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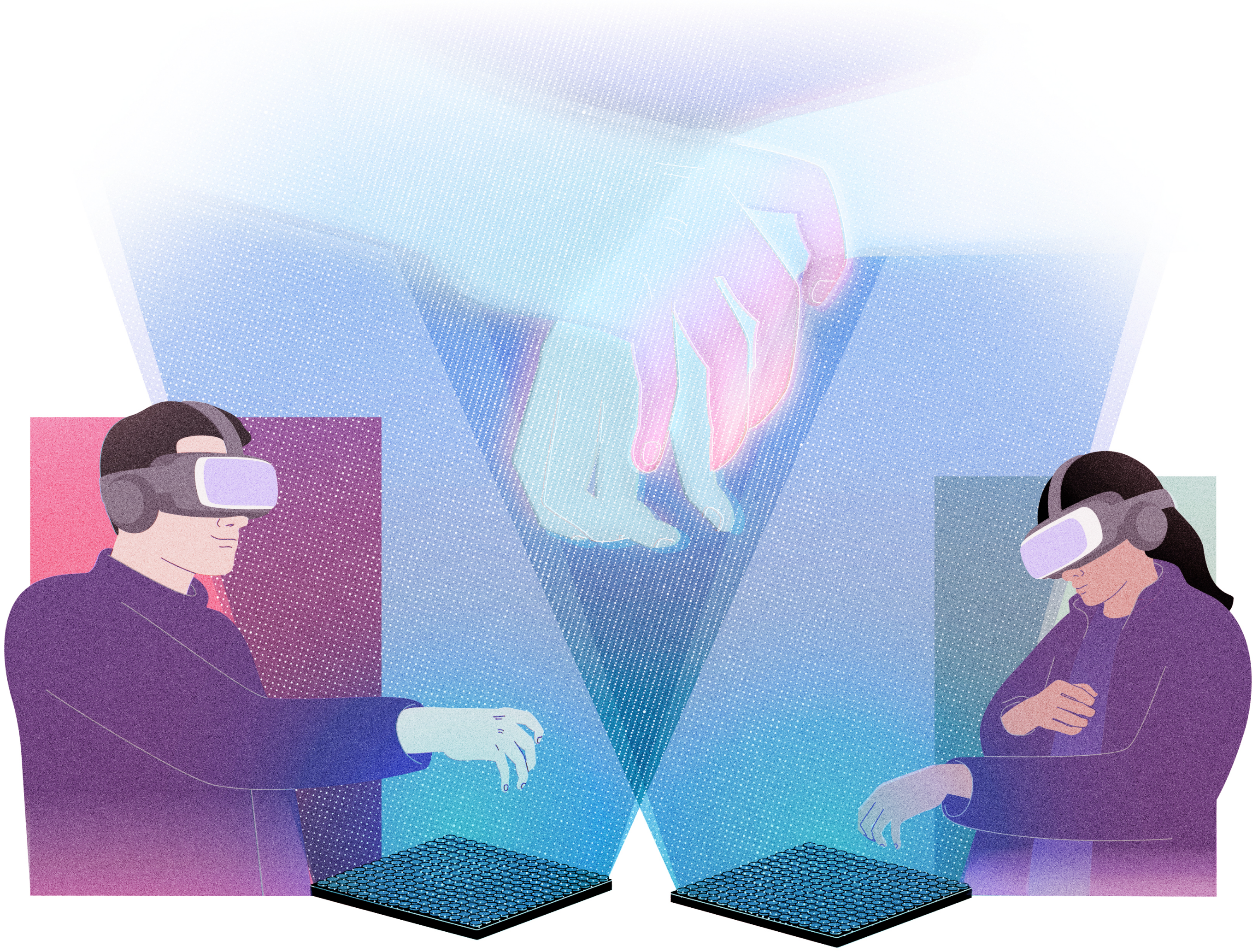

Reinventing the Haptics Lost in Mid-Air Interactions

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Lay on Hands

1st-level Paladin

Your blessed touch can heal wounds. You have a pool of healing power that replenishes when you take a long rest. With that pool, you can restore a total number of hit points equal to your paladin level x 5.

As an action, you can touch a creature and draw power from the pool to restore a number of hit points to that creature, up to the maximum amount remaining in your pool.

Alternatively, you can expend 5 hit points from your pool of healing to cure the target of one disease or neutralize one poison affecting it. You can cure multiple diseases and neutralize multiple poisons with a single use of Lay on Hands, expending hit points separately for each one.

This feature has no effect on undead and constructs.

Wizards RPG Team. (2014). Player's Handbook (Dungeons & Dragons). Wizards of the Coast.

Abstract

TOUCH makes human-computer interactions feel tangible, natural, and intimate. However, current haptic techniques are inadequate for social mid-air interactions. In this Ph.D. project, I show why and how to reinvent mid-air haptic feedback instead of imitating feedback from physical interactions. I use an interdisciplinary understanding of how our body responds to touch for the reinventions. Body responses like our nervous system only reacting to specific frequency ranges, cutaneous vibrations propagating through the limbs on contact, and how we adapt our touches based on what we feel and have experienced. In five core papers, I show how to use these aspects to reinvent mid-air haptics for interactions such as user interfaces and interpersonal touches.

"Whole-Hand Haptics for Mid-Air Buttons" shows how haptic feedback originating at a fingertip press and propagating down the hand increases the performance of using mid-air buttons. We conducted a user study to compare haptic feedback imitating physical buttons with whole-hand haptic feedback.

"Mediated Social Touching: Haptic Feedback Affects Social Experience of Touch Initiators" explores digital touches from the view of touch initiators. We conducted a user study where participants believed they were touching another person while feeling either ultrasound, passive, or no haptic feedback.

"Mediated Social Self-Touch: The Null Effect of Duplicating Haptic Communication to One's Own Body" examines a way of solving the *reciprocity issue* with mediating social touches. In contrast to physical touches, we can not adapt how we digitally touch another as our touches are not reciprocated. We duplicate mediated touches onto one's own body ("self-touch") and measure whether this improves the communication of distinct emotions and improves usability.

"MAMMOTH: Mid-Air Mesh-based Modulation Optimization Toolkit for Haptics" presents a haptic rendering technique and an open-source toolkit to enable haptic designers and researchers to auto-generate ultrasound haptic feedback. The paper includes use cases such as interpersonal touch.

"The Black Box of Digital Touch: Possible Consequences and Dilemmas in Designing Haptic Communication" is a responsible research and innovation perspective on digital touch as an emerging communication form. We constructed futuristic scenarios and deconstructed them through workshops and surveys to understand the possible consequences and dilemmas for users.

Through these four empirical papers, one artifact, and this thesis, I show the significance of reinventing instead of imitating and the need to understand the elements that make a digital touch feel social. I hope these contributions will be adopted to create better, more responsible mid-air interactions.

Resumé

Berøring får menneske-datamaskine interaktioner til at føles håndgribelige, naturlige og intime. Men de nuværende haptiske teknikker er utilstrækkelige til sociale interaktioner midt i luften. I dette ph.d. projekt viser jeg hvorfor og hvordan man kan genopfinde haptisk feedback midt i luften i stedet for at imitere feedback fra fysiske interaktioner. Jeg bruger en tværfaglig forståelse af hvordan vores krop reagerer på berøring til genopfindelserne. Kropslie reaktioner som at vores nervesystem kun reagerer på specifikke frekvensområder, kutane vibrationer forplanter sig gennem lemmerne ved kontakt, og vi tilpasser vores berøringer baseret på hvad vi føler og har oplevet. I fem artikler viser jeg hvordan man kan bruge disse aspekter til at genopfinde midt-i-luften haptik for interaktioner såsom brugergrænseflader og sociale berøringer.

"Whole-Hand Haptics for Mid-Air Buttons" viser hvordan haptisk feedback, der stammer fra et fingerspidstryk og forplanter ned i hånden, øger ydeevnen af midt-i-luften knapper. Vi udførte en brugerundersøgelse for at sammenligne haptisk feedback, der imiterer fysiske knapper med haptisk feedback langs hele hånden.

"Mediated Social Touching: Haptic Feedback Affects Social Experience of Touch Initiators" udforsker digitale berøringer fra afsenderens synspunkt. Vi udførte en brugerundersøgelse, hvor deltagerne troede, at de rørte ved en anden person, mens de enten følte ultralyd, passiv eller ingen haptisk feedback.

"Mediated Social Self-Touch: The Null Effect of Duplicating Haptic Communication to One's Own Body" undersøger en måde at løse *gensidighedsproblemet* med digitale sociale berøringer. I modsætning til fysiske berøringer kan vi ikke tilpasse, hvordan vi digitalt rører en anden, da vores berøringer ikke bliver gengældt. Vi dublikerer digitale berøringer på ens egen krop ("self-touch") og måler, om dette forbedrer kommunikationen af distinkte figurer og forbedrer brugervenligheden.

"The Black Box of Digital Touch: Possible Consequences and Dilemmas in Designing Haptic Communication" er et responsible research and innovation-synspunkt på digital berøring som en ny kommunikationsform. Vi konstruerede futuristiske scenarier og dekonstruerede dem gennem workshops og undersøgelser for at forstå de mulige konsekvenser og dilemmaer for brugere.

Gennem disse fire empiriske artikler, en artefakt og denne afhandling, viser jeg betydningen af at genopfinde i stedet for at imitere, og behovet for at forstå de elementer, der får en digital berøring til at føles social. Jeg håber, at disse bidrag vil blive brugt til at skabe bedre og mere ansvarlige interaktioner midt i luften.

Contents

Contents **3**

1 Introduction **6**

2 Haptics and Our Skin **8**
2.1 Haptic Perception . . . 8
2.2 Haptic Feedback . . . 9
2.3 Ultrasound Mid-Air Haptics . . . 11
2.4 Ultrasound Haptic Rendering . . . 12
2.5 Mid-Air Haptic Experiences . . . 14

3 Core Paper Reinventions and Perspectives **15**
3.1 Whole-Hand Haptics . . . 15
3.2 Mediated Social Touching . . . 17
3.3 Mediated Social Self-Touch . . . 19
3.4 MAMMOTH . . . 20
3.5 The Black Box of Digital Touch . . . 21

4 Whole-Hand Haptics for Mid-Air Buttons **24**
4.1 Introduction . . . 24
4.2 Mid-Air Button Design . . . 26
4.3 User Study . . . 26
4.4 Results . . . 28
4.5 Discussion and Conclusion . . . 30

5 Mediated Social Touching: Haptic Feedback Affects Social Experience of Touch Initiators **32**
5.1 Introduction . . . 33
5.2 Related Work . . . 34
5.3 Methods . . . 35
5.4 Results . . . 38
5.5 Discussion . . . 42
5.6 Conclusion . . . 44

6 Mediated Social Self-Touch: The Null Effect of Duplicating Haptic Communication to One's Own Body **45**
6.1 Introduction . . . 46
6.2 Related Work . . . 47

6.3 Methods 50
6.4 Results 54
6.5 Discussion 56
6.6 Conclusion 57
6.7 Appendix 58

7 MAMMOTH: Mid-Air Mesh-based Modulation Optimization Toolkit for Haptics 59
7.1 Introduction 60
7.2 Related Work 61
7.3 Path Routing Optimization 61
7.4 Evaluation 65
7.5 Use Cases 67
7.6 Conclusion 68

8 The Black Box of Digital Touch: Possible Consequences and Dilemmas in Designing Haptic Communication 69
8.1 Introduction 70
8.2 Related Work 71
8.3 Scenario Workshops 75
8.4 Dilemma Survey 84
8.5 Discussion 90
8.6 Conclusion 92
8.7 Appendix 93

9 Discussion 95

10 Conclusion 97

Bibliography 98

Chapter 1

Introduction

Mid-air interactions use bare-hand movements to control human-computer interactions. They are envisioned as natural, enabling us to reach out and interact with digital content as we would with physical content – bringing human-computer interactions closer to human-human interactions [222]. While *contact-based* mid-air devices such as VR controllers, wearables, and gloves may provide haptic feedback (touch experienced through technology), *touchless* mid-air devices such as sensors and motion control cameras do not. As the name implies, touchless mid-air interactions lack physical contact between the human and computer, meaning they in most cases also lack touch. Touch; the sense perceived through our largest sensory organ (the skin), the first sense to develop [64], the sense to communicate physical intimacy, and a sense that can hurt us. Touch is a natural part of human development, well-being, behavior, and communication of affect [98]. If mid-air interactions are to feel natural, touch is a necessity. This begs the question: why and how do we create the feeling of touch in touchless interactions?

Mid-air haptic feedback can trigger our sense of touch without contact with any devices. Some types of mid-air haptic feedback have been used in commercial applications including air jets (e.g., 4D cinemas) and temperature (heat and cold). Mid-air haptic feedback is also possible with laser, electrostatic, and ultrasound. In this PhD project I focus on the use of ultrasound haptic feedback. Ultrasound haptic feedback work by timing the phase of several ultrasound transducers to collide in a focal point. This focal point stimulates the receptors in our skin, creating the sensation of touch. Throughout my studies and demonstrations, people have described the feeling as "air" or "tingling". Ultrasound haptic feedback does not generate a strong sensation and is therefore primarily used to stimulate the glabrous skin due to its higher sensitivity compared to other body regions. The palmar side of the hand, the sole of the feet, and our lips contain glabrous skin. My work focuses on the palmar side of the hand, as this is the body region in focus for mid-air interactions [124]. Ultrasound haptic feedback has a high expressivity compared to other types of mid-air haptic feedback [192]. It is possible to rapidly move the focal point around in a 3D space, creating the sensation of shapes (e.g., squares, circles) or patterns (e.g.,"hand scan", "alarm"). This has enabled researcher to add touch to otherwise touchless mid-air interactions.

Ultrasound haptic feedback has been used for button presses [36, 103, 163], mouth-haptics [193], communicating emotions [159], fluids [104], gasses [10], mid-air gestures [59, 154, 189, 232], and understanding the receptors in our palm [23]. While the

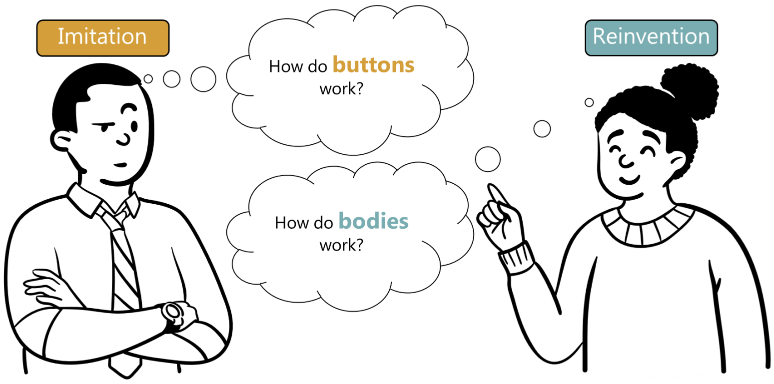

Figure 1.1: To reinvent haptic feedback in mid-air we need to look at how the body works instead of only imitating how physical objects work.

expressivity is higher than its counterparts, ultrasound haptic feedback is generally perceived as weaker and is spatially limited to up to 70 cm above the device [192]. This has posed many issues for ultrasound haptic feedback. When attempting to imitate the feedback of physical buttons in mid-air, ultrasound haptic feedback comes up short. It does not create enough force to stop movements in mid-air nor create the natural pull-back effect that happens when a button is pressed. The feedback is often a faint representation of its physical counterpart. In many other examples, ultrasound haptic feedback plays a mere supplemental role in an overall interaction.

My approach is to look beyond the physical limitations of ultrasound haptic devices and reinvent mid-air haptics based on the knowledge of haptic perception. To do this, my co-authors and I utilize how we physically and psychologically respond to touch to enhance the design opportunities afforded by the small parameter space of ultrasound haptic devices (position and intensity). Instead of being technically limited by the parameter space, we use interdisciplinary insights to use it in new ways. As Cook [34] writes when using sound for instruments: “Copying an instrument is dumb, leveraging expert technique is smart”.

This PhD project includes an introduction to the reinvention of mid-air haptics and five core papers showing specific ways to achieve this. After this introduction, I will dive deeper into haptic perception, haptic feedback, and ultrasound mid-air haptics. I will then further explain the need to reinvent instead of imitating in the context of the five core papers. Finally, I will draw my conclusions on whether the reinvention is achieved through this PhD project and desiderata for future improvements.

Chapter 2

Haptics and Our Skin

THE skin is our natural outer layer greeting all the world's elements. It is an overcoating filled with thousands of sensors connecting our whole being, only interrupted by minor slots reserved for other senses and functions. These sensors are called mechanoreceptors and make up the cutaneous subsystem. This is the "what" system, enabling us to understand *what* objects we touch and *what* their properties are [129]. The other subsystem is the kinesthetic system, made up of mechanoreceptors in our muscles, tendons, and joints, that tell us "where" something is located [129]. Additionally, the nociceptive pathways inform the brain of pain, and the thermal signals indicate cold, cool, warm, and hot sensations [115]. This thesis primarily focuses on feedback to the cutaneous subsystem with occasional mentions of the kinesthetic subsystem. Before introducing haptic feedback (*inducing* touch sensations) I will first introduce haptic perception (*sensing* touch sensations).

2.1 Haptic Perception

The understanding of the mechanoreceptors in our skin is regularly changing. This introduction is based on a tutorial by Lederman and Klatzky [129] and Kandel et al. [115]. When our receptors are stimulated, they send signals from the periphery to our central nervous system [105]. It is believed our skin contains four types of mechanoreceptors that act as "input" to our sense of touch: Merkel disk, Ruffini ending, Meissner corpuscle, and Pacinian corpuscle. The receptors are categorized into slow- or fast-adapting, and small (type I) or large (type II). Slow-adapting receptors (SA) are slow to respond to changes but maintain a continued response when deformed while fast-adapting (FA) are quick to respond to changes, but the response is not felt under sustained pressure. The size refers to the area of its receptive field [129].

The receptors are summarized in Table 2.1 by Kandel et al. [115]. The table shows what type of stimulus is best suited for the mechanoreceptors and their frequency range. The maximum frequency range here is 1000 Hz, while the best frequency is close to a maximum of 200 Hz. Compared to our ability to hear up to 20,000 Hz, the range of touch is limited. While our sense of hearing can decipher complex signals consisting of many sine waves, touch can not decipher complex signals.

There are two classic methods to study the response of the receptors in our skin. Both methods use human participants who are stimulated in two locations on the skin before answering a perception query. The *two-point discrimination method* is used

	Type 1		Type 2	
	SA1	**RA1**[1]	**SA2**	**RA2**[2]
Receptor	Merkel cell/neurite complex (multiple endings)	Meissner corpuscle (multiple endings)	Ruffini ending (single ending)	Pacinian corpuscle (single ending)
Location	Base of intermediate ridge surrounding sweat duct	Dermal papillae (adjacent to limiting ridge)	Skin folds, skin over joints, nail bed	Dermis (deep tissue)
Axon diameter (μm)	7–11	6–12	6–12	6–12
Conduction velocity (ms)	40–65	35–70	35–70	35–70
Best stimulus	Edges, points	Lateral motion	Skin stretch	Vibration
Response to sustained indentation	Sustained with slow adaptation (irregular firing pattern)	Phasic at stimulus onset	Sustained with slow adaptation (regular firing rate)	Phasic at stimulus onset
Frequency range (Hz)	0–100	1–300		5–1,000
Best frequency (Hz)	5	50		200
Threshold for rapid indentation or vibration (best) (μm)	8	2	40	0.01

[1]Also called RA, QA, or FA1.
[2]Also called PC or FA2.
RA1, rapidly adapting type 1; **RA2**, rapidly adapting type 2; **SA1**, slowly adapting type 1; **SA2**, slowly adapting type 2.

Figure 2.1: Overview of the four receptors that enable our sense of touch. Used with permission of McGraw Hill LLC, from Principles of Neural Science, Eric Kandel, 6, 6, 2020; permission conveyed through Copyright Clearance Center, Inc.[115]

to study how close two points can be stimulated before they feel like a single point. The result is a value in mm that tells the difference between points in order for them to feel like individual points. This value differs depending on the stimulant and skin location. An often-used stimulant is vibrotactile feedback, where various frequencies can be induced. The *point localization method* is also used to study spatial acuity. One point is stimulated, followed by a second point. The participant informs whether the point feels like it is in the same or another location. The result is how far from the first point the second can be while still feeling like the same location.

The palmar side of the hand is often studied due to its large amount of receptors [37], which has provided a good understanding of the receptors in the hand. A 2020 paper by Corniani and Saal [37] showed the density of receptors in the skin around the body, as seen in Figure 2.2. It is clear that the most densely innervated regions are the distal limbs: the palmar side of the hand and the face, followed by parts of the feet. Mechanosensations are also shown to be important in distal limbs for other species like fish and vertebrates [83].

2.2 Haptic Feedback

Haptic feedback is used to stimulate our sense of touch. The cutaneous subsystem is affected when we feel touch, and the kinesthetic subsystem is affected in proprioception. There have been proposed multiple ways to categorize the types of haptic feedback. I will focus on the types that affect the mechanoreceptors in our skin, inducing tactile sensations as described in Section 2.1, as opposed to proprioception

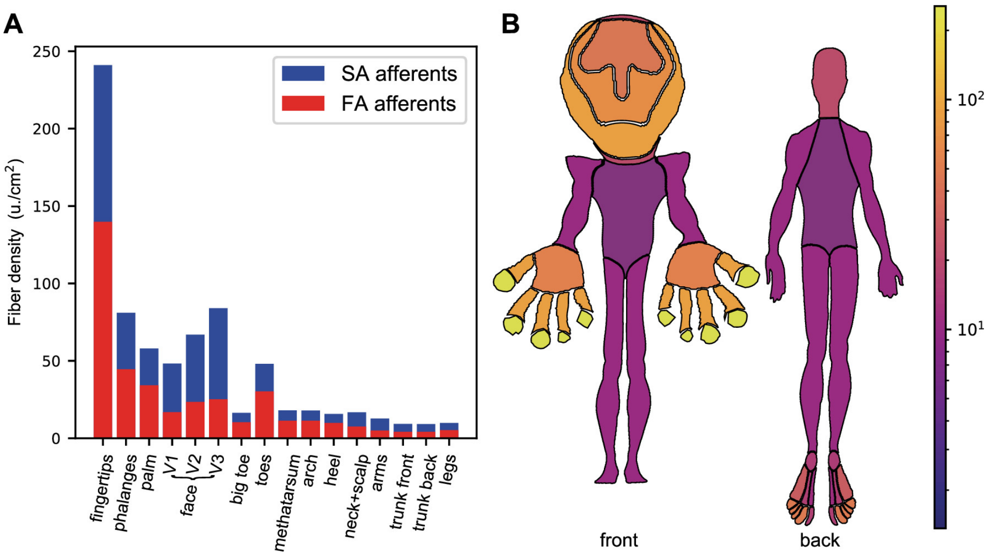

Figure 2.2: Receptor densities across the body. Reused with permission: "Tactile innervation densities across the whole body" by Corniani and Saal [37], Copyright © 2020 the American Physiological Society, Copyright © 2020 the Authors. Licensed under CC-BY 4.0.

(kinesthetic subsystem), temperature (thermal signals), and pain (nociceptive pathways). Additionally, I will differentiate between tactile feedback and force feedback. Tactile feedback refers to the perception of pressure, vibration, and texture, while force feedback concerns a device's use of force and torques [162]. There are multiple types of tactile feedback, including vibrotactile, mechanical, electrotactile, air, and ultrasound.

Vibrotactile feedback refers to feedback vibrating at certain frequencies. This a commonly used technology we perceive when receiving a notification on our phone or playing video games. The motors used to induce vibrotactile feedback have decreased drastically in size and can resemble a coin with a 10 mm diameter. Vibrotactile feedback is often used to simulate touch in virtual interactions that lack touch. While this is used to a great extent in video games, like shooting a gun or driving a car, it requires a leap of imagination to map vibrations to what it compliments visually.

Haptic feedback can also be induced with mechanical objects. When in VR, passive objects can be placed in the same location as virtual objects in VR, creating proxy touch sensations when interacted with [155]. It can also be used in shape-changing interfaces, where the physical shapes conform to the interaction it is complimenting [145, 202]. The shape-changing device shapeShift by Siu et al. [198] created the opportunity to interact with objects of many shapes by moving 288 actuated pins in a 12 × 24 array up or down aided by motion-tracking of the user.

Electrotactile feedback can be used to create sensations ranging from "tingling" to force feedback [166]. It works by sending an electrical current through the skin to stimulate the receptors, and the sensation felt is affected by the features of the electrodes, the current, and anatomy [123]. Compared to the other forms of tactile feedback, it can be harder to induce the desired feedback, and hapticians inducing electrotactile feedback have to ensure no damage can occur. Electrotactile feedback has been used in VR and AR [113], telerobotics [184], for assisting blind and low vision people [110], and more.

Actuation	Ultrasound Phased Array	Fans / Turbines	Vortices	Conventional Jets	Synthetic Jets
Reference System	STRATOS (Ultraleap)	Head Mounted Wind (Cardin et al.)	AIReal (Sodhi et al.)	Gwilliam et al.	This Work
Cost	>$2000	~$180	~$100	>$500	$6 – $410
Power	60 W	12 W	60 W	Tank @ 0.5MPa	0.2 – 100 W
Expressivity	High	Low	Low	Low	Medium
Saliency	Low	High	Medium	High	High
Size	54×43×19 cm	54×54×16 cm	12×8×8 cm	11×5×5 cm	0.15-30.5 cm
Scalablity	Hard	Easy	Hard	Hard	Easy
Demonstrated Range	70 cm	~20 cm	100 cm	1.4 cm	150 cm

Figure 2.3: Ultrasound haptic feedback compared with four types of air feedback. Cite correctly. Table reused by permission: "Expressive, Scalable, Mid-air Haptics with Synthetic Jets" by Shen, Harrison, and ShultzShen et al. [192], Copyright held by the owner/author(s). Licensed under CC-BY 4.0.

Air can be used to direct mid-air tactile feedback at the human body [79]. Air feedback is commonly used in 4D cinemas and for immersive VR experiences. Air vortex rings can be generated using vortex generators, where the air is moved through an aperture by a speaker [79]. This type of feedback was used back in 1867 [211] and has been expanded upon to affect not only the sense of touch but also the sense of smell [231]. Shen et al. [192] created "synthetic jets" capable of air feedback of a demonstrated range up to 150 cm. While ultrasound haptic feedback is often described as feeling like air, Figure 2.3 by Shen et al. [192] highlights the difference in expressivity, saliency, and physical parameters between airborne haptics and ultrasound haptics.

2.3 Ultrasound Mid-Air Haptics

Stimulation of the receptors using ultrasound can be traced back to 1972 [66]. The stimulation was felt as tactile, temperature, and pain [67]. Over 40 years later, Carter et al. [21] introduced "UltraHaptics", a mid-air haptic device using ultrasound to induce the sensation of touch in the skin. The device emitted ultrasonic waves through transducers. At a hardware level, it is only possible to change the intensity of the output. By using signal processing and modulating the amplitude and phase, it is possible to change the frequency and spatial parameters of the sensation.

The ultrasound was emitted at 40 kHz. As seen in Figure 2.1, we can not detect frequency above 1 kHz. In fact, some research has measured the detectable range to be 0.4 to 500 Hz [69]. To be within the detectable range, the ultrasound is either modulated through amplitude modulation (AM) or spatiotemporal modulation (STM), as seen in Figure 2.4. AM is a sinusoidal modulation. Sinusoidal modulation is used for the most pure frequency response, as other modulations such as square, triangle, or sawtooth create unwanted frequency sidebands. STM does not modulate the intensity of the signal but the position of its emission. The stimuli can be moved around rapidly, creating a sense of shapes and patterns. Using STM, positions that make up a shape are usually stimulated in a continuous order. By giving each position on the skin a "rest" while other positions are stimulated, we can feel the haptic feedback because the receptors-perceived frequency is the rate at which each position is repeated. The rate at which a whole pattern is repeated is called the repetition rate and is the frequency of STM [60].

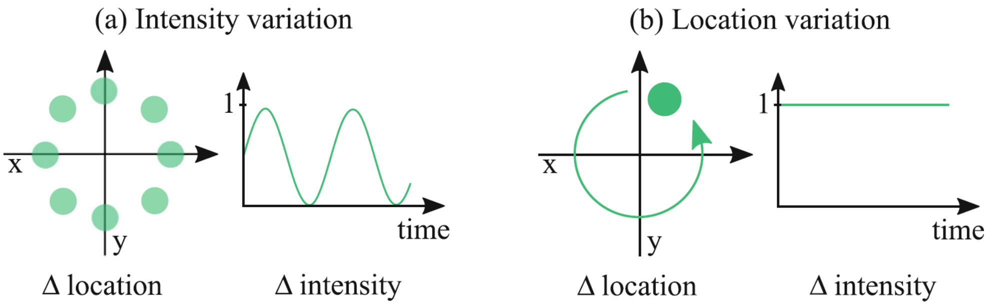

Figure 2.4: Amplitude Modulation and Spatiotemporal Modulation. Reused with permission: William Frier, Damien Ablart, Jamie Chilles et al, "Using Spatiotemporal Modulation to Draw Tactile Patterns in Mid-Air", Haptics: Science, Technology, and Applications, 270-281, 2018, Springer Nature [60].

