Touching is believing: creating illusions and feeling of embodiment with mid-air haptic technology

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A dissertation submitted to the University of Sussex in accordance with the requirements of the degree of DOCTOR OF PHILOSOPHY in the School of Engineering and Informatics.

OCTOBER 2019

"Touch is far more essential than our other senses. [...] and it affects damn near everything we do. No other sense can arouse you like touch. (Touch) it's not only basic to our species but the key to it."

by Saul Schanberg in - A Natural History of the Senses

AUTHOR'S DECLARATION

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Any views expressed in the dissertation are those of the author. Studies done in collaboration with, or with the assistance of others, is indicated as such below:

- Chapter 7 - Frier W., Pittera D., Ablart D., Obrist M., Subramanian S. "**Sampling strategy for ultrasonic mid-air haptics**". In *Proceedings of the CHI Conference on Human Factors in Computing Systems*, Glasgow, UK, 2019. Pittera D. - 15%, brainstorming and data analysis.
- Chapter 8 - Hajas D., Pittera D., Nasce A., Georgiou O., Obrist M. "**Mid-Air Haptic Rendering of 2D Geometric Shapes with a Dynamic Tactile Pointer**". In *IEEE Transaction on Haptics*, 2019 - submitted. Pittera D. - 45%, brainstorming, study design, data analysis, partial write-up.
- Chapter 9 - Pittera D., Obrist M., Israr A. "**Hand-to-Hand: an intermanual illusion of movement**". In *Proceedings of the 19th ACM International Conference on Multimodal Interaction*, Glasgow, UK, 2017. Pittera D. - 90%, programming, study design, data collection, data analysis, write-up.
- Chapter 10 - Pittera D., Ablart D., Obrist M. "**Creating an illusion of movement between the hands using mid-air touch**". In *IEEE Transaction on Haptics*, 2019. Pittera D. - 90%, study design, data collection, data analysis, write-up.
- Chapter 11 - Pittera D., Gatti E., Obrist M. "**I'm sensing in the rain: spatial incongruity in visual-tactile mid-air stimulation can elicit ownership in VR users**". In *Proceedings of the CHI Conference on Human Factors in Computing Systems*, Glasgow, UK, 2019. Pittera D. - 90%, programming, study design, data collection, data analysis, write-up.

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SUMMARY

Over the last two decades, the sense of touch has received new attention from the scientific community. Several haptic devices have been developed to address the complexity of the sense of touch, the latest addition being mid-air (contactless) haptic technology. An interesting series of previous research has suggested an easier way to tackle the complexity of designing convincing tactile sensations by exploiting tactile illusions. Tactile illusions rely on perceptual shortcuts based on the psychophysics of the tactile receptors.

Currently, studies exploring the perceptual space of mid-air haptics and its applicability in the tactile illusions field are still limited in number. This thesis aims to contribute to the field of Human-Computer Interaction (HCI) by investigating the perceptual design space of ultrasonic mid-air haptics technology.

Specifically, in a first set of three studies, we investigate the absolute thresholds (minimal amount of a property of a stimulus that a user can detect) for control points (CP) at different frequencies on the hand and arm (Study 1). Then we investigate the optimal sampling rate needed to drive the device in an optimal fashion and its relationship with shape size (Study 2). Next, we apply a new technique to increase users' performance in a shape discrimination task (Study 3).

In Study 4, we start the exploration of a tactile illusion of movement using contact touch and later, we apply a similar procedure to investigate the feasibility of creating a tactile illusion of movement between the two non-interconnected hands by using mid-air touch (Study 5).

Finally, in Study 6, we explore our sense of touch in VR, while providing an illusion of rain drops through mid-air haptics, to recreate a virtual hand illusion (VHI) to explore the boundaries of our sense of embodiment.

Therefore, the contribution of this work is threefold: a) we contribute by adding new knowledge on the psychophysical space for mid-air haptics, b) we test the potential to create realistic tactile sensations by exploiting tactile illusions with mid-air haptic technology, and c) we demonstrate how tactile illusions mediated by mid-air haptics can convey a sense of embodiment in VR environments.

Acknowledgements

During this PhD a lot has happened. I hope I will be fair to every one of you that contributed to my personal and professional development. Probably this will be one of my last written thank you, so, here goes the long list:

I would like to start thanking Dr Roberta Ferrucci that first encouraged me to pursue a career abroad and Dr Alberto Gallace for further giving me a push to start this incredible experience. Dr Max Di Luca and his family, for being my first tutor in a foreign land, when I had no experience, making me feel welcomed and at home, showing me the exciting world of haptics through his great expertise and ultimately being the oblivious orchestrator of what it would have been my next four years of life. Dr Elia Gatti, first Italian friend abroad, for offering his support, personal and professional, his help was fundamental. Dyar Karim for being positive and supportive during my time in Birmingham.

Obviously, all of this would have not been possible without a great supervisor: Marianna Obrist. When I wrote my motivational letter I asked you to give me "the possibility to continue to think big and to improve myself in life". You gave me that chance, and if I could go back in time I would make again the same choice. These, will be years I will not easily forget. It is impossible to say how much I value this doctorate, and you made it possible. I thank you for supporting me, morally and professionally, for always trying to make me believe in myself, to encourage me, to push me to do better, for allowing me to visit the world (for science of course), for answering at night, in the weekends, when in the middle of your schedule, for making me hating those moments when a paper was coming back with your suggestions :) that always enhanced a lot its content, for being open to discussions, for being tactful, and for coping with my personality and my cosmic pessimism showing always great strength and enthusiasm. I always felt you had my back, a sincere thank you.

Thanks to my second supervisor Prof Anil Seth for targeted advice and his critical and expert point of view.

I would like to thank my supervisor at Disney Research Pittsburgh (another unforgettable experience made possible by my supervisor), Ali Israr, for our spontaneous conversations, his helpful advice and his way to put in perspective some of those research problems I believed insuperable. Thanks to my colleagues I met there, in particular, to Alexandra Delazio and Nobuhisa Hanamitsu, for making me feel a little less homesick. Thank you, Carlos and Markus, incredible landlord and housemate in Pittsburgh, for your cheerful and extravagant personalities, our chats, evenings, and parties (even if you know I am not a party guy).

To this regard, I would like to thank the friends which I abandoned in Milano (sorry if I am a ghost but I think about you anyway): my brother Salvatore, my friends Lollo, Matieau, Fulvio e Marghe, Silvia, Pianzi, Andrev, Ema, Teo, Leo, Albi, Giannis, Mengus, Max, Dida and more back in time Minjun, Gae, Nadir, Lele, il cane leso, il pazzo, my university classmates Manuel, Fra, Vale, Stefanone e la Beri. Thank you for the laughs via WhatsApp and Viber, and for those moments we shared in our beautiful city. I haven't seen some of you for a long time, but you all made the history of my life. Thanks to all the housemates and landlords I met during my PhD, I changed lots of places and everyone gave me a different point of view, new information, and experiences (good and bad). My colleagues at the Policlinico di Milano, in particular, Fabiana, who surely is now an amazing psychotherapist.

I would like to thank the beautiful minds of the SCHI Lab, for having shared good and bad times, for the long conversations, for the jokes, the puzzles completed together, the research done together, my colleagues, the original 3Ds group (me, Damien, and Dmitrijs), the expanded 4Ds group (ditto + Daniel), the people that were hired not for their name :) : Chi, Giada, Luis, Rob, people from other labs: Anthony, Patricia, Roberto, Luis video, William, Yutaka, Michi, Deepak, their supervisor, Sriram. I would like to thank Dr Emanuela Maggioni and his fiancé Juan, for being friends, for their helpful advice, laughs, and chitchats. I hope we won't be strangers.

Thank you to all the people I met during my student volunteer time, during conferences, especially Assunta, Andrea, Leonardo, Silvia for a good time in Eindhoven.

I would like to include in my thank you list, the European Research Council (ERC) for funding my research under the European Union's Horizon 2020 research and innovation program Grant No.:638605.

An impossible to not include, big, fat, thank you to my family. To my father Alfio and to my mother Vincenza, that made me the person I am now. For their hard work, for their values which helped me in tough decisions, for their continued support, psychological, emotional, financial, for having sacrificed whatever possible for my and my brother's future even when we were/are not able to say thank you, for wanting my own good against theirs, for giving without receiving, for being role models, for having kept me with my feet on the ground but being able to dream big, for the hours of Skype and Viber calls listening to every detail because I am an OCD and I cannot cut short, for believing in me, for having me in Italy, and for the possibility of knowing one of the best food in the world :). Thank you to my brother Salvatore, for our continuous fights during our childhood, for taking the blame for our childhood mischief (even if I took mine as well :P), and for the evenings in our adulthood.

Last, but absolutely not least, my wonderful half, Erika. Thank you for supporting me and putting up with me (in Italian is kind of funnier) for almost 14 years. Retrospectively, I feel all of this would have not been possible without you. All the sleepless nights spent being worried about our future, all the dreams we shared, the great moments, the sad ones, the moments in which I felt I didn't fit but you sustained me, the moments in which we talked, laughed, studied, danced, fought. Your fundamental point of you. Your brain. The times when I acted like I wasn't listening to you, but then I did, and you were right. Thank you for being loving, patient, for making me a better person, and for being by my side no matter what. I hope we will never change.

Finally, I promise, I would like to thank the creators and workers of Netflix for having provided hours of entertainment in our flat, Amazon with its Amazon Prime service, and my favourite DJ, Gigi D'Agostino, and all the other Italo-dance artists, for reminding me who I am and have my brain relaxed when I needed it. Thank you, England for welcoming me, for your politeness, and for the numerous opportunities you gave me. Thank you, Italia, for your beautiful culture and traditions, for having shaped me inside and outside, I will always remember where I come from and I hope to meet you again.

Ultimately, I think that every person and event happened to me led me to the moment where I am now. I am sure I forgot someone. For those who I forgot, I say thank you now, because I am sure I thought of you in a way or in another, or I will soon be thinking of you.

Even if I couldn't thank you all in detail, one final thank you for this wonderful, hard, happy, frustrating, satisfying experience that makes me proud!

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List of Abbreviations

AR Augmented Reality: is a technique to enhance by computer-generated perceptual information, real world objects.

ATM Apparent Tactile Motion: a perceived single movement generated by two separate but closely placed stimuli on the skin with different onset times.

CIPA Congenital Insensitivity to Pain with Anhidrosis: a rare hereditary neuropathy characterised by insensitivity to pain and temperature, and impossibility to sweat.

