation*. ESF, Issy-les-Moulineaux. ISBN: 978-2-7101-1790-2.

[398] Pierre Vermersch. 2018. *The explicitation interview*. Independently published, CNRS. ISBN: 1-09-016925-6.

[399] Chi Thanh Vi, Damien Ablart, Elia Gatti, Carlos Velasco, and Marianna Obrist. 2017. Not just seeing, but also feeling art: Mid-air haptic experiences integrated in a multisensory art exhibition. *International Journal of Human-Computer Studies*. DOI: 10.1016/j.ijhcs.2017.06.004.

[400] Chi Thanh Vi, Asier Marzo, Damien Ablart, Gianluca Memoli, Sriram Subramanian, Bruce Drinkwater, and Marianna Obrist. 2017. TastyFloats: A Contactless Food Delivery System. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces* (ISS '17). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3132272.3134123.

[401] Steeven Villa, Sven Mayer, Jess Hartcher-O'Brien, Albrecht Schmidt, and Tonja-Katrin Machulla. 2022. Extended Mid-air Ultrasound Haptics for Virtual Reality. *Proceedings of the ACM on Human-Computer Interaction*. DOI: 10.1145/3567731.

[402] Ana Villanueva, Zhengzhe Zhu, Ziyi Liu, Feiyang Wang, Subramanian Chidambaram, and Karthik Ramani. 2022. ColabAR: A toolkit for remote collaboration in tangible augmented reality laboratories. *Proceedings of the ACM on Human-Computer Interaction*. DOI: 10.1145/3512928.

[403] Pauli Virtanen, Ralf Gommers, Travis E. Oliphant, Matt Haberland, Tyler Reddy, David Cournapeau, Evgeni Burovski, Pearu Peterson, Warren Weckesser, Jonathan Bright, Stéfan J. van der Walt, Matthew Brett, Joshua Wilson, K. Jarrod Millman, Nikolay Mayorov, Andrew R. J. Nelson, Eric Jones, Robert Kern, Eric Larson, C J Carey, lhan Polat, Yu Feng, Eric W. Moore, Jake VanderPlas, Denis Laxalde, Josef

Perktold, Robert Cimrman, Ian Henriksen, E. A. Quintero, Charles R. Harris, Anne M. Archibald, Antônio H. Ribeiro, Fabian Pedregosa, Paul van Mulbregt, and SciPy 1.0 Contributors. 2020. SciPy 1.0: Fundamental algorithms for scientific computing in python. *Nature Methods*. DOI: 10.1038/s41592-019-0686-2.

[404] Nadine Wagener, Alex Ackermann, Gian-Luca Savino, Bastian Dänekas, Jasmin Niess, and Johannes Schöning. 2022. Influence of passive haptic and auditory feedback on presence and mindfulness in virtual reality environments. In *Proceedings of the 2022 international conference on multimodal interaction* (ICMI '22). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3536221.3556622.

[405] Chi Wang, Da-Yuan Huang, Shuo-Wen Hsu, Cheng-Lung Lin, Yeu-Luen Chiu, Chu-En Hou, and Bing-Yu Chen. 2020. Gaiters: Exploring skin stretch feedback on legs for enhancing virtual reality experiences. In *Proceedings of the 2020 CHI conference on human factors in computing systems* (CHI '20). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3313831.3376865.

[406] Qinglong Wang, Xiangshi Ren, Sayan Sarcar, and Xiaoying Sun. 2016. EV-Pen: Leveraging electrovibration haptic feedback in pen interaction. In *Proceedings of the 2016 ACM international conference on interactive surfaces and spaces* (ISS '16). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2992154.2992161.

[407] Yu-Wei Wang, Yu-Hsin Lin, Pin-Sung Ku, Y ko Miyatake, Yi-Hsuan Mao, Po Yu Chen, Chun-Miao Tseng, and Mike Y. Chen. 2021. JetController: High-speed ungrounded 3-DoF force feedback controllers using air propulsion jets. In *Proceedings of the 2021 CHI conference on human factors in computing systems* (CHI '21). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3411764.3445549.