The use of a single ultrasound transducer is not enough to create a strong or movable sensation. Carter et al. [21] used 320 transducers arranged in a 16 × 20 grid formation for the 2013 "UltraHaptics". By using the phase equation to time the output of the transducers, it is possible to create a focal point in which the waves of all the transducers collide. This can be used to create multiple focal points and move them around independently of each other. When points are moved, noticeable artifacts may be felt and heard due to the rapid change in output. Even though many transducers are used, the final focal point is not strong enough to induce sensations that can be felt all over the body. Sensations are primarily felt on the palmar side of the hands, lips, and the soles of the feet. As seen in Figure 2.2 these locations are the most densely innervated regions. These areas contain glabrous skin, as opposed to hairy skin.

Newer ultrasound haptic devices like the Ultrahaptics Evaluation Kit[1] with a 16 × 16 grid formation produce point stimuli perceived with 8.6 mm in diameters [60]. When rendering shapes using STM, users preferred the stimuli to move around with a speed of 5–8 ms^{-1} when tested on three different circles [60].

2.4 Ultrasound Haptic Rendering

Ultrasound haptic feedback has been used to render 2D shapes [82, 96, 152], 3D objects [134, 141], toolkits [186], communicating emotions [159], and even dynamic whole-hand interactions [10, 144]. Multiple approaches have been suggested to render 2D shapes.

Korres and Eid [122] conducted a perception study using their ultrasound haptic feedback system, "Haptogram". They considered four shapes: a circle, a triangle, a line, and a plus sign. Participants were asked to recognize the shapes individually

[1] Ultraleap: https://www.ultraleap.com/haptics/

by holding one hand over the device and pressing a key to indicate which of the four shapes they thought it was. The average recognition rates can be seen in table 2.1.

Hajas et al. [82] studied whether a dynamic tactile pointer (DTP) could improve the recognition rate. When rendering the shape, an amplitude-modulated point moved along the perimeter of the shape. In their single stroke (SS) condition, only one point moved. In the multi-stroke (MS) condition, multiple points were used. Similarly to Korres and Eid [122], they evaluated the shapes by asking participants which out of three choices they were feeling. The SS condition included the option to select "I don't know". Table 2.1 shows the results of their DTP perception study. I have not included their comparison to shapes with no DTP, which performed worse in three out of four comparisons.

Mulot et al. [152] found the intensity of DTP to be weak due to the use of amplitude modulation. They built upon DTP to investigate whether spatio-temporally-modulated tactile pointers (STP) could improve the perception. They studied the perception using a task where participants drew the shapes they felt and a discrimination task similar to the previous two. The discrimination task included six choices in the SS conditions, which affected the accuracy of the results. They also used different shapes like hexagons, octagons, and ellipses, making a direct comparison difficult.

Table 2.1: Perception studies with a shape discrimination task. Three shapes were selected that were used in most of the studies.

	Author	**Choices**	**Circle**	**Triangle**	**Square**
Haptogram	Korres and Eid [122]	4	62 %	66 %	76 %$^+$
DTP-SS P	Hajas et al. [82]	4*	69 %	59 %	42 %
DTP-SS A			66 %	60 %	32 %
DTP-MS P		3	**83 %**	92 %	74 %
DTP-MS A			81 %	**93 %**	**80** %
STP-SS	Mulot et al. [152]	6	37 %	35 %	15 %
DTP-SS			60 %	22 %	15 %
STP-MS		4	48 %**	78 %	73 %
DTP-MS			50 %**	83 %	72 %

DTP: Dynamic Tactile Pointer. STP: Spatio-Temporally-Modulated Tactile Pointers. SS: Single stroke. MS: Multi-stroke. P: Passive touch. A: Active touch.
*One choice was "I don't know"
**The shape was an octagon
$^+$The shape was a plus sign

Rendering standard shapes like circles, triangles, and squares does not always suffice for an interaction. Barreiro et al. [10] introduced a path-routing algorithm for ultrasound haptic rendering that enabled a haptic sensation to be generated dynamically based on an interaction. They used virtual hand interactions with a dynamic fluid simulation, where the contact between hands and a virtual liquid determined the ultrasound haptic feedback intensity and positions. Jang and Park [104] also demonstrated ultrasound haptic rendering with a liquid but based the haptic feedback on rigid-fluid interactions, where fluid particles were dropped on a hand and discretized using a point cloud. These two types of haptic renderings enable dynamic interactions, where the ultrasound haptic feedback is not dependent on pre-determined shapes but on human-computer interaction.

2.5 Mid-Air Haptic Experiences

Ultrasound haptic feedback has been used for various experiences such as user interfaces (UI) [36, 103, 148, 163, 182, 185], virtual reality [4, 140, 188, 193], liquid interactions [10, 104], automotive [36, 68, 127, 189, 201], social touch [159, 167, 188], and more. For this PhD thesis I will focus on UI and social touch.

Ultrasound haptic feedback for UI in mid-air has been introduced to increase agency [36], create unobtrusive tactile feedback [185], increase the performance of gestures [182] and more. Researchers have especially investigated how ultrasound haptic feedback can lower the "eyes-off-the-road" time [189] by removing the visual aspect of UI in cars. Without visual interfaces, drivers have no need to look at UI widgets and can focus their attention on the road. In the automotive context, [36] explored how mid-air haptic feedback significantly increased the implicit agency using the intentional binding method compared to a visual condition. The designed feedback was created to imitate another study condition using a vibrotactile glove. Ito et al. [103] attempted to imitate how the "finger can always feel the mouse surface" when designing haptic feedback for a mid-air button. Shakeri et al. [189] used ultrasound haptic feedback for mid-air gestures designed to imitate the movements of the gestures: circle for circular motion, swiping pattern for swipe motion etc. While some UI experiences with ultrasound haptic feedback do attempt to reinvent the design, they are often based on the idea of imitating a physical interaction.

There are two types of social touch using ultrasound haptics: affective touch and interpersonal touch. Affective (or "pleasant") touch refers to an inherent feeling of social pleasantness in touch. This is signaled by C-tactile afferents that are stimulated and stroked at a velocity of 1-10 cm^{-1}. The C-tactile afferents are found only in the hairy skin on our body. Löken et al. [136] found that the C-tactile afferents "constitute a privileged peripheral pathway for pleasant tactile stimulation that is likely to signal affiliative social body contact". Affective touch has often been studied with feathers or brushes. Two projects studied whether this effect also existed when stimulated with ultrasound. While one study found the ultrasound to have a similar effect to the physical brush stroking [167], another found higher velocities were the most pleasant [216]. Both projects attempted to imitate previous studies proving affective touch using other stimuli.

Interpersonal touch refers to social touch interaction between two or more individuals. [187] explored the emotional and physiological response to being caressed while in VR. They designed their ultrasound haptic sensation to feel like stroking with velocities within the optimal range to stimulate C-tactile afferents. They compared ultrasound haptic feedback to no touch and real touch (person or feather). They found that no touch had significantly lower body ownership when compared to either touch condition.

Chapter 3

Core Paper Reinventions and Perspectives

The reinventions are realized in the five core papers. I present the abstracts for the core papers, followed by how this paper reinvents haptics for mid-air interaction and other perspectives.

3.1 Whole-Hand Haptics for Mid-Air Buttons

Mid-air buttons are currently slow and error-prone. One reason is that their haptic feedback are attempts at replicating physical button feedback instead of being designed specifically for interaction in mid air. We present an approach to haptics for mid-air buttons that extends the feedback beyond the fingertip. Our approach is inspired by recent findings that show how skin vibrations from fingertip presses extend to the whole hand. We apply the haptic feedback across the whole hand to simulate the pull-up effect that triggers users to withdraw their finger upon button activation. We conduct a user study with two tasks to evaluate the whole-hand feedback and compare it with prior work. Our results show that the whole-hand haptic feedback reduces the overall button press duration and allows for more successful button activations compared to the localized haptic feedback. We discuss the reasons behind the improved performance and further steps to improve mid-air presses. [143]

Reinvention

In this project, my co-authors and I propose a novel way of inducing haptic feedback for mid-air buttons instead of imitating physical buttons. We focus on finger-pressed buttons, where the feedback usually is induced on the fingertip [36, 150] as opposed to larger palm-pressed buttons [103, 150, 163].

Shao et al. [191] showed how cutaneous vibrations propagated down the hand: "Contact at the distal end of the digit yielded vibrations that propagated along the digit, across the dorsal surface, and to the wrist, before dissipating". Figure 3.1 shows how they captured the propagating of tapping similar to a button press. We use this information about how our body reacts to touch to inform our mid-air haptic

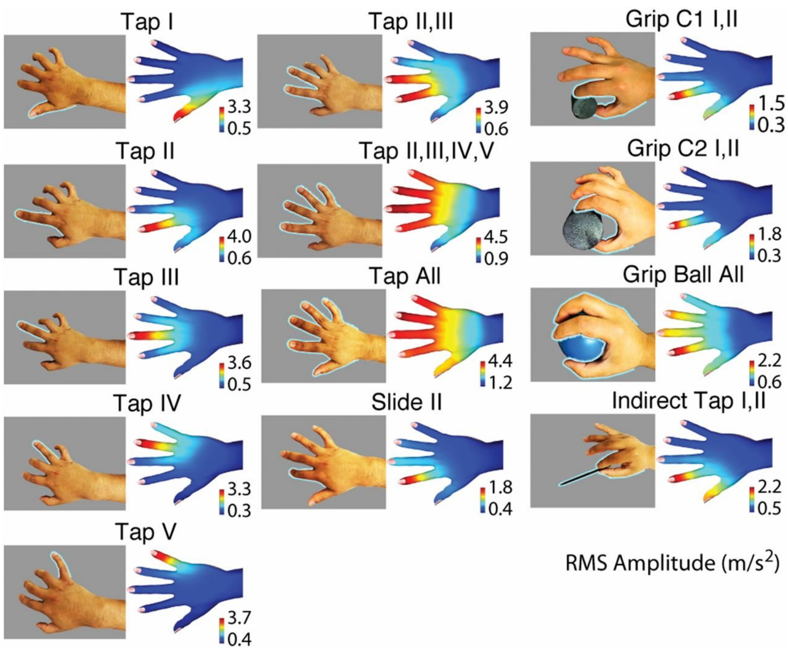

Figure 3.1: Spatial patterns of cutaneous vibrations propagating from the contact point down the hand. Reused for noncommercial use from Shao et al. [191].

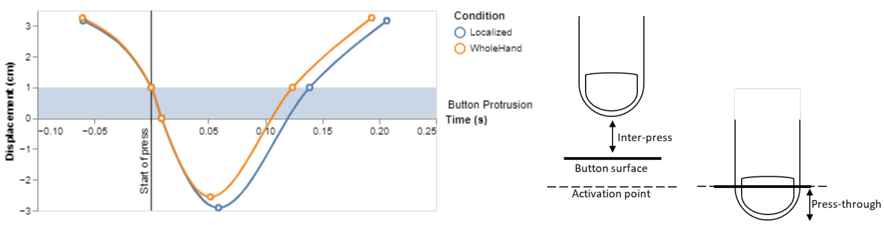

Figure 3.2: A visual representation (left) of the results from Table 4.1 in the paper. It shows how the pull-up duration of the button press interaction is shorter for whole-hand haptic feedback. The pull-up duration begins when values are beneath 0 and ends when they are above 1 again. A model of a mid-air button's stages of interaction (right).

design. Instead of imitating single-point contact of physical buttons upon activation, we design a sensation that propagates from the fingertip down the hand.

Our results indicate a significant improvement to the amount of buttons pressed in a time-frame when using whole-hand haptic feedback compared to haptic feedback imitating physical buttons. Participants were asked to press the button as many times as possible. Figure 3.2 shows the average movements of pressing a 3D button with the two conditions. It is a visualization of Table 4.1 in the paper. The figure shows the improvements to the pull-up duration and overall button press duration with whole-hand haptic feedback.

While our results indicate a significant improvement in performance, our four phases of feedback (proximity, protrusion, activation, and release) could have been improved. The propagating effect was induced during activation, where a wide line traversed to the root of the hand with a frequency of 90 Hz in 100 ms [143]. We designed two different sensations for the proximity (simulating near-contact) and protrusion (simulating pressing). It is unclear from the study design whether these two sensations increased the performance or if activation alone increased the performance. A follow-up study could be conducted to verify that whole-hand haptic feedback was the driver of the increase in performance and evaluate whether the other phases are needed.

3.2 Mediated Social Touching: Haptic Feedback Affects Social Experience of Touch Initiators

Mediated social touch enables us to share hugs, handshakes, and caresses at a distance. Past work has focused on the experience of *being* touched by a remote person, but the touch *initiator*'s experience is underexplored. We ask whether a variation in haptic feedback can influence the touch initiator's social experience of the interaction. In a user study participants stroked a remote person's hand in virtual reality while feeling no haptic feedback, ultrasonic stimulation, or passive feedback from a silicone hand. In each condition, they rated the pleasantness of the interaction, the friendliness of the remote person, and their sense of co-presence. We also captured the velocity of their stroking and asked for reflections on the interaction and mediated social touch as a whole. The results show significant effects of haptic feedback on co-presence, pleasantness, and stroking velocity. The qualitative responses suggest that these results are due to the familiarity of the solid silicone hand, and the participants' assumption that when they felt feedback, the remote person felt similar feedback. [144]

Reinvention

Our initial discussions on mediated social touch began with the question: "Can a touchless touch be social?" To answer this question, we have to look at the definitions of social touch. Huisman [98] proposed a simple definition based on other definitions [64, 81, 210]:

> Touch occurring between two or more individuals in co-located space is often referred to as interpersonal, or social touch [...]

This definition does not consider any psychological effects of a touch for it to be social. Hertenstein [91] proposed a definition that took this into account:

> [...] tactile communication occurs whenever there are systematic changes in another's perceptions, thoughts, feelings, and/or behavior as a function of another's touch in relation to the context in which it occurs. This definition, which derives from a functionalist conception of communication, encompasses both emotional and non-emotional communication [...]

We must look at these systematic changes in the actors to reinvent the haptics lost in distanced communication.

Table 3.1: Additional characteristics to the 2017 review of social touch technology prototypes Huisman [99]

Prototype	Measured*	Directionality	Reciprocity	Synchronicity	Morphology
Vibrobod [47]		Bi	No	Synchronous	Indirect
The Bed [48]		Bi	No	Synchronous	Indirect
The Hug [46]		Uni	No	**Asynchronous**	Indirect
Hug over a distance [151]		Uni	No	Synchronous	Indirect
Huggy pajama [208]	Receiver	Uni	No	Synchronous	Indirect
HaptiHug [214]		Uni	No	Synchronous	Indirect
Thermal hug [74]	Both	Uni	No	Synchronous	Indirect
Squeeze device [227]	Receiver	Uni	No	Synchronous	Indirect
Stroking device [52]		Bi	No	Synchronous	Indirect
Kissenger [183]		Bi	No	Synchronous	**Direct**
Affective tele-touch [20]	Receiver	Uni	No	Synchronous	Indirect
Tele-handshake system [88]		Bi	No	Synchronous	Indirect
Tele-handshake [5]		Bi	**Yes**	Synchronous	Indirect
Remote Handshake [153]	Both	Uni	No	Synchronous	Indirect
YourGloves [75]	Both	Bi	No	Synchronous	Indirect
HotHands, HotMits [75]	Both	Bi	No	Synchronous	Indirect
Shaker [203]		Uni	No	Synchronous	Indirect
inTouch [18]		Bi	Yes	Synchronous	Indirect
HandJive [57]		Uni	No	Synchronous	Indirect
Tug of War [14]	Both	Bi	**Yes**	Synchronous	Indirect
KUSUGURI [62]		Bi	No	Synchronous	**Direct**
The Tickler [120]		Uni	No	N/A	Indirect
HaptiTickler [215]		Uni	No	Synchronous	Indirect
Telephonic arm wrestling [65]		Bi	**Yes**	Synchronous	Indirect
ComTouch [29]		Bi	No	Synchronous	Indirect
CheekTouch [164]		Bi	No	Synchronous	**Direct**
ForcePhone [93]		Bi	No	Synchronous	Indirect
POKE [165]	Both	Bi	No	Synchronous	**Direct**
RingU [170]		Bi	No	Synchronous	Indirect
Gestural haptic interface [175]		Bi	No	Synchronous	Indirect
TaSST [100]		Bi	No	**Asynchronous**	**Direct**

*Social experience measured for initiator and/or receiver.

I conducted a supplementary review (see Table 3.1, where I added additional analysis to the 2017 review of MST prototypes by Huisman [98]. I examined communication design choices and whether the social experience (i.e., systematic changes) was measured. If the social experience was evaluated, I examined which actor was the target of this evaluation (*Measured*). Mediated social touches can be both unidirectional, with only one actor sending touches, or bidirectional, with both actors able to send touches. The review showed that most interactions are unidirectional (*Directionality*). Touches can only be reciprocal (*Reciprocity*) if they are also bidirectional. In my definition of reciprocity in MST, movements of one actor must affect how the other actor can touch them. The *Synchronicity* refers to whether touches are transmitted in real time or saved to be played back later. Finally, *Morphology* refers to whether a touch is body-congruent ("Direct") like finger touching a palm or in-congruent, like touching a button to send touches to a body part ("Indirect").

Most of the focus in HCI literature has been on the receiver of touches. But as social touch is an interpersonal interaction, we wanted to look at what aspects affect the touch initiator (i.e., "sender"). Without knowing how the person who initiates touches is affected by the interpersonal touch experience, we can not make design decisions that make creating mediated social touch feel *social*. Our paper reinvents haptics for mid-air social touch by adapting an ultrasound rendering algorithm by Barreiro et al. [10] for social hand touches. We explore the social experience by inquiring about the pleasantness and co-presence, adapted from HCI theory.

3.3 Mediated Social Self-Touch: The Null Effect of Duplicating Haptic Communication to One's Own Body

We can touch each other at a distance by mediating touch through haptic technology. However, the ability to refine our touches based on the reciprocated touch we feel when touching another is often lost in the mediation. We propose to use the ability to feel one's own touch before sending it to another person. The "self-touch" enables touch initiators to refine their touches based on what they feel the receiver will feel. We introduce a mediated social touch system using mid-air haptics, where users can communicate digital touches in real-time and save them as digital touch recordings. The digital touches are body-congruent hand interactions, where users' touch locations are mapped to the same location on a receiving hand. We evaluate the self-touch through a pattern discrimination task and system usability (n=20). While all recall rates were above the level of randomness, our results do not support that adding self-touch to mediated social touch interactions increases the recall of individual patterns nor the overall accuracy of pattern discrimination. There was no significant difference between the usability with self-touch and without self-touch. Our results indicate that other approaches to solving the issue of reciprocity in mediated social touch are necessary.

Reinvention

This project builds directly on what we learned from the previous project. Five avenues were discussed for further exploration while reviewing the results of the study. The first was how thermal feedback would affect the pleasantness of digital social touches. In the previous study we found participants focused on thermal feedback when discussing their experience. We used an unheated silicone hand in the study, which led to connotations of "death" and "sewer". Mid-air haptic feedback has been shown to be able to carry thermal properties [114], which could have been utilized in a MST study. Another approach could have been to use more haptic devices. Our study focused on no haptics, mid-air haptics, and passive haptics with the silicone hand. This could have been extended with haptic gloves, hands of other materials, and real hands [188]. Our interaction was limited to a stroking gesture. Additional gestures could be explored, or users could have decided which gestures they themselves would use, creating a more natural interaction. We also believe that the lack of feedback from the person they were touching greatly affected the measurement of "friendliness". By adding visual feedback or reciprocating touches, the friendliness could have increased. Finally, many participants wondered what the other person would feel, as they did not know how their touches were mapped to the receiver.

We propose self-touch as a feature in the reinvention of mediated social touch. Self-touch has been studied in neuroscience, showing that our mind attenuates certain touch signals. This explains why it is hard to hurt or tickle ourselves. Figure 3.3 shows a mediated self-touch setup by Cataldo et al. [22] to explore spatial self-perception. They found that spatial perception in self-touch "may be less subject to attenuation

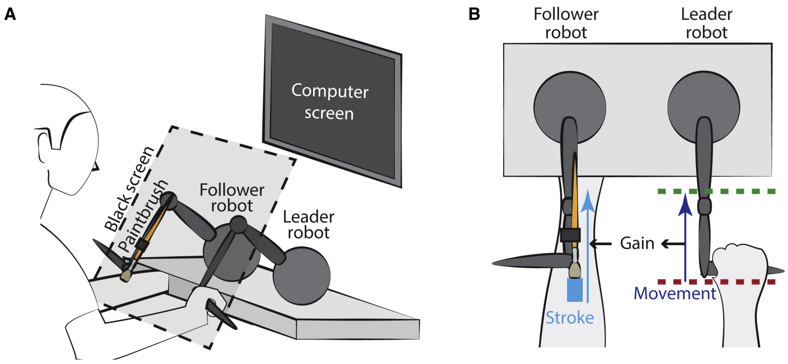

Figure 3.3: Self-Touch using a leader robot with the right hand and a follower robot with the left hand. Reprinted from The Lancet, Vol. 32, Antonio Cataldo, Lucile Dupin, Harriet Dempsey-Jones, Hiroaki Gomi, Patrick Haggard, Interplay of tactile and motor information in constructing spatial self-perception, Pages 1301-1309, Copyright 2022, with permission from Elsevier [22].

than intensity information". To our knowledge, no mediated social touch interaction evaluates the ability to feel what the receiver of touches will feel. The MST system "ComTouch" by Chang et al. [29] included local feedback, and the MST system "Tactile Emoticon" by Price et al. [171] included the ability to feel touches on the initiator's own hand. However, what effect this has is unclear. This led us to create of a mediated social touch system using ultrasound haptic feedback that includes both the ability to send touch in real time (synchronous) and save them as recordings to be played back later (asynchronous). We use a shape discrimination method commonly used for ultrasound rendering [82, 152] to evaluate the effects of self-touch.

3.4 MAMMOTH: Mid-Air Mesh-based Modulation Optimization Toolkit for Haptics

Mid-air ultrasound can recreate the missing touch from contactless interactions, such as bare hand gestures in extended reality. But designing ultrasound haptics either relies on inadequate static sensations or experts who can create dynamic sensations. We introduce MAMMOTH, an open source toolkit for Unity that automatically generates dynamic ultrasound sensations for interactions with 3D objects. The haptic feedback is achieved by extending and generalizing a path-routing algorithm for intersections between meshes. We first describe how the toolkit works and then demonstrate how it builds on previous techniques. Finally, we present how to use the toolkit to implement three distinct use cases. [142]

Reinvention

The Touchless Hackathon of 2022 was about creating experiences using ultrasound haptic devices. As a co-organizer on this project, I was in charge of creating technical guidelines and helping participants with programming examples and the technical

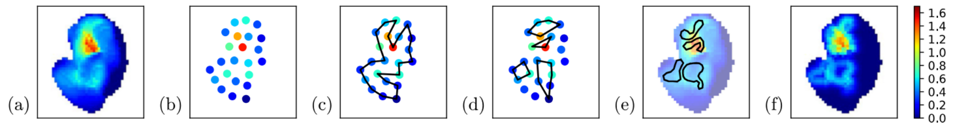

Fig. 2. Steps of our PRO-STM algorithm: (a) input target pressure field, (b) clustering, (c) initial path, (d) split into multiple paths to satisfy length constraints, (e) refinement of the paths to maximize pressure intensity, (f) resulting reconstructed pressure field.

Figure 3.4: The PRO-STM rendering algorithm. Reused by permission: Barreiro et al. [10], © 2020 IEEE.

setup. I co-authored the paper by Dalsgaard et al. [41] about the the knowledge gained from the hackathon. The participants created four prototypes: a social touch interaction ("Diddle Engine"), two prototypes for people with visual impairments ("Hapticolor" and "Mutics"), and a musical instrument ("String"). While the hackathon lasted 3 days, the prototypes were rushed, mainly due to the time it takes to program for mid-air haptics. The tools available to create mid-air haptic feedback made it difficult for participants to create custom sensations in a short time span.

Mid-air haptic sensations can be static or dynamic. Static sensations are often pre-made and time-bound. They can quickly be integrated but not customized to specific needs. Dynamic sensations are often programmed for specific interactions. One of the dynamic sensations made by Barreiro et al. [10] (PRO-STM) generated the sensation based on interactions between a tracked hand and a gaseous fluid media.

Figure 3.4 shows the steps of the PRO-STM algorithm [10]. The algorithm takes a big step in the reinvention of haptics for mid-air interactions, as it is made possible by the mechanoreceptors' response to ultrasound haptic feedback. The algorithm traverses a set of points making up a 140 mm long path at 7 m/s. This results in a rendering frequency of 50 Hz, within the range perceivable by our skin. An interpolation between points made the distance between each point 0.175 mm. In MAMMOTH, we build upon this reinvention using a wider range of frequencies and dynamically changing the interpolation. We dynamically alter the frequency based on the overall length of the path instead of sections of 140 mm. This allows us to render coherent long paths ($> 2m$). The interpolation is a function of the frequency while staying below the two-point discrimination threshold (8.6 [60]) for most hand interactions.

The technique introduced in the paper is released as an open-source toolkit. We hope this allows people like the hackathon participants to quickly and effortlessly create and reinvent mid-air haptic experiences, where the haptic feedback is generated specifically for their interaction.

3.5 The Black Box of Digital Touch: Possible Consequences and Dilemmas in Designing Haptic Communication

Digital touch communication is emerging as a counterpart to audio and video communication. But compared to physical touches, digital touches are easily manipulated, re-mediated or misinformed about due to technology acting as a mediator between senders and receivers. For future users of digital touch communication, the mediator can become a black box full of consequences they will not be aware of. Consequences we have seen examples of Deepfakes in video communication, private picture leaks in photo communication, wire-tapping in audio communication, and catfishing in text communication. To conduct responsible research and innovation with digital touch communication, we need to uncover the potential consequences for users. Consequences include being touched by a stranger while believing it is a friend, harming another while believing you are caressing them or having your touch data used for AI while believing it was a private, intimate touch message. We used scenario building to construct three future digital touch communication scenarios through an iterative process. The scenarios were presented in a series of workshops where participants were asked to describe the possible foreseen and unforeseen consequences. We analyzed the consequences and extracted dilemmas from them. The dilemmas were evaluated through a user survey. We hope digital touch communication creators will use the uncovered consequences and dilemmas to conduct responsible research and innovation when working with a sense as intimate as touch.

Reinvention

Through the Touchless EU project, I co-authored a paper on "Responsible Innovation in Touchless Haptics" with Cornelio et al. [35]. The paper was based on 48 touchless haptic ideas "dreamed" up by experts on haptic technology. We critically analyzed the ideas and presented recommendations for using touchless haptic feedback. This project inspired exploring the responsible research and innovation concerns involving mediated social touch. The Black Box project was conceived to think critically about my own reinvention of mediated social touch in the previous papers.

My co-authors and I used pragmatic thematic analysis [6] to look at mediated social touch as a communication form – digital touch communication – and found three themes to cluster the communication into. We used a scenario construction method to explore the three themes and the consequences that can arise from them. The scenarios were deconstructed in workshops where participants formulated the consequences. We constructed an affinity diagram based on the consequences and discussed its themes. Finally, we surveyed 100 people about novel dilemmas found in digital touch communication by looking at methods found in philosophy.

The Black Box project does not suffice to make digital touch communication safe, ethical, and private. It highlights many consequences, but further interdisciplinary research is needed to create recommendations and inform lawmakers on how to handle digital touch as a communication form.

Prelude: Design implications of Digital Touch

A year before starting the "Black Box" project at University College London, I planned to use another method to study this perspective. I planned on applying Baumer and Silberman's three questions on the implications of design [12] to digital touch communication. The following represents a short paper where eleven participants (University of Copenhagen colleagues) tackled the questions in a one-hour session.

With the digital transformation and the evolution of the metaverse, digital touch communication has become an emergent social imaginary [106]. Many prototypes are developed [98], yet little is known about the prospective implications and appropriateness of this technology. Baumer and Silberman formulated three questions for the appropriateness when designing new technology [12]. The following sections highlight responses to these three questions when put in the context of MST. Eleven (*1-11*) participants wrote down responses to each question before discussing them aloud (A) with the rest of the participants.

Is there an equally viable low-tech or no-tech approach to the situation?
As MST is a mediated high-tech alternate to no-tech physical touches (PT), participants gave examples of scenarios where PT was not viable, but MST could be. One example was people in isolation, such as during the Covid pandemic (1,2,5). MST could allow family, friends, and strangers alike to recover the touch lost during isolation. Other examples include touching people who are no longer alive (1,A), sharing touch memories (1), mimicking the real world (3,5), and forms of long-distance touch (e.g., with distanced partners) (1,3,5,6,7,10,A). But even then, MST will have a hard time being equally viable in quality as physical touch - touch is only 1 modality of communication (6,10,A), and mimicking the real world can be very difficult (4,5,6,A). Sometimes mimicking real touch may even be undesirable (5,A).