CNS Central Nervous System: in humans, the brain and the spinal cord. In contrast with the peripheral nervous system, which is formed by the nerves external to the brain and the spinal cord.

CP Control Point: point at which the different sound waves of an array of ultrasound speakers converge, creating a tactile sensation

DC Direct Current: flow of electric charge that does not change direction

FA Fast Adaptive: regarding tactile receptors, are those receptors that stop sending information in answer to a sustained, continuous stimulation.

fMRI Functional Magnetic Resonance Imaging: a nonscientific technique that help visualising the activity of the brain by detecting changes associated with blood flow.

HCI Human-Computer Interaction: is a multidisciplinary field that studies the interaction between humans (the users) and computers.

HMD Head-Mounted Display: a screen mounted on the head of the user (e.g., Oculus, HTC, etc. headsets)

IAT Implicit Association Task: a test used in social psychology to detect people implicit association between mental representations of objects/concepts/people.

JND Just Noticeable Difference: the amount of the property of a stimulus that must be changed in order for a difference to be noticeable.

OBE Out of Body Experience: a phenomenon in which people experience the world from outside their own body.

PCA Principal Component Analysis: is a dimensionality-reduction technique to reduce the dimension of a data set while still carrying the same information.

PSE Point of Subjective Equality: any of the points at which an observer judge a stimulus to be equal to a reference one.

PTSD Post-Traumatic Stress Disorder: a disorder that can develop in some people following a shocking, scary, or other life threatening events.

RA Rapid Adaptive: regarding tactile receptors, are those receptors that stop sending information in answer to a sustained, continuous stimulation.

RHI Rubber Hand Illusion: an illusion where a rubber hand is placed in an anatomically plausible location instead of the real (hidden) arm. When the participants' real hand is stimulated synchronously to the fake (and visible) hand, they will feel that the rubber hand is their own.

ROC Receiver Operating Characteristic: is graphical representation of the ability of a classifier system (e.g., a user) to discriminate between target and noise as its discrimination threshold is varied.

S1 Primary Somatosensory Cortex: that part of the cortex located in the post-central gyrus (part of the parietal lobe), which is part of the somatosensory system for the receptions of general bodily sensation.

S2 Secondary Somatosensory Cortex: is that part of the brain located more dorsally to the Primary Somatosensory Cortex and it seems involved in the perception of pain, the evaluation of size, shape and texture of touch or pressure.

SA Slow Adaptive: regarding tactile receptors, are those receptors that continue sending information in answer to a sustained, continuous stimulation.

SCR Skin Conductance Response: the phenomenon in which, while stimulated, the skin becomes a better conductor of electricity.

SDT Signal Detection Theory: it is a technique to measure the ability of a human to discriminate between a stimulus (target) and random patterns (noise) that distract from the information.

SOA Stimulus Onset Asynchrony: the difference in time between the activation of a first stimulus and the next one.

SoE Sense of Embodiment: briefly, the sense of embodiment can be defined as the system that makes us distinguish ourselves from the rest; it is the perception of our physical boundaries. The embodiment is telling us what is to be considered self-related and what it is the external world.

TOJ Temporal Order Judgment: a task in which an observer is asked to express the temporal order of two stimuli.

VE Virtual Environment: environments as presented inside a virtual reality setting.

VHI Virtual Hand Illusion: this is the same illusion as in the Rubber Hand Illusion, but the illusion happen in virtual reality with a virtual hand representation.

VR Virtual Reality: a simulated experience similar (or not) to the real world.

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Chapter 1

Introduction

From a historical and philosophical point of view, touch has been considered a secondary sense. Furthermore, the sense of touch is multifaceted and complex. This complexity has not allowed for a rapid evolution of tactile rendering as has happened for vision and hearing. However, the recent breakthrough of virtual reality systems into the consumer market has sparked new interest and a need to integrate the sense of touch in virtual scenarios. VR fascinates game designers for its possibility of creating impossible, desired, or simple everyday life situations that have a power of immersion without precedent. It also fascinates the scientific community, which now has the possibility of controlling variables of interest when it was previously impossible to do so. Designers and scientists can trick the brain to make it experience new worlds and situations that cannot be encountered in reality. Intuitively, the first VR headsets exclusively relied on visuals and auditory techniques. With the high availability of VR head-mounted displays (HMDs) for private use, it was soon felt that our sense of touch needed to be included.

Tactile sensations are an intrinsic part of our everyday life. We use these components of our complex somatosensory system even in the easiest part of our routine, probably without being aware of it – when we walk, when we talk, when we eat, when we sit, and when we turn our head. Touch is extremely important in our everyday life and so inherent to it that we might take it for granted. Yet, when it is missing, we cannot continue to have a normal existence. The same can apply to a virtual scenario: when we are in a new world we do not know, one of the first things we do is to touch things to test our effect on our surroundings. If an action is not followed by a reaction, our sense of immersion will vanish. That is why the sense of touch must be taken into account in this new immersive technology. This is known to VR companies, and they are starting to implement tactile feedback in their products (e.g., Oculus Touch, HTC Vive Cosmos controllers, Sony PlayStation VR, etc.). Research on VR has shown how tactile feedback enhances immersion in virtual environments (VEs) [190] and how it is important that the technology becomes "transparent" to the user [149]. The transparency we refer to here alludes to that situation in which the user is not aware of the device but naturally perceives its effect. In other words, this is a perceptual illusion of non-mediation [149], intended in the way that Nardi refers to transparency in HCI, describing a supportive, unobtrusive interface to which the user needs to pay little attention [168]. This renewed interest has been followed by the development of new haptic technology for more advanced tactile rendering.

In the realm of haptic devices, a particular technology seems to satisfy the "need for transparency": mid-air haptic devices. These devices allow a natural interaction with the environment without the requirement of any attachment on the skin. Hence, when in action, the user will not perceive its presence. Regardless of the haptic device used, it is important to understand the perceptual effect those have on users. Research from psychophysics provides important information for the development of compelling tactile sensations. This is especially true for traditional contact haptic technology (e.g., world-grounded and body-grounded technology (see Chapter 4). Instead, mid-air haptic technology is relatively recent and psychophysical understandings of it are still in their infancy. There are different kinds of mid-air haptic systems (see Chapter 4, Section 4.3). In this thesis, we will focus on mid-air haptic devices that use ultrasound to create tactile experiences (which we will refer to as "ultrasonic mid-air haptics technology").

Generally, all haptic devices aim to mimic the complexity of the tactile sense. A plethora of haptic devices has been developed for specific use-cases and specific tactile properties. A computationally and actuation-economic alternative to deliver complex tactile sensations is represented by tactile illusions. Perceptual illusions arise when our sense organs transmit misleading information to the brain. Illusions can help to render a complete tactile percept, and even when we render only a part of the percept (e.g., apparent tactile motion), the brain will fill in the gaps of the tactile stimulation. Illusions can also serve as tools to study psychological concepts, like with the feeling of embodiment that plays a key role in interactive spaces as VR.

1.1 Research aim and objectives

This thesis aims to deepen understanding of tactile perception in the new ultrasonic mid-air haptic technology. Furthermore, we aim to explore tactile illusions to provide new tactile sensations and deliver a sense of embodiment in VR scenarios. We will achieve this aim by focusing on the following key objectives, represented as the three core research questions of this thesis:

- **RQ1**: How do we perceive ultrasonic mid-air haptic technology? What are the psychophysical properties of mid-air haptics?
- **RQ2**: How can we create realistic haptic and specifically mid-air haptic sensations by applying the principles of tactile illusions?
- **RQ3**: Using tactile illusions, can we convey the feeling of embodiment using mid-air haptics in VR?

The above three research questions were addressed in a series of six studies undertaken during this PhD. An overview of the research path is illustrated through three stages, displayed in Figure 1.1: 1) Understand 2) Create, and 3) Apply.

The first stage includes three studies labelled as "**Understand**". In Study 1, 2, and 3, through a series of psychophysical experiments, we aimed to expand basic

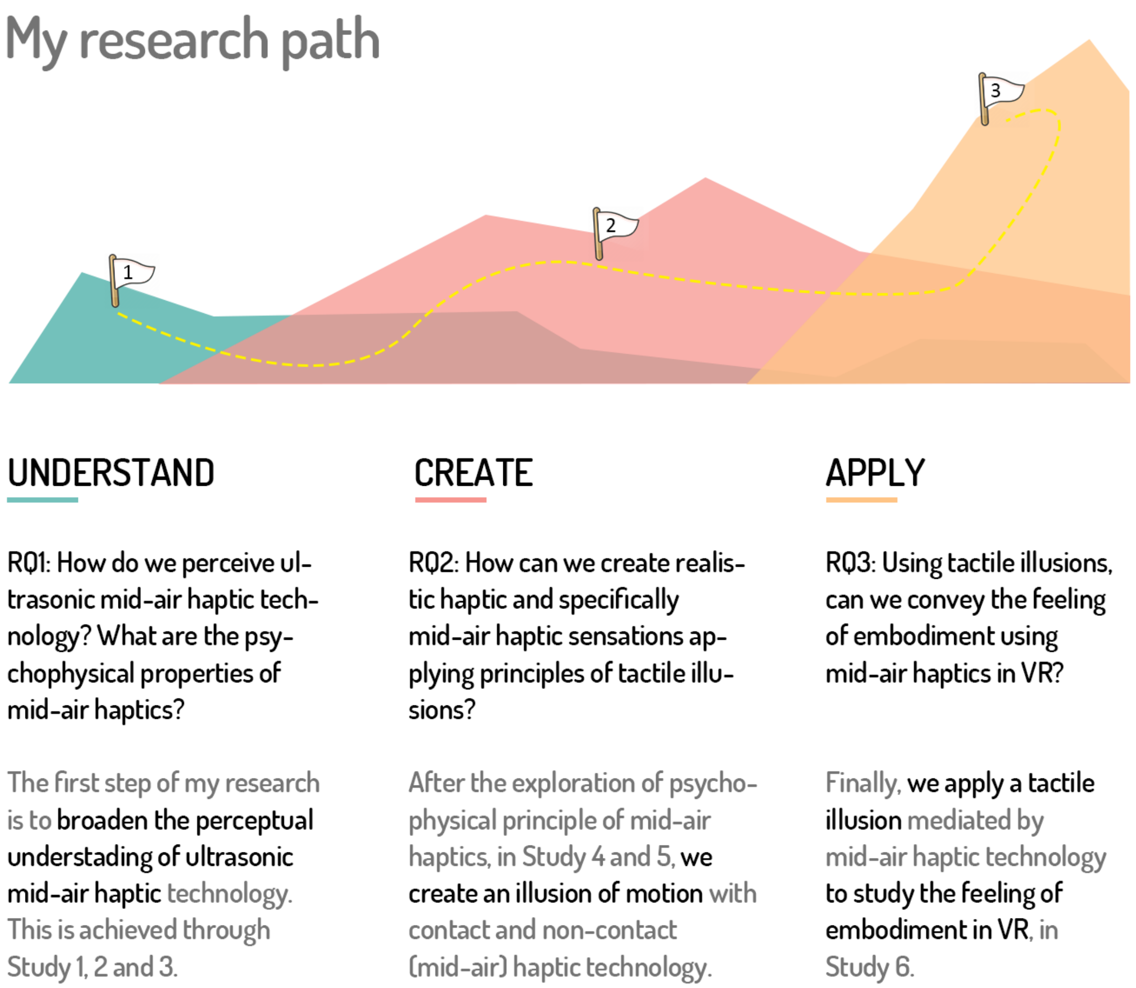


Figure 1.1: An illustration of my research path. The mountains of knowledge are based on top of each other. The path was not always that linear.

knowledge on the perceptual effects of ultrasonic mid-air haptics on users in terms of absolute thresholds, optimal sampling rate, and optimal parameters for perceiving 2D shapes on the hand.