[408] Cindy Ward. 2016. Some like it hot! Sensory analysis of products containing chemesthetic compounds. In *Chemesthesis*. John Wiley & Sons, Ltd. DOI: 10.1002/9781118951620.ch10.

[409] Yannick Weiss, Steeven Villa, Albrecht Schmidt, Sven Mayer, and Florian Müller. 2023. Using pseudo-stiffness to enrich the haptic experience in virtual reality. In *Proceedings of the 2023 CHI conference on human factors in computing systems* (CHI '23). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3544548.3581223.

[410] David A. Whetten. 1989. What Constitutes a Theoretical Contribution? *The Academy of Management Review*. DOI: 10.2307/258554.

[411] 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). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3173574.3173660.

[412] Wesley Willett, Bon Adriel Aseniero, Sheelagh Carpendale, Pierre Dragicevic, Yvonne Jansen, Lora Oehlberg, and Petra Isenberg. 2021. Perception! Immersion! Empowerment! Superpowers as Inspiration for Visualization. *IEEE Transactions on Visualization and Computer Graphics*. DOI: 10.1109/TVCG.2021.3114844.

[413] Bob G. Witmer and Michael J. Singer. 1998. Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence: Teleoperators and Virtual Environments*. DOI: 10.1162/105474698565686.

[414] 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* (TEI '22). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3490149.3501307.

[415] S. N. Wood. 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *Journal of the Royal Statistical Society (B)*.

[416] Peter Wright, John McCarthy, and Lisa Meekison. 2018. Making Sense of Experience. In *Funology 2: From Usability to Enjoyment*. Human–Computer Interaction Series. Mark Blythe and Andrew Monk, (Eds.) Springer International Publishing, Cham. DOI: 10.1007/978-3-319-68213-6_20.

[417] Bing Wu, Sung Hun Sim, Andinet Enquobahrie, and Ricardo Ortiz. 2015. Effects of visual latency on visual-haptic experience of stiffness. In *2015 seventh international workshop on quality of multimedia experience (QoMEX)*. IEEE, Pilos, Greece. DOI: 10.1109/QoMEX.2015.7148129.

[418] Jackie (Junrui) Yang, Hiroshi Horii, Alexander Thayer, and Rafael Ballagas. 2018. VR grabbers: Ungrounded haptic retargeting for precision grabbing tools. In *Proceedings of the 31st annual ACM symposium on user interface software and technology* (UIST '18). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3242587.3242643.

[419] Zhizhuo Yang and Dongdong Weng. 2016. Passive haptics based MR system for geography teaching. In *Proceedings of the 15th ACM SIGGRAPH conference on virtual-reality continuum and its applications in industry - volume 1* (VRCAI '16). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3013971.3013995.

[420] Yuan-Syun Ye, Hsin-Yu Chen, and Liwei Chan. 2019. Pull-ups: Enhancing suspension activities in virtual reality with body-scale kinesthetic force feedback. In *Proceedings of the 32nd annual ACM symposium on user interface software and technology* (UIST '19). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3332165.3347874.

[421] 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). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3379337.3415859.

[422] Yongjae Yoo, Taekbeom Yoo, Jihyun Kong, and Seungmoon Choi. 2015. Emotional responses of tactile icons: Effects of amplitude, frequency, duration, and envelope. In *2015 IEEE World Haptics Conference (WHC)*. IEEE, Evanston, IL, USA. DOI: 10.1109/WHC.2015.7177719.

[423] JungKyoon Yoon, Anna E. Pohlmeyer, Pieter M. A. Desmet, and Chajoong Kim. 2021. Designing for Positive Emotions: Issues and Emerging Research Directions. *The Design Journal*. DOI: 10.1080/14606925.2020.1845434.

[424] 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). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3313831.3376358.

[425] Gareth Young, Hamish Milne, Daniel Griffiths, Elliot Padfield, Robert Blenkinsopp, and Orestis Georgiou. 2020. Designing Mid-Air Haptic Gesture Controlled User Interfaces for Cars. *Proceedings of the ACM on Human-Computer Interaction*. DOI: 10.1145/3397869.