Does a technological intervention result in more trouble or harm than the situation it's meant to address?
A concern for participants was *privacy* (1,2,3,10). How do we ensure touch only happens on consent? And can this consent be digitally overridden? A lot of novel technology comes with privacy concerns, but MST has the unfortunate property of being physically intrusive. For school kids, where digital harassment is a recurring problem, the ability to touch could add a whole new dimension to online harm. Control over what we transmit and receive, such as customization settings, being able to block or "mute" people, and kill switches, can, to some degree, limit unwanted connections. But what if these *personalizations* fail and we are caught in an unwanted touch we are unable to get out of? Haptic suits such as the Tesla suit can encapsulate almost the whole body. When the sensation is at its strongest, it can be hard to get out of the suit or even move the body at all (A). What if we could open up a new field of biometric data (3) and biomechanical data? This can lead to computer-generated touches based on real touches (1,7,9), *AI touch* masquerading as human, and even substitute human connection (5,10,11).

Does technology solve a computationally tractable transformation of a problem rather than the problem itself?
Following the previous two questions, some participants noted that MST seems to create more problems than it solves (1,4,9). This is clear with all the unknowns in *privacy* concerns, how to mimic real touches, and how to personalize the touch experience. So when does MST solve actual problems? One participant noted that MST is a useful tool only when the absence of physical touch is a problem (5). This could be related to isolation or medical issues. There was also the fear that MST could be used to police user actions (7). This could be subconsciously, like how advertisements affect buying habits or physical commanding.

Some unmentioned responses include topics like cultural boundaries, video call greetings, touch resolution, and Photoshop for touch. The responses to the three questions shows only a snippet of the implications of MST. However, a pattern of serious consequences is already forming that requires further exploration.

Chapter 4

Whole-Hand Haptics for Mid-Air Buttons

Martin Maunsbach, Kasper Hornbæk, and Hasti Seifi

Martin Maunsbach, Kasper Hornbæk, Hasti Seifi. (2022). Whole-Hand Haptics for Mid-air Buttons. In: Seifi, H., et al. Haptics: Science, Technology, Applications. EuroHaptics 2022. Lecture Notes in Computer Science, vol 13235. Springer, Cham. https://doi.org/10.1007/978-3-031-06249-0_33

Mid-air buttons are currently slow and error-prone. One reason is that their haptic feedback are attempts at replicating physical button feedback instead of being designed specifically for interaction in mid air. We present an approach to haptics for mid-air buttons that extends the feedback beyond the fingertip. Our approach is inspired by recent findings that show how skin vibrations from fingertip presses extend to the whole hand. We apply the haptic feedback across the whole hand to simulate the pull-up effect that triggers users to withdraw their finger upon button activation. We conduct a user study with two tasks to evaluate the whole-hand feedback and compare it with prior work. Our results show that the whole-hand haptic feedback reduces the overall button press duration and allows for more successful button activations compared to the localized haptic feedback. We discuss the reasons behind the improved performance and further steps to improve mid-air presses.

4.1 Introduction

Mid-air buttons are commonly used in extended reality or holographic interactions. In a pandemic-touched and increasingly germophobic world, contactless interactions cause less hygiene concerns for multi-user buttons. While current technology allow their visual and audio feedback to resemble physical buttons, mid-air buttons have poor performance due to their lack of physicality [15, 161, 163]. The fingertip can rest on the surface of physical buttons, but mid-air buttons have no surface to rest on. Where physical buttons reach a hard barrier upon being fully pressed, mid-air

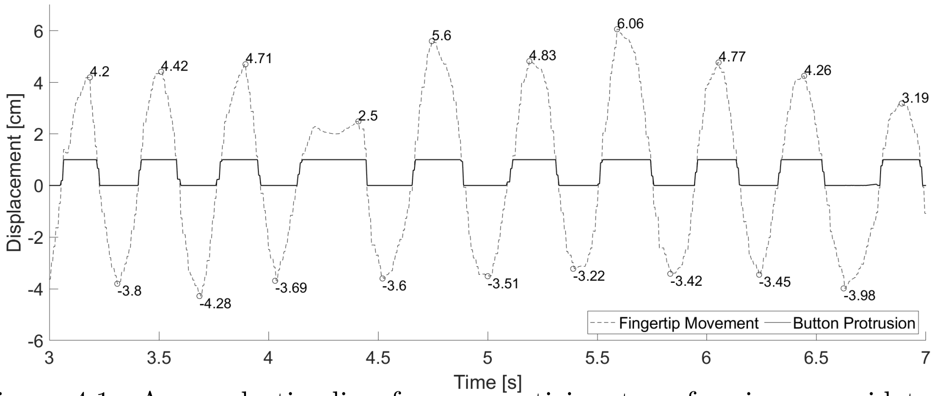

Figure 4.1: A sample timeline from a participant performing a rapid tapping task with a 3D mid-air button. The timeline shows the finger and button movements. The local maximums show the fingertip displacements between button presses (inter-press displacement) while the local minimums show the displacement beyond the button activation point (press-through displacement). All measurements were captured using the Oculus Quest 2 hand tracking.

buttons can be pressed far beyond their activation point as seen in Fig. 4.1. The physical barrier creates a natural pull-up sensation with physical buttons that is not present in mid-air buttons, leading to an increase in the press duration or failed button activations.

Researchers have proposed various solutions to add haptic feedback in mid-air [95] including wearable devices like haptic gloves, encounter-type devices that can move to make contact with users, or airborne feedback. The latter approach is power efficient and does not require users to wear a device. Ultrasound feedback has been shown to improve user interactions with mid-air widgets. Adding ultrasound haptics to the gestural control of an automotive dashboard reduced the eyes-off-the-road time and the driver's mental workload [189]. Martinez et al. showed that ultrasound haptics can increase users' sense of agency over mid-air buttons [36]. Sand et al. studied text entry in virtual reality (VR) by adding an array of ultrasound transducers to a VR headset. They found that ultrasound feedback significantly reduced user report of temporal demand compared to no haptic feedback, but there was no significant difference in user performance [185]. Ito et al. presented a dual-layer button with varied ultrasound intensities and quality for the button press and activation phases, but they only showed that people could locate the two haptic layers [103]. The current solutions only apply ultrasound feedback to the surface of the hand that is in contact with the button. They report little performance improvements, possibly due to the limited intensity of ultrasound haptics.

We propose whole-hand haptic feedback for mid-air button presses and report user performance with it. When tapping a physical surface with the fingertip, the skin vibrations propagate down the hand [191]. As the intensity of ultrasound haptics is low, we induce the vibrations to the whole hand by moving the ultrasound's focal point over the hand instead of relying on the strength of the fingertip feedback to propagate down the hand. The objective of the whole-hand haptics is to mitigate the lack of pull-up effect in mid-air. To achieve this, we consider the three following measurements as the main indicators of an improved pull-up effect: a decrease in the pull-up time after an activation, a decrease in the finger displacement beyond the activation point, and an increase in the amount of presses in a time frame. We ran a user study to evaluate user performance with mid-air buttons using our whole-hand haptic feedback approach. Participants interacted with 2D and 3D mid-air buttons in a VR environment while they received either localized haptic feedback at their fingertip or whole-hand feedback over their dominant hand. Our results show that whole-hand haptics affect the button press duration and increase the number of button activations in a time frame compared to the localized haptics. We discuss possible reasons for these improved results.

4.2 Mid-Air Button Design

We divide the user interaction with buttons into four phases where the finger movement and haptic feedback from physical buttons are distinct [119]. 3D buttons include all four phases, while 2D buttons have no protrusion. The draw frequency, which is the number of times the pattern is drawn in a second, is indicated with Hz. The sensations are rendered using Spatiotemporal Modulation [60]. Fig. 4.2 shows how the haptics are spread across the palmar side of the hand. We design whole-hand haptics for user interaction in these phases based on a pilot study:

1. Proximity: When the user's finger is near the button without touching it. We set this value to 10 mm above the button and present a haptic sensation over the whole finger by moving the focal point between the distal, middle and proximal phalanx (70 Hz).
2. Protrusion: When the fingertip is pressing the button. We set the button depth to 10 mm and present a haptic effect that is a 10 mm in radius circle (Hz = 70). The sensation is focused on the fingertip to match the visual contact area of the button.
3. Activation: A transient phase starting from when the button is successfully pressed. The sensation is a 80 mm wide line that traverses from the fingertip to the root of the hand (90 Hz) in 100 ms.
4. Release: From the end of the activation phase until the button is unpressed. We provide no sensation in this phase.

We kept the visual feedback minimal to avoid interference with the haptic effect. Based on a pilot study, we opted for 10 mm press distance and used a 40 by 40 mm button to ensure participants could accurately hit it. The 2D button had no visual feedback for any phases. The 3D button's visual protrusion followed the fingertip, indicating to users that it was activated or released when it no longer followed the fingertip.

4.3 User Study

To evaluate the impact of whole-hand haptic feedback on user performance with 2D and 3D buttons, we conducted a user study with two user tasks.

Participants

We recruited 20 participants (4F/16M) 23-57 years old (M = 31, SD = 9.93). No one reported any sensory impairment in their dominant hand. Seven users had prior experience with mid-air haptics[1]. The experiment took around 30 minutes and participants received a gift worth around 100 DKK.

Tasks

The first task was a rapid tapping task, where participants pressed the button as quickly as possible. This task was chosen to capture whether more presses are possible with whole-hand feedback and the effect it has on the press duration and finger movement. Each trial of the task lasted 20 seconds. The second task was to double-click the mid-air button as quickly as possible after hearing a randomly timed sound cue. This reaction task is a modified version of the moving target selection task [130] without the visual element. We require two presses (i.e., a double click) to capture measures on the inter-press duration.

Study Design

The experiment used a within-subjects design with the three independent variables *dimension* and *haptic* and *trial*. The button dimension was either 2D or 3D to study the effect of the protrusion phase on user performance. The haptic sensation was either the whole-hand haptics or a localized sensation used as a baseline. The localized haptics was based on the activation sensation by Martinez *et al.*, that showed improvement to the sense of agency for mid-air buttons [36]. Instead of the five focal points they used to cover 1 cm^2, we used a 200 ms transient version similar to the protrusion sensation in Fig. 4.2. The combination of button dimension and haptics yielded four conditions. Each condition was repeated three times for a total of 12 trials in each task.

[1]Recruitment used the same mailing list as a previous study involving mid-air haptics.

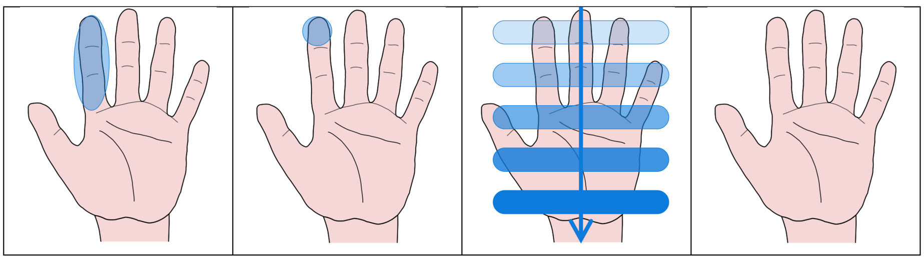

Figure 4.2: The whole-hand sensation set showing the spread of the haptic sensation in each of the phases. Picture of the palm is adapted for non-commercial use [168].

Apparatus

We used the ultrasound device STRATOS Explore to induce haptic feedback on the palmar side of the hand. The participants wore an Oculus Quest 2 VR head-mounted display with a refresh rate of 90 Hz to interact with the mid-air button. The button was calibrated to be approximately 20 cm above the ultrasound device's surface, where the ultrasound focal point is the strongest. We used Oculus Quest 2's hand tracking (60 Hz refresh rate) to measure the movements of all limbs in the hand as well as the visual representation of the hand. The displacement of the button followed the fingertip while being constrained to one dimension with an upper and lower limit. The Leap Motion's hand tracking (120 Hz refresh rate) was used to position the haptic feedback only. Measurements were recorded at 200 Hz.

Procedure

After signing a consent form, the participants were introduced to the mid-air technology by feeling common 2D shapes like circles and lines. They were informed of the two tasks and that they needed to press a variation of 2D or 3D virtual buttons with haptic sensations. They were not told how the sensations would differ. The participants were instructed to complete the press interaction as quickly as possible. They were told that the goal of the rapid tapping was to press as many times as possible and that the time from the sound cue to the release of the second click was important for the reaction task. Before the first trial of each condition, the participants could practice the button press for up to a minute to get conditioned to the button dimension and haptic feedback. During this training, the participants were given visual feedback after each interaction on their performance. After the training, each trial was started. There was a five to ten second break between each trial of the same condition and a two minute break between the two tasks. The condition order was counterbalanced. Pink noise was played to mask the sound of the device.

4.4 Results

We recorded the movements of the button and the index finger for both tasks. With the button movements we captured the number of times the button was successfully activated (i.e., the *press count*). We obtained the *press duration* as a sum of the *down-press duration* (from button contact until the button is activated) and the *pull-up duration* (from activation until the button is released). The *press-through displacement* quantifies how far the finger moves beyond the button activation point. The *inter-press displacement* is how far the finger moves away from its released state between each press. Additionally, the reaction task included the *reaction time* from the sound cue until contact with the button, the duration between the two presses (*inter-press duration*), and the *success rate*.

Rapid Tapping Task

A total of 16,609 successful presses were recorded. Outliers in each participant's trials were removed using the IQR method, where outliers are values more than 1.5 times above or below the trial's inter-quartile range.

Table 4.1: The differences in press count, durations and displacements (Disp.) between the localized and whole-hand haptics (top) and 2D and 3D buttons (bottom) in the rapid tapping task.

Measurement	Localized	Whole-hand	p-value	η_p^2
Press Count [per 20s]	67.517 ± 2.690	70.892 ± 2.678	**0.010**	0.298
Press Duration [s]	0.147 ± 0.008	0.133 ± 0.006	**0.023**	0.243
Pull-Up Duration [s]	0.139 ± 0.008	0.124 ± 0.006	**0.016**	0.268
Down-Press Duration [s]	0.009 ± 0.001	0.009 ± 0.001	0.370	0.042
Press-Through Disp. [cm]	2.912 ± 0.289	2.557 ± 0.219	0.141	0.111
Inter-Press Disp. [cm]	3.169 ± 0.235	3.261 ± 0.233	0.451	0.030
Measurement	3D	2D	p-value	η_p^2
Press Count [per 20s]	66.783 ± 3.203	71.265 ± 2.205	**0.010**	0.303
Press Duration [s]	0.155 ± 0.008	0.126 ± 0.007	**<0.001**	0.538
Pull-Up Duration [s]	0.137 ± 0.008	0.126 ± 0.007	0.094	0.141
Down-Press Duration [s]	0.018 ± 0.001	N/A	N/A	N/A
Press-Through Disp. [cm]	2.635 ± 0.267	2.834 ± 0.265	0.470	0.028
Inter-Press Disp. [cm]	3.746 ± 0.254	2.685 ± 0.230	**<0.001**	0.603

We ran three-way repeated measures ANOVAs with the six measurements as the dependent variables and dimension, haptics, and trial as the within-subjects factors (Table 4.1). The results showed main effects of haptics for *press count*, *press duration*, and *pull-up duration* without any significant interaction effects with dimension nor trial. The participants pressed significantly quicker (9.52%) and had more successful button presses (4.76%) with whole-hand haptics. The *pull-up duration* was significantly decreased (10.87%). The *press-through displacement* showed an improvement of 12.19%, but this difference was not significant due to the high standard errors. The *inter-press displacement* was lower with localized haptics but not significantly.

The repeated measures ANOVA also showed a main effect of dimension for the *press count*, *press duration* and the *inter-press displacement* (Table 4.1). These values are significantly different for 2D buttons due to no down-press time in the dimension. Importantly, we found no interaction among dimension and haptics for these dependent variables ($p > 0.713$). Fig. 4.3 shows the results for the six measurements under the four conditions.

Reaction Task

We ran three-way repeated measures ANOVAs with the nine measurements as the dependent variables and dimension, haptics, and trial as the within-subjects factors. There were no significant effects of the haptic conditions on any of the dependent variables ($p \geq 0.064$ for all the measures). The 2D condition showed a significant improvement in *press-through displacement* ($p = 0.024$) and *inter-press displacement* ($p < 0.001$).

4.5 Discussion and Conclusion

This paper set out to improve haptics for mid-air buttons, exploring the idea that whole–hand haptics could improve the interaction due to an enhanced pull-up effect. To support this idea we examined the pull-up duration, press depth, and press count as main indicators. The results suggest that it is possible to design haptic feedback that improves the performance for rapid presses. In the rapid tapping task, whole-hand haptics significantly improves the pull-up duration. Since the pull-up duration accounts for 94% of the overall press duration according to our measurements, it is a major factor in the improved performance. We believe the decrease in the press duration is the main factor behind the increase in the press count. Improving the press count shows that whole-hand haptics is an improvement to the overall press interaction, not just the release phase. While the reduction in press-through displacement was not significant, it did trend towards improvement. The standard error of the whole-hand condition (0.219 cm) is lower than the localized (0.289 cm), suggesting it is easier to control the finger movement with the whole-hand haptics.

There are multiple reasons for improved performance with the whole-hand haptics. One is the overall intensity felt on the hand. Some participants mentioned they perceived the whole-hand haptics as stronger compared to the localized, even though their focal point intensity is equal. The design of the haptic feedback upon activation can also be a reason. The sweep-back sensation from the fingertip to the root of the hand can signal users to follow that direction. An instant whole-hand sensation, like a clap, may not have the same effect on user performance.

The lack of significant improvements in the reaction task can be due to the high frequency of repetitions in the rapid tapping task compared to the controlled double clicks. As participants continuously press in the rapid tapping task, their motor system likely takes over. With each press, it tunes the motor command to infer the moment of activation [161]. The intensity of the rapid tapping task forces participants to rely more on the haptic feedback, whereas the reaction task allows them to rely on the visual feedback in the short period between each double click. The proximity sensation also did not seem to improve user performance in the reaction task. Our recordings show that the participants moved their fingers beyond the 2-cm mark where the proximity effect stops (Fig. 4.1). We hypothesize that removing the proximity sensation may improve user performance.

As touchless interactions are becoming more valued, it is important that perfor-

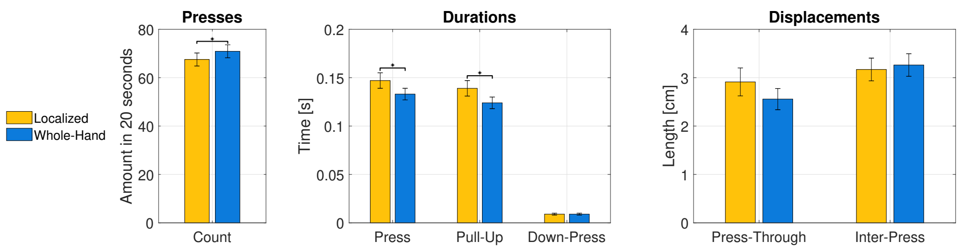

Figure 4.3: The mean and standard error of the localized and whole-hand conditions in the rapid tapping task. The number of presses in 20 seconds increased significantly with the whole-hand haptics. A significant decrease is evident in the press and pull-up duration, while the differences for the displacements were not significant.

mance is not lost. In this paper, we show how whole-hand haptics can significantly improve the performance of button pressing.

Acknowledgements

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Chapter 5

Mediated Social Touching: Haptic Feedback Affects Social Experience of Touch Initiators

Martin Maunsbach, Kasper Hornbæk, and Hasti Seifi

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Abstract

Mediated social touch enables us to share hugs, handshakes, and caresses at a distance. Past work has focused on the experience of *being* touched by a remote person, but the touch *initiator*'s experience is underexplored. We ask whether a variation in haptic feedback can influence the touch initiator's social experience of the interaction. In a user study participants stroked a remote person's hand in virtual reality while feeling no haptic feedback, ultrasonic stimulation, or passive feedback from a silicone hand. In each condition, they rated the pleasantness of the interaction, the friendliness of the remote person, and their sense of co-presence. We also captured the velocity of their stroking and asked for reflections on the interaction and mediated social touch as a whole. The results show significant effects of haptic feedback on co-presence, pleasantness, and stroking velocity. The qualitative responses suggest that these results are due to the familiarity of the solid silicone hand, and the participants' assumption that when they felt feedback, the remote person felt similar feedback.

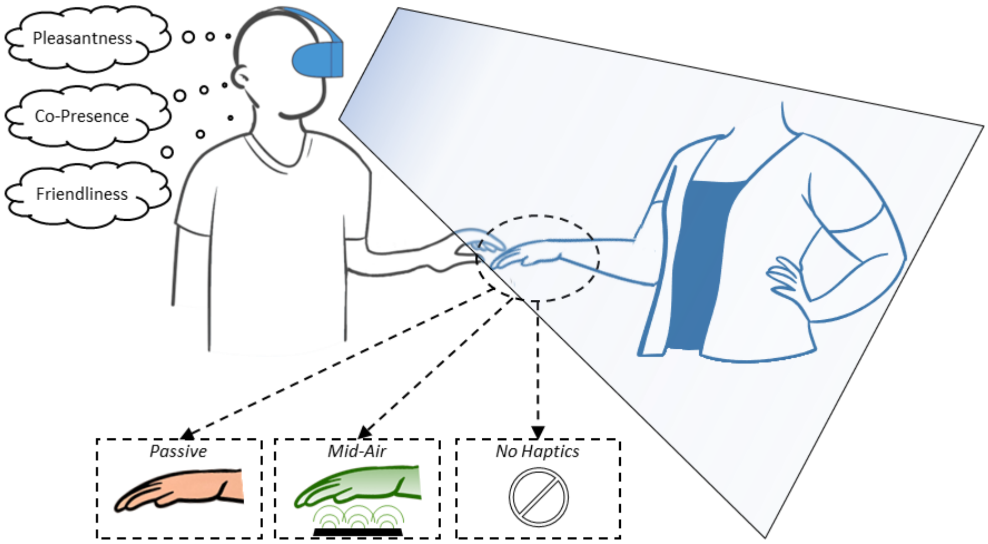


Figure 5.1: A touch initiator (left) stroking the virtual hand of a remote avatar (right). The touch is mediated to a body-congruent point on the remote person's hand. The touch initiator can feel the virtual hand with one of three types of haptic feedback.

5.1 Introduction

Physical social touch is essential to human life. Social touch interactions can increase people's well-being and attachment, change their behavior, and communicate affect [98]. Touch can also positively impact people's feelings towards partners [221] and increase their pro-social actions [40]. But our remote communication lacks social touch.

Mediated social touch (MST) has explored means of touching others at any distance. A vast amount of prototypes have been developed where touch is transmitted through sleeves [100], scarfs [17], hands [153], gloves [171], phones [31, 62, 164], and in Virtual Reality (VR) [94, 188, 206].

While a lot is known about how *being touched* affects us, little work has examined how haptic feedback affects the social experience of the *touch initiator* [173]. Most of the literature focuses on either evaluating the user experience (UX) of an MST prototype, or the social experience of the person *being touched*. For example, these studies have shown that touch can increase well-being and bonding [17, 33, 146, 223]. However, the social experience of the *touch initiator* is also affected when touching others, as seen in research with co-located physical touching [112, 160, 213, 225]. The observations about physical touches raise questions about how the touch initiator is affected when sending virtual touches with MST. For instance, we do not know what touching a remote person should feel like, and how the haptic sensation of touching affects one's perception of the remote person and the social interaction. When physically touching someone, the sensation on our skin impacts our experience of the interaction. This paper focuses on the impact of this sensation on the social experience including friendliness between actors and the feeling of co-presence. How does haptic feedback alone affect the social experience of the touch initiator?

To address this question, we conducted a study in a VR environment with three types of haptic feedback. Eighteen participants acted as touch initiators and stroked a remote person's avatar hand. We provided limited information about the remote person to the participants. We conceived the haptic feedback conditions to roughly vary along a continuum from nothing to life-like: no haptic feedback, ultrasonic mid-air feedback, and passive feedback from a silicone hand. The participants rated the pleasantness of stroking, the friendliness of the remote person, and their co-presence. We also asked what they thought the remote person was experiencing and asked for their reflections on the interaction.

5.2 Related Work

We review the literature on social touch and MST.

5.2.1 Social Touch

What makes a touch social? The answers range from skin-to-skin interaction between people to considering the psycho-social context. One perspective is that touch is social when occurring between two or more co-located individuals [98]. In another definition, social touch requires systematic changes in one's perceptions, thoughts, feelings, or behavior as a function of another person's touch in a given context [91]. In this definition, touch is only social if it results in a cognitive transformation for the actors. Elkiss and Jerome expressed this as: "To touch another is to be touched back. Touching, like dialogue, is bidirectional and reciprocal." [53]. This definition suggests that touch interaction also has an impact on the touch initiator.

Huisman discussed four areas where social touch has been shown to have a major impact on human life [98]. Physical touch is essential for *physical and emotional well-being* (especially in infants' development [85]). *Attachment and bonding* is impacted by caring touch throughout all stages of life. Touch can have a direct impact on *attitude and behavior change*, as in the phenomenon known as the Midas Touch [40], where a simple touch can lead to pro-social behavior like tipping a waiter more. Finally, similar to other forms of communication, touch can *communicate affect* or emotions [92].

The social experience of touch can also be linked to the receptors in our skin. Brushing on hairy skin at a velocity of 1-10 cm s^{-1} can signal social body contact by stimulation of c-tactile afferents [136]. Past studies have explored whether being stroked at this velocity affects social behavior [121, 180, 223], but the results are conflicting.

We acknowledge that social touch is more than merely a physical interaction, and we ask how the experience of social touch can be influenced by the design of haptic feedback to the touch initiator. Touch, and the social experience it can facilitate, is an interdisciplinary topic covering many factors including the relationship, norms, environment, context, and cognitive states of the individuals [107]. Social mid-air interactions add an additional layer to this, especially in terms of responsible research and innovation [35]. In our study, we attempt to control for these factors to the extent possible and focus on the haptic factor.

5.2.2 Mediated Social Touch

Social touch interactions and their effects are missing from our distanced communications. Jewitt et al. described "digital touch" as an emergent sociotechnical imaginary: "the immediacy and intimacy of touch make remote personal relationships a primary market for the promise of digital-touch" [106]. Many MST devices have been prototyped (see Huisman for a review [98]). MST devices can help promote well-being by reducing stress [17, 33, 146], increase attachment and bonding to others [223], and enhance the feeling of "togetherness" for parent-child dyads [212].

MST can provide both *direct* and *indirect* interactions. With physical touch, the point the touch initiator touches is the same point where it is felt on the person being touched. Some MST prototypes have adopted *direct* interactions [137, 188]. For example, Makino et al. created HaptoClone, where mid-air haptics were transferred directly from one part of the hand to another (e.g., fingertip to fingertip) [137]. However, most prototypes provide *indirect* interactions like buttons and knobs [171], teddy bears [195], and tactile displays [7]. *Direct* interactions enable more natural touches, as the input point is virtually congruent with the output point.

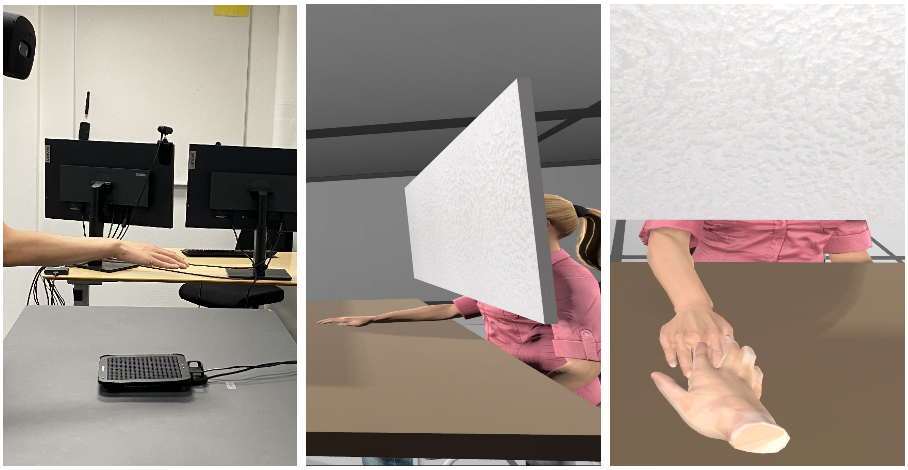
While the social effects of MST devices on the person being touched (the "receiver") are widely researched [7, 20, 28, 80, 94, 167, 223], the social effects on the touch initiator are not explored. Price et al. created a haptic glove, where interactions were given indirectly through buttons and knobs, but the impact of using buttons and knobs on the touch initiator was not evaluated [171]. Nakanishi et al. proposed direct interactions by shaking a robot hand to initiate remote handshaking, but the focus was on the positioning of the hand. Devices such as TaSST [100] allow touches to be recorded and reproduced on a receiver, but the focus is often on reproducing the touch, and not how the touch initiator socially connected with the person being touched.