The second stage includes two studies and is labelled "Create". In Study 4, we start to explore a tactile illusion of movement, namely the apparent tactile motion. In this study, we created for the first time a sensation of continuous motion that extends beyond the body from one hand to the other. Previous studies on apparent tactile motion were conducted on contiguous parts of the body. In Study 4 we used a custom contact haptic device. Study 5 was based on the experimental design of Study 4, but replacing the contact haptic device with an ultrasonic mid-air haptic device testing two tactile rendering techniques. For both Study 4 and 5 we provide perceptual models for achieving a smooth (continuous) illusion of motion that extends from one hand to the other. With these two experiments, we confirm that tactile illusions are an effective method for delivering compelling tactile stimulation and demonstrate how mid-air devices can effectively provide an illusion of motion, thus making them suitable for the delivery of traditional tactile illusions in VR.

The last stage includes one study and is labelled "Apply". In Study 6, we apply the rubber hand illusion (RHI) in VR, namely virtual hand illusion (VHI). In this study, we investigate additional variables (i.e., multiple congruent and incongruent tactile stimulation and hand posture) compared to the traditional method. We demonstrate how mid-air haptic devices can promote embodiment in VR, thus potentially helping to increase presence levels in a virtual environment.

To conclude, in this thesis we want to show how the use of mid-air haptic technology can be a valuable tool to convey tactile feedback and favour embodiment in VR. We provide psychophysical information on the human perception of mid-air haptics and how to use this new technology to best achieve some tactile illusions in VR. We hope designers and scientists will be inspired by this work and will expand knowledge on mid-air haptics to deliver more immersive and realistic experiences in VR. We believe that, after the achievement of a good level of graphical realism in VR, to enhance the realism of the VE we need to program the fine details of our everyday experiences. These could be the feeling of the wind on our skin, moving from one side to another, feeling the rain on our body, being able to perceive the shape of an object with our hands. It is our view that by adding all these details and more from future research, we will become closer to feeling and believing in the "reality" part of "virtual reality".

1.2 Research context

My PhD research was carried out in the Sussex Computer-Human Interaction (SCHI) Lab at the Department of Informatics in the University of Sussex and included a four-month research internship at Disney Research in Pittsburgh, USA. Before commencing my doctoral studies, I completed a master's degree in "Clinical, developmental and neuropsychology" with a specialisation in neuropsychology at the Università degli studi di Milano-Bicocca, Italy.

During and after my degree, I worked at the Fondazione IRCCS Ca' Granda Ospedale Maggiore Policlinico di Milano in Milan for one year. There, we assessed the cognitive capacities of patients with different kinds of neurocognitive disabilities and tried to rehabilitate the residual functions. After my experimental master's thesis on Parkinson's disease patients, I decided to expand my knowledge in the experimental psychology field.

Hence, I spent one year in the University of Birmingham, UK, in the psychology department. There, I had the opportunity to use for the first time different haptic devices and virtual reality headsets. I decided to investigate the topic further and applied for my current PhD research position. Before this PhD, I had no programming experience and no engineering skills. This journey therefore helped me to challenge myself and work beyond my comfort zone.

The starting point of my research was to acquire a better understanding of the perceptual side of the new mid-air haptic technology. I started with a systematic exploration of mid-air haptic sensations by applying psychophysical methods. The first aim was to expand our tactile sensations from the hand to the whole body. I followed an iterative trial and error approach to define the design space around mid-air haptics. Although the idea was to expand touch beyond the hands, the results of this exploration revealed that the most sensitive parts of the body were mostly the glabrous parts, in other words, the non-hairy parts, such as the hands and feet. After this exploration and after reflecting on the actual sensation the device inspired in participants, like a gentle blow of air, or cold air/water, I started to envision a VR experiment to study the possible effects of embodiment on a virtual arm, mediated by mid-air tactile drops of water.

In the meantime, I had the opportunity to do an internship at Disney Research Pittsburgh. While at the Disney lab, an idea already simmering in my mind took form; I started to become more interested in tactile illusions, an area in which I could make the best use of my disciplinary background, gain new knowledge, and challenge myself with new programming languages and software. Later, I was able to use VR and apply my research curiosity in virtual environments.

Back in the SCHI Lab, I finalised and published the work from my internship at Disney and deepened my research on illusions using mid-air haptic technology. At the same time, I had the opportunity of collaborating with my colleagues on other research ideas not presented in this thesis[1].

I consider myself lucky as I have had the opportunity to be immersed in a multi-disciplinary laboratory, travel the world presenting my research, and meet and listen to brilliant minds in the field of HCI and haptics. Finally, I have had the opportunity to extend my skill set through new programming skills which complement my background in neuropsychology. I think research is a never-ending journey, and fortunately, I have secured a position as a haptics research engineer at Ultraleap, where I hope to continue to deepen knowledge in mid-air haptic perceptions and create new, compelling experiences in VR.

1.3 Thesis structure

This thesis is composed of two main sections. In the first part, "Theory", we present the theoretical understanding behind the work. In the second part, "Practice", we present a series of studies aimed at deepening understanding of ultrasonic mid-air haptics, of the creation of tactile illusions, and of their application in a VR scenario. More specifically, this thesis is organised as follows:

- Chapter 1 - "Introduction": this is the introduction chapter. It provides an overview of this thesis, the research questions, contributions, and thesis con-

[1] 1) E. Gatti, D. Pittera, J. Berna Moya, and M. Obrist, "**Haptic rules! Augmenting the gaming experience in traditional games: The case of foosball**" 2017, in *IEEE World Haptics Conference 2017 (WHC17)*, Munich, 2017, pp. 430-435.

2) Brianza G., Tajadura-Jiménez A., Maggioni E., Pittera D., Bianchi-Berthouze N., and Obrist M. "**As Light as Your Scent: Effects of Smell and Sound on Body Image Perception**", in *Human-Computer Interaction – INTERACT 2019*, 2019, Cyprus.

text.

- Chapter 2 - "The sense of touch": in this chapter we describe the functioning of our sense of touch. We describe its physiology, the way tactile information reaches the brain, and how it is represented in the brain. Finally, we reflect on the importance of the tactile sense.

- Chapter 3 - "Measuring tactile perception": in this chapter we present psychophysics, that branch of psychology that aims to study the relation between a physical stimulus and its percept. We introduce the main methods of psychophysics and review related work on tactile thresholds and spatial and temporal acuity.

- Chapter 4 - "Touch and technology": in this chapter we introduce the range of haptic technologies that have emerged in the last 20 years and are used in HCI to explore new interaction and interface opportunities. This also includes a variety of mid-air haptics technologies.

- Chapter 5 - "Tactile illusions and embodiment": in this chapter we report a few examples of perceptual illusions with a focus on those illusions exploited in this thesis. We also define the concept of embodiment and introduce the VR technology.

- Chapter 6 - "Understand: basic mid-air haptic perception": this is Study 1 (S.1), an initial study of absolute thresholds for ultrasonic mid-air haptics on the hand and arm.

- Chapter 7 - "Understand: varying technical parameters": this is Study 2 (S.2). It is a published paper (CHI 2019) aimed at the investigation of the optimal sampling rate for ultrasonic mid-air haptic technology. The study is composed of two experiments: one that finds the optimal sampling rate and one that investigates the relationship between the sampling rate and figure size.

- Chapter 8 - "Understand: perception of mid-air shapes": this is Study 3 (S.3). It is a submitted paper (IEEE Transaction on Haptics) that investigates the optimal parameters to use for ultrasonic mid-air haptics to render 2D shapes. This study is composed of four experiments, and the first experiment investigates users' performance in discriminating between three 2D geometric shapes. Two further pilot experiments research the best parameters for increasing users' discrimination performance. The final experiment demonstrates how the parameters obtained from the two pilot experiments increase the accuracy by 30%.

- Chapter 9 - "Create: tactile illusions of movement": this is Study 4 (S.4). This is a published paper (ICMI 2017) in which we study for the first time the possibility of delivering an apparent tactile motion between two non-interconnected hands with contact haptic technology. This study is composed of four experiments. The first experiment finds the optimal parameters needed to render a smooth illusion of motion between hands. The second is a pilot experiment to tune the parameters to be used later in the third experiment. The latter experiment explores whether adjustments in arm posture change order perception in a temporal order judgement task (TOJ). Finally, the fourth experiment studies the multisensory integration of vision and touch for the apparent tactile illusion in VR.

- Chapter 10 - "Create: mid-air tactile illusion of movement": this is Study 5 (S.5). It is a published paper (IEEE Transaction on Haptics) aiming to replicate the apparent tactile illusion, this time, exploiting ultrasonic mid-air haptics. This study is composed of two experiments. In the first experiment, we obtain the optimal parameters to deliver a smooth sensation of motion between the hands using a fixed focal point on each hand. In the second experiment, we investigate apparent tactile motion by using a moving point between the two hands.