[426] Tao Zeng, Frédéric Giraud, Betty Lemaire-Semail, and Michel Amberg. 2011. Haptic perception of curvature through active touch. In

2011 IEEE World Haptics Conference. DOI: 10.1109/WHC.2011.5945542.

[427] Zhuang Zhang, Zhenghao Xu, Luoqian Emu, Pingdong Wei, Sentao Chen, Zirui Zhai, Lingyu Kong, Yong Wang, and Hanqing Jiang. 2023. Active mechanical haptics with high-fidelity perceptions for immersive virtual reality. *Nature Machine Intelligence*. DOI: 10.1038/s42256-023-00671-z.

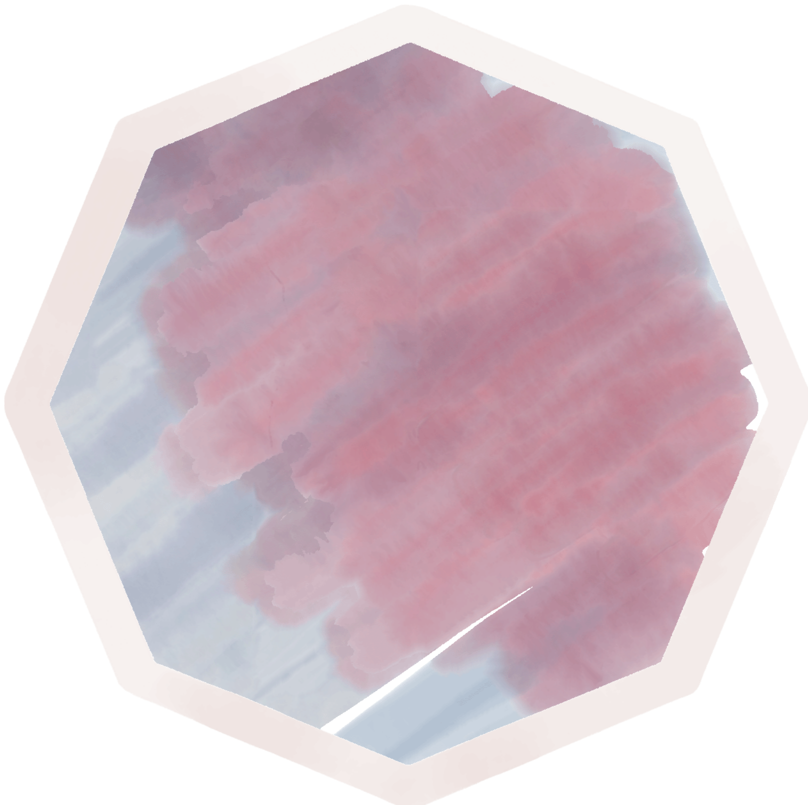
[428] Ran Zhou, Harpreet Sareen, Yufei Zhang, and Daniel Leithinger. 2022. EmotiTactor: Exploring how designers approach emotional robotic touch. In *Designing interactive systems conference* (DIS '22). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3532106.3533487.

[429] Mounia Ziat. 2023. *Haptics for Human-Computer Interaction: From the Skin to the Brain*. Now Publishers, Norwell, MA, US. ISBN: 978-1-63828-147-4.

[430] Mounia Ziat, Rishi Jhunjhunwala, Gina Clepper, Pamela Davis Kivelson, and Hong Z. Tan. 2022. Walking on paintings: Assessment of passive haptic feedback to enhance the immersive experience. *Frontiers in Virtual Reality*. DOI: 10.3389/frvir.2022.997426.

[431] Simone Zimmermann, Sonja Rümelin, and Andreas Butz. 2014. I feel it in my fingers: haptic guidance on touch surfaces. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction* (TEI '14). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/2540930.2540938.

[432] Asnat R. Zohar and Sharona T. Levy. 2020. What do atoms feel? Understanding forces and energy in chemical bonding through the ELI-Chem environment. In *Proceedings of the interaction design and children conference* (IDC '20). Association for Computing Machinery, New York, NY, USA. DOI: 10.1145/3392063.3394416.



Appendix

A. Research Ethics

This thesis presents research based on human subjects. All conducted research followed the ethical guidelines of the University of Copenhagen and was approved by the Research Ethics Committee of Science and Health, University of Copenhagen. Two ethics approvals are attached.