5.2.3 Mid-air haptics

Ultrasonic mid-air haptic feedback can stimulate our skin receptors without physical contact with an object. The haptic feedback is induced by ultrasound waves colliding in one focal point to create vibrations on the skin [21]. Ultrasound haptics have been used for many mid-air interactions such as interacting with buttons [36, 143], rendering volumetric shapes [134, 141], mouth haptics [193], and more. In social contexts, specific emotions can be communicated through ultrasound mid-air haptic icons [159]. This work indicates that ultrasound haptics can go beyond discriminative touch and induce emotional experiences. Affective touch through the stimulation of c-tactile afferents has also been studied with ultrasound with varying results [167, 216].

5.3 Methods

To compare the impact of haptic feedback on the social experience of the touch initiator, we conducted a study with participants acting as touch initiators. They stroked a virtual hand while receiving variations of haptic feedback. They rated the *Pleasantness*, *Co-Presence*, and *Friendliness*, and we captured the stroking *Velocity*.



(a) Real-world view (b) VR side view (c) VR front view

Figure 5.2: The setup seen from outside VR, inside VR, and the first-person perspective. Participants did not see the physical objects (e.g., ultrasound device) on the table.

5.3.1 Design

The study used a within-subjects design where each participant conducted a stroking task three times, each with a distinct haptic feedback condition. The order of the haptic feedback conditions was counterbalanced. Each session ended with a short interview with the participant, and a reflective post-study interview was conducted at the end.

5.3.2 Apparatus

We used an HTC VIVE Pro head-mounted display (HMD) for VR, OptiTrack for tracking, and the Ultrahaptics STRATOS Explore ultrasound haptic device by Ultraleap Ltd. To render the ultrasound feedback, we adapted the PRO-STM algorithm by Barreiro et al. [10]. Instead of the pressure field in PRO-STM algorithm, we found the contact points between the participant's virtual hand and the avatar hand. The output intensity was consistent across the whole surface and the frequency was variable depending on the total distance between all contact points. We stimulated each point 0.3 mm apart. A pilot study helped verify the robustness of the hand tracking and that the ultrasonic haptic rendering followed the shape of the virtual hand. To mask the noise of the UltraHaptics, the participants listened to pink noise.

5.3.3 Participants

We recruited 18 participants (5 females, 13 males) 21-59 years old (M = 29.9) by advertising on the university mailing lists and social media channels. The study lasted 30 minutes and participants received a gift worth approximately 13 €.

5.3.4 Virtual Environment

The visual setting was inspired by a recent study by Seinfeld et al. [188]. The virtual room showed a virtual table and an avatar representing a remote person. The participant and avatar were seated at opposite sides of the table as seen in Figure 5.2. The participant could place their real hand over a physical table and saw a virtual representation of it in VR (Figure 5.2c). To avoid confounds based on the avatar's facial features, we placed a opaque glass screen in front of the avatar's face in the virtual room. We used an avatar from Microsoft Rocketbox Avatar Library [73].

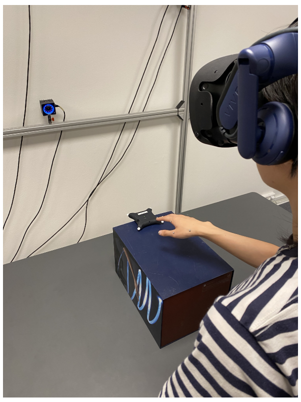
5.3.5 Haptic Feedback

The haptic conditions were hidden from participants until all the responses had been collected.

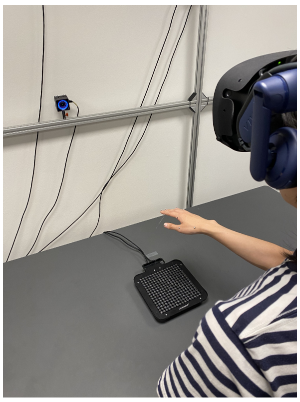
The *No Haptics* condition (fig. 5.3a) was our control condition. The setup was a tracked box on the table. The box was placed on the table to elevate the interaction to the same height as the mid-air haptics stimulus (23 cm in height). The virtual table matched the height of the box.

The *Mid-Air* condition (fig. 5.3b) was induced by the ultrasound device placed on the physical table. The top of the virtual hand, and thus the maximum height of the ultrasound rendering was about 23 cm above the physical table.

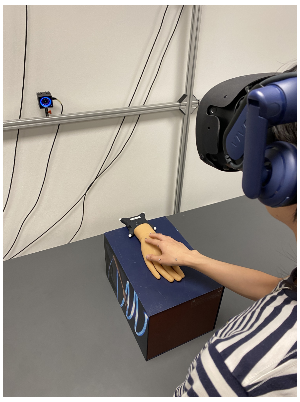
The *Passive* condition (fig. 5.3c) using a silicone hand was selected to represent the shape and elasticity of a human hand. The silicone hand was selected over a human hand to avoid confounds from human movements and avoid the risk of linking the social experience to the experimenter. The hand rested firmly on the same box as the *No Haptics* condition and worked as a haptic proxy for the remote person's avatar hand. The top of the silicone hand approximately matched the *Mid-Air* condition (23 cm).



(a) No Haptics



(b) Mid-Air Haptics



(c) Passive Haptics

Figure 5.3: The three haptic conditions. The box on the *No Haptics* and *Passive* conditions were tracked by active markers, while the *Mid-Air* device was tracked by passive markers. The box was used to match the height for all conditions.

5.3.6 Mediation Deception

We informed participants that a *remote person* was receiving their touch. In reality, there was no actual human receiver of the mediated social touch. We provided participants minimal information to form a similar perception of the receiver with the following text at the start of the study: "The receiver is a 20-30-year old woman, located in London". Before starting each condition they were asked to wait with the in-VR message: "Please wait for the remote person to be ready...". Participants were informed that their hand-tracked stroking was mapped to the remote person's hand. In the post-study questions, we checked whether the deception was effective.

5.3.7 Procedure

The experimenter introduced the participants to the study procedure including the deception of the remote person. After collecting the consent form, the experimenter placed the tracking markers in ten locations on the participant's hand and calibrated the system. Participants chose their avatar's skin texture from six skin texture resources [169]. To limit the variation in stroking, the experimenter demonstrated the stroking on their own hand and directed participants to stroke as if they were stroking a real hand, and that the stroke should last three seconds from the wrist to the tip of the middle finger. With an 18 cm virtual hand, the instruction would result in a stroking speed of 6 cm s^{-1} within the affective touch range of 1-10 cm s^{-1} as reported in the literature [136].

The participants stroked with one haptic feedback condition at a time. In each condition, participants were asked to put on the VR HMD and headphones, and wait for the remote person to signal they were ready. They then stroked the virtual hand for 20 seconds two times. After the first 20 seconds, they rated their experience according to the *Pleasantness*, *Friendliness* and *Co-Presence* questions in Table 5.1. The questions were inspired by co-presence questions from Slater et al. [200] and telepresence by Nakanishi et al. [153]. After the answers were confirmed, they stroked the hand for another 20 seconds. The setup was then hidden, and the HMD was removed as a palate cleanser to reduce carryover effects between conditions. They then answered the open-ended questions Q1 and Q2 in Table 5.1. They repeated this for the two other conditions. The experimenter switched the haptic setup in between conditions without the participant seeing it.

After all conditions, the post-condition interview was conducted outside of VR. We asked the final two open-ended questions, Q3 and Q4 in Table 5.1. Q3 was designed to both get their reflections, but also check whether they believed the deception. Finally, the experimenter debriefed the participants and explained that there was no remote person.

5.4 Results

We report the ratings and measurements followed by the interview results.

5.4.1 Quantitative Ratings and Movement Velocity

The dependent variables consisted of the three subjective Likert-scale ratings, *Co-presence*, *Pleasantness*, and *Friendliness*, and one objective measurement, *Velocity* of

Table 5.1: The questions posed to participants. The first three were answered on a 7-point Likert-scale ratings ("not at all" to "very much so"), while the last four (Q1-Q4) were qualitative.

ID	Question
Pleasantness	Stroking the hand felt pleasant
Friendliness	I felt that the remote person was friendly
Co-Presence	I felt that the other person was together with me in that room
Q1	How does the interaction compare to stroking a real hand?
Q2	How do you think the stroking is felt by the remote person?
Q3	How do you think your stroking affected the remote person's perception of you?
Q4	After trying these examples, what do you think touching a virtual hand should feel like?

stroking. Each dependent variable consisted of 18 measurements (one per participant) repeated three times (once per condition), resulting in 54 measurements for each variable. Figure 5.4 provides an overview of the results for the three Likert-scale ratings. According to the literature, a rating scale with more than five levels can be viewed as interval data [87]. Thus, we ran one-way repeated measures ANOVA on the three ratings and velocity. All p-values were adjusted using Bonferroni-correction for post hoc comparisons.

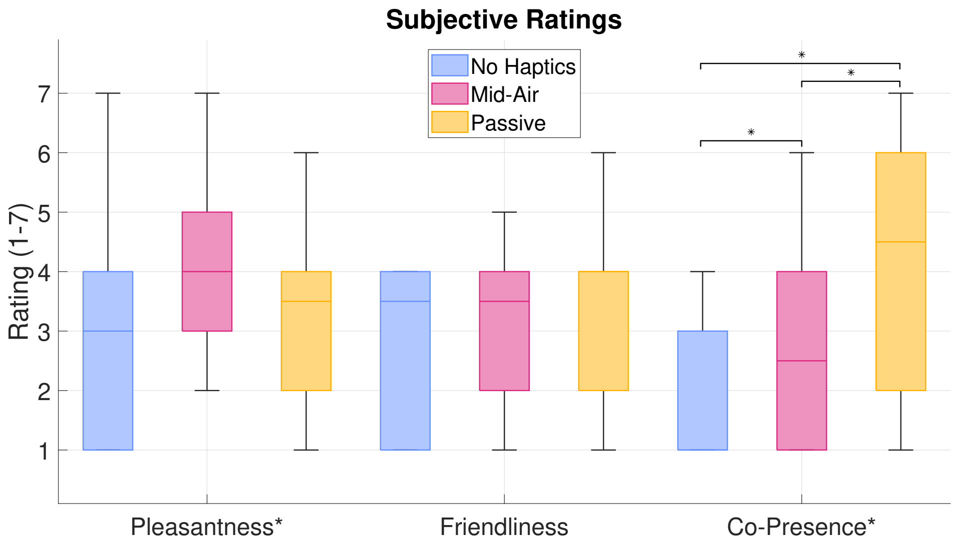


Figure 5.4: The participant ratings for *Co-Presence*, *Pleasantness*, and *Friendliness*. Significant effects are indicated by *. Pairwise comparisons are adjusted with Bonferroni correction.

Pleasantness: The repeated measures ANOVA showed a significant effect of haptic condition on *Pleasantness* ($F(2, 34) = 3.30$, $p < 0.05$, $\eta_p^2 = 0.16$). The pairwise comparisons in Table 5.2 showed no significant results ($p > 0.05$). Thus, the feedback conditions have an effect on Pleasantness, but we cannot determine which conditions were significantly different. Except for one participant, the *No Haptics* condition was only rated four (neutral) or below. Thirteen participants rated the *Mid-Air* condition the highest or tied for highest. The *Passive* condition and *No Haptics* conditions were rated the highest or tied for highest by six and five participants respectively. No participant rated the *Pleasantness* uniformly across the three conditions, indicating the physical experience varied based on the haptic feedback for all participants.

Friendliness: The test showed no main effect on *Friendliness* ($F(2, 34) = 3.19$, $p = 0.08$, $\eta_p^2 = 0.16$). Seven participants rated the conditions uniformly, indicating that distinguishing friendliness from haptic feedback alone was difficult.

Co-presence: The one-way repeated measures ANOVA showed a significant effect of the haptic condition ($F(2,34) = 13.17$, $p < 0.01$, $\eta_p^2 = 0.47$). Post hoc analyses showed that *Co-Presence* ratings were significantly different among all conditions (Table 5.2). Specifically, the ratings were significantly higher in the *Passive* condition ($M = 4.00$, $SD = 2.03$), followed by the *Mid-Air* condition ($M = 2.78$, $SD = 1.59$), and the *No Haptics* condition ($M = 1.89$, $SD = 1.18$). *Mid-Air* was rated significantly higher than *No Haptics*. All the ratings for the *No-Haptics* condition were four (neutral) or less, whereas the other two conditions had higher ratings. The participants had an enhanced feeling of being together with the remote person with *Mid-Air* compared to *No Haptics*. The feeling of being together was even stronger in the *Passive* condition. Sixteen participants rated the *Passive* condition the highest or tied for highest. The *Mid-Air* and *No Haptics* conditions were rated the highest or tied for highest by eight and five participants respectively. Three participants gave a uniform rating for *Co-Presence* across the three conditions.

Table 5.2: Pairwise Comparisons for the four dependent variables. All the p-values (the two rightmost columns) are adjusted using the Bonferroni correction.

Variable	Condition	M	SD	No Haptics	Mid-Air
Pleasantness	No Haptics	2.89	1.68	–	
	Mid-Air	4.06	1.39	0.05	-
	Passive	3.44	1.34	0.66	0.66
Friendliness	No Haptics	2.72	1.45	–	
	Mid-Air	3.06	1.35	0.17	-
	Passive	3.39	1.54	0.19	0.69
Co-Presence	No Haptics	1.89	1.18	–	
	Mid-Air	2.78	1.59	**0.04***	-
	Passive	4.00	2.03	**<0.01***	**0.03***
Velocity	No Haptics	10.02	2.21	–	
	Mid-Air	10.67	2.93	0.62	-
	Passive	8.18	1.83	**<0.01***	**<0.01***

Velocity: The repeated-measures ANOVA showed a significant effect of haptic feedback on *Velocity* ($F(2, 34) = 11.43$, $p < 0.01$, $\eta_p^2 = 0.40$). The post hoc tests showed significant differences between the *Passive* condition and the other conditions. Stroking in the *Passive* condition ($M = 8.18$, $SD = 1.83$) was significantly slower than the *No Haptics* condition ($M = 10.02$, $SD = 2.21$), and the *Mid-Air* condition ($M = 10.68$, $SD = 2.93$). The velocities indicate participants stroked faster than they were instructed (approximately 6 cm s^{-1}).

5.4.2 Qualitative Responses

The participants answered four questions verbally. They answered the first two questions (Q1, Q2) after each condition and the last two questions (Q3, Q4) at the end of the experiment. We summarize their answers for each question below.

Q1. How does the interaction compare to stroking a real hand?

The perceived resistance and solidness of the hand was a major factor in the comparison to stroking a real hand. All the participants noted that the *No Haptics* condition was not comparable to real stroking since they could not feel anything: *"extremely different, because you only see the image of my hand, but you'll feel - I felt just air. No physical touch."* (Participant P7 in the *No Haptics* condition). Participants noted the same issue with mid-air haptics (7 out of 18 participants), while others thought the slight resistance from mid-air haptics was still useful (5/18): *"Like, just the fact that you feel some resistance as you touch. Or in this case, whatever it was... air or electric input does a lot."* (P1, *Mid-Air*). Feeling physical resistance and hand contours were the main reasons for the similarity of the silicone hand to touching a real hand (11/18).

The sensation of the stroking was another important factor to the participants. In the *Mid-Air* condition, several participants noted the sensation did not resemble real stroking. The ultrasound sensation felt like vibration (P3, P14), wind (P6, P12, P13), blurry (P5), or weird (P6, P11, P16, P18): *"I think it feel kind of weird because it feel like there's a wind coming from that hand."* (P6). Similarly, the participants noted that the texture and temperature of the silicone hand did not match a real hand. They noted that the hand felt sticky (4/18) or cold (4/18) or even "dead" (P2).

Q2. How do you think the stroking is felt by the remote person?

Several participants responded that they did not know what the other person felt (7/18 in all conditions). Some guessed that the feedback would be like what they felt (4/18 *No Haptics*, 7/18 *mid-air*, 13/18 *Passive*). *"I would say it's similar tingling, maybe it has some... pressure on where I go with my stroke."* (P7, *Mid-Air*).

Some participants thought that the remote person may get different feedback from their own. In the *No Haptics* condition, four participants described that the remote person may get an unnatural sensation such as tingling (P7), electrical impulses (P1), or a choppy sensation (P2). Similarly, in the *Mid-Air* condition they thought the sensation could be electric vibrations (P8), weird (P17), or not normal (P18). Interestingly, some participants (5/8 *No Haptics*, 4/18 *Mid-Air*) worried that their hand penetrating the avatar hand would lead to unnatural sensations for the remote person: *"I think again it would feel a bit clumsy or unnatural because... it was harder to keep, like, a natural rhythm..."* (P17, *No Haptics*).

Q3. How do you think your stroking affected the remote person's perception of you?

The point of this question was both to test whether participants believed there was a remote person (the deception) and to gauge what they imagined the other to take away from the social interaction. No responses indicated that they did not believe the deception. Most participants (10/18) noted that they had no idea about the remote person's impression, or described that the remote person's impression depended on their stroking, and how it was translated: *"I think that depends on how well I did it... It could either be a bit creepier perception or better perception."* (P17). Even though they had no idea, their responses indicated they believed the deception. Furthermore, no participant claimed they had seen through the deception after completion of the study. Six participants thought the interaction created a positive impression and a sense of social connection in the remote person: *"I would say it should make that person feeling more like in touch with me and like I'm a real person as well."* (P7). One participant thought they *"overstepped some boundaries"* (P10) by touching someone they did not know. As such, they were concerned that their touch may have created a negative impression in the remote person.

Q4. After trying these examples, what do you think touching a virtual hand should feel like?

Several participants thought the touching sensation should closely replicate the feel of a human hand (8/18) as it would help them stroke it naturally. Others wanted something in-between the silicone hand and the mid-air feedback (4/18). Four participants thought the warmth was especially important to replicate, and some aspects can be left to the user imagination: *"[I] really think that the warmth of the third one (Mid-Air) is very, very important... So in that I don't think you necessarily have to be like 100 percent accurate... Because then I think your brain does the rest of the work for you."* (P2). Finally, P10 and P17 mentioned that their touch should be reciprocated: *I would want [...] just to feel that there is some movement back, because when you touch a hand in real life [...] you can feel like in some way as that was a human being who can move and have feelings* (P10).

5.5 Discussion

We discuss the results and reflect on the implications for future work on the haptic design for remote touch interactions.

5.5.1 Materiality

The material feeling of the avatar's hand impacted the touching experience. *Co-Presence* was rated significantly higher in the *Passive* condition than in both the *Mid-Air* and *No Haptics* conditions. The interviews suggest that the higher rating was due to the solidness of the silicone hand. The solid hand allowed participants to control their stroking. The slight resistance from the ultrasound stimulation provided them with some cues, but it was not adequate for stopping their hand from penetrating the avatar hand. This is reflected in the stroking velocity, as participants stroked more in line with the instructions in the *Passive* condition. Only the stroking velocity in the *Passive* condition is within the 1-10 cm s^{-1} range associated with affective or social touch[136]. On the other hand, the material feeling also had negative consequences on user impressions. The participants could discern the absence of life in the silicone hand from its temperature and texture.

Designing material experiences for remote social touch is an interesting direction for future research in haptics. Recent advances in the design of synthetic materials for touch [156] as well as skin-like sensors [209] and soft actuators [118] can help create lifelike proxy hands. Alternatively, the feel of existing proxies such as the silicone hand may be augmented through ultrasound or other haptic technologies.

5.5.2 Reciprocity

Remote touch experiences should inform the users how their touch actions are felt by the remote person. In the study, many of the participants did not know what their touch felt like, they were unsure of how it was perceived by the remote person, and how to perform their stroking gently. This uncertainty was exacerbated when their hands penetrated the avatar's hand in the *No Haptics* and *Mid-Air* conditions. When physically stroking we can adjust based on the movements and expressions of the person being stroked. Without reciprocal feedback, there are no reactions or consequences to the stroking. A bidirectional scenario, where the remote person moves or even reciprocates touches, could likely affect the *Friendliness* of the remote person. Reciprocal touches could also help users understand what the other person feels.

5.5.3 Limitations

Since our focus was the effect of haptic stimulation, we designed the study to control for non-haptic factors as much as possible. For example, we deliberately placed a opaque screen in front of the VR avatars face (Figure 5.2b) to avoid the effect of facial reactions. In addition, we provided a short description of the remote person to the participants, and all participants interacted with a White female avatar. Nevertheless, a few participants noted that these parameters matter to their experience. Some claimed they could not estimate the *Friendliness* without any feedback in the form of facial expressions or reciprocating their touch actions. These factors could explain the lack of statistical difference in the *Friendliness* ratings across the three conditions.

The decision to use only one interaction, stroking, was due to technical and design limitations. The tracking with passive markers was more accurate when participants' hands were flat as in stroking compared to other motions (e.g., tapping), and we could provide consistent instructions for the stroking.

Feedback from a real hand was considered as one of the conditions, but discarded due to the complexities of the deception and whether the participant would link the experience to the researcher. Also, such a condition is not realistic for remote interactions.

We collected Likert-scale ratings, stroking velocity, and interview responses. Future studies can use behavioral measures or conduct in-depth interviews to replicate our results or provide further insights into the experience of touching remote people.

Finally, the ethics of remote social touch is an interesting avenue for future research [199]. One of the participants raised a point about consent and overstepping boundaries of the remote person by touching them. The contactless nature of ultrasound mid-air haptic technology raises questions about how to best design for consent in remote touch interactions.

5.6 Conclusion

Our work suggests that the social experience of touch initiators can be affected by haptic feedback alone. As MST is still in its infancy, it is important to research the haptic factors that impacts not just the receiver of touches, but also the touch initiator. We conducted a user study in VR, where participants stroked a remote person's avatar hand while receiving haptic feedback. We varied the feeling of touching the remote person through different types of haptic feedback. Our results suggest the importance of haptic feedback on touch initiators' perception of co-presence, pleasantness, and the velocity of stroking. The participants' responses illustrate the need for surface familiarity, knowing how the touch is felt by the remote person, and the need for reciprocity. Our work provides insights into the user experience of touch initiators and provides avenues for research and development in haptic interaction design and social touch domains.

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Chapter 6

Mediated Social Self-Touch: The Null Effect of Duplicating Haptic Communication to One's Own Body

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Manuscript

Abstract

We can touch each other at a distance by mediating touch through haptic technology. However, the ability to refine our touches based on the reciprocated touch we feel when touching another is often lost in the mediation. We propose to use the ability to feel one's own touch before sending it to another person. The "self-touch" enables touch initiators to refine their touches based on what they feel the receiver will feel. We introduce a mediated social touch system using mid-air haptics, where users can communicate digital touches in real-time and save them as digital touch recordings. The digital touches are body-congruent hand interactions, where users' touch locations are mapped to the same location on a receiving hand. We evaluate the self-touch through a pattern discrimination task and system usability (n=20). While all recall rates were above the level of randomness, our results do not support that adding self-touch to mediated social touch interactions increases the recall of individual patterns nor the overall accuracy of pattern discrimination. There was no significant difference between the usability with self-touch and without self-touch. Our results indicate that other approaches to solving the issue of reciprocity in mediated social touch are necessary.

6.1 Introduction

When physically touching another person, the contact is felt by both the initiator and the receiver of touches. The reciprocal nature of touch interactions enables us to adjust our touch force, speed, and pattern based on what we feel and perceive through our senses. Being able to conform our touches is what makes a caress nicer, a kiss softer, and a tickle more ticklish. Without the ability to make these micro-adjustments, social touches would likely not have the major impact on human life that it does. Social touches are essential for human development, attachment, and well-being [98].

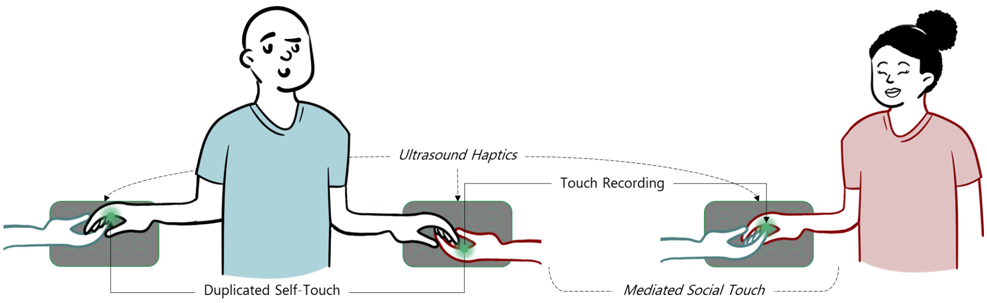


Figure 6.1: Self-touch enables users to feel what the receiver of mediated social touches will feel. Our system uses mid-air ultrasound haptics to communicate digital hand touches in real-time. We use the system to explore whether self-touch improves the ability to communicate distinct patterns and increases usability.

But skin-to-skin contact is not possible when the receiver is out of reach. Mediated social touch (MST) enables digital touches at a distance. MST adds an intermediary medium to the contact system, resulting in a skin-to-medium-to-skin system. The medium can consist of multiple entities, such as an input device for the touch initiator, a transmission system, and an output device for the touch receiver. The sensory feedback of touching another becomes dependent on the medium instead of how the initiator touches the receiver. Without appropriate feedback, the touch initiator can not optimize their touches based on what they feel the receiver will feel.

Many MST prototypes have been developed to transmit digital touches. MST prototypes have been created to transmit touches through haptic gloves [171], belts [214], Virtual Reality [144], phones [165] and much more. Few of these provide the ability to give local feedback to the initiator of touches. The system "ComTouch" by Chang et al. [29] presented local feedback on an adjacent area, and the haptic mittens by Price et al. [171] could play back haptic signals users designed on their own hand. Any effects of the local feedback in these systems were not evaluated. Without the feedback, initiators can not adjust their touch and struggle to understand what the receivers feel.

Our solution to the lack of reciprocity is to add local feedback in the form of self-touch to the MST interaction. Self-touch is enabled by touch initiators feeling haptic feedback created by one hand duplicated onto the other hand. The touch initiators also feel haptic feedback on the hand that creates the touch. This allows touch initiators to feel what the receiver will feel. Our system is realized by extending the ultrasound haptic MAMMOTH system [142] with the ability to feel digital hand touches in real-time and the ability to record them as digital touch recordings.

This project contributes to the mediated social touch literature by introducing a haptic system to mediate mid-air digital touches in real-time and record digital touches. With the system, we explore whether feeling self-touch when creating digital touches improves the ability to communicate distinct patterns and increases usability. The recall of each pattern compared between the two condition types can reveal whether using self-touch increases the recognition rate. We use the standardized System Usability Scale (SUS) [19] to compare the usability. With the addition of self-touch, we anticipate that communicating distinct touches will be more effective, efficient, and satisfactory, leading to a higher usability score. We pose the following two hypotheses[1]:

- H1: Patterns will be identified more correctly (recall) when using self-touch compared to no self-touch.
- H2: SUS will be rated higher when using self-touch compared to no self-touch.

The hypotheses are tested by conducting a pattern discrimination study where participants attempt to communicate distinct emotions to a receiver. The setup is asynchronous between the initiator and receiver. The initiator records digital touches that later are played back on another participant's hand. In the self-touch condition (Self-Touch), initiators create digital touches with the right hand and feel self-touch on the left hand. In the condition without self-touch (¬Self-Touch), initiators only use the right hand. In the discrimination study, participants acted as receivers and only felt the touch recordings played back on their left hand.

6.2 Related Work

In this section, we describe MST and the current challenges of the emerging communication form. We present self-touch, our solution to one of these challenges.

6.2.1 Mediated Social Touch

MST provides a solution to social touch deprivation in an increasingly distanced and online world. Understanding MST requires a definition of unmediated social touch. Multiple definitions have been proposed and used. Huisman [98] defined unmediated social touch as "touch occurring between two or more individuals in co-located space". The definition from Haans and IJsselsteijn [81] was similar: "Social touch entails all those instances in which people touch each other, for example, in a crowded train, when shaking hands, or when giving a "simple" touch of appreciation. Obviously, people need to be in each others immediate proximity (e.g., as in face-to-face interaction) to touch.". They claim MST differs in multiple ways from physical social touch in that it e.g., can use less modalities and be asynchronous., and defined it as "the ability of one actor to touch another actor over a distance by means of tactile or kinesthetic feedback technology" [81]. The definition from Hertenstein et al. [92] of *tactile communication* took it a step further, as it also required an effect on

[1] The study was pre-registered on OSF, where "no Self-Touch" is called "Active Touch": https://doi.org/10.17605/OSF.IO/ZM7HS

another person: ”tactile communication occurs when there are systematic changes in another’s perceptions, thoughts, feelings, or behavior as a function of another’s touch in relation to the context in which it occurs [91]. For the scope of this paper we define MST similarly to Haans and IJsselsteijn [81] as touch communicated between two or more perceived individuals through a technological medium. We focus on interpersonal interactions between perceived individuals (e.g., humans, robots, AI) and not touches that are perceived as innately social, such as affective touch [136]. The medium includes all technology that realizes the transmission of touch between individuals.