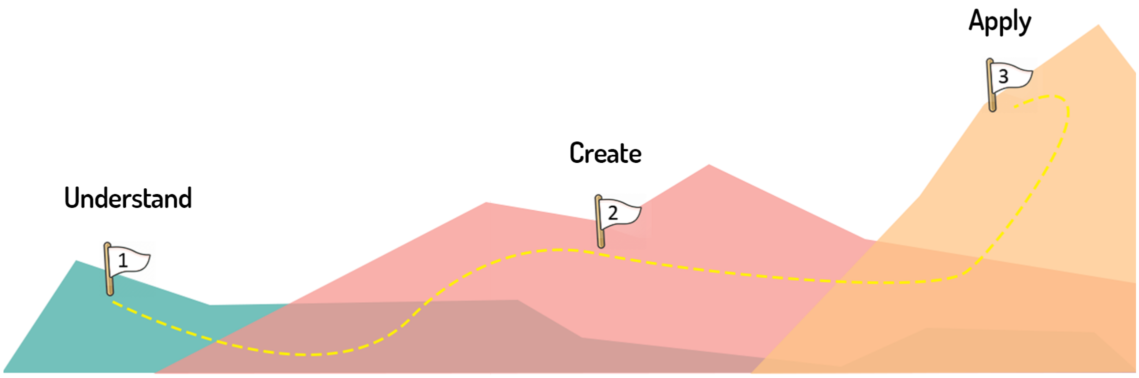
- Chapter 11 - "Apply: tactile illusion for embodiment in VR": this is Study 6 (S.6).

It is a published paper (CHI 2019) in which we apply the phenomenon of the virtual hand illusion mediated by an ultrasonic mid-air haptics device to convey a sense of embodiment in VR. This study is composed of three experiments. In the first experiment, we investigate the possibility of conveying the sense of embodiment with ultrasonic mid-air tactile technology as well as further variables with respect to the traditional paradigm. In the second and third experiments, we control for the additional variables under analysis.

- Chapter 12 - "Discussion": in this chapter we present the implications of our research. In addition, we discuss the limitations and future work.
- Chapter 13 - "Conclusions": in this chapter we present the conclusions of this thesis.

Figure 1.2 illustrates how the studies presented in this thesis fit the research questions previously individuated.

Studies 1, 2, and 3 are part of the stage "Understand". With these studies we aim to deepen the psychophysical knowledge of ultrasonic mid-air haptic technology. We contribute to **RQ1**: "How do we perceive mid-air haptics? What are the psychophysical properties of mid-air haptics?". **Study 1** explores the tactile absolute thresholds on different locations on the hand and arm. Results from Study 1 will be used as a starting point for Study 4, 5, and 6. In **study 2** we investigate the optimal sampling rate to choose to maximise our perception with an ultrasonic mid-air device. Further we discuss the relationship with sampling rate and tactile shape size. Results from Study 2 are not applied to subsequent studies because the results were available only at a later stage or because the studies are focusing on different aspects of touch. Nevertheless, study 2 results will be useful to scientist who needs to render 2D shapes on the hand or to make sense of data coming from tactile investigations of shapes through mid-air haptics. Finally, the purpose of **study 3** is to provide designers and researchers with optimal parameters that can be used to deliver 2D shapes with ultrasonic mid-air haptics.



Study	Theory chapters	Stage	Research Question
Study 1: Absolute thresholds for ultrasonic mid-air haptics Study 2: Sampling strategies for ultrasonic mid-air haptics Study 3: Strategies to render 2D shapes with ultrasonic mid-air haptics	Chapter 2 - The sense of touch Chapter 3 - Measuring tactile perception Chapter 4 - Touch and technology	Understand	RQ1: How do we perceive mid-air haptics? What are the psychophysical properties of mid-air haptics?
Study 4: Creating an illusion of movement with contact haptics Study 5: Creating an illusion of movement with ultrasonic mid-air haptics	Chapter 2 - The sense of touch Chapter 3 - Measuring tactile perception Chapter 4 - Touch and technology Chapter 5 - Illusions and embodiment	Create	RQ2: How can we create realistic haptic and specifically mid-air haptic sensations applying principles of tactile illusions?
Study 6: Illusion of embodiment in VR mediated by ultrasonic mid-air haptics	Chapter 2 - The sense of touch Chapter 4 - Touch and technology Chapter 5 - Illusions and embodiment	Apply	RQ3: Can we convey a sense of embodiment using mid-air haptics in VR?

Figure 1.2: Schemata of the studies presented in this thesis, how they link to the stages and research questions individuated.

Studies 4 and 5, while still maintaining a psychophysical objective, start to "Create" a tactile illusion. Here, we try to answer to **RQ2**: "How can we create realistic haptic and specifically mid-air haptic sensations applying principles of tactile illusions?". **Studies 4** and **5** focus on a tactile illusion of movement; the apparent tactile motion (see Chapter 5, Section 5.1). These studies follow a psychophysical approach and are intrinsically related. In **study 4**, for the first time, we investigate the optimal parameters to provide users with an illusion of movement between two non-interconnected hands. Further, we provide a perceptual model to obtain the effect of a smooth illusion of movement between the hands. We verify if changing the position of the hands (e.g., left hand forwards) changes users' perception in a temporal order judgment task (TOJ). Finally, we test how visual and tactile information interact in a VR environment. **Study 5** replicates the apparent tactile motion between two non-interconnected hands investigated in Study 4, although, this time, employing ultrasonic mid-air haptics. Since we could exploit some advantages of mid-air haptics, we tested two different techniques. First, we used a static point delivered on each hand modulating stimulus duration, frequency, and onset time asynchrony. Then, we tested the same parameters using a point moving from one hand to the other hand. For both techniques we provided a perceptual model to obtain a smooth illusion of movement between the hands, and we compare the two methods.

Finally, with **Study 6**, we enter into the "Apply" stage aimed to answer to **RQ3**: "Can we convey a sense of embodiment using mid-air haptics in VR?". Study 6 is composed of four experiments that explores and exploits the flexibility of our body schema to provide users with a virtual experience of rain on their hand. Study 6, exp. 1 and 2 investigate the VHI phenomenon using mid-air haptic stimulation. Instead of the traditional conditions, we tested if users can embody a virtual arm by delivering congruent visuo-tactile mid-air stimulation, incongruent visuo-tactile mid-air stimulation or multiple congruent/incongruent visuo-tactile mid-air stimulation. Study 6, exp. 3 and 4 serve as control experiments for the new setup employed.

Ethics approval for Study 1, 2, 3, 5, and 6 was obtained by the University of Sussex's Science and Technology Ethics Committee. Ethics approval for Study 4 was obtained through the Ethics Committee of the Carnegie Mellon University.

Theory

CHAPTER 2

THE SENSE OF TOUCH

Since ancient time, the study of the sense of touch was often upstaged by that of sight. According to Aristotle, the most important sense is the sense of sight [6]; he believed that sight, better than the other senses, allows grasping differences between objects. Besides, it can be used for the sole purpose of selfless see objects, even not necessarily with the purpose of an action. Sight is "way over all other eminent" for Galileo Galilei [63]. This view might be supported by studies which show how often sight dominates on tactile sensations [91]. Finally, in comparison to a visual percept, the tactile sensation is difficult to communicate. For instance, to describe something we see we can take advantage of terms for colours, shapes, and space; on the contrary, we do not have a proper vocabulary to express tactile sensations.

In the last two decades, however, the sense of touch became of primary interest (see Figure 2.1), especially in virtual reality (VR) research, where it represents an important factor to enhance the immersion in virtual environments (VEs) [20].

The sense of touch is the first to develop in the fetus [5, 44]. After born, we cannot clearly distinguish the shapes of an object by looking at them, but we start instinctively to touch their edges and contours. In premature babies and institutionalised kids, touch deprivation may result in developmental delays [46]. In our everyday life, we use our tactile sense to touch the clothes' fabric before buying them, we caress our beloved ones, we put our hands ahead in the dark for fear of hitting something. Our need for touch is constant, and it is fundamental when we explore objects; we retrieve information regarding their texture, temperature, compliance, and weight by means of precise exploratory procedures [141]. Contrarily to what Aristotle believed, touch can be more reliable than vision in specific cases, as in case of perceptual ambiguity [51]. However, more generally it seems that vision and touch focus on different aspects of an object [133]: touch on texture and hardness, vision on shape and size. Indeed, the sense of touch can be considered as effective as vision when judging texture, and superior when evaluating the hardness of an object [133]. Touch is highly personal; we invite you to imagine being in a busy underground in the City of London. Generally, we do not mind seeing other people, and sometimes to hear them, or smell them (if they smell good), but being touched can be annoying. After all, the skin is the interface that sets the boundaries between our person and the external world. What touches our skin, can activate our temperature sensors, our pain receptors, and potentially, can enter into our body affecting us in a multitude of ways.

The sense of touch is so pervasive in our everyday life that its importance is reflected in our language. We say that "someone is not in touch with reality"

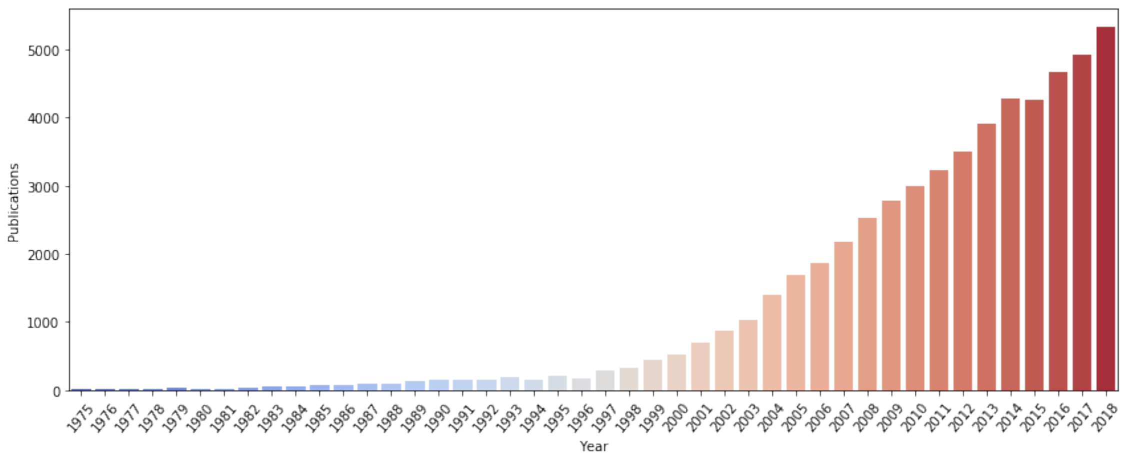


Figure 2.1: A bar plot showing the number of publications on Google Scholar with the keyword: "haptics" from 1975 to 2018. For further info, see the repository: [222].

when we think someone lost his/her ability of clear, rational thought. We describe a respectful and sensitive person as a "tactful person". If we want to maintain a relationship with someone we hope to "keep in touch" with them. In some languages, the corresponding sentence of "it doesn't bother me" is translated as "it doesn't touch me". On the contrary, when an event hit us, we say that "it touches our heart", and if we are really happy, "we can touch the sky with a finger". More essentially, the sense of touch is necessary for the act of speaking itself.