Appendix A.1 shows the ethical approval (case 504-0245/21-5000) for the TOUCHLESS research project, covering Dalsgaard et al., *Haptic Magnetism* [68], Dalsgaard et al., *A User-Derived Mapping for Mid-Air Haptic Experiences* [63], and studies 2 and 3 in Dalsgaard et al., *Ultrasound can deliver chemical stimulants to the skin and modulate their perception* [65].

Appendix A.2 shows the ethical approval (case 504-0376/23-500) for studies 1 and 2 in Dalsgaard et al., *Ultrasound can deliver chemical stimulants to the skin and modulate their perception* [65].

A.1. Ethics approval for the TOUCHLESS project

UNIVERSITY OF COPENHAGEN
RESEARCH ETHICS COMMITTEE FOR SCIENCE AND HEALTH

Hasti Seifi
hs@di.ku.dk
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Department of Computer Science (DIKU),
Universitetsparken 1, 2100 København

23. FEBRUARY 2021

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REF: SUSTA
CASE: 504-0245/21-5000

Ethical review of research project: Touchless Haptic Experiences with Neurocognitive AI

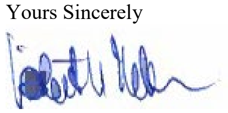
The Research Ethics Committee for SCIENCE and HEALTH has examined your application for a research ethics review at a meeting on 22nd March 2021.

The project period is from 1st January 2021 – 30th December 2024.

The participation will be completely voluntary. Only participants who can give informed consent will be included in the study. The participants can withdraw their consent anytime during or after the experiment without any consequences. The haptic and VR/AR equipment are commercial devices. Interaction with the devices and the data collection methods involve minimal risk to the participants and the participants are not chosen from vulnerable populations. Only data necessary for the research questions of the project will be recorded and processed and in accordance with KU's information Security Policy.

The project outline and data handling is satisfactory described. The Research Ethics Committee for SCIENCE and HEALTH finds, according to information received, that the project is compliant with relevant Danish and International standards and guidelines for research ethics.

Yours Sincerely



Lisbeth Knudsen
Chair

A.2. Ethics approval for the chemical haptics project

UNIVERSITY OF COPENHAGEN
RESEARCH ETHICS COMMITTEE FOR FACULTY OF SCIENCE & FACULTY OF HEALTH AND MEDICAL SCIENCES

Tor-Salve Dalsgaard
torsalve@di.ku.dk
SCIENCE
Department of Computer Science.

Ethics approval of research project: *"Ultrasonic Delivery of Chemical Stimulants to the Skin".*

27TH OF MARCH 2023

The Research Ethics Committee for SCIENCE and SUND has examined your application for a research ethics review at a meeting on the 25th of January 2023. The project period is from the 01st of February 2023 to the 30th of December 2023.
This project will be executed in collaboration with partners at University College London (partners in the EU FET project TOUCHLESS).
Acoustic levitation and topical chemical stimulants are combined to apply drops of these stimulants on the human skin. These chemicals are known to produce haptic sensations when applied to the skin, ranging from tingling and stinging to cool and warm. With the system, the haptic stimulus can be manipulated in three ways: first, levitate a droplet to the right position; second, through rapid changes in ultrasonic frequency, the droplet is atomized to a mist; and third, applying ultrasonic mid-air haptic feedback to the skin. In a human-subject study, the aim is to show the perceivability of the stimulants delivered through acoustic levitation when the stimulant is atomised. The aim is to show how the perceived sensation can be changed when ultrasonic haptic stimulation is applied to the location of the chemical stimulant.

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REF: SUSTA
CASE: 504-0376/23-5000

Research Ethics Committee for SCIENCE and SUND finds, according to information received, that the project is compliant with relevant Danish and International standards and guidelines for research ethics.
The assessment is based on the following documents:

- Application
- Research Protocol
- Informed consent
- Information letter
- Former approval letter from the Research Ethics Committee regarding a project with essential similarities to this project.

Yours Sincerely

Lisbeth E. Knudsen, Chair