MST prototypes have been designed to convey forms of *meaning* through forms of *interaction*. They can target different *body areas* and are implemented using a wide range of *haptic technologies* (see Huisman [98] for a review and importance of social touches).

Some prototypes are developed to convey affection [27, 31, 144, 171, 214], greetings [13, 153], or functional information like patterns or intensities [29, 100]. Most prototypes are created with a purpose of meaning in mind, such as calming the receiver [20] or making up for the touch lost when dyads are distanced [171].

Some interactions attempt to replicate their physical counterparts such as handshakes [153], stroking [100, 144], and kisses [31]. The types of interactions can also be as simple as one person pressing a button to trigger touches for a receiver [171], while other interactions resemble natural body-congruent interactions, where the position touched is where it is felt on the receiver [144, 148].

The most targeted body location in a 2017 review by Huisman [98] was found to be the hand. There can be multiple reasons for this. On a functional level, it is the body part we conduct most of our daily interactions with such as brushing our teeth, using a keyboard and mouse, and using tools and cutlery. On a neurological level, the palmar side of the hand is the most densely innervated body region [37], leading to higher spatial acuity for both touch and pain [138]. But MST prototypes have also targeted the arm [100], face [31, 164], and upper body [17, 214].

MST prototypes have been implemented using vibrotactile feedback, force feedback, thermal feedback, and ultrasonic feedback. To our knowledge, no MST prototypes are using electrotactile feedback. Prototypes such as Pressages [93] and CheekTouch[164] utilize the vibration actuators in phones to create vibrotactile feedback on the skin of receivers. The vibrotactile sleeve TaSST [100] was used to communicate different types of touch such as a poke, hit, and stroke. Park and Nam [165] augmented a phone with an inflatable surface to create force feedback for users. Force feedback has also been used to mediate handshakes [88, 153]. Thermal feedback has been used to warm the head using a headband [204] or lying on a heated pillow [48]. Ultrasonic feedback has been used with hand interactions while in VR [144, 188].

6.2.2 The Reciprocity Issue of MST

Touch is not a one-way street. Physical touches are reciprocal. When we touch someone, we are touched back by our own actions. Bidirectional touches, where both actors are initiators and receivers, enable *active* reciprocation. Both actors can actively touch each other, and their touch and movements affect how the other person can touch them (e.g., in a thumb fight both actors feel the other person and how they can touch depends on the other person’s movements). Even without *active* reciprocation from the receiver, there will intrinsically be *passive* reciprocation due the touch felt when touching (e.g., in a high-five where one person is holding their hand still, the one moving their hand will feel the impact with the still hand).

In nursing, touch is more than skin-to-skin contact – it is like "bumping souls" [54]. This relationship is essential to caring for patients. Hall [84] describes touch as a "relation and a meeting between two humans". The reciprocity of the touch is not solely of functional value. A hand can work as a "warm hood" for the patient, who in return responds by calming down, felt through touch [84].

In Human-Robot Interactions, the effects of a robot actively reciprocating touch has been studied. Shiomi et al. [195] found the reciprocation led to a higher interaction time and willingness to self-disclose information. In another study, Shiomi et al. [194] found that the simple act of a robot touching a human hand while itself being touched by the same human made the humans more willing to do more requested tasks.

When we press a button, our motor systems construct a model of "what happened" [161]. This enables us to "tune" the motor command, optimizing our button-pressing performance. Touching another person carries more meaning and context than pressing a button. Yet, we can similarly use the reciprocity of touch to tune not only how we touch objects but also how we touch other humans.

The addition of the medium as a middle-man carrying touch creates an issue of reciprocity for MST. Touches initiated by pressing a button, sensor, or hand tracking do not create an intrinsic relationship between the initiator and the receiver. A button rarely contains information about what it feels like to touch the receiver, nor how the receiver reacts to the touch. Without feedback, the touch initiator's ability to conform touches is limited. One solution is to allow touch initiators to feel what the receiver will feel by duplicating this touch to their own body.

6.2.3 Self-Touch

Self-touch is a widely studied subject within neuroscience. It relates to the ability to touch oneself and how that touch differs from interpersonal or material touches. Physical self-touch is thought to be attenuated by the brain by using a copy of the motor command to predict the feedback induced by the self-touch [16]. Touches to one's own body feel less intense than similar touches induced by another person. This explains why it is difficult to harm or tickle oneself. Self-touch has been studied with skin-to-skin contact and when mediated with tools (e.g., through a haptic technology medium). Spatial perception does not seem to be affected by the attenuation in tool use [117].

Mediating Self-Touch

To our knowledge, only two MST prototypes have provided local haptic feedback analogous to self-touch.

Chang et al. [29] introduced ComTouch, a vibrotactile device to communicate bidirectional touches using an asymmetric mapping. One iteration consisted of a flat pad, where users interacted by laying their hand on the outline of a hand. Their index finger rested on three parts: the distal phalanx on a force sensing resistor, the middle phalanx on a dime-sized acoustic speaker for local feedback, and the proximal phalanx on an another acoustic speaker for receiving touches. This setup allowed users to send (distal phalanx) and receive (proximal phalanx) touches at the same time while receiving local feedback (middle phalanx). The local feedback was used to gauge the intensity of the touch to be sent. Through a study, they concluded that the vibrotactile feedback could convey useful information, while also conveying redundant information such as word emphasis in a multimodal audio and tactile scenario. There was no evaluation of any effects of the local feedback, such as whether it made conveying information easier, increased the cognitive load, usability, or created difficulties when feeling your own touch while receiving it from another at the same time.

Price et al. [171] introduced the Tactile Emoticon (TE) system, which consisted of an inflatable neoprene mitten lying on top of an acrylic box. The box had buttons and dials mounted on the side and touch sensors mounted on top of the box, under the palm and fingers. The controls were used to send vibrotactile feedback through vibration motors, thermal feedback through a temperature module, and force feedback by inflating the mitten. The feedback was not only felt in an identical TE system in use by another user. Pressing a button allowed users to feel it locally ("feel own mode"). Price et al. [171] studied how context shaped participants' use of the system and the process of creating and interpreting touch messages. The local feedback was not evaluated in the studies, even though video cameras recorded changes made to the devices when creating touches. It is unclear whether participants utilized the local feedback to understand and improve their own touches or whether they had any preference to using it or not.

6.3 Methods

We conducted a study to evaluate the effect of self-touch when sending digital touches. The aim of the study was 1) to determine whether self-touch improved touch initiators' performance of creating distinct patterns and 2) to measure how self-touch affected usability. Participants were tasked with touching a virtual hand in mid-air in a predetermined pattern. The patterns were designed as low-level shapes (e.g., line, square, and circle) following a discrimination task by Hajas et al. [82] and Mulot et al. [152] instead of high-level emotions (e.g., happy, sad, angry) as this is a novel system that renders ultrasound haptics. When evaluating ultrasound rendering, it is common to study the efficiency of pattern or shape discrimination [82, 96, 141, 152]. The touches were felt in real-time for the Self-Touch condition and recorded to be played back later. Participants first acted as touch initiators (*Initiator task*) and performed the patterns with or without self-touch. After acting as touch initiators, the participants acted as touch receivers (*Receiver task*) and performed a discrimination task using another participant's recorded touches. Our setup replaces the pre-programmed sensation in the discrimination task by Hajas et al. [82] with human-created sensation. We evaluated the usability of self-touch using the System Usability Scale (SUS)[19] (see appendix 6.7). and the touch receiver task with a confusion matrix.

6.3.1 Design

We used a within-subjects design for participants to compare the two conditions of self-touch (Self-Touch) or no self-touch (¬Self-Touch). The order of the conditions was counterbalanced. After the touch initiator tasks were completed for both conditions, the participants filled out SUS for both. The touch receiver task followed the qualitative questions, and the order was counterbalanced.

6.3.2 Apparatus

Participants sat by a desktop table with a screen in the middle and an Ultrahaptic ultrasound device on either side as seen in Fig. 6.2. Each ultrasound device was attached with a Leap Motion controller for hand-tracking. All participants used their right hand to create touches and their left hand to receive those touches in order to keep the recorded touches consistent for all participants. While holding their right hand above the first device, the participants saw a virtual representation of the hand and could touch a virtual representation of a static target hand. They felt haptic feedback upon touching the target hand. In the Self-Touch condition, they could feel the touches made by the right hand duplicated on their left hand while holding that hand over the second device. In the ¬Self-Touch condition, the left hand rested on a table. In the receiver discrimination task, participants held their left hand above one device and felt touches played back on their hands. They could not see any virtual representation of their hand during the task.

Figure 6.2: Participants created touches using their right hand. They saw their hand tracked to a virtual hand on the screen while being able to touch another virtual hand. In the ¬Self-Touch condition, they only felt haptic feedback on their right hand when creating touches. In the Self-Touch condition, they felt both haptic feedback on their right hand and self-touch duplicated onto their left hand. Participants used the mouse to begin recording in the initiator task and to play back a previous participant's recordings in the receiver task.

6.3.3 Digital Touch Recordings

The interaction was implemented by modifying the open-source MAMMOTH toolkit [142] to record the touches and play them back. MAMMOTH works by determining the intersection between virtual objects – in our case, two tracked hands. The palmar surface of the hands are discretized using a Poisson distribution, resulting in a surface filled with landmark positions. When the target hand is in contact with any of these landmark positions, haptic feedback is rendered using a 2-opt algorithm based on all triggered landmark positions. Each landmark is given a unique ID, and we save the triggered IDs every 10 ms. This enables the haptic feedback to be played back on a hand with a different pose and position than the recorded one, as we match the landmark positions instead of the 3D position. The relative intensity is also saved. The intensity is determined by the depth the users push their virtual through the target hand. The digital touch recordings are comma-separated files where each line consists of triggered *ID*s and their relative *Intensity*. When playing back the recordings, a line is read every 10 ms and converts the IDs to 3D positions based on the current pose and position of the user's virtual hand. The 3D positions and average intensity are sent to the MAMMOTH rendering algorithm. The algorithm dynamically renders the haptics based on the 3D positions.

6.3.4 Patterns

Participants were asked to perform three categories of touches, with each category containing three patterns. Participants were shown a visual representation of each pattern. Each category was recorded for both conditions, resulting in a total of eighteen touches per participant. Figure 6.3 shows the image prompts shown to participants in both the initiator and receiver tasks. To test the communication of intensity, the first category depicted single points with a relative intensity indicated (softest to highest). To communicate one-dimensional lines, the second category depicted lines ranging from a single point to a long line. To communicate two-dimensional shapes and be comparable to other ultrasound shape discrimination tasks by Hajas et al. [82] and Mulot et al. [152], the third category depicted a square, a circle, and a triangle.

6.3.5 Participants

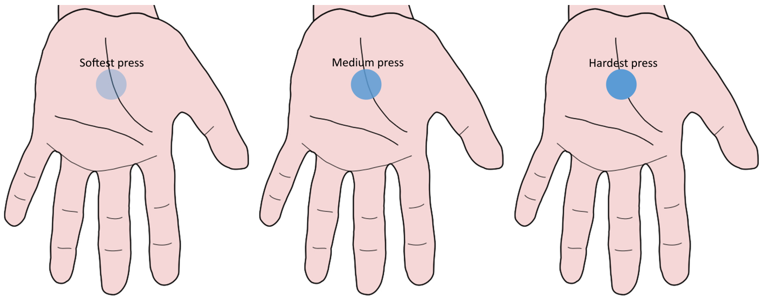
We recruited 20 participants using a mailing list and advertising at a university. The study lasted 30 minutes and participants were compensated with a gift worth approximately 13$ for their time. The participants signed an informed consent form and GDPR form.

6.3.6 Procedure

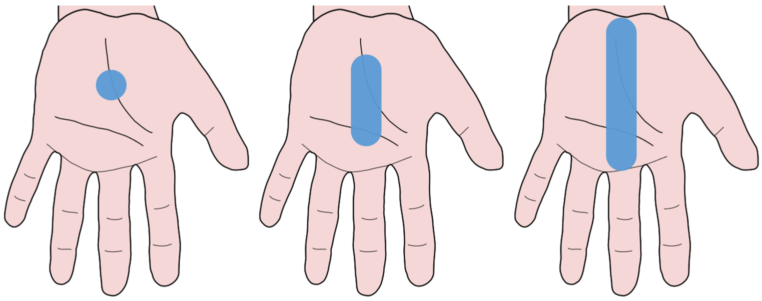
Before signing the consent form, all participants were introduced to mid-air haptics and tracking technology. They were informed that touch recordings would be saved. They were informed that the study was about social touches and that touches they performed would be played back on another person's hand. There was no time limit to any part of the study.

Initiator task

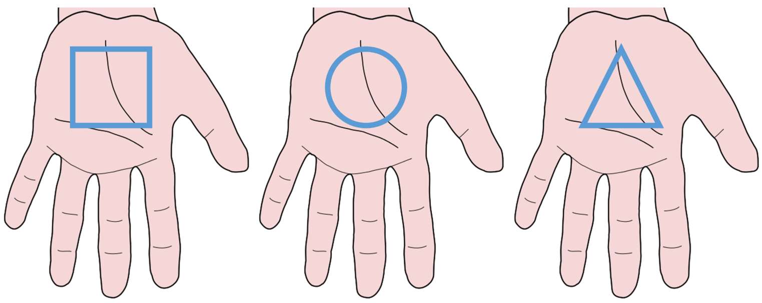
In the touch initiator task, participants were asked to perform the patterns one category at a time. All three prompts of the touches in the category were seen on a



(a) Low intensity (b) Medium intensity (c) High intensity



(d) Single dot (e) Medium line (f) Long line



(g) Square (h) Circle (i) Triangle

Figure 6.3: Participants were asked to draw the pattern with their index finger on the receiver's palm. The first category (a-c) was related to intensity, the second category (d-f) was to explore one-dimensional patterns, and the third category (g-i) explored two-dimensional shapes. Hand figure is adapted for non-commercial use [168].

screen in front of them in the same order as seen in Fig. 6.3. Fig. 6.2 shows three *intensity* patterns ready to be recorded. Participants were allowed to practice the patterns until they felt ready to record them. Once they were ready, they used the mouse to press a record button, and the recording started after three seconds. The recording lasted 5 seconds. If the participant was not satisfied with their recording, they were allowed to re-record it any number of times.

After using one condition, they performed the same task in the other condition.

After both conditions, the participants filled out SUS.

Receiver discrimination task

In the receiver task, participants performed six trials (three categories × two conditions) of the discrimination task. They felt three recorded touches from the previous participant in each trial and were asked to match each recorded touch with a pattern in its category. It was possible to replay recorded touches in each category any number of times until the participant locked in their choice and moved on to the next category. It was a forced-choice selection where each pattern had to be selected once.

6.4 Results

We recorded 360 digital touch recordings at 100 Hz, each consisting of triggered landmark positions and their intensity. The 360 recordings were used for the 360 discrimination attempts, resulting in eighteen identification attempts per participant.

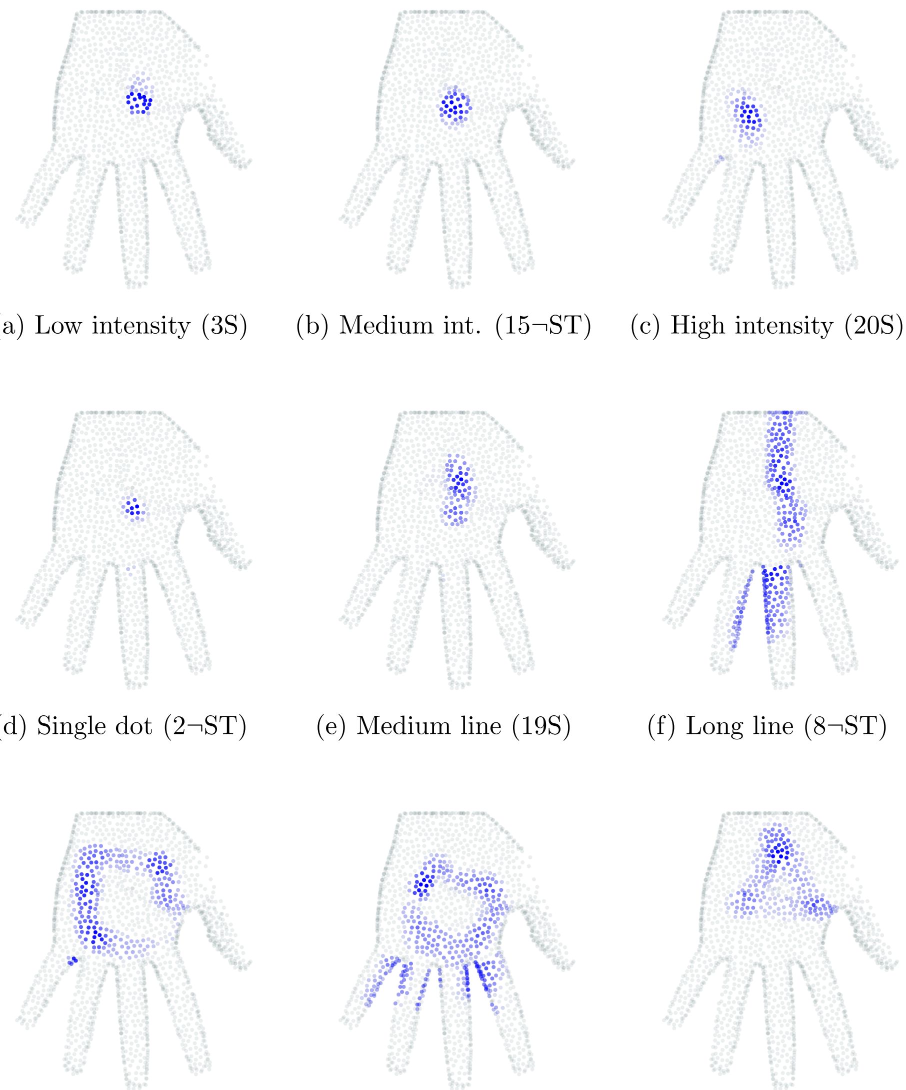
Fig. 6.5 shows the confusion matrices with the recall for each pattern in each condition. As the values are dichotomous ("identified" or "not identified"), we conducted a McNemar's test[2] to evaluate the recall between Self-Touch and ¬Self-Touch. The results indicate no significant differences between recall for individual patterns between conditions ($p > 0.50$). Thus we can not reject the null hypothesis of hypothesis H1. This does not indicate that patterns will be identified more correctly (recall) when using self-touch compared to no self-touch.

A Shapiro-Wilks test showed that the accuracy followed a normal distribution. We conducted a paired t-test on the accuracy between conditions. The results from Self-Touch ($M = 0.57$, $SD = 0.24$) and ¬Self-Touch ($M = 0.62$, $SD = 0.26$) indicated no significant difference between conditions, $t(19) = 0.65$, $p = 0.52$. A one-sample t-Test showed significantly higher accuracy than the level of randomness (33.33 %) for both Self-Touch, $t(19) = 4.31$, $p = 0.003$, and ¬Self-Touch, $t(19) = 4.77$, $p = 0.001$. Fig. 6.6 shows the accuracy distributions between Self-Touch and ¬Self-Touch. There was no significant correlation for each participant's performance when comparing their accuracy using Pearson's correlation coefficient, $r = 0.03$, $p = 0.18$.

To calculate the SUS score, the ratings were converted to values (0-4), summed, and multiplied by 2.5 [19]. The result of a paired t-test do not indicate that Self-Touch ($M = 47.25$, $SD = 6.12$) has a significantly higher usability than ¬Self-Touch ($M = 47.75$, $SD = 7.15$) according to SUS, $t(19) = 0.32$, $p = 0.75$. Thus, we can not reject the null hypothesis for H2. There was no significant correlation between how participants rated SUS and how well their patterns were recognized for either condition ($p > 0.25$).

The conditions were counterbalanced. To explore whether there was a training effect and if patterns were more accurately identified in the *receiver task* if they were created as the second condition in the *initiator task*, we conducted a Wilcoxon Ranked Test. There was a significant difference between the First Condition ($M = 0.67$, $SD = 0.19$) and the Second Condition ($M = 0.51$, $SD = 0.28$), $Z = -2.05$, $p = 0.04$. This indicates that participants did not record more recognizable patterns over time

[2] As opposed to the paired t-test listed in the pre-registration because of the dichotomous values



(a) Low intensity (3S) (b) Medium int. (15¬ST) (c) High intensity (20S)

(d) Single dot (2¬ST) (e) Medium line (19S) (f) Long line (8¬ST)

(g) Square (1S) (h) Circle (17¬ST) (i) Triangle (15S)

Figure 6.4: Visualization of a selection of the digital touch recordings. The blue points identify the landmark positions and their opacity is relative to the amount of times that landmark was triggered in the recording. The caption for each image indicates the participant number and Self-Touch (ST) or ¬Self-Touch (¬ST) condition. Note: intensity values are not reflected in the opacity.

but that the accuracy worsened. Wilcoxon Ranked Test on the order in the receiver task showed no significant results, $p = 0.64$.

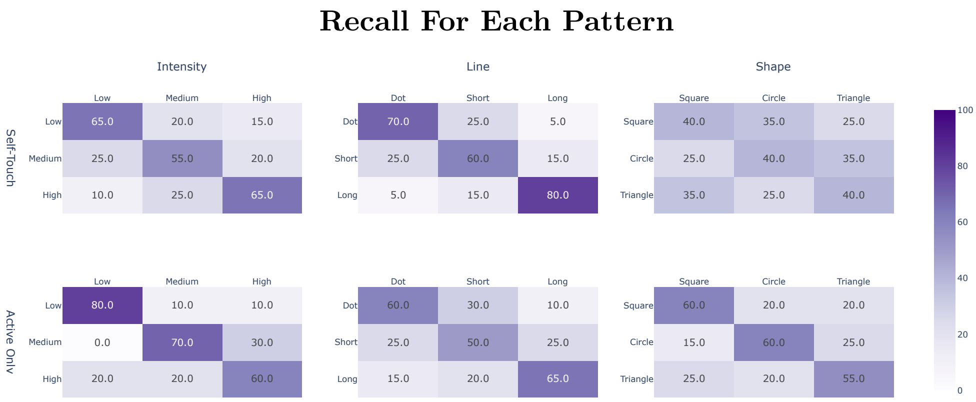


Figure 6.5: Multiple confusion matrices for each pattern and condition. The values are the recall percentage. All recall values are above the randomized level of 33.33%.

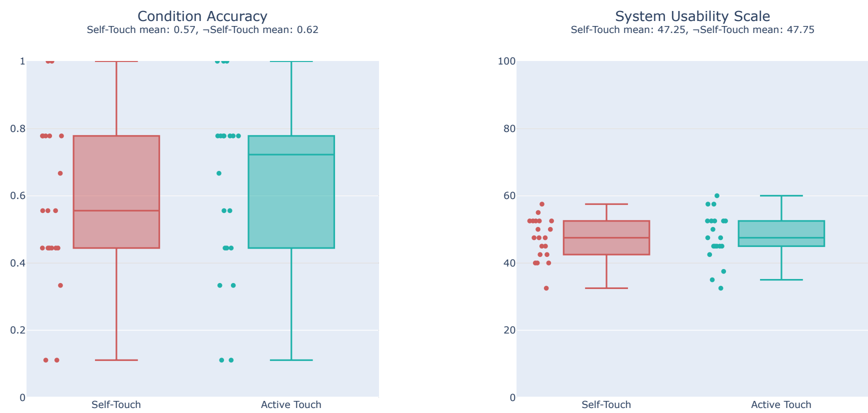


Figure 6.6: The overall accuracy across patterns for each condition (left) and the results of the System Usability Scale (right). There are no significant differences in either.

6.5 Discussion

Our results do not support the idea that Self-Touch in our setup improves the communication of distinct patterns or usability. This can be caused by the technical setup, the study design, or that self-touch does not improve these aspects.

With the recall of all patterns above the level of randomness, the results indicate that participants could communicate distinct patterns. This shows that the technical setup was capable of capturing virtual mid-air touching and remapping them to a receiver's hand asynchronously. With overall accuracies of 49.16 % for the *shape* category, our identification results are slightly below the "Single-Stroke Shapes" from

Hajas et al. [82] with accuracies between 52.7% and 57.3% in their active touch condition. Using "Multi-Stroke Shapes", their accuracies increased up to 83 %. Identification of four shapes (triangle, square, hexagon, and octagon) from Mulot et al. [152] used three different rendering techniques. They found an identification rate of 40 % using spatio-temporal modulation, 65 % for Dynamic Tactile Pointers (see Hajas et al. [82]), and 62.5 % using spatio-temporally-modulated Tactile Pointers. Their shapes were "hardcoded in C++" [152] to be exact shapes, whereas ours are user-created and contain human errors.

Some participants noted that using two devices required more coordination, making it harder for them to create the touches. In the ¬Self-Touch condition, they coordinated their hand movements by looking at their virtual hand on the screen and feeling active haptic feedback. When using Self-Touch, they additionally had to register the feedback on their left hand while holding it 20 cm above the device. This could have an effect on both the physical effort and mental workload. Whether the mental workload had an effect could be studied using a standardized questionnaire like NASA-TLX.

Given the visual representations of the patterns, participants themselves decided how to create their touch recordings. Looking at the individual recordings (see Fig. 6.4 for an excerpt), it was clear that participants made individual choices in how to "draw" their patterns. Some used time as a factor in the design, only touching the hand for a subset of the five seconds. Others repeated patterns multiple times in the time frame. For the circle shape, some people touched for one revolution while others attempted to include as many revolutions as possible. Stricter control over how patterns were to be created may have led to higher accuracies but may undermine social context, where touches are personal and individualized. Participants only felt the patterns created by one other participant, identifying eighteen patterns per participant. Identifying more patterns would lead to a higher chance of a significant result (e.g., Mulot et al. [152] repeated each pattern four times). In a future study, the touch recordings can be reused where participants only conduct the receiver task with more patterns. This would remove bias from their own design process on how the touches should feel.

Finally, it is possible that self-touch does not improve the communication of distinct digital touches and usability. In natural touch interactions, we do not feel self-touch and are therefore not used to this novel type of setup. This could mean that self-touch will never be relevant for digital touches or that training is needed for it to be useful. Our results do not significantly prove that self-touch decreases the communication of distinct patterns or usability, meaning more studies are needed.

6.6 Conclusion

The ability to conform our touches based on what we feel when we touch is essential for the experience of touches. This ability is often lost when communicating digital touches with mediated social touch. We proposed self-touch, the ability for touch initiators to feel the touch they will send duplicated onto themselves. We anticipated that self-touch would improve the recognition rate when communicating distinct patterns and increase the usability

To study this, participants mediated digital touches with and without self-touch. They were tasked with drawing distinct patterns on a virtual hand using their index finger in mid-air. To measure the usability, participants filled out a usability questionnaire. While using the setup, they also recorded digital touches, which were used in a discrimination method to identify distinct patterns. We realized this study by creating a mediated social touch system that enabled the transmission of mid-air hand touches in real-time and the ability to record the touches as digital touch recordings.

While users of the system were able to communicate distinct patterns, the results do not support the hypotheses that self-touch increases the communication of the patterns or the usability. The overall accuracy in the discrimination task indicates that this is not due to the technical setup. Further research is needed to determine how self-touch affects the ability to communicate distinct social touch patterns.

Acknowledgments

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6.7 Appendix

System Usability Scale (SUS)

All items are rated from 0 ("strongly disagree") to 4 ("strongly agree"). The total value is calculated and multiplied by 2.5 for a score between 0 and 100 [19].

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

Chapter 7

MAMMOTH: Mid-Air Mesh-based Modulation Optimization Toolkit for Haptics

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Abstract

Mid-air ultrasound can recreate the missing touch from contactless interactions, such as bare hand gestures in extended reality. But designing ultrasound haptics either relies on inadequate static sensations or experts who can create dynamic sensations. We introduce MAMMOTH, an open source toolkit for Unity that automatically generates dynamic ultrasound sensations for interactions with 3D objects. The haptic feedback is achieved by extending and generalizing a path-routing algorithm for intersections between meshes. We first describe how the toolkit works and then demonstrate how it builds on previous techniques. Finally, we present how to use the toolkit to implement three distinct use cases.

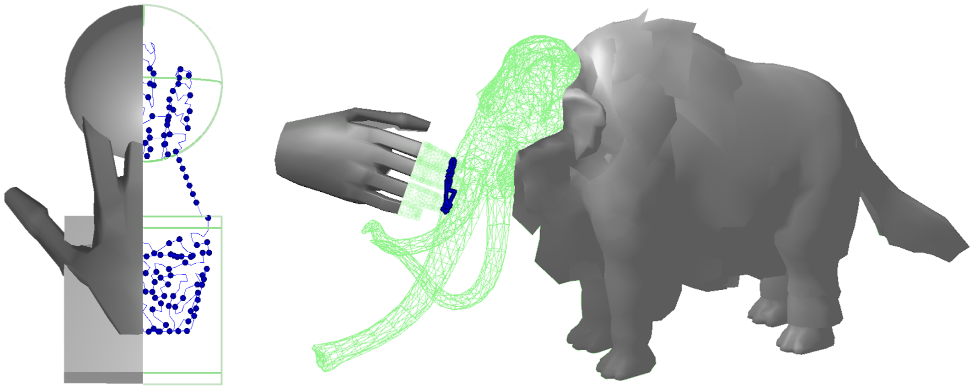


Figure 7.1: MAMMOTH is an open source toolkit implementing a technique to for rendering ultrasound haptic feedback. The haptics are computed from the intersection between 3D objects using the 2-Opt algorithm. In the figure, the tracked hands touch standard 3D objects and a custom model (grey) with attached colliders (green), resulting in the intersection points and shortest path (blue). The shortest path is used to render the ultrasound haptics. The Mammoth 3D model is adapted from: "MAMMOTH", https://skfb.ly/oM76B, by seth the yutyrannus. Licensed under CC BY.