It is clear that touch is a very important sense (see Section 2.5) but there is still confusion when it comes to its definition. Below, we will first define the sense of touch and its active/in-motion counterpart, the haptic sense. We will then describe its mechanical functioning and how it is represented in the brain. Finally, we will discuss the relevance of the sense of touch in our everyday life.

2.1 Defining the sense of touch

What we commonly define with a unique word as *touch* is, in reality, a complex sense. This sense, conveys information about pressure, pain, proprioception, movement, temperature, pleasure, texture, wetness, etc. The term touch can be used in the strict sense as *cutaneous touch*, to indicate the mechanical deployments of the skin, thermal reception, and pain; or in a wider sense as *haptic sense*, which includes the perception of the internal sensations coming from the muscles, tendons, and joints that inform us about the position of our limbs in the space and how they are moving in it. This information is also called kinaesthetic.

It was the German psychologist Max Dessoir in 1892 to first propose the introduction of the term "*haptik*" (haptic) to refer to the study of the sense of touch [83, 195]. Dessoir was the first to address the problem of the terminology of the tactile sense. During his studies, the scientist empirically encountered the numerous components of touch, the ones we currently know. He felt that using only the term "touch" was not enough any more to encapsulate all the different tactile sensations. Therefore, the new word *haptic*, indicated not only the aspects of contact and pressure but also the perceptions coming from muscles and tendons. He called the firsts, "contact sense", and the seconds, "Pselaphesie" (to feel) [195], giving rise to a classification that opposed a static versus an active part of touch.

Later in the 1950s, Géza Révész, a psychologist representative of the Gestalt school, formulated ten general principles characteristic of the haptic function [194]:

1. Stereoplastic principle: when getting hold of an object with the hand, vision being excluded, subjects will not only touch the object, but they will enclose it in the hand, trying to experience its plastic three-dimensional mode of appearance.

2. Principle of successive perception: even when the object falls in the size of the palm, subjects will make a series of piecemeal tactile actions that do not yet provide a comprehensive view of the object.

3. Kinematic principle: this principle states that haptic can only take place through the movement of the sensory apparatus.

4. Metric principle: the structural identification of an object always assumes an orientation with respect to the location and the quantitative relationships of the parties with each other and with respect to the whole.

5. Receptive attitude and the purposive attitude: receptive attitude derive qualitative information about the objects, such as shape. The purposive attitude derives structural information.

6. Tendency to establish types and schemata: haptic generally categorise objects in groups, according to types and well-known groups of shapes and objects.

7. Tendency to transpose: it consists in the optimization of haptic data into visual information.

8. Principle of structural analysis: the haptic perception tends to the recognition of the structure more than the shape of an object.

9. Principle of constructive synthesis: after the preliminary analysis and the perception of the structure, it begins a constructive process that summarizes information on the form into a homogeneous whole.

10. Autonomous formative activity: the tendency to visualize shapes for touch, is specific of the haptic domain and separate from sight.

In 1962 also Gibson ([76]), influenced by Révész, distinguished between two tactile experiences: passive touch and active touch. In passive touch, people are passively touched by an external agent and the focus of their attention tend to be aimed at their subjective bodily sensations. Instead, during active exploration, people focus on the properties of the external environment. Inputs from the cutaneous receptors are sufficient to explain the nature of the passive touch perception, but they seem crucial also in the active touch exploration. Further to this classification, Gibson wanted to underline the volitional characteristic of active touch; when we actively move our arms and hands to touch or grasp something, we are doing it for a specific purpose [233].

Hence, haptic perception means sensing and/or manipulating objects in a natural or synthetic environment through the use of *active touch* with the hand or a tool acting as such. It can be considered a combination of tactile perception derived from the objects in contact with the surface of the skin and the information obtained from the proprioception that informs us about the position of the hand relative to an object. In this respect, Lederman and Klatzky systematically described a set of exploratory procedures used to recognise objects' properties [141] (the most studied are represented in Figure 2.2). For instance, to retrieve temperature information, we tend to keep our hand static on the object's surface, or to understand the firmness of a mattress, we tend to press it.

Whether it is touch or it is haptic, these senses are mediated by a series of receptors pervading the skin, joints, and muscles. The skin is the largest organ of the human body. It is the interface between oneself and the external world. We will now present the physiology of touch.

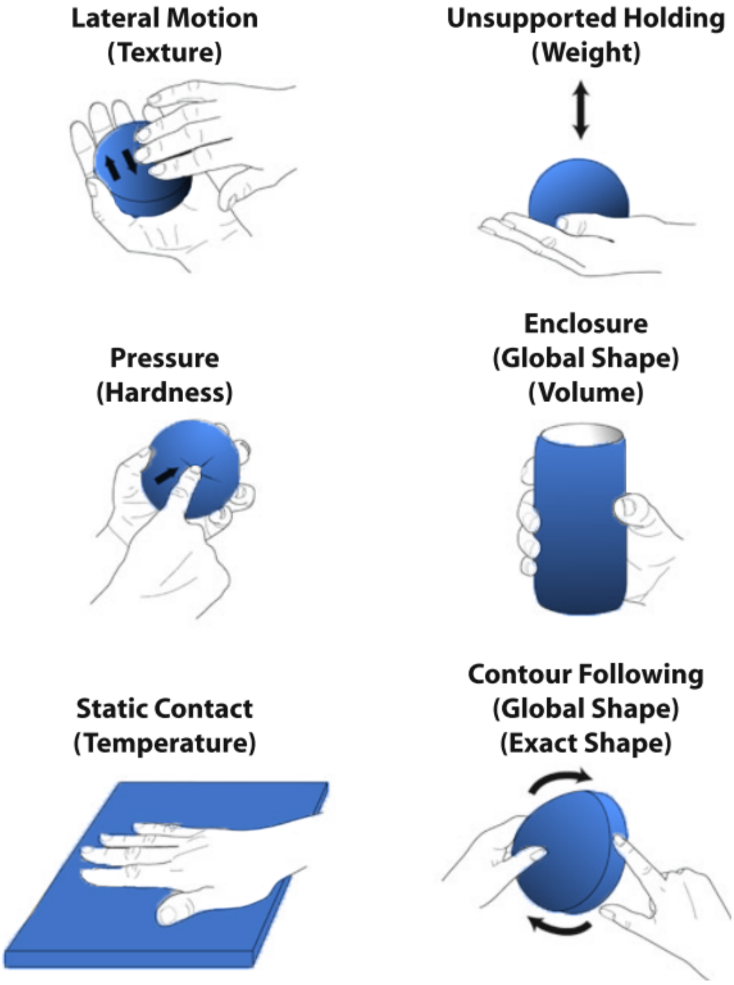


Figure 2.2: Adapted from [142]. Six of the most studied exploratory movements used to recognise objects' properties with our sense of touch.

2.2 Touch physiology - tactile receptors

The sense of touch begins in the skin. This is the most extended organ in the human body and is divided into three layers: epidermis, dermis, hypodermis (Figure 2.3a). The receptors that allow the tactile sensations are contained in the skin. The most numerous are the mechanoreceptors, which can be also found in the blood vessels, internal organs, and joints. There are four fundamental receptors (see Figure 2.3b):

1. the Meissner corpuscles
2. the Merkel discs
3. the Pacinian corpuscles
4. the Ruffini corpuscles

Distributed throughout the skin there are also free nerve endings responsible for delivering signals related to pain and temperature to the brain. Some of these nerve endings are twisted around the base of the hair follicles and the stems of the hairs emerging from the skin; these fibres collect the hair movements. Each mechanoreceptor differs from the others based on the sensory function, structure, density, location, receptive field area, tactile channels, stimulus adaptation, and psychophysical properties (see Figure 2.4).

Following, we report the frequency ranges for each of these mechanoreceptors (note: different sources may indicate different values). The Merkel disks and the corpuscles of Ruffini provide information about pressure and low-frequency vibrations [22, 42, 167, 188] (from 0 to 100 Hz). The Pacinian corpuscles perceive mechanical stimuli, especially high-frequency vibrations (5 to 1000 Hz) [27, 94, 178], while the Meissner corpuscles respond to low-frequency vibrations (1 to 300 Hz) and small taps [22].

In the tactile neurons, the receptive field is the area of the skin, or of another tissue, which provides information to that particular receptor. Pacinian and Ruffini corpuscles have very large receptive fields (the entire hand and 60 mm^2 respectively) [22, 167], providing information on the general boundaries of a stimulus, while Meissner corpuscles and the Merkel discs have very small receptive fields (22 mm^2 and 9 mm^2 respectively), allowing to identify the spatial limits of a small stimulus

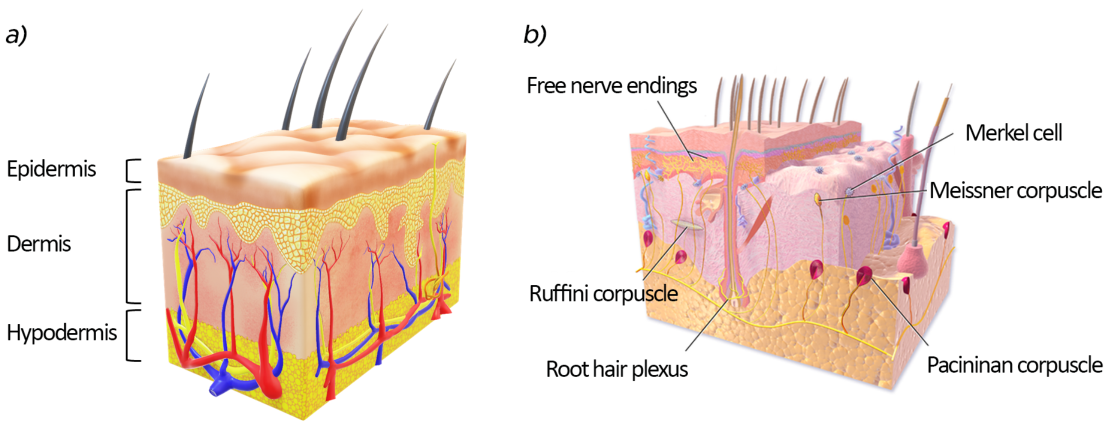


Figure 2.3: a) The skin. It is the largest organ of the body. It can be divided in three layers: epidermis, dermis, and hypodermis. b) the main tactile receptors.