7.1 Introduction

Sensor technology has enabled the implementation of contactless interaction (e.g., hand tracking, proximity sensors, motion sensors). Unfortunately, the intrinsic lack of contact in such interactions has translated into a lack of haptic feedback. However, our sense of touch is, as Linden put it, "what makes us human" [132]. Aiming to alleviate this issue, the HCI community has focused their effort on re-introducing haptic feedback to contactless interactions through so-called mid-air haptic technology.

One mid-air haptic technology enabling the re-introduction is ultrasound haptics. Ultrasound haptic devices consist of a 2D array of transducers that focus ultrasound in a single point, creating a haptic sensation on the skin. This focal point can be moved around rapidly, creating the illusion of a pattern or shape.

One recurring application of the technology is the ability to touch virtual objects in extended reality scenarios. For instance, Barreiro et al. proposed the path routing optimization technique (PRO-STM) to render haptics for a gaseous fluid interaction. However, this technique does not work for general objects and the approach renders larger areas sequentially, resulting in a sensation that is moving sensation instead of steady.

We build upon PRO-STM to create a new rendering technique and generalize it in a toolkit, MAMMOTH. The technique enables mid-air haptic designers to automatically create haptic interactions between tracked hands and 3D objects. The sensation changes in real time depending on the points of intersection between the hand and other 3D objects by computing the shortest path that travels all the points. The haptic sensation is rendered by interpolating between each point in the path and outputting it through the ultrasound device. Our technique includes optimizations such as dynamic frequency modulation to render long paths as a steady sensation.

This paper introduces the technique used in the MAMMOTH toolkit, and three use cases including two MAMMOTH instances at once, enabling mediated social touch. MAMMOTH will be released as an open source toolkit for Unity. Our implementation uses the Ultrahaptics device and Leap Motion, but the steps described in the technique can be followed for use with other ultrasound devices and engines. MAMMOTH enables both experts and novices to easily add dynamic mid-air haptics to their contactless interactions.

7.2 Related Work

Many mid-air haptic technologies can create a sense of touch to contactless interactions. Mid-air feedback can be achieved through airflow, laser, heat, electrostatic, ultrasound, and more. These technologies all have advantages and disadvantages, pertaining to intensity, spatial resolution, ability to generate warmth, and accessibility. One of the leading forms of mid-air haptics uses focused ultrasound to stimulate our sense of touch.

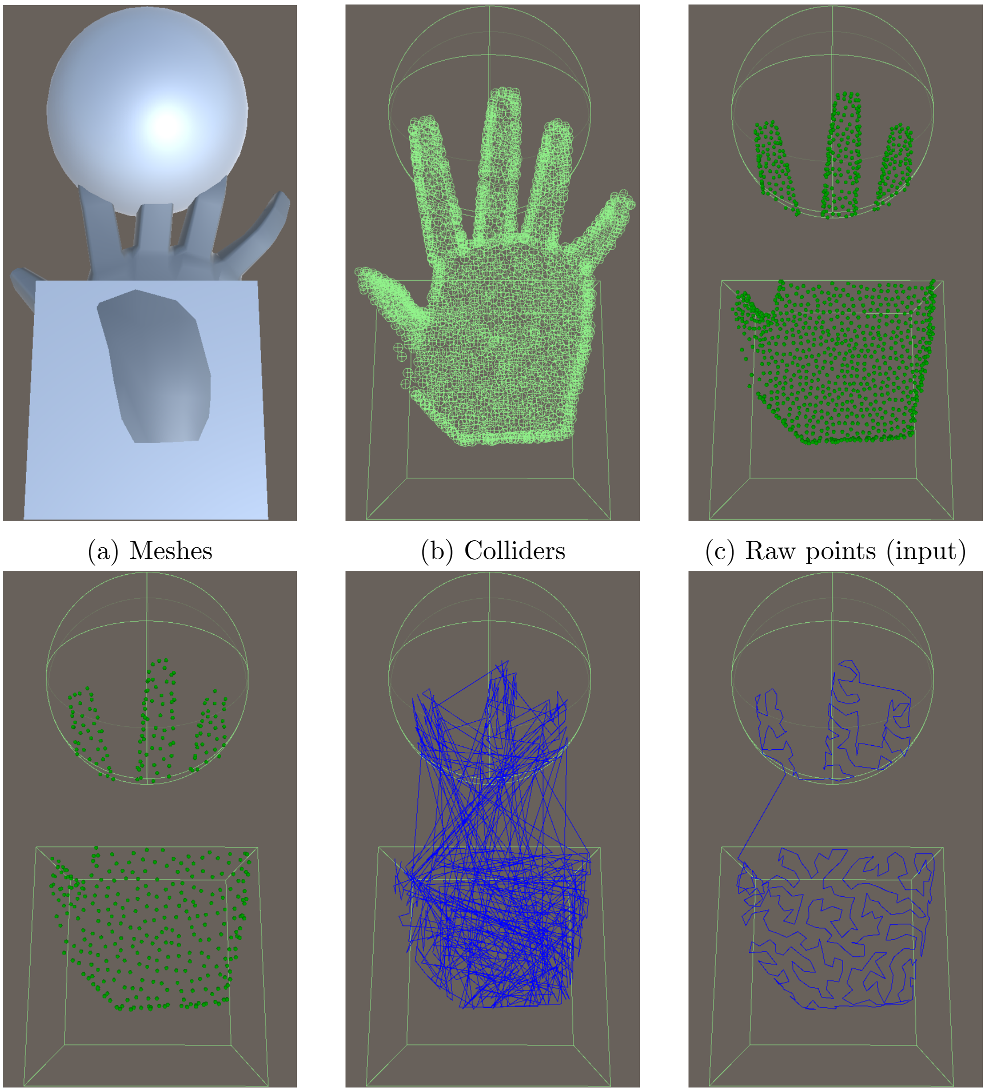
Ultrasound haptics are achieved by timing the output of multiple ultrasonic transducers to collide at the same focal point. This focal point can be moved around to generate the sense of shapes and patterns on the palmar side of the hand. Although ultrasound haptics can stimulate other parts of the body such as the forearm [167, 216], face [70, 193], and feet [109], the palmar side of the hand is the main target for contactless applications. One reason is that the hands are the body's tool for everyday interactions (e.g., holding a coffee mug, shaking hands, typing this paper). Another is that the hands are one of the most densely innervated regions of our body [37], making the ultrasound sensations feel stronger. Ultrasound haptics have been used to create the contactless sensation of touching another person [144, 188], a heart [179], mid-air buttons [143, 150, 201], fluids [104], gases [10] and more. There are two general approaches for modulating ultrasound haptics: amplitude modulation (AM) or spatiotemporal modulation (STM). MAMMOTH uses the spatiotemporal approach and we consider the frequency of each sensation to be its repetition rate [60]

There are two primary types of ultrasound haptic sensations: static and dynamic sensations. Static sensations are time-bound and often repeating. They can be anchored to the hand, but do not conform to the interaction such as changing the size or pattern. Static sensations include pre-made sensations of circles and squares [219] and "Hapticon" sensations designed and exported through Ultraleap's Sensation Designer [186, 220]. The designer's sensations do not conform to objects, and apart from being anchored to the hand, are static once designed. Dynamic sensations can change in real time and conform to the shape of interactions. This includes bare hands interactions with objects [141], fluids [104], and gasses [10]. Implementing the dynamic sensations requires expert knowledge of signal processing and geometry, and no existing tool is publicly available.

7.3 Path Routing Optimization

Our technique generates a sensation on the intersecting meshes based on the 2-opt path routing algorithm. This implementation is based on PRO-STM by Barreiro et al. [10].

The following six steps are taken to generate the haptic sensation:



(a) Meshes (b) Colliders (c) Raw points (input)

(d) Point Exclusion (e) Before 2-Opt (f) After 2-Opt

Figure 7.2: The first steps in our technique. (a) shows the 3D objects, (b) are the colliders, (c) are the intersection points, (d) are the remaining points after exclusion, (e) shows the path before and (f) after the 2-Opt algorithm.

1. Mesh Selection
2. Collisions with Discretized Hand
3. Intersection Points
4. Point Exclusion and Initial Path
5. 2-Opt Algorithm
6. Interpolation with Dynamic Frequency Modulation

7.3.1 Meshes

MAMMOTH works with most objects in Unity, such as standard 3D objects (e.g., cube, sphere in figure 7.2a) and custom 3D objects (such as the mammoth in figure 7.1). The meshes can move, overlap each other, and change shape and size, as long as the intersections are triggered by the collision system. The objects must have a collider component attached to them to recognize the intersection with the tracked hand.

7.3.2 Collisions with Discretized Hand

MAMMOTH uses the physics collision system in Unity to generate the intersecting points in a 3D space. Figure 7.2b shows the standard cube and sphere colliders, as well as a custom set of colliders created for the tracked hand in the MAMMOTH toolkit. The mesh of the tracked hand implemented with Leap Motion is fitted with sphere colliders on each limb. The positions of the sphere colliders are generated using a Poisson-Disc sampling over the hand mesh surface. Each sphere is then attached to a limb to follow the movements of the hand. Each sphere is 5 mm in diameter and is triggered as an intersecting point upon collision with another mesh collider. The other mesh colliders can be standard shapes like cubes or cylinders, or any other 3D mesh in Unity that can be used as a 3D collider as the mammoth in Figure 7.1.

7.3.3 Intersection Points

To capture intersections and enable haptics, a custom *MammothInteractable* component (i.e., C# script) is attached to each object. The component transmits the intersection points to a custom *MammothRenderer* component placed anywhere in the Unity scene, which runs the algorithm and transmits the final path to the component connected to the haptic device. Intersection points from each *MammothInteractable* component are combined to a single set of points in the *MammothRenderer*. Figure 7.2c shows the intersection points captured from the cube and sphere. All points captured used in the following steps are 3D coordinates.

7.3.4 Point Exclusion and Initial Path

To optimize the performance of the 2-Opt algorithm, several intersection points can be excluded to generate an initial path. We exclude contact points that are within a specified range of another point, keeping only one of them. Excluding points too close together is tolerable due to the focal point's size of 8.6 mm in diameter [60] and the two-point discrimination between approximately 15 mm (50 Hz) and 22 mm (200

Hz) for AM [23]. Figure 7.2d shows the resulting points using an exclusion range of 5 mm. The unoptimized initial path is seen in the path of Figure 7.2e. This path is not suited for ultrasound rendering because the path is too long and has overlapping edges, making it impossible to control the frequency of the sensation when considering one period to occur when the pattern repeats the same path.

7.3.5 2-Opt Algorithm

The 2-opt algorithm is a solution to the traveling salesman problem. With a set of points, the aim is to visit all points using the shortest path possible [39]. To achieve this, the 2-Opt algorithm checks whether reordering two edges on the path results in a shorter path. This is repeated until no improvement is found. As 2-Opt can be an expensive $O(n!)$ operation [217] where n is the number of vertices, there are several steps to optimize the implementation.

In the initial 2-Opt algorithm, a 2-Opt "swap" is executed on every check of nodes, and the total length of the path is computed. The amount of swaps and length calculations can be reduced by calculating the difference in length between the edges about to be removed and the new edges that will exist due to the swap. If the new edges result in a shorter path, they will also result in a shorter total length, and the 2-Opt swap can be executed. If they do not, the algorithm can move on to checking the next possible edges without the swap and length computation.

The next optimization is to use the Euclidean squared distance when checking whether the new edges will result in a shorter total path length, as the square root removed in the distance computation has no impact on the result.

Once the 2-Opt algorithm is completed, it results in a reordered list of points that form the shortest possible path for the haptics sensation, as seen in Figure 7.2f.

7.3.6 Interpolation with Dynamic Frequency Modulation

To render the path, we must interpolate between each point. If the points were sent directly to the device's buffer, it would result in an inconsistent experience due to the changing length of the path and the distance between each point. By interpolating between each point with the same separation we achieves a more consistent experience.

Barreiro et al. [10] introduced an interpolation separation of 0.175 mm. A path traversing the many contact points on the hand mesh can generate paths too long to render when using low separations. The lower the separation, the more points are sent to the buffer, resulting in a longer rendering time. The two-point discrimination threshold and focal point size allow us to use a higher interpolation separation. To render long paths, we dynamically modify the separation for each path. If paths are long and would result in a too long rendering time, the separation is increased. If paths are too short, the separation can be decreased. We determine the separation by bounding the rendering frequency (path repetition rate) between two values and computing a new interpolation separation whenever a new path is introduced. The interpolation separation s between each point is computed using the lower and upper frequency bounds f_l and f_u:

$$s = \begin{cases} \frac{f_l \cdot L}{F}, & \text{if } f_l > f_0 \\ \frac{f_u \cdot L}{F}, & \text{if } f_u < f_0 \\ s_0, & \text{otherwise} \end{cases} \tag{7.1}$$

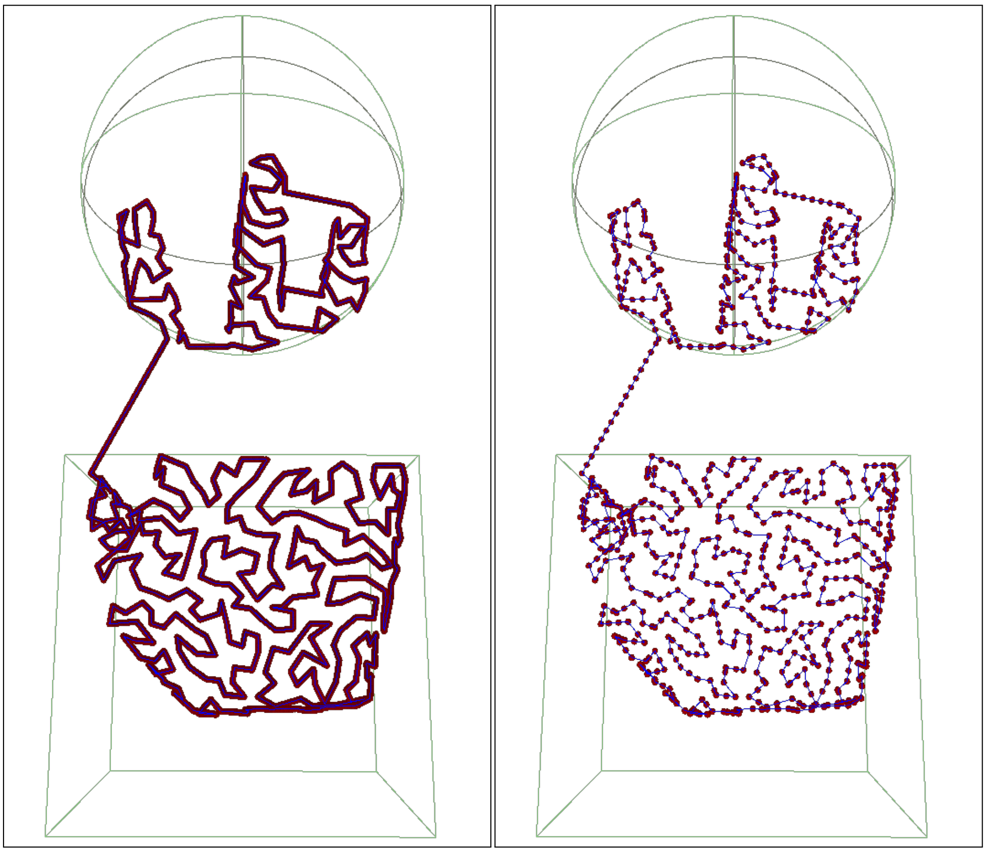


Figure 7.3: The final step in our technique is the dynamic interpolation separation. The top shows a 0.175 mm separation (static). The near proximities of the points resemble a continuous line. The bottom shows a 2.5 mm separation (dynamic), based on the path length, with visibly discrete points.

where

$$f_0 = \frac{F}{\frac{L}{s_0}} \tag{7.2}$$

The default interpolation separation is denoted by s_0 and the sampling rate is F (40Khz for the Ultrahaptics). f_0 is the frequency for the given path using the default separation of s_0. The interpolated paths are shown in Figure 7.3 using static interpolation separation (top) and dynamic interpolation modulation (bottom). To render the haptic sensation, the interpolated points are sent to a buffer for the ultrasound device.

7.4 Evaluation

7.4.1 Static vs. Dynamic Frequency

Barreiro et al. separated paths over 0.14 m into multiple paths of 0.14 m with 800 points 0.175 mm apart and rendered each path separately in 20 ms [10]. With observed shortest paths of total length L over 2 m, this approach would result in approximately 14 paths rendered in 280 ms. Instead of feeling a steady sensation, it feels like moving sensations on smaller surface areas. Figure 7.3 shows the shortest path rendered with an interpolation separation of 0.175 mm (left). Even though the points are the same size as in the dynamic path (right), the proximity of the points (red) results in a visually uninterrupted line, and the haptic sensation feels like a moving point along the path. The interpolation separation s of 0.175 mm and no dynamic frequency modulation renders a 3.5 Hz sensation. Using dynamic frequency modulation and a lower frequency bound f_l of 50 Hz, the points are interpolated 2.5 mm apart as seen in figure 7.3. At 50 Hz ultrasound patterns feel like steady sensations.

7.4.2 Performance Comparison

As the exact 2-Opt optimizations are not visible from the paper of Barreiro et al. [10], we can not conduct timing measurements for a direct comparison. Dynamic frequency modulation allows us to eliminate multiple steps in the PRO-STM algorithm. To separate the points into different segments, they conduct K-means clustering before the 2-Opt and recurring 2-Opt runs if the shortest paths found are greater than 0.14 m. Since we keep the entire path, there is no need for this separation.

Calculating the dynamic frequency modulation separation is an inexpensive $O(1)$ operation, and changing interpolation separation should not have an impact on performance. Point exclusion is a $O(n^2)$ operation where n is the number of points. MAMMOTH computes the path using 3D points, which decreases the performance compared to Barreiro et al.'s nodes projected to a 2D plane.

Barreiro et al. include a final *path refinement* step in their algorithm to align the path with "pressure peaks and ridges". This affects the intensity of the felt sensation to emulate highs and lows in a pressure field. As the Ultrahaptics emits a low force, the perceived range of intensity is low. The intensity of MAMMOTH is mapped between 0 and 1 at an API level, thus saving the performance required for the *path refinement* operation.

7.4.3 Improvements

As this is the first version of MAMMOTH, multiple performance and feature improvements are to be added later. Being an open source project allows us to make improvements transparent for users and for users to add their improvements.

Performance

Performance is key to creating a pleasant haptic experience, as an expensive algorithm results in both visual and haptic latency. The major contributors to decreased performance are the physics collision system using the discretized hand, and the 2-Opt algorithm.

We chose to use the collision system to generate the intersection points. This means Unity's physics system must register all collisions of the spheres in figure 7.2c placed on the tracked hand. Instead of using spheres, we could improve performance with mesh intersection algorithms such as 3D-EPUG [45]. Other custom hands could be created and use MAMMOTH, as long as they have surface points that can act as a "trigger" in Unity's collision system. With the intersection mesh, we can sample points across the surface and use those as the input intersection points. The accuracy of the rendered haptics also relies on the performance of the hand-tracking, in this instance the Leap Motion. If the hand-tracking is inaccurate or delays occur, the haptics will feel misaligned or sluggish.

There are several ways to improve the 2-Opt algorithm. Other algorithms such as 2-Opt++ [217] and 3-Opt [172] have tackled the traveling salesman problem. The 2-Opt algorithm involves calculating the lengths of the edges multiple times upon each iteration. This can be avoided by pre-computing a length array with the lengths between all spheres on the discretized hand. For all spheres on the same limb, this distance remains static. For spheres on different limbs, the actual distance depends on the movements of the limbs, creating possible errors by using the pre-computed array.

Features

We aim to continue updating the toolkit with new features.

One feature is the ability to specify that distinct objects should have individual paths, splitting the total path into smaller paths. This is not to segment the path like Barreiro et al. [10] but to eliminate the haptic feedback rendered in-between objects, as seen in the line between the sphere and cube in figures 7.2f and 7.3.

The addition of filters can change the sensation of the rendered path. This could be a simple moving average filter, which smooths the final path. A filter could also remove the inner parts of a path, keeping only the bounding outline.

Martinez et al. [141] explored ten variations of rendering haptics for objects in mid-air. This included approaches where haptics only was felt on the surface of objects. By setting up colliders on the boundary of objects, MAMMOTH can achieve a similar effect. But as our aim is a plug-and-play toolkit, a future feature is the option to enable surface-only haptics. This can be expanded upon with a feature to vary the intensity between the surface and the inside of objects.

7.5 Use Cases

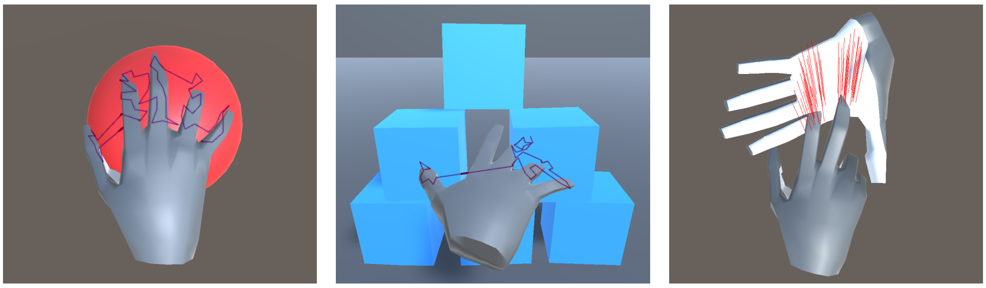
In this section, we show three use cases for MAMMOTH. For all examples, the toolkit must be imported and use the custom discretized hand.

7.5.1 Single object

Rendering haptics for a single 3D object is simple with MAMMOTH. In this use case, the haptics match a 3D sphere resembling a ball. The sphere has the *MammothInteractable* attached and a sphere collider. Upon interacting with the ball, the user feels ultrasound haptic feedback. The feedback is felt both on the surface and inside the ball. Figure 7.4a shows the interaction with the ball.

7.5.2 Multi-object

Figure 7.4b shows an interaction with six objects. The objects are dynamic and move upon collision. MAMMOTH combines the intersection points of all the objects into



(a) Single object (b) Multiple objects (c) Dual MAMMOTH

Figure 7.4: Use cases. The figure shows the application with (a) a single object, (b) multiple moving objects, and (c) two MAMMOTH instances at once enabling mediated social touch.

a single set and computes the optimized 2-Opt. MAMMOTH works with moving objects since existing intersecting points are reevaluated at a specified interval. The interval is the update rate of the haptic pattern.

7.5.3 Dual-instance

Using two instances of the *MammothRenderer* component and specifying its use for independent sets of Leap Motion and Ultrahaptics enables a social interaction between users. The users feel active haptic feedback when touching each other's virtual hands. Figure 7.4c shows the reciprocal interaction with the intersection points highlighted in red.

7.6 Conclusion

Adding ultrasound mid-air haptics to contactless interactions is achieved with either static or dynamic sensations. The static sensations can be inadequate to capture the shape of custom models and the dynamic sensations require expert knowledge to implement. We have introduced MAMMOTH, a toolkit with a rendering technique that automatically generates interaction-based haptics for contactless interactions. Our approach builds on previous techniques to generate the shortest path between points of intersection and render the haptics using spatiotemporal modulation. The technique provides a generalizable solution that works with most 3D objects and can be extended with new features. The toolkit can be used by both experts and novices alike. MAMMOTH is open source and available at github.com/maunsbach/MAMMOTH.

Acknowledgements

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Chapter 8

The Black Box of Digital Touch: Possible Consequences and Dilemmas in Designing Haptic Communication

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Manuscript

Abstract

DIGITAL touch communication is emerging as a counterpart to audio and video communication. But compared to physical touches, digital touches are easily manipulated, re-mediated or misinformed about due to technology acting as a mediator between senders and receivers. For future users of digital touch communication, the mediator can become a black box full of consequences they will not be aware of. Consequences we have seen examples of Deepfakes in video communication, private picture leaks in photo communication, wire-tapping in audio communication, and catfishing in text communication. To conduct responsible research and innovation with digital touch communication, we need to uncover the potential consequences for users. Consequences include being touched by a stranger while believing it is a friend, harming another while believing you are caressing them or having your touch data used for AI while believing it was a private, intimate touch message. We used scenario building to construct three future digital touch communication scenarios through an iterative process. The scenarios were presented in a series of workshops where participants were asked to describe the possible foreseen and unforeseen consequences. We analyzed the consequences and extracted dilemmas from them. The dilemmas were evaluated through a user survey. We hope digital touch communication creators will

use the uncovered consequences and dilemmas to conduct responsible research and innovation when working with a sense as intimate as touch.

8.1 Introduction

Telecommunication is a cornerstone of the modern world. Where would we be without text communication? The encrypted Morse codes transmitted during the Battle of the Atlantic [38] would never have happened. We would not be able to send business e-mails about matters small as large, nor complete contractual agreements digitally. We would not be able to text our loved ones goodnight when distanced. Where would we be without audio communication? Calling 911 to state and get help in an emergency is essential to saving lives. We would not be able to call the local game store to hear if they have the next game in stock. Sharing daily plans with elderly parents in the car on the way to work would not be possible. Where would we be without image and video communication? We would not be able to see the video of the moon landing. Online meetings have drastically reduced the need for airplane travel – the greener choice. We would not be able to re-watch that personal birthday video from a late grandmother.

The evolution communication forms come with *consequences*. Consequences that can change how we use the communication form, how much we trust it, and our eagerness to use it. Think of the previous examples. Interception and decryption of communication helped the Allies defeat the Axis during World War II, business e-mails can be spied on by competitors, and our intimate goodnight messages can be used to create the next generation of AI. Text communication can now be analyzed in millions of ways, manipulated, and shared without proper permissions. Calling 911 puts pressure on the caller to follow directions by the emergency responder, the local game store can use telemarketing to try to sell us games we do not want, and our family can get tricked into transferring money by phone scammers. While phone calls are decreasing, audio communication combined with video is increasing. It is possible to predict emotions through audio analysis [3], modify one's voice to sound like another [26], and much more. Videos can be faked (the moon landing is not), that online meeting could have been an e-mail, and your grandmother's birthday video was embarrassing, and she accidentally sent it to everyone. The consequences have led to new *dilemmas* we have to consider in a digitized world. They make us question how much of our personal information we are willing to share to be able to use certain services, whether manipulating digital content is appropriate, and whether we trust the people we are communicating with.

While audio and video communication has taken off to the clouds, *touch* is left deteriorating by the launch pad. Almost all our major communication forms are digested by only two senses: seeing and hearing. Touch is our first sense to develop and shape us [9, 64, 76], and "constitute both the oldest and the largest of our sense organs" [64]. The sense of touch is used to communicate love, anger, sympathy, and many more emotions [92]. Our body can be used to kiss a loved one, hit a stranger, and hug family and friends to comfort them. Emotions communicated through physical touches can be very intimate and personal, cordial with business intentions, and affected by religious and cultural beliefs and pandemics. Touch is critical to our well-being – especially for the nurturing of children [125]. Yet, the closest the average human comes to touch communication is the informative vibration a phone makes when receiving a notification.

Emerging haptic devices are enabling us to communicate touch at a distance. The devices take the input from one actor and mediate it through technology to output for another actor. Digital touch devices are often positioned as a step towards a solution to a virtuous problem; how can we make up for the touch lost when distanced? Touch communication may inherit or bring forth a new slate of consequences and dilemmas. Rarely does the research in digital touch communication take into account the potential impact the emerging communication form can have on society in the future. Jewitt et al. [106] looked at digital touch as a sociotechnical imaginary, and Cornelio et al. [35] discussed responsible research and innovation in mid-air haptic scenarios.

This paper looked to the past for consequences in other forms of long-distance communication. We used this to construct three futuristic scenarios for touch communication and iterated them through pilot workshops. The scenarios were presented and discussed at a series of workshops to uncover the "foreseen and unforeseen consequences" they potentially could induce. The scenarios were clustered using an affinity diagram, and the clusters were discussed as themes with comparisons to other communication forms, responsible research and innovation frameworks, and legal issues. To analyze how touch brings forth new dilemmas and differs from other communication forms, we extracted five dilemmas from the analysis. The dilemmas were presented in an online survey with 100 participants, where they were forced to make a choice related to a dilemma and explain their reasoning behind this choice.

This paper will allow digital touch, mediated social touch, and other haptic researchers and creators to reflect on their emerging technology while in the design and development process. The results of the dilemma survey can help make informed design choices. Far too often, research in technological advancement is done with two eyes on the future while being blind to the unforeseen consequences. Responsible research and innovation are a necessity – especially for interactions as intimate as touch. We hope other researchers will follow up on the consequences and dilemmas discovered here to uncover more consequences and dilemmas, create ethical guidelines, and limit privacy risks. Digital touch communication will for users always involve a black box as a mediator. Our hope is that designers can better anticipate it when they unwittingly fill the black box with consequences or can make it more transparent for the users when they wittingly do so.

8.2 Related Work

8.2.1 Social Touch

Physical social touches are essential to human development, well-being, and expression and entail legal implications (see Gallace and Spence [64] for a review). Touch shapes us from when the day we are born. In neonatal nursing, touch is an essential way to communicate support and protection and create a feeling of attachment between children and their caregivers [50]. Touches are a safe and effective way to reduce pain for newborn children in intensive care units [90], and are "gentle, calm and caring tools among "all the other harsh things"" [85]. Elkiss and Jerome [53] described touch in osteopathic manipulative treatment as both "diagnostic and therapeutic". Touch adds a nearness to the relationship between a physician and a patient. This relationship is not one-directional from the person being touched to the person touching them, the physician is likewise affected: "To touch another is to be touched back. Touching, like dialogue, is bidirectional and reciprocal" [53]. Like dialogue, touch can communicate distinct emotions such as anger, embarrassment, and love [92]. With the exception of instrumental use or accidents, all touch interactions hold meaning [111], be it of an informative or emotional nature. Touching someone without intent is much harder to deny than other types of non-verbal communication: "It is much easier, for example, to engage in provocative looks and gestures and then, when confronted, to deny that any message was conveyed than it is to deny the intent of a sexual touch" [111]. While touch communication can act on its own, it can also amplify other communication forms. Like a being told "good job" accompanied by a pat on the back, or saying grace while holding hands. Lack of touch when being in isolation or physically distanced, like long-distance relationships, can have adverse effects. During the COVID-19 pandemic the lack of intimate touches led to higher anxiety and greater loneliness [224]. The touch deprivation during the pandemic may have added to the already existing problem of touch deprivation, or "touch hunger" [56].

It is no surprise then, that researchers and designers are using technology to mediate social touch at a distance (see Huisman [98] for a review). Jewitt et al. [106] described the possibility of digital touch as "the desire for more felt digital experiences that reconfigure the place of touch – pointing to an opening, albeit a complex and contested one, for digital touch.". The complex and contested nature of touch in a digital world is often overshadowed by the novelty of distanced touch. Digital touch communication is enabled by haptic technology such as vibrotactile, force feedback, and ultrasonic feedback. The input, mediation, and output can be implemented using various technologies such as sensors [171], virtual reality (VR) [188], hand-tracking [144], teddy bears [226], pillows [48], and more. This has enabled distanced interactions such as hugging [214], caressing [144], kissing [31]. While the aim of the devices is often noble – to enable social touch wherever needed – social touches are not always encouraged. Touch is intimate, private, and often restricted for good reasons. As mentioned above, it is almost impossible for touch not to hold meaning. When this meaning can be interpreted as dangerous for health reasons, boundary crossing, power or sexual abuse, or otherwise inappropriate, legal implications occur. The legalities are upheld by each country's legal institutions. Digital touch may add additional foreseen or unforeseen consequences not present with physical touch such as new privacy risks, ethics issues, and legal repercussions.

8.2.2 Communication Counterparts

We look to non-touch communication forms to discern past consequences and their impact on society. Communications through text, audio, image, and video have all seen their share of consequences, of which we here provide a non-exhaustive overview.

Text Communication

Text communication can take many forms from ancient letters carried by pigeons to our everyday interactions with e-mail, SMS, and instant messaging. In his 1871 book, Tegetmeier [207] claims carrier pigeons can be traced back to the sixth century before the Christian era. The foreseen aim of using carrier pigeons was simple; to carry a message from A to B. This required not "mysterious power or instinct" as it was publicly thought, but by training and observation of landmarks [207]. Even though the aim is simple, birds become the prey of cats and hawks, get lost in the fog, or can get intercepted during their journey. A tale of the siege of Ptolemais mentions such an interception. A pigeon was carrying a message from a sultan to the city proclaiming aid was on the way, but the besiegers intercepted the message and forged a new message that stated the sultan had "such other important affairs" [149]. As carrier pigeons always fly back home to where they were bred, the city did not question the source to be true and immediately surrendered the city [207].

Fast forward to today, similar questions to the source of written communication occur because accounts can be hacked, people and groups can be impersonated (e.g., phishing scams, cat-phishing), devices (e.g., smartphones, computers) can be stolen, and more. Do we actually know who we are communicating with? It can be difficult to know when all the information provided is text. If we see a text from a friend or an e-mail from a colleague, we are likely to believe they are the true source. The city of Ptolemais thought they knew the source of the pigeon's communication, leading to a fatal defeat.

Sourcing is not the only issue surrounding text communication. We share massive amounts of data throughout the year in messages, which can be shared further by the apps we use. Not only can the communication be captured by illegal actors, but it can also be legally analyzed and abused. Employees of major American companies such as Walmart and Starbucks have their messages on Slack, Teams, and other apps captured and analyzed using AI by the third-party company Aware AI for use in internal surveillance [55]. The companies can monitor reactions to corporate policies, identify discrimination, and much more. Aware AI uses data from its clients to train its machine learning models. The data repository contains "about 6.5 billion messages, representing about 20 billion individual interactions across more than 3 million unique employees" [55]. Facebook used to scan private messages for malicious intent but now claims to use AI to proactively detect "patterns of behavior" without analyzing the end-to-end encrypted messages [147].

Audio communication

In 1983, the band Styx released their hit song "Mr. Roboto". The song's hook centers on Japanese lyrics sung through a vocoder. The vocoder transforms the sound of a sung melody into what one might imagine a robot sounds like. In sound processing, the input is affected by a transfer function, which results in the output we hear in the song. Over 40 years later, we can transform audio to sound like much more than robots. Deepfake technology can change your voice to sound like another person [26]. The vast amount of speech data from people like Barack Obama enables other people to sound like him without the need for impersonation skills and for actors like Mark Hamill to sound like younger versions of themselves [177]. A song using the AI voices of famous artists was even submitted for an award at the Grammy's [42]. In the 2024 American election, a robocall sounding like President Biden was used to dissuade voters from going to the polls. The voice was seemingly AI-generated, and the campaign manager confirmed it to be fake [205].

In 2013, it was revealed that the United States National Security Agency (NSA) was collecting telecommunications metadata from US citizens. It was later revealed that this collection also targeted non-US citizens [78, 126] and extended beyond audio communication metadata to live chats through the Prism program in cooperation with companies such as Apple, Google, and Facebook [77]. Communications thought to be private between senders and receivers were shared with government agencies without informed consent.

Image and Video Communication

The cosmetic retouching of photographs has long been a discussed topic. In the fashion world, the digital manipulation of model photographs has amplified the ”thin ideal”, which has been linked to body dissatisfaction, low confidence, and eating disorders [176]. While retouching used to require the aid of professional “photoshoppers”, it can now be achieved with the press of a button in apps such as Snapchat and Facetune [174]. Snapchat can apply quirky filters such as dog features and devil horns, while Facetune is a “quick photo touch-ups to a complete makeover” [131]. In a 2021 report from the University of London, 95 % of respondents said they felt pressure over their body image [71]. It is no surprise then that two out of three of the respondents reported editing pictures of themselves, spending up to ten minutes to “prepare” a photo for sending or posting [71]. The pressures of the body ideals and ease of editing pictures have reached the point of normalization, so much so that “there is often an a priori assumption that filtering has been applied” [128]. The real world we wish to share is often not the one we end up communicating. These digital manipulations are used when presenting ourselves on social media, job applications, dating apps, and more.

Digital photo manipulation is not just widely used for social interactions. Similar to audio, it is possible to manipulate videos using Deepfake technology digitally. Deepfake technology can modify faces in videos [229], and whole videos can be created using artificial intelligence [133].

8.2.3 The Black Box Perspective

In the previous examples, there is always the mediator of communication between the actors. We will refer to this as the *mediation* in digital communication. For common users, this mediation poses many unknowns. Take a simple phone call. It requires one to call a number, the audio to be sent in packages following network protocols through telephone towers, the phone company, to the receiver who may or may not respond, and for the audio to be output through their speakers of choice. Throughout this process, there are several steps wherein the audio can be stored by the phone company or government, hackers can listen in on the call, or the call can be manipulated along the way. Callers rarely know the details of how the voice is transmitted from A to B but primarily care that it does so. As it is known in many other technologies, we refer to this as a *black box* system and use this as our perspective when constructing digital touch communication scenarios and analyzing the possible foreseen and unforeseen consequences within them.

While the “black box” term was not coined by Cauer, his work set the precedent for its use in electronic circuits [24, 25], interdisciplinary in fields such as engineering [116], philosophy [230] and psychology [181]. The black box refers to a linear system consisting of three parts: input, black box, and output. A known input entity is given to the unknown capabilities of the black box, which returns a known output.

The black box perspective can be compared to the Shannon-Weaver model of communication [190]. As with the common use of their model, we view the black box on a technical level, i.e., as a model for the transmission of communication data. Many

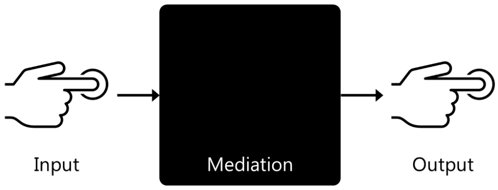

Figure 8.1: The basic black box model for touch communication data. This is the view of the common users of digital touch communication.

other factors affect communication between actors, such as context, psychological states, and power balance. Fig. 8.1 shows the simplified model with mediation as an unknown. This is the basis of the black box definition – a known input, an unknown transfer function (black box), and a known output. It allows us to pose the broad question: “What can happen to communication data between being sent and received?”.

We consider *digital social touch* as an interpersonal interaction between two or more actors, providing haptic sensation to each other through haptic technology. In the black box perspective, each actor creates an input, which, through a mediation system, results in a haptic output for another actor. In recent research, the system has been in the form of buttons [108], hugging teddy bears, prosthetic handshakes [153], body-congruent virtual reality interactions [144] and more.

8.3 Scenario Workshops

We first conducted two workshops in which the participants deconstructed future digital touch scenarios to capture the consequences for users. After analyzing the results, dilemmas were extracted and surveyed to explore the reaction (see Section 8.4).

8.3.1 Scenario Construction

The construction of these scenarios aims to throw light on the potential consequences of digital touch communication, providing a foundation for responsible research and innovation. By anticipating and analyzing possible outcomes, we can better prepare for the ethical, social, and technical challenges that may arise. To construct the scenarios, we look to the past consequences of other communication forms in Sec. 8.2.2. By analyzing text, image, video, audio, and the current state of touch communication through the black box perspective, recurring themes occur. We believe the consequences can be grouped into three categories: sharing, source, and transformation. Fig. 8.2 shows the black box with the three categories. The three scenarios constructed are based on these themes in text form with an accompanying teaser image. The scenario based on *touch sharing* is constructed to explore the consequences that come with the conversion of touch to data bits. Data can be shared, reused, stolen and more. The scenario on *touch source* asks what happens if we find out who we thought we were interacting with was in fact someone else. The final scenario on *touch transformation* shows how the digitization of touch can enable us to modify a touch between its creation and reception.

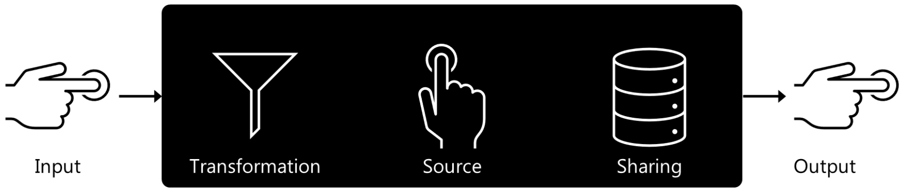

Figure 8.2: Caption

The scenarios are devoid of technological artifacts. This is to keep the focus on digital touch communication as a sociotechnical potential and not be limited by the current state of haptic prototypes.

Durance and Godet [51] laid out five conditions for a scenario to be credible and useful: pertinence, coherency, likelihood, importance, and transparency. The scenarios are pertinent as the technology is based on interactions between human individuals. By constructing scenarios for users and deconstructing them using the possible eventual users, we gain direct insight into the real-world consequences. We ensure the scenarios are coherent by constructing encapsulated stories and iterating on them through two pilot workshops. As these are normative futuristic scenarios ("alternative images of the future" [51]), we cannot guarantee they become true. By basing the scenarios on the existing progress in digital touch communication and imagining the future progress through other communication forms, we hope to ground likelihood in reality. This grounding also scopes the scenarios to the three themes, which narrows the results in an otherwise infinite space. As touch is one of our most intimate of senses and consequences in other communication forms have had severe psychological and societal effects, it is important that we prepare for responsible innovation with technology. We ensure transparency by introducing the participants to the topic of digital touch communication and consequences in other communications before the scenarios are presented.

Scenario Premise

While current haptic technologies are limited to basic vibrations and feedback, ongoing advancements suggest that more sophisticated and realistic touch communication devices are plausible. This following premise allows us to speculate on the broader implications of such future technologies.

> Imagine a future where our touches can be digitally shared. Just like video and image communication, we can touch each through technology and the touch can be transmitted through apps and other parts of the internet. Touches can even be recorded to be shared and played back later. They can be very realistic and require a yet-to-be-invented technology.
>
> You will be presented to three digital touch communication scenarios and questions about them. While these scenarios may seem unrealistic at this point in time, our focus is not on the technological feasibility, but to speculate on the possibilities issues as if they were real.

Scenarios

We here present the three scenarios that were used in the workshops. The scenarios are about specific cases, and are based on historical consequences found in other communication forms. Touch Sharing relates to how we sign over the rights to data when we use social media services. Touch Sources relates to how we can be hacked or cat-phished, and may not know who we are communicating with. Touch Transformation relates to photoshopping and deepfakes, and how the representations of the real world are modified digitally.

1: Touch Sharing

> *Sam and Alex are in a long-distance relationship. To make up for the touch lost because of the distance, they record personal touch messages for each other. They use a program by the TouchCom company, which enables them to feel like they actually are touching each other. Initially, these touches were simple stroking on the arm, but as the technology progressed, this became hugs, kisses, and eventually full-body interactions. When interacting through digital touches they feel more connected which is aided by the realism the technology provides. Before being able to record the touch messages they signed a consent form to TouchCom. The company now owns all the recorded touches and stores them in its database. TouchCom can use the touch data as they wish and can for example see when and how these touches have been interacted with as well as analyse, share, and reuse the data.*

2: Touch Source

> *Robin is playing a social virtual reality game. In the game, they can embody a personalised digital avatar and interact with other avatars controlled by other people. For a greater immersion, Robin is wearing a full-body haptic suit that allows them to feel interactions like being hit with virtual paintball, do high-fives, as well as touch other avatars. Robin can specify their privacy settings – for example, which avatars are allowed to send touches to their haptic suit. After playing the game with some of their real-life friends, Robin finds out one of them, Andy, has been hacked, and someone else was controlling their virtual avatar.*

3: Touch Transformation

> *To get a great start to the morning, River goes bouldering. After bouldering, their hands can be quite rough and tend to twitch a little bit. They are a marketing consultant and often works from home. When meeting clients online, the client sometimes insists on starting with a digital handshake. To perform the digital handshake, they do a handshake in mid-air in front of the computer screen. While shaking, they can feel the other person's hand using realistic mid-air haptic technology. Their handshake is in real-time converted to feedback for the recipient. River has read that a firm, but pleasant handshake leaves the best impression but fears their digital handshake doesn't leave that impression on the recipient. To*

(a) Scenario 1: Touch Sharing. AI prompt: A blurry person hugging a solid human person.

(b) Scenario 2: Touch Source. AI prompt: A person playing a virtual reality game where people can talk and touch each other, wearing a full-body suit.

(c) Scenario 3: Touch Transformation. AI prompt: A handshake during an online meeting where one of the people is inside the computer screen.

Figure 8.3: Teaser images shown to participants while deconstructing each scenario. AI-generated through DreamStudio [49].

improve their handshake, River has installed a handshake mod[1] *for an improved handshake. This mod allows them to adjust the strength, pleasantness, and other factors of their handshake. The receivers are unaware of the modification.*

8.3.2 Scenario Deconstruction

The three scenarios were presented at two scenario workshops to deconstruct the scenario and obtain the consequences. In the workshops, participants were asked to write down answers to: "What foreseen or unforeseen consequences may arise for the users in this scenario? ... or other users using similar interactions?". The responses were written down on post-it notes on a digital whiteboard. Following the participants' deconstruction, the authors clustered the notes using an affinity diagram. Themes were extracted and explored based on the affinity diagram to identify common concerns and insights.

8.3.3 Participants

We recruited 16 (7W/8M/1Other) participants for the two workshops in two different countries. All participants filled out a background questionnaire, signed an informed consent form, and were given a gift worth approximately 18 to 27 EUR for their participation. Eight participants were in long-term relationships and two were parents/guardians. Their backgrounds ranged from HCI researcher with extensive knowledge of haptic technology to nurses, translators, light technicians, and people in sales and communication.

8.3.4 Procedure

The participants were introduced to the workshop after signing the consent form and filling out a background questionnaire. The introduction included related work on digital touch communication devices and consequences in other communication forms found through the black box perspective. The black box model was not introduced. To prepare participants for the scenarios, we presented the futuristic premise of the technology (see Sec. 8.3.1).

The main part of the workshop was centered on the three scenarios. The participants were split into groups of two to three. An interactive "MIRO" board was used for participants to write their thoughts on digital post-it notes. The following procedure was repeated for each scenario:

1. **Scenario presentation:** The researcher read the scenario aloud while participants could read along. Afterward, the participants could ask any clarifying questions about the scenario.

2. **Speculation:** The participants were asked to speculate on the foreseen and unforeseen consequences. For inspiration, each group was given a print-out of an example of consequences found in other communication forms. The speculation consisted of the three phases:

[1] Modification: software that changes an existing application

a) **Individual brainstorm (3 min.):** Participants were given time to think for themselves and formulated consequences they could envision on the post-it notes.

b) **Group discussion (7 min.):** The groups discussed their post-it notes internally and decided on 1-2 that they could extend and present in plenary.

c) **Plenary presentation (10 min.):** The chosen consequences were presented by the groups. Clarifying questions could be asked by other participants and the experimenters. The researcher took notes.

The workshop concluded with the opportunity for participants to provide any overall thoughts on the scenarios, our premise, or digital social touch as a concept.

8.3.5 Results

We captured 282 notes from the workshops. 156 of these were participant-written post-it notes on the interactive whiteboard, and 126 were notes written by the researcher during the plenary presentation to record the additional discussion that can arise when thoughts are presented in the plenary. The length of the participant-written notes ranged from single words (e.g., “scary”, “deceptive”) to sentences totaling up to 49 words. Participants wrote the most notes about scenario one (61), followed by scenario two (48) and scenario three (47).

The notes were clustered using the Affinity Diagram method as seen in Fig. 8.4 (see App. 8.7.2 for the distribution of the notes). The first author created an initial clustering after which the other authors edited the clustering.

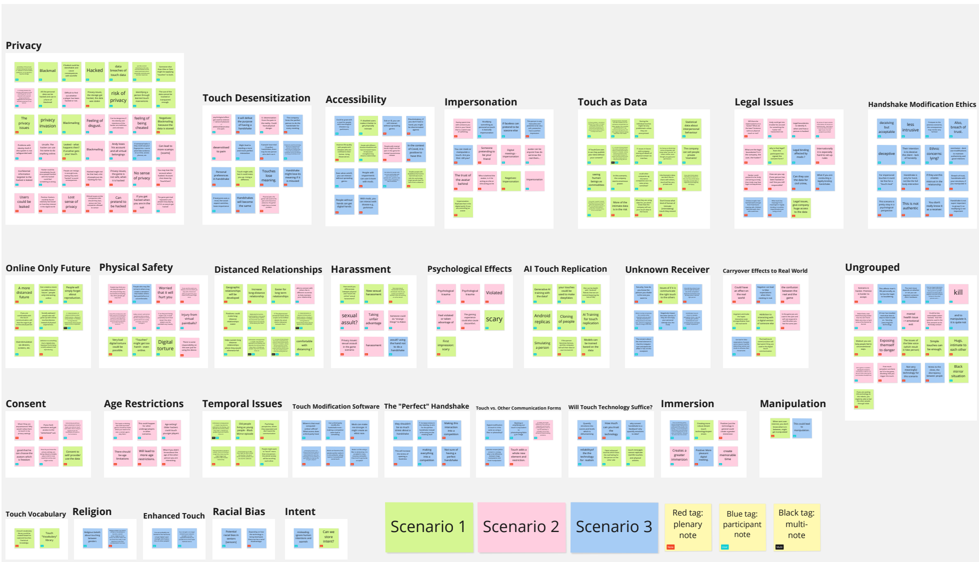

Figure 8.4: The Affinity Diagram. A clustering of the participant and plenary notes.

8.3.6 Themes

We clustered the notes with the Affinity Diagram. We will here derive themes [6] from the clusters and discuss them in relation to their foreseen and unforeseen consequences and how they relate to similar issues in other communication forms. We will indicate whether quoted notes originate from participant notes (**Participant**) or the researcher's notes from the plenary discussion (**Plenary**), and if it is written during scenario one (**Scenario 1**), two (**Scenario 2**), or three (**Scenario 3**)

Privacy of private touches Participants established a large concern for privacy in the workshops. In our digitized world, where privacy invasions lurk around every corner, it is no surprise that this is a major concern for participants.

Participant – Scenario 1 "*Just like current ransomware, this very intimate dataset can be stolen particularly from vulnerable and those who lost their loved one*"

Participants linked the fact that these touches are *digital* to the privacy issues found in our online interactions. These concerns have major consequences for both private citizens and major corporations. It is unclear how many private citizens are victims of ransomware scams, but in a survey of a representative sample of American adults, Simoiu et al. [197] estimated that 2%-3% were victims over a 1-year period and that the average payment demand was $530 (4% reported paying). In January of 2023, United Kingdom's Royal Mail was the victim of a ransomware attack that blocked international shipments [43]. Refusing to pay the hackers, Royal Mail's files were ultimately published on the dark web. But what does this mean for touch?

Participant – Scenario 1 "*All the personal data can be hacked and use in a form of blackmail*"

While ransomware attacks like the attack on Royal Mail affected operation files, other ransomware attacks hackers threaten to leak private images or videos. In 2023, a plastic surgery clinic had to inform their patient that their sensitive information, including naked photographs, were leaked online after they decided not to pay ransomware hackers [2]. And it was not the first time such a thing happened [89]. If digital touches were to feel realistic and be realized in multi-modal 3D experience, hackers could blackmail people by exploiting the possession of their most intimate interactions in digital form.

New opportunities for accessibility When we do not have to be in proximity of another person to touch them, we can not spread germs to them.

Participant – Scenario 3 "*Even when sick/ill, you can interact without spreading germs*"

Working from home increased greatly during the COVID-19 pandemic [196]. Our digital tools have reached a point where many occupations can be conducted remotely. But this also led to social touch starvation [224].

Participant – Scenario 1 "*In the context of Covid, it is positive to have this*"

While most people's isolation during the pandemic was temporary, some people are isolated for longer durations due to long-term illnesses like severe immunodeficiency. The spreading of germs works both ways, with digital touch allowing people to interact with others while staying protected.

Plenary – Scenario 3 "*People with impairments can use it more with mods.*"

Some participants thought this could increase accessibility for people with disabilities or impairments. Modification software can remap any input to interactions.

Like the Xbox adaptive controller, input and touches can be mapped to other limbs and devices such as "*bite switches, foot pedals, touch-sensitive pads*" [72]. But without the ability to remap touches or if people for other reasons would be unable to use it, it could also add another aspect of discrimination.

Plenary – Scenario 3 "*Discriminatory, if you don't have a hand, you might be discriminated against*"

Will touch lose meaning? Another modality to coexist and be combined with our existing arsenal of online communication forms may lead to overstimulation. Participants questioned whether this would lead to a more online future.

Participant – Scenario 1 "*Can create a more sociably distant future - people only interacting online*"

Using social media platforms like Facebook may increase our well-being with online relationships but decrease our well-being with offline relationships while also depending on personality characteristics [97].

Participant – Scenario 3 "*People who need this technology will use it to create the most 'pleasant' handshake. that means they are creating similar or even the same feeling for handshake. hence, the meaning for having a handshake is lost.*"

Participants noted that modifying a handshake may cause touch to lose its meaning. When we digitally alter something to make a perfect version of it, is there any authenticity left? With photos, there is often an assumption that they are digitally manipulated [128]. If we believe a touch we receive will be manipulated, will it still make us feel anything?

Participant – Scenario 3 "*Can lead to false expectations if people are to meet in real life where they cannot use mods to enhance their movements.*"

Online-first interactions can lead to awkward situations when meeting in real life for the first time. People sometimes share intimate secrets before meeting for the first time and regret this when meeting. What if we shared intimate touches before meeting in real life? An interaction that is usually reserved for later in relationships. Wang et al. [228] outlined seven reasons why people made posts on Facebook that they later regretted, including "*they are in a "hot" state of high emotion when posting, or under the influence of drugs or alcohol*" [228]. The possibility of being physically intimate with another could lead to a state of high emotion. But what if we know we later may regret a digital touch? Will it still hold intimate meaning?

Touch as a data commodity For some companies, customer data is one of their most valuable currencies. Companies like YouTube, Facebook, and Reuters earn money through targeted advertising. The targeting may be "behavior-based advertising" and focus on "who they are, what they like and what they are most likely to purchase" [61].

Participant – Scenario 1 "*Privacy problem - interactions between the couple is no longer acting within them but also shared with third parties. For close interactions like kisses, it may be quite terrible for others to analyse and share it*"

But what if companies also knew who we liked to touch, why we liked to touch, and how we touch? And what if this was combined with biometric data easily available through devices like Apple Watch and FitBit? This combination could indicate how we react to specific touches.

Participant – Scenario 1 "*your touches could be used to make deepfakes*"

AI is making a continuous impact on our everyday lives. AI image generators can create life-like images, where people struggle to tell which is real [135], and deepfake technology can be used to generate video and audio content. But none of this is possible without a massive amount of training data. If companies store digital touches, we are giving them the opportunity to create digital AI touches.

Participant – Scenario 1 "*The company can sell people private 'moments'*"

If a company owns our data, what stops them from reselling it without modification? The resold touch may be of a personal nature. It could be a private hug between a grandchild and their grandparent before their passing. This digital hug may provide lasting value for the grandchild, but what if a company resells that touch? Deceased people are not covered by GDPR.

If modifying a handshake is ok, what about other body parts? Handshakes are common everyday interactions we can conduct with people we have just met. It can be used to signal greetings, start business meetings, and complete legal transactions.

Plenary – Scenario 2 "*Handshake is not super important to group 3, so modifying is not important*"

Hall and Hall [86] called it a ritual we should maintain to sustain social order. If it is purely of symbolic value, does it matter how it feels? [30] claims it has an effect on first impressions: "*A firm handshake was related positively to extraversion and emotional expressiveness and negatively to shyness and neuroticism*". The sentiment of the low importance of the modification of handshakes was shared by several participants.

Plenary – Scenario 2 "*Handshake is only for hand, not like the full body interaction*"

Fusaro et al. [63] explored the appropriateness of virtual caresses on body areas. The hand was rated as very appropriate to touch and not very erogenous. Almost all other body parts were rated more inappropriate to touch and more erogenous. If handshakes are appropriate to modify digitally, is there digital contact from a body part that is inappropriate to modify?

Digital touches can cause actual harm Unwanted touches can cause great harm. As one of our most intimate touches, it can create experiences that can stay with us for our whole life.

Participant – Scenario 3 "*People who may like to harm others may create a sensation that makes others feel painful/hurt or uncomfortable.*"

Physical safety is essential for haptic technology. If we hear something we do not want to, we can take our headphones off, turn off speakers, or cover our ears like a toddler. If we are watching something we find uncomfortable, we can avert or close our eyes, although even a quick glance at unsolicited pictures may feel intrusive [139]. If we are using a hand-held haptic device, we can let go of it. If we use mid-air haptics, we can move away from the emission area. But if we use technology like haptic gloves or full-body suits, it may take a while to take it off. If there is no immediate off button, users could get captured in unwanted touches. The ability to turn off devices is essential for sensory autonomy [11].

Plenary – Scenario 2 "*People may think you are playing a game in VR and punching very hard without knowing the other people get very hurt*"

There is also the possibility of unwittingly creating harm or inappropriate touches. If we are unaware of the technical setup of the receiver of our digital touches, we do not know how our transmitted touch data is mapped to their body. They may apply a "gain" to the intensity, resulting in hurtful touches. They could remap the touches, for example, changing the target of a high-five to the foot or an intimate body part. Barrow and Haggard [11] argue that active touch "*implies a degree of implicit consent and expectation*". We may implicitly consent to how *we* feel when conducting active touch, but do we consent to how the receiver reconstructs our touch onto their body?