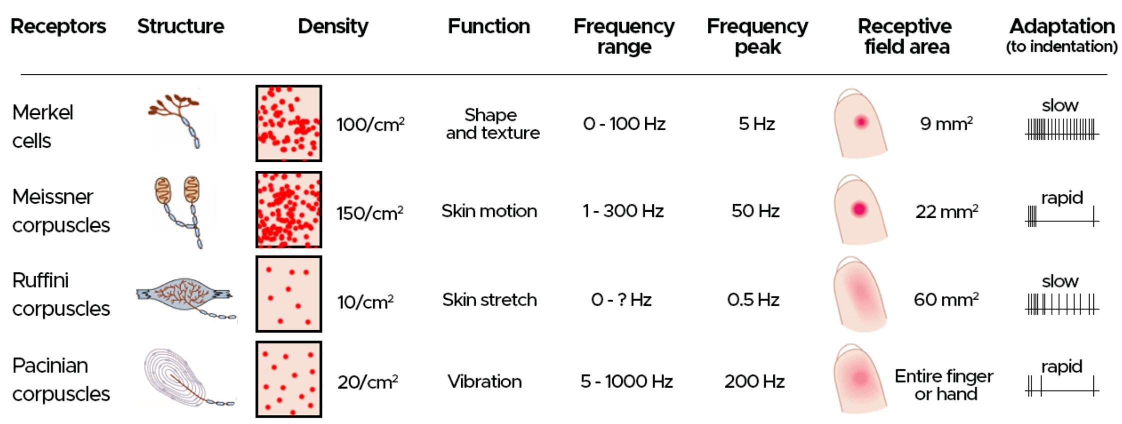


Figure 2.4: A summary of the mechanoreceptors properties. Adapted from [188] and [126]

[115, 188]. Based on the area of their receptive field, the mechanoreceptors are named *I*, for small receptive fields, and *II* for bigger receptive fields.

These skin sensors are not equally distributed across the body [188] (Figure 2.4, third column), with the Pacinian and Ruffini receptors being the scarcest in density. For instance, if we consider the skin that covers the hand there is a higher density of RA-I and SA-I receptors in comparison to the deeper localised RA-II and SA-II receptors [92]. Overall, the sensitivity of tactile stimuli varies from part to part of the body accordingly to the density and the size of the receptive field of the receptors that serve that area. The peripheral parts of the body (arms and legs) are more densely innervated than the trunk and the proximal parts [117]. This translates in lower sensitivity thresholds in the former areas. We will discuss the absolute thresholds and the spatial acuity of our sense of touch in a later section (see Section 3.9).

Finally, Pacinian and Meissner corpuscles are not sensitive to prolonged stimulation, meaning that if the stimulus is kept constant on the skin, these receptors will stop to "*fire*" (transmit information) to the central nervous system (CNS) (see Figure 2.4, last column). These receptors are also called *fast adaptive* receptors (FA or rapid adaptive, RA). On the contrary, Merkel and Ruffini receptors, are responsive to sustained indentations on the skin. These receptors are also called *slow adaptive* receptors (SA). Together with the nomenclature referring to their receptive fields, the mechanoreceptors are therefore called, RA-I (Meissner), RA-II (Pacinian), SA-I (Merkel), SA-II (Ruffini).

2.3 Touch physiology - tactile pathways

Not every tactile information follows the same path to get to the CNS. The information from the skin, internal organs, and muscles go through the spinal nerves; while the information from the face and the head pass through the fifth cranial nerve, the trigeminal nerve. Further, localised tactile information (fine touch, proprioception, vibrations) follow the so-called "dorsal column-medial lemniscal pathway". Proprioceptive information that does not reach the level of consciousness, follow the "pathway to the cerebellum". Finally, poorly localised tactile information (crude touch, pain, and temperature) follow the "spinothalamic pathway".

Information entering the dorsal column-medial lemniscal pathway ascends from

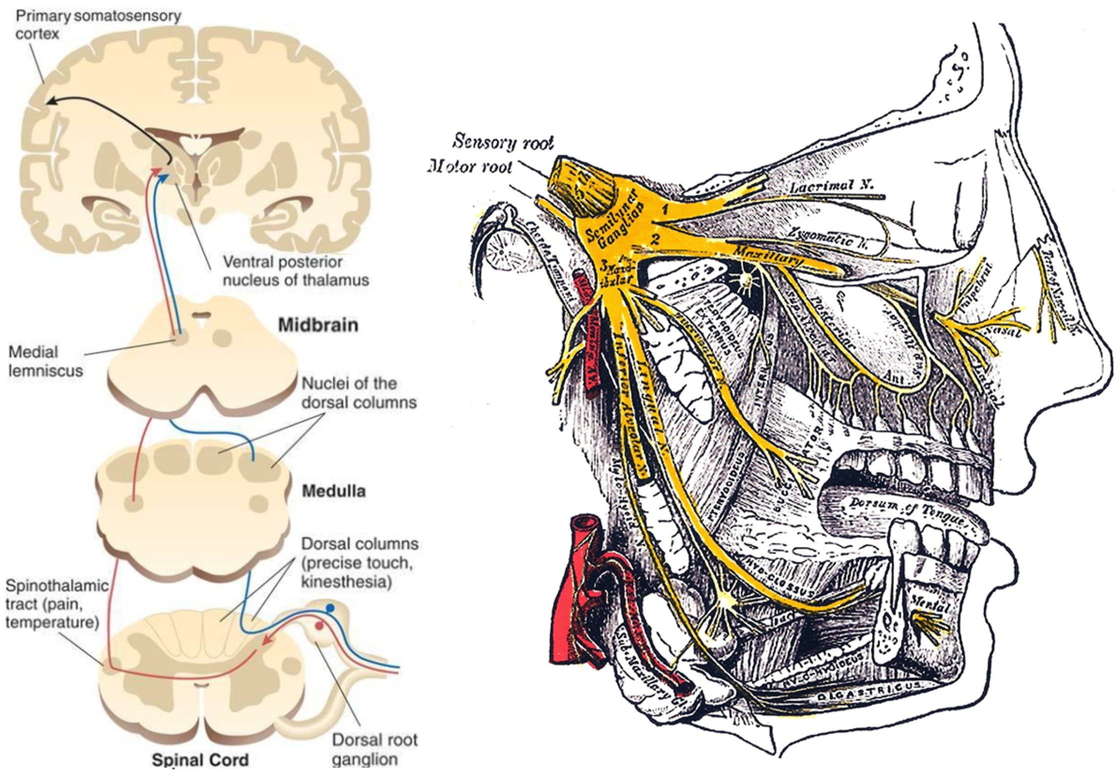


Figure 2.5: (Left) Tactile pathways: how the tactile information reach the CNS. Blue arrow: the dorsal column-medial lemniscal pathway, for localised info. Red arrow: the spinothalamic pathway, for poorly localised info. Tactile information from the face is mediated by the trigeminal nerve (right, in yellow).

the nerves through the dorsal columns to the lower bulbar nuclei. Then it decussates and continues the ascent through the medial lemniscus to the ventral posterior nuclei of the thalamus, to finally reach the primary somatosensory cortex (S1) that then projects information to the secondary somatosensory cortex (S2) (Figure 2.5). Information following the pathway to the cerebellum is ipsilateral and is transmitted directly to the cerebellum bypassing the thalamus and S1. Lastly, the information travelling through the spinothalamic pathway forms synapses with the neurons in the spinal cord, then it decussates towards the opposite side of the body and ascends through the spinothalamic tract to the posterior ventral nuclei of the thalamus (Figure 2.5).

It might exist an additional pathway that bypass S1. Brochier et al. [21] reported the case of a patient with a lesion to S1 who lost his somesthetic sensitivity to his left arm. The patience was still capable of locating the tactile stimulation occurring on his arm, even if he was not aware of that stimulation. This case led the authors to hypothesize an additional tactile pathway that bypass S1. To date, even if this hypothesis represents a possibility, there is only scarce evidence from neurophysiological studies.

Concluding, the tactile information arising from the mechanoreceptors in the skin travels along one of the pathways described. Each receptor signal would not be enough by itself to make a neuron release info to the brain. The process is allowed by temporal and spatial summation of mechanoreceptors signals. How the information is integrated into the CNS is still a matter of study. The latest studies hypothesize that the brain works following a Bayesian framework when processing tactile information [75, 174]. When we gain information from our environment, these are encoded from our senses and passed to the brain, while our prior knowledge of the world, works to modify the final percept. From this process, we will elaborate posterior knowledge that will serve as prior knowledge when new information will enter into our (neural) system. This process will repeat continuously for every information gained from the external world.

2.4 Tactile representation in the brain

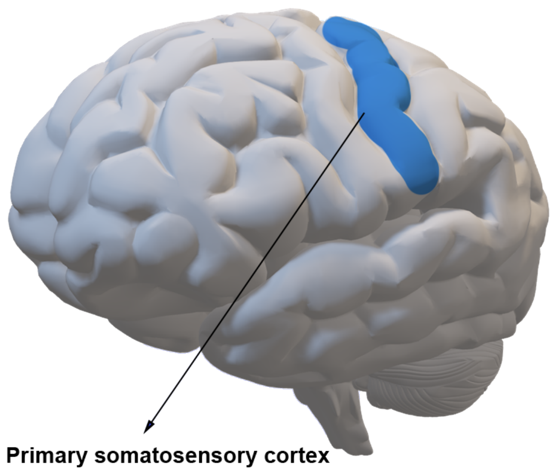


Figure 2.6: The primary somatosensory cortex. It is responsible of the tactile sensation we receive from our body parts.

When we experience a tactile sensation, our receptors are stimulated, and close receptors send information to close neurons in the brain. The primary somatosensory cortex (Figure 2.6) resides in the parietal lobe and contains a neural representation of the different parts of the body. S1 is responsible for analysing the tactile information coming from our body parts. In 1940, Wilder Penfield, American-Canadian neurosurgeon, in the process of individuating problematic areas in epilepsy patients' brain, mapped S1 following the quantity and density of receptors in various parts of the body, giving birth to the so-called "sensory homunculus". In this illustration (Figure 2.7), the size of the different body parts is not proportional to the absolute size of the body surface, but the density of the tactile receptors contained in it. That is why the hands, lips, and tongue appear as the biggest. It is to note that this representation is far from being fixed. There is a phenomenon called *neuroplasticity* which is responsible for the reorganisation of the body parts at a neural level. Neuroplasticity is the reason why blind people can have an enhanced sense of touch, or pianists, a larger area in S1 underlying the representation of the fingers. More generally, neuroplasticity is an adaptive mechanism that our brain uses to face changes in the amount or quality of stimulation.

We know from studies on the visual system, that there are two streams in the cortical visual processing: a ventral stream that analyses the shape and visual features (the "what" way), and a dorsal stream that analyse spatial characteristics of an object (the "where" way). In 2005, Reed and colleagues, hypothesize the existence

Figure 2.7: (left) A representation of S1 with Penfield's homunculus superimposed (right) Penfield illustration of the sensorial homunculus. The bigger the body part, the bigger its receptors' quantity and density.

of a similar organisation for the cortical tactile processing [193]. In their fMRI study, participants performed two separate tasks. The first task aimed to recognise an object ignoring its spatial features, while the second task aimed to localise an object ignoring the physical properties of an object. Their results confirmed separate processing streams for the two tasks. In particular, the object recognition task activated the frontal pole as well as bilateral inferior parietal and left prefrontal regions, and the object spatial recognition task activated bilateral superior parietal areas. A subsequent behavioural study confirmed the existence of separate "what" and "where" ways in the tactile system [29]. In particular, they demonstrated how two "what" tasks or two "where" tasks interfere while mixing one "what" and one "where" tasks reduce this interference.

2.5 The relevance of the sense of touch

In everyday life, probably without realizing it, we make use of all those modalities related to touch; when we have to decide if to buy a new dress, and we ensure the fabric is to our liking, when we find ourselves in the darkness trying to make our way between obstacles, when we press the virtual buttons of our phone, when we walk, when we talk. Without the sense of touch, we would not even be able to light a match easily. Touch is the first sense to develop and seems to appear already in the fetus [10, 44, 137]. It has been shown that at stimulations of the abdominal wall of the mother correspond an increased activity of the child [137].

Touch also plays a key role from birth and during the child's development, managing to calm the infant in case of pain and discomfort. Winnicott identified three important maternal functions for the healthy development of the child, including that of handling, or the number of maternal physical manipulations (cares, cleaning, caresses, etc.) that facilitate the psychosomatic integration. Some authors indicate the sense of touch as the most reliable sense [15]. "Seeing is believing, but feeling is the truth" according to the English clergyman and historian, Thomas Fuller (1732). When we see an unknown object, we touch it to snatch the characteristics of form, material composition or simply for curiosity; not surprisingly traders have to exhibit the famous sign "DO NOT TOUCH". In this respect, Peck and Childers developed the "need for touch" scale, aimed to measure individual differences in preference for haptic information [179].

Our sense of touch is involved in many voluntary and involuntary functions, some of those we might take for granted, as the following cases illustrate.

2.5.1 The need of contact

Studies illustrate how the lack of contact in infants and children (in nursing) is related to a delay in cognitive and neurological development [154] which are often below the average, and that, unfortunately, persist even several years after the adoption or even for life [12]. The same can occur in cases of depressed mothers who do not provide enough caresses to their children, who will spend more time touching their skin as if to compensate for the maternal deficiency [98]. Other researches show that the contact given by depressed mothers to their children can make up for the lack of facial emotional and verbal communication [180]. Field et al. [56], demonstrated how an additional amount of contact given to mothers with a depressive disorder, such as massages, decreases their depression and promotes the growth and development of their infant. After the sixth week, they saw that the child showed improvements in emotional and social skills, with decreased awake time, thus promoting proper sleep. Importantly, both, the sender as well the receiver of this type of tactile stimulation obtained some benefits.

Massage therapy was found to be effective on many hardships including pain, stress, depression, attention deficit disorders, autoimmune diseases such as asthma, dermatitis, diabetes, AIDS and diseases such as breast cancer [55]. Finally, contact can also favour the level of attention associated with increased activity of the vagus nerve that would reduce the heart rate typically associated with attentional performance [54].

2.5.2 The importance of proprioception

The case of Ian Waterman helps us to realise how important the sense of touch is and in particular the proprioceptive sense. IW contracted a viral infection at the age of nineteen that destroyed the larger fibres of the cutaneous nerves that connect the mechanical receptors to the central nervous system. As a result, he lost the sense of touch and proprioception from the neck down. The patient had no awareness of his body position in space, and without constantly watch his limbs, he was not even able to walk. It was impossible for him to move in the dark as well as to focus on more than one thing at the same time. IW never healed completely, but he learned to live with his condition managing to walk, drive, and work.

Similarly, Oliver Sacks, in his book "The man who mistook his wife for a hat" [199], describes the case of Christina. Christina developed a rare acute polyneuritis that deprived her of the proprioceptive sense. The woman became unable to move, and she had to come up with compensation methods to start walking again. She had to constantly monitor herself with the eyes: "*[...] looking carefully at each part of her body as it moved, using an almost painful conscientiousness and care*".

2.5.3 The importance of pain in our life

Pain is part of the sense of touch. It has an adaptive function. It warns us about something that is not working as it should. Even if at first sight it could seem something relieving, the absence of pain leads to very serious consequences. This is the case of the congenital insensitivity to pain with anhidrosis disease (CIPA). The CIPA is a very rare autosomal recessive disease (less than sixty cases in the medical literature [203]), characterized by congenital insensitivity to pain, lack of temperature perception, intellectual disability, and self-mutilating behaviour.

> “Pain is an unpleasant sensory and emotional experience associated with actual or potential tissue injury, in other words, described in terms of such damage. Pain is always subjective. Everyone learns the use of the word through the experience of an injury at an early age" [34].

When this unpleasant experience is missing, inevitably we undergo more or less serious problems, ranging from the lesion of the oropharynx tract to fractures by trauma, bone deformation, and early death [202].

2.6 Summary

In this chapter, we introduced the sense of touch, a multifaceted sense composed of an active and a passive modality, that help us to feel the world around us through receptors located in the skin, muscles, tendons, and internal organs. We described the different routes to the CNS the signal deriving from the tactile receptors follows depending on the information encoded. We presented how this information is represented in the brain and observed how not every part of the body has the same density of receptors. Hence, tactile sensitivity is not uniform across the body. Finally, we discussed the importance of the sense of touch in our everyday life providing some examples. Those examples make it clear how all the constituting part of touch we give for granted, in addition to the cutaneous sensations, are essential for our life, even for the simplest everyday routine. This chapter gives us an idea of the complexity of the sense of touch. A complexity that we need to take into account when designing and implementing tactile/haptic feedback in human-computer interfaces and applications. From our discussion, it appears how tactile information is intrinsic in every aspect of our life. If we want to make users engage with technology in a way that feels more natural and enjoyable, we cannot neglect our sense of touch. Indeed, previous research highlights how tactile feedback can be considered an important factor for the user immersion in a virtual reality (VR) application (see Chapter 5, Section 5.4.2).

Following, we will introduce part of the main techniques at our disposal to measure the human perception of tactile stimuli.

Chapter 3

Measuring tactile perception

We use our senses daily. We enjoy the colours of a beautiful sunset, we listen to our favourite music, we foretaste our dishes inhaling their scents, to finally eat carefully the food tasting it in our mouth, and we share emotions through touch with our dears. Most of us can perceive the world through the five senses, but how can we measure these percepts? Throughout the history of science, a methodology has been developed that aims to answer this question: the psychophysics.

3.1 Birth of the classical psychophysics

Psychophysics is the branch of psychology that studies the relationship between physical stimuli and the sensation associated with those stimuli. Psychophysics is a methodology to develop objective measures of all the human sensory systems. The term "psychophysics" was coined by the German Psychologist Gustav Theodor Fechner, who elaborated as a theoretic model a relationship discovered by Ernst Heinrich Weber in 1834. Weber expressed as $\Delta R = kR$, the relationship between R (stimulation) and ΔR, that is the differential amount of stimulation needed to

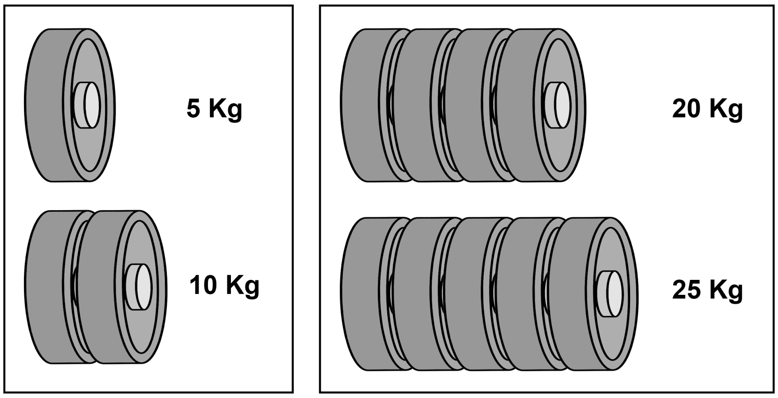


Figure 3.1: An illustration of the Weber-Fechner law. 5 Kg (ΔR) were added to an initial amount of weight (R). However, the perception is different: on the left side, the difference between weights will be easily perceived. On the contrary, the difference between the weight on the right, will feel almost the same.

make a human aware of the change in stimulation. For instance, an athlete in the gym is lifting some cast iron (R). To perceive an increment in the weight lifted, the athlete will need to add a certain amount of cast iron to his dumbbell (ΔR) before feeling an increment of weight. Weber discovered that the ratio ΔR / R does not change with changing the stimulus R. The Weber constant (k) is a constant that is specific for each sensorial channel, and varies depending on what we are measuring. For instance, for lifted weights is 0.02, for sound intensity is 0.04, for electric shock is 0.01. The Weber law introduces the concepts of differential threshold or *just noticeable difference* (JND). The JND is defined as the minimum difference in stimulation that a person can detect 50% of the time. The greater the stimulation R, the more ΔR needs to be increased (or decreased) to experience a change in the corresponding subjective feeling (see Figure 3.1). In other words, we are less sensitive to differences in stimulus intensity as the intensity of a stimulus increases.

Starting from the assumption that the Weber law holds, and that the JND is the basic unit of perceived magnitude, Fechner derived a mathematical relationship where the perceived magnitude (P) and the stimulus intensity (I) are in a logarithmic relationship: $P = k\log I$. Where k is the Weber's constant. Therefore, doubling the light in a room, will not be equivalent to perceiving the room as twice bright. Indeed, the relationship between perception and stimulation is not linear.

At a later time, the Weber-Fechner law was expanded to a wider range of sensory measurements with the so-called "Stevens's power law". As anticipated by the name, in this law the relationship between the stimulus and the percept are expressed exponentially: $S = c * I^{a}$. Where S is the intensity of the sensation, I is the intensity of the stimulation, c is a constant that depends on the unit of measure of the stimulus, and a depends on the kind of measured stimulus. Therefore, the results will be a family of curves where the intensity of the percept will be proportional to the intensity of the stimulus powered to exponents typical of the investigated sensory channel (Figure 3.2). Stevens's Law was found to better describe the perception of different kind of stimulations in comparison to Weber-Fechner's law.

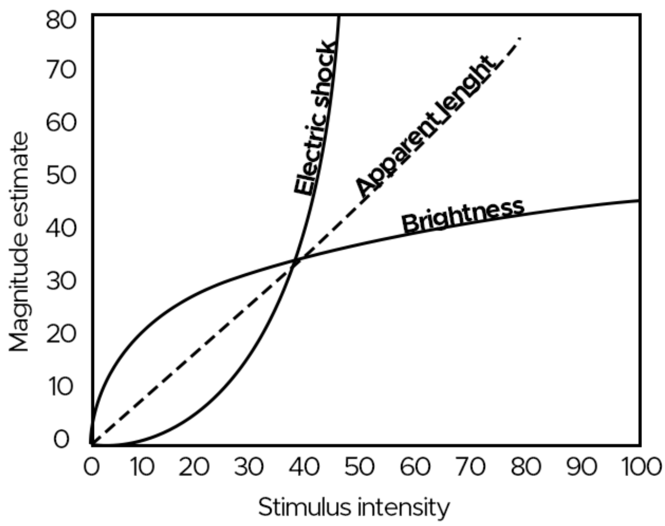


Figure 3.2: Possible curves originated from the Steven's law. Depending on the exponent of the stimulus investigated, the the perceived magnitude of a stimulus will result in a different curve.

3.2 Psychophysics: areas of investigation

Psychophysics mainly focuses on three areas of investigation:

1. **Absolute thresholds**: it is the lowest intensity of a stimulus that can produce a change in the neural activity. In other words, it is the minimum amount of stimulation needed to be perceived by a system and create a sensation. For

instance, the minimum amount of light in a dark room needed to perceive that the light is on. A synonym of "threshold" is "*limen*". When a stimulation remains under limen, we call it "*sub-liminal*".

2. **Discrimination thresholds or difference threshold**: it is the difference in intensity between two stimuli needed to produce a change in the neural cell. In other words, it is the minimum amount of difference between two stimuli needed for the system to perceive that those stimuli are different 50% of the time. For instance, the amount of brightness difference between two lights that make an observer notice a difference between their brightness. As explained in Section 3.1, the amount by which two stimuli must differ for the observer to detect the difference is referred to as *just noticeable difference* or JND. When studying differential thresholds, another key concept is that of *Point of Subjective Equality* (PSE). The PSE is defined as the point where two stimuli are subjectively perceived as the same. Thus, an observer would choose randomly between them. In practise, it is the X-axis intercept that corresponds to the 50th percentile of the Y-axis of a psychometric function (see Section 3.8).

3. **Scaling**: it is that branch of research that uses rating scales to assign quantitative values to express qualitative constructs or sensory experiences. Examples of scales used in psychophysics include Likert scale, Guttman scale, and Thurstone scale.

Each of these areas can make use of different methods elaborated by psychophysics researchers. We will briefly introduce them in the following sections.

3.3 Classical methods

We will first introduce three methods used to investigate stimuli detection (if the stimulus is present or not) and stimuli discrimination (if the stimulus changed in some manner). These methods are now called *classical* and they were developed in the nineteenth century:

1. Method of adjustments
2. Method of limits
3. Method of constant stimuli

Method of adjustments: the participant is given a chance to directly modify the intensity of the stimulus object of investigation. The experiment starts with the intensity set at high (descending trials) or low (ascending trials) levels so that the stimulus is surely perceived or not by the participant. The number of descending and ascending trials must be equal. At this point, the participant modifies the stimulus intensity until it can just perceive it, and this process is repeated many times. The absolute threshold is the arithmetic mean of the chosen intensities.

Method of limits: the researcher set different stimuli organised in different discrete levels of intensity. The stimuli are presented in a descending or ascending intensity series. During the descending series, the participant will answer "no" when the stimulus is not anymore perceived. In the ascending series, the participant will answer "yes" when the stimulus is finally perceivable. The threshold is estimated through the arithmetic mean of the values when the participant changes his/her answer from "yes" to "no" and vice-versa.

Method of constant stimuli: a certain number of stimuli of different intensity is presented to the participant many times, in randomised order. In each trial, the subject will communicate if he/she perceived the stimulus. The threshold will be that stimulus that has 50% of the probability of being perceived. Differently from the method of limits, here the stimuli are presented in a randomised order.

There are several limitations concerning the methods presented above. For instance, in the method of adjustments there can be sensory fatigue (neural adaptation) working against accurate stimulus discrimination. In other cases, the observer could have expectations regarding the next test stimulus. In the method of limits, starting from subliminal stimulations will create an expectation of a supraliminal stimulus, and vice-versa. The method of constant stimuli usually takes a long time to be completed. Generally, the classical methods also include many trials at levels far from threshold (with the exclusion of the method of adjustments). To obviate this issue, adaptive methods have been developed.

3.4 Steven's methods

After Fechner's methods, psychophysics continued to evolve. An example is represented by the Thurstone's *law of comparative judgement*. This law can be used to compare physical stimuli and qualitative comparative judgements. The stimuli to measure are presented pairwise, and the participant has to express which of the two stimuli is expressing a certain characteristic in a greater or lesser extent. After the whole series of comparisons, it is possible to order stimuli by the presence or absence of the target quality.

As mentioned at the end of Section 3.1, Stevens was another protagonist of the psychophysics evolution and creator of the direct psychophysics. Stevens thought that the Weber-Fechner methods were unnecessarily indirect. For Stevens, it was possible for participants to directly assign numerical values to the stimulation received. These numerical values correspond to psychological values that are directly communicable. The main methods introduced by Stevens are the *magnitude estimation*, the *magnitude production*, and the *cross-modal matching*. In the magnitude estimation method, extreme values for a certain stimulus (modulus) are showed, as example, to the subjects. During the testing phase, subjects have to assign numerical values to the stimulation perceived in each different trial. In the magnitude production method, participants have to match a certain value given to them by the researcher, to a stimulus. Lastly, in the cross-modal matching, participants need to express their judgement on the intensity of a certain stimulus choosing an intensity of a stimulus that belongs to another sensory modality. For example, consider to set up a study to evaluate the brightness of a LED light. The researcher will present different levels of brightness to the participants, and the participants will need to express the light brightness by choosing a certain loudness of sound. Brighter lights will correspond to louder sounds (in dB).

3.5 Modern heuristic-based methods

Another set of methods of the psychophysics are those called *modern* methods. These, originate from the classical methods, but they are usually *adaptive*. A method is said to be adaptive if the intensity of a certain stimulus in a trial, depends on the answer given by a participant on a previous trial. Following, we will describe the main adaptive methods.

Simple Up-Down Staircase method: in this method, usually, the stimulus is set at a supraliminal intensity, so that it is certain the participant will perceive the stimulus. Later, the intensity is reduced to the point the participant can not feel anymore the stimulation. When this happens, the staircase is reversed, and the intensity increased back again until the participant perceives the stimulus again. At this point, the staircase is reversed again, and the intensity decreased. After a set number of inversions (termination rule), the experiment is concluded and the values of a certain amount of last inversions are averaged and taken as a threshold (decision). In practice, when the participant answers correctly one time in a row, the stimulus intensity is reduced by one step size. When the participant makes an incorrect response the stimulus intensity is increased by one step size. The threshold is calculated averaging the mean midpoint of all runs. However, there are different designs of staircase procedures, with different termination rules and decisions.

Transformed Up-Down Staircase method: The X-up-X-down staircase method is maybe the most used staircase procedure. In general, we can have X up - X down parameters where the X up decides the number of wrong answers for rising the stimulus intensity, and X down decides the number of correct answers needed to lower the stimulus intensity.

Details on further staircase procedures can be found in [66].

3.6 Model-based methods

Bayesian and maximum-likelihood procedures: these two techniques can appear similar to the staircase procedures, in that they are adaptive procedures. In the maximum-likelihood procedure, the threshold likelihood is calculated from the set of all previous stimulus-answer responses. The point of maximum likelihood is chosen as the threshold estimate, and the participant will be tested on stimuli at that value. In a Bayesian procedure, we calculate the value of the next stimulus by inserting a prior belief, or a prior likelihood.

3.7 Signal Detection Theory

In 1966 an important innovation was introduced in the realm of the psychophysical methods, the Signal Detection Theory (SDT). The theory had already been developed in the 1950s but applied only now in psychophysics, for the first time, by two American psychologists, David Green and John Swets. The SDT theory assumes that every sensorial process happens in a noisy background. That is, when an observer needs to decide if the target stimulus (signal) is present in an environment, he/she has to try to discriminate it from everything else that might be confused for the target (noise). Here, noise is to be understood in a broad sense. We consider noise external confusing stimuli, and random internal neural disturbance.

Let's assume as an example that we want to test when observers discriminate between an aeroplane in the sky (target), or a bird (noise). We collect the subjects' answers under the form of four possible couplings between the physical presence of the stimulus (aeroplane) and noise (bird), see Figure 3.3.

Hit: when an observer detects the presence of the signal that indeed it exists (aeroplane when it is an aeroplane). Miss: when an observer does not detect the presence of the signal that instead, it exists (birds when it is an aeroplane). Correct rejection: when an observer does not detect the signal and indeed there is no signal (bird and it was a bird). False alarm: when an observer detects a signal, but