Digital touch crosses legal borders Who has jurisdiction when digital touches online become unlawful? And who determines these laws?

Plenary – Scenario 2 "*Internationally it is especially hard to set up rules*"

A similar issue exists with doxing [2], which is not defined in international human rights law or many national laws. This led to recommendations that governments need to check whether existing laws apply to doxing, that governments and industries must cooperate on the issue, and that laws must exist to hold tech platforms accountable [157]. It is unclear whether laws on physical touch also pertain to digital touches.

8.4 Dilemma Survey

The workshop participants highlighted several dilemmas that will arise with digital touch as a communication form. To understand whether and why people have differing views on these dilemmas, we conducted an online survey in which a selection of the dilemmas was presented.

8.4.1 Dilemma Construction

We constructed five dilemmas based on the workshops. The dilemmas were constructed following the framing of the "Experience Machine" [44, 158]. The dilemmas are presented in the form of a futuristic scenario. At the end, the reader is presented with a choice ("Would you plug in?" in the Experience Machine) to be answered with a forced "yes" or "no". Readers can not answer conditionally (i.e., "yes, but only if...") but are asked to explain their choice afterward, where nuances and considerations can be captured. Each dilemma is designed to probe the consequences of some of the themes identified in the scenario workshops including privacy, trust, and manipulation.

Our dilemmas asked participants whether a choice by a person was "morally appropriate". To guide the participants in the definition of this, we included the following definition of "moral" from Cambridge Dictionary in an introduction: *"relating to the standards of good or bad behaviour, fairness, honesty, etc. that each person believes in, rather than to laws"* [1].

Dilemma Premise

Similarly to the workshop scenarios, participants were introduced to a futuristic premise:

[2] Doxing: "Doxing refers to the online researching and publishing of private information on the internet to publicly expose and shame the person targeted." [58]

> *Imagine a future where our touches can be digitally communicated. Just like we can see each other realistically in video technology, we can touch each other through haptic technology. Haptic technology refers to technology that can create an experience of touch, such as vibrations and force feedback. The touch can be transmitted through apps and other parts of the internet. Touches can even be recorded to be played back later. They can be very realistic and require a yet-to-be-invented technology. While these digital touches may seem unrealistic at this point in time, you should not focus on the technological feasibility but think of the following as if they are possible.*

Dilemmas

We constructed the following five dilemmas. The second dilemma has a follow-up question to capture how digital touch differs from the other communication forms.

1: Is it morally appropriate to digitally touch a younger version of a partner? This dilemma is inspired by workshop notes about old people living as young people and reliving memories through photos and videos. Similarly, we can possibly relieve touches in the future as they are stored as data. Seeing old photos, movies, or social media posts can be awkward for some people. In researching how people remember through old content (e.g., photos and written posts), Robards et al. [178] wrote: "earlier posts sometimes provoked embarrassment, shame or awkwardness, as they confronted difficult, sometimes life changing moments." But reliving digital touches may add an additional layer to this that transcends the awkwardness, making it inappropriate.

> *Sam and Alex are in a long-distance relationship. They use haptic technology to digitally touch at a distance (e.g., hugs, kisses, full-body interactions). The touches feel realistic, and Sam saves old recordings to be played back later. Alex finds out Sam recently has been interacting with an old touch recording of Alex without Alex' knowledge. All the recordings are above the legal age limit.*
> *- Is it morally appropriate for Sam to digitally touch a younger version of Alex?*

2: Is it morally appropriate to keep digital touch recordings after a break-up? This dilemma was constructed to understand the views on ownership over digital touch recordings. If a person can be identified from a photo, it is considered personal data under GDPR [101]. The "right to be forgotten" under GDPR gives those it applies to the right to request their personal data be deleted. In some circumstances, the requested party must comply with, while they may have a legal basis to not do so in other circumstances. It is unclear how this would apply to digital touch. One workshop participant noted: "*If break-up, people may find it hard to move on*". If two people have been intimate, they may be able to identify the other person as the source of a touch recording due to experience, or they may already know the identity due to the history of its creation (i.e., they recorded it or were sent it). Our dilemma explores this in the context of intimate touches shared between partners.

> *Robin and Kim are using similar haptic technology. After they break up, Robin insists they delete all the touch recordings they have saved. Kim declines.*
> *- Is it morally appropriate for Kim to save the recordings?*

We added a follow-up question to the dilemma to understand how digital touch compares to videos, images, audio, and text communication. We anticipate touch to be more intimate than the other communication forms.

> *- Should they also have to delete the following saved communications?*

- Video (e.g., video messages, camera recordings)
- Images (e.g., pictures)
- Audio (e.g., audio memos, voicemails)
- Text (e.g., text messages, SMS)
- None of the above

3: Is it morally appropriate for companies to use digital touch data for AI? When we subscribe to a social media service, we often do so freely under the guise that the company behind can use our data for directed advertisement or artificial intelligence. As a user, it is nearly impossible to know exactly how our data is being used. Multiple workshop participants noted that our digital touch data could be used for "*Android replicas*", "*Cloning of people*", and "*your touches could be used to make deepfakes*". This dilemma explores whether it is appropriate for companies to use digital touch data for AI when a user subscribes to their digital touch communication service.

> *Charlie uses the haptic technology to interact with other people. When signing up to use the technology, Charlie had to sign over the rights to their digital touch data to the company behind the technology for AI touch creation. Charlie does not know what the AI touches are used for.*
> *- Is it morally appropriate for the company to use Charlie's touches data for AI touches?*

4: Is It Morally Appropriate to Sell Someone's Personal Digital Touch After They Die? Similar to using digital touch data in the previous dilemma, our touch data can also be resold without modification. Non-modified data may keep the personal nuances and intent of the person who recorded it. In the premise (Sec. 8.4.1), we situated future haptic technology as "realistic", which may lead to identifying who is touching.

> *Parker's grandmother recorded a digital hug before dying. When Parker interacts with the digital hug, it feels like they are hugging their late grandmother. Parker finds out a company is selling the grandmother's digital hug in their store so that other people can feel their grandmother's hug. Parker demands the company stop selling the digital hug.*
> *- Is it morally appropriate for the company to sell the hug?*

5: Is It Morally Appropriate to Modify a Digital Handshake? This dilemma explores whether the modification of a digital handshake is morally appropriate. The scenario is modified from the third scenario in the workshops. The views on whether handshake modification was appropriate was split in the workshop. Some participants thought it barely mattered as "*Handshake is only for hand*" and that it was "*deceiving but acceptable*". Others thought it was a breach of trust: "*If they use this creates mistrust in the relationship*".

> *River is a marketing consultant. Online clients often insist on starting meetings with a digital handshake. While shaking, they can feel the other person's hand using realistic haptic technology. River has read that a firm and pleasant handshake leaves the best impression but fears their digital handshake leaves a poor impression. To improve their handshake, River has installed additional handshake software, that modifies their handshake. It allows them to adjust the strength, pleasantness, and other factors. The receivers are not aware of the modification.*
> *- Is it morally appropriate for River to modify their digital handshake?*

8.4.2 Participants

We recruited 100 (53F/47M) participants through the online service Prolific. The participants were paid £3.50 each (median of £18,53 per hour). See App 8.7.1 for demographics breakdown.

8.4.3 Results

Each participant answered the five dilemmas and the additional follow-up questions, resulting in 600 quantitative "yes"/"no" choices and 600 qualitative explanations of "why" the choices were made. One participant was omitted for answering the "why" questions inappropriately. Fig. 8.5 shows the results of the dilemma choices.

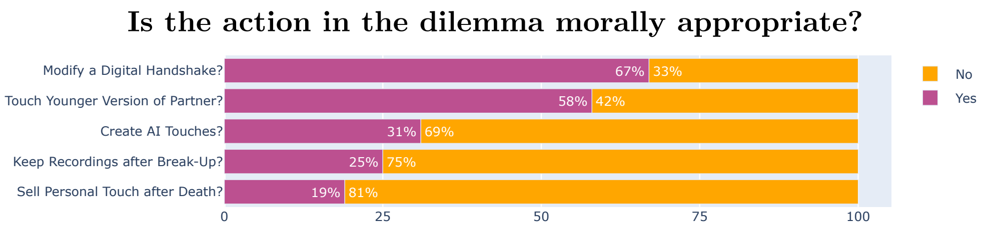

Figure 8.5: Results of the forced choice dilemmas. The participants were asked whether a choice was morally appropriate or not.

58 % of the participants thought it was morally appropriate for a person to touch a younger version of their partner with whom they had exchanged digital touches. Some based their choice on the fact that the exchanges likely were consensual: "*they are both consenting and over the age limit and in a relationship*" (Participant 2) and "*If Alex consented in the original recording, then it's not a problem even now.*" (P74) Other explanations relied on them still being in a relationship: "*if they are in a long term relationship and they sent these to each other, then it is okay*" (P5). Finally, some compared this to seeing old photographs: "*[...]it's similar to looking at old photos. He should, however, be up front about it*" (P75). Some of the 42 % who thought

it was morally inappropriate also based their decision on consent: "*Interacting with recordings featuring a younger version of Alex raises ethical dilemmas, especially concerning consent and the preservation of personal boundaries*" (P59). One participant put it in a perspective of growing older together in a relationship: "*[...] it may really stunt the perception of Sam, as he uses a non-existent form of Alex, that this difference might break open the relationship. It should be about progressing together(changing continuously)*" (P95).

Three out of four participants thought it was morally inappropriate for the actor to keep digital touch recordings after a break-up when the other requested they delete them. This was the dilemma where most participants thought a choice was morally inappropriate (i.e., keeping the recordings). Some participant explained their choice was due to the relationship being over. Fourteen participants mentioned that the aggrieved actor no longer consented to the recordings. One participant noted: "*It's a request to delete personal data given with consent. Now it's asking for the data to be deleted. It's very similar to what we have today with data protection laws but instead of third parties these are people*" (P16). Some of the people who thought it was morally appropriate to save the recordings claimed it is Kim's decision to make. One participant noted they may not be ready to delete them yet: "*Maybe Kim is not ready to let go just as yet and will delete them when she is ready*" (P64).

69 % of participants thought it was morally inappropriate for a company to create AI touches based on Charlie's data in Scenario 3. Some participants based their decision on the dilemma description, that "*charlie does not know what the AI touches are used for*" (P77). They noted: "*Even though Charlie may have signed their rights, it's not right for AJ to use the haptics without disclosure*" (P9) and "*the company must enclose what it uses the saved touches for, and users must be allowed to decide whether they want to hand over the recordings knowing these conditions*" (P33). Some indicated that if this information was provided, it would have been morally appropriate of the company to use Charlie's data for AI touches: "*I think it is acceptable for him to sign over the rights but only if Charlie is told what they will be used for*" (P75). Others based their decision on their knowledge of AI and AI companies: "*One should have absolute autonomy of their bodies and it's product. We can obviously can't make sure that the AI won't abuse it, so it would be better to rule out altogether*" (P95). Some participants also thought Charlie should be compensated if his data was used for AI touch creation. Most of the 31 % who thought it was morally appropriate of the company to use Charlie's data for AI touch creation based their choice on the fact that Charlie consented when signing up: "*Charlie should read all the terms before signing and ask for more information about her data*" (P25).

81 % of participants thought it was morally inappropriate for a company to resell a digital hug from a late grandmother, some calling it "*sick*" and "*morally terrible*". While some based their choice on a possible lack of consent, one also noted consent did not matter when that person now is deceased: "*Even if they have the rights, it is very wrong to sell a dead person's information*" (P22). One person noted the choice may depend on the relative: "*Parkers right in his feeling on that you're essentially selling his grandmother to other people. It personally wouldnt bother me because it's giving other people that happy feeling. but i get that it feels wrong to be selling off digital pieces of people*" (P93). Some of those who thought it was morally appropriate based it on a possible contract with the company: "*yes, since people signed some contract to the company, they can do whatever is more beneficial to them*" (P31).

67 % thought it was morally appropriate of River to modify their digital hand-

shake to leave a better impression. Most people based this on the fact that it was "*just a handshake*" (P5, P19, P43, P45, P74, P82, P88, P101) "*not hurting anyone*" (P9), and "*a marketing strategy*" (P53). Some also based their choice on the fact that the receiver was unaware of the modification: "*The receiver wouldn't know any different [...]*" (P3). One person called it "*a logical thing to do under these circumstances*" (P75). One participant compared this to the normalization of plastic surgery: "*It's his handshake being changed and nobody else's so why not. I can go through plastic surgery to change my nose or what not, its the same*" (P12). Of the 33 % who thought it was morally inappropriate, some based this on the intent of the handshake in the meeting: "*It's not appropriate in a setting where there's the intent of being genuine and upfront like a meeting*" (P6) and "*Building trust and maintaining integrity are essential in professional relationships*" (P62). While some though it was morally appropriate since the receiver did not know about the modifications, other thought this made the action inappropriate: "*No, it is deception. I know that everybody wants to show their best self but, it is still decepting the others. If this gets found out, it will really have a negative effect on the trust between these people*" (P95).

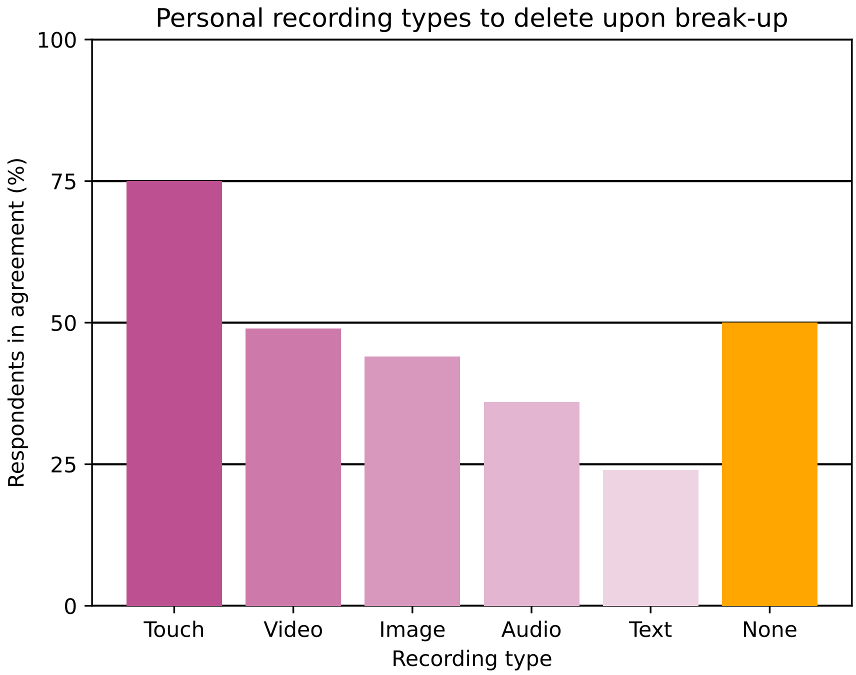

Figure 8.6: Results of the difference between the required deletion of communication data in the context of a relationship in Sec. 8.4.1. Participants were asked whether the data in the communication forms should be deleted upon a break-up.

Fig. 8.6 compares the different communication forms in the follow-up question to Scenario 2[3]. Participants were asked whether recordings from these communica-

[3] The data for *"Touch"* stems from the Scenario 2 choice. *"None of the above"* does

tion forms should be deleted upon break-up. More participants thought digital touch recordings should be deleted than any other communication form. Some participants who wanted touch recordings to be deleted but not any other types explained this with: "*They are less personal*" (P15), "*because they are not feelings just communication*" (P20), and "*Touch is very intimate. Much more than other senses. It's new to me and maybe for this reason it seems ackward*" (P81). Some participants who selected all communication forms based their decision on moving on after ending a relationship: "*Deleting this stuff helps to have a clean break in the relationship as opposed to hanging on to an idea of someone*" (P8) and "*Because they will both move on and the new partner will not like it*" (P42).

8.5 Discussion

Touch is an indispensable part of our personal lives and society. As many of our other ways to communicate have been digitized, it is likely that touch will get a similar movement in the future. While we do not know when and what this movement will look like, it is important to be a step ahead and consider what consequences communicating touch digitally may have. It is impossible to innovate responsibly without daring to glimpse into the future. Through future scenario workshops and a dilemma survey, we glimpse the future consequences digital touch communication may have by viewing the communication form through a black box perspective. Our results and analysis show that touch not only inherits some of the same consequences as other communication forms but also brings forth new consequences and increases the effects of others due to the intimate nature of touch.

Will digital touches be safe? Safety regulations that apply to all other technology also apply to haptic technology. So, why are there concerns about the safety of haptic devices? This may be a novelty effect, because participants were uncertain of the unknowns. It may also be due to the personal nature of touch. Our other senses can be experienced from outside our periphery – without being in contact with our body. Touch *is* physical contact. It is always an invasion of our personal space. Even though touchless haptics exist [32], the stimulation is still in contact with the mechanoreceptors in our skin. As Barrow and Haggard [11] proclaimed, an off switch is a necessity for these devices. It should not be possible for hackers to override this switch. But as with unsolicited photographs [139], even a sliver of violation can be unsafe.

What laws govern digital touch? While most countries have strong laws on unwanted physical touches, they are far from perfect. Consent is often a contention point in sexual assault cases, and while some countries have implemented laws requiring consent for sexual interactions [102], the effect of these are still unknown, and it is "*important to keep in mind the distinction between law in books and law in practice*" [218]. If the laws do not suffice for physical touch, how will they suffice for digital touch? And what if the touch crimes are across borders? It is unclear what laws encompass this.

therefore not relate to *Touch*.

Will my digital touches be private? No. While some communication technologies like Signal [4] and Facebook Messenger[5] include end-to-end encryption, the world of digital data has shown us that our personal information and media can get into the wrong hands. From the black box perspective, multiple privacy issues can occur. The *source* of digital touches may not be who users think. The person we think we are interacting privately with may have been hacked, leading to us touching and being touched by a stranger. Related to *sharing*, the touch can get hacked and exploited through blackmail, or companies legally entitled to the data can resell or use it for AI. If digital touches are realized as private, personal touches, controls are needed to ensure they stay private.

Can my touches become ethically inappropriate? Yes. Who ethically owns our intimate digital touches was a major concern for both the workshop and the dilemma survey participants. But many other factors, such as cultural norms and religion, affect how and who we can touch. For cultures that do not prefer touches or religions where people avoid touching the opposite sex, does digital touch have the same connotations?

Will digital touches be intimate? We can not know how haptic technology will develop, but it poses a possible future where touch communication follows trends from other communication forms, such as video and audio. The realism achieved in these forms, such as the high-quality video recordings possible today, questions whether haptic communication can achieve the same fidelity. In order for digital touches to feel *intimate*, they may require high realism. But for them to feel *meaningful*, body-congruent realism may not be required. Bales et al. [8] found that simple vibrotactile cues from a mobile phone sufficed to keep "*connectedness and peace of mind for their partner's safety*".

8.5.1 Limitations and Future steps

Our black box perspective revealed three aspects the scenarios were constructed around. While this ensures we capture different aspects of the consequences, it also limits the scope. The possible consequences to be found with digital touch communication are endless and impossible to call capture, but this framing grounds it in the existing aspects of other communication forms. A future study could explore more scenarios, changing the actors in scenarios (e.g., names, backgrounds, activities like bouldering), and pose them to participants in more workshops for a wider demographic background. As an iterative process, the scenarios can be built upon the consequences found in the first scenarios or remade to avoid finding the same consequences again.

Our dilemma survey presented five dilemmas. Many more could be derived from the scenario consequences and posed to participants where the cultural or religious influences could be captured. The dilemmas are framed as specific scenarios where actors make choices the participants find morally appropriate or not. Our results are dependent on the framing of the dilemmas. By asking participants why they made their choice, we captured nuances of their forced choices. Adding neutral or positive

[4] https://signal.org/

[5] https://www.messenger.com/

vignettes [44] to the dilemmas, such as "Charlie's AI touches will be used to the well-being of elderly", could affect the forced choices of the participants, leading to a better understanding of when digital touches are perceived as morally inappropriate or not.

8.6 Conclusion

In this paper we presented the black box perspective on digital touch as a communication form. This perspective was used to explore the foreseen and unforeseen consequences and dilemmas through futuristic scenario workshops and a dilemma survey.

Our results show that digital touch is a communication form that society is not ready to responsibly handle. There are major ethics concerns like the ownership of intimate touch data, privacy risks like who we touch and who can touch us, and legal issues like what laws govern touch harassment and assault across borders. Touch is more intimate than our other senses, and lessons learned from the other senses and their respective communication forms do not suffice when designing digital touch interactions and their controls.

The scenarios presented were not grounded in current haptic technology but presented a futuristic view, where digital touches feel like realistic touches. While this view means not all these consequences are relevant at this point in time, it shows that continued research in digital touch communication needs to consider these consequences and dilemmas before it becomes a viable communication form, when it will be too late.

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8.7 Appendix

8.7.1 Dilemma: Survey Demographics

All data was acquired from Prolific.

Table 8.1: The distribution of sex and age.

	Count	Age (mean)	Age (std)
Female	53	33.65	12.06
Male	47	29.07	6.87
Total	100	32.34	11.12

Table 8.2: The distribution of participant nationalities.

Nationality	Count (each country)
South Africa	29
United Kingdom	12
Portugal	9
Hungary, Poland	7
Italy, Spain	5
Greece	3
Australia, Israel	2
Bolivia, Canada, Chile, Egypt, Estonia, India, Iran, Ireland, Japan, Morocco, Netherlands, Nigeria, Pakistan, Peru, Puerto Rico, Turkey, United States, Vietnam, Zimbabwe	1

8.7.2 Workshop: Affinity Diagram Note Distribution

Fig. 8.7 shows the distribution of notes in the affinity diagram.

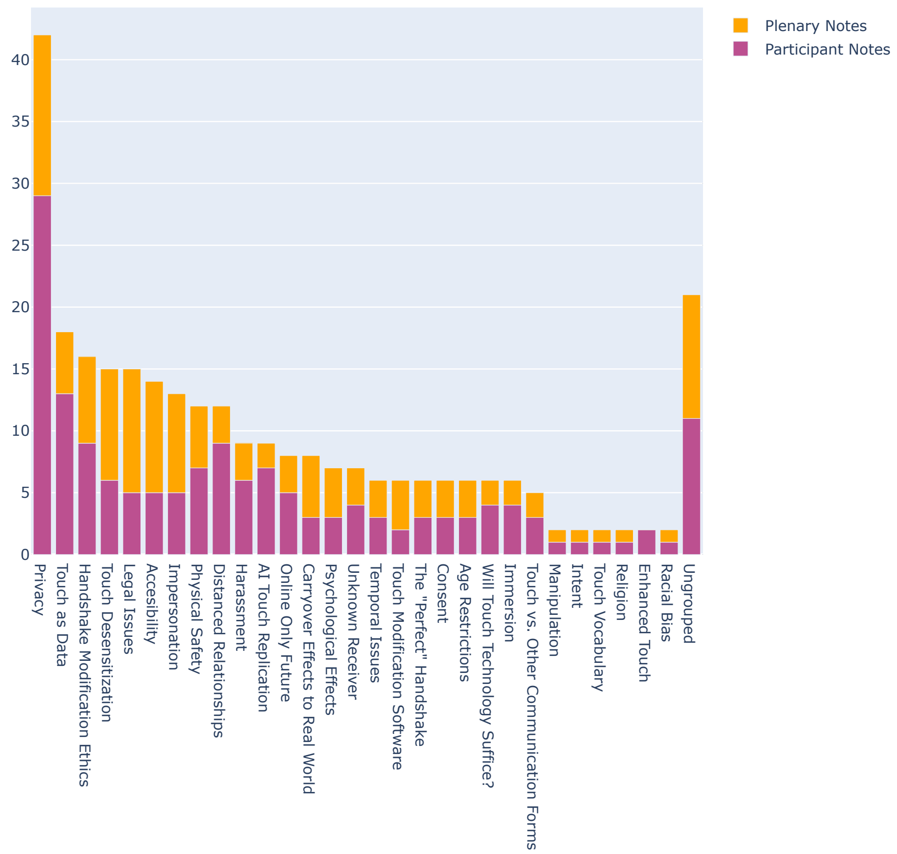

Figure 8.7: The distribution of notes in each cluster.

Chapter 9

Discussion

USING interdisciplinary insights into how our body reacts to touch, me and my co-authors have shown how to reinvent the design of haptic feedback instead of imitating physical objects. Our results show that mid-air haptic feedback for user interfaces does not have to rely on the same spatial properties as physical buttons. Our haptic design is informed by bodies, not objects. We can extend this beyond what is expected from the physical, with increased performance. We can create ultrasound rendering algorithms utilizing the spatial perception properties of our skin to make dynamic and custom sensations that previously were limited to pre-made shapes or 14 cm patterns.

Through five core papers, my co-authors and I contribute to the human-computer interaction and haptic feedback field by conducting empirical studies, creating a haptic toolkit, and conducting responsible research and innovation. The papers include the following contributions:

1. **Whole-Hand Haptics** shows why and how to design haptic feedback for the whole-hand during finger press buttons in mid-air
2. **Whole-Hand Haptics** models how to measure the stages of a mid-air button press
3. **Mediated Social Touching** shows how various forms of haptic feedback affect the digital *touching* experience
4. **Mediated Social Touching** shows the importance of reciprocating feedback (including haptic and multi-modal) for the social experience of digital touch experiences
5. **Mediated Social Self-Touch** shows the null effect of duplicating digital touch communication onto one's own body
6. **Mediated Social Self-Touch** introduces a mid-air haptic mediated social touch prototype enabling real-time and recording of digital touches
7. **MAMMOTH** proposes an ultrasound rendering technique for dynamic auto-generated mid-air haptic feedback
8. **MAMMOTH** realizes the technique in an open-source toolkit
9. **The Black Box of Digital Touch** shows the possible consequences and dilemmas of digital touch as an emerging communication form

Based on each of the papers, it is clear that more work can be done to reinvent haptics for mid-air interactions. More types of widgets for user interfaces in mid-air exist that can be improved with mid-air h. Our approach shows how to use the waves propagating through the hand on contact as design inspiration. The same approach can be used for other widgets or extended with more knowledge of our body. We conducted our study in a lab. This limits the generalizability to real-world scenarios. But as we learned from the COVID-19 pandemic, people have become wary of touching publicly placed interfaces or objects like door handles. Field studies with mid-air interactions and ultrasound haptic feedback could be valuable for interactions with everyday devices, such as digital kiosks, light switches, door openers, and keypads. The MAMMOTH toolkit can be utilized for these interactions. The toolkit is envisioned as an evolving code base that can improve with input from the community.

The mediated social touch papers can inspire studies using real-time social touch interactions. Further exploration can also be conducted on the four remaining aspects mentioned in Section 3.3. Standardized questionnaires can be used to measure the social experience, including co-presence theory, creating results that are comparable to other research. Comparing it to Table 3.1, our final mid-air mediated social touch prototype enables bidirectionality, reciprocity, both synchronous (real-time) and asynchronous (recording), and direct touch interactions. We can learn more about the social experience – the "systemic changes" [91] – from the features this device affords users. Finally, the Black Box project is only the first step in what should be individual long-term projects discussing the ethical, privacy, sociotechnical, and legal consequences of digital touch communication. Our project reveals many novel issues that need addressing if we are reinventing touch in the digital realm.

Does reinvention work better than imitation? With mid-air buttons, it is clear that reinvention affects the results. There is an upper limit when imitating physical buttons based on the strength and spatial properties of the mid-air haptic devices. As strength currently does not suffice to create an experience like the pull-back effect, reinvention is not just an option but a necessity. Without the reinventions found in the ultrasound haptic feedback used in MAMMOTH, the ultrasound rendering would not work. It relies on the perceptual properties of our skin. Should we reinvent touch as a communication form? The answer is unclear. If we do, we need to understand what aspects of haptic feedback affect the experience for both the sender and receiver. We also need to understand the consequences of these reinventions.

Chapter 10

Conclusion

My co-authors and I have shown why and how to reinvent mid-air haptic feedback instead of imitating it. Touch is our most intimate sense; it shapes us and affects our well-being. It can be used for its discriminatory and affective functions. Without tactile affirmations when using mid-air interfaces, they will never be utilized the same way as the mouse and keyboard. Without tactile interactions in distanced social communication, increased online communication and times of isolation will lead to touch starvation, leading to a decrease in well-being. But when answering "why?" we must also answer "why not?". Our responsible research and innovation perspective on digital touch as a communication form shows many ethical concerns, privacy issues, and legal frailties. Instead of moving full-speed ahead with novel touch interactions, we must be prepared for the possible outcome.

With reinvented mid-air haptics, bare-hand interactions in mid-air are a step closer to feeling natural. While users may be more familiar with haptic feedback imitating physical objects, this does not mean our reinventions feel unnatural in comparison, as they are based on the natural responses of our skin. To design for the skin, we must understand the skin. I hope these contributions will be valuable and meaningful for years to come.

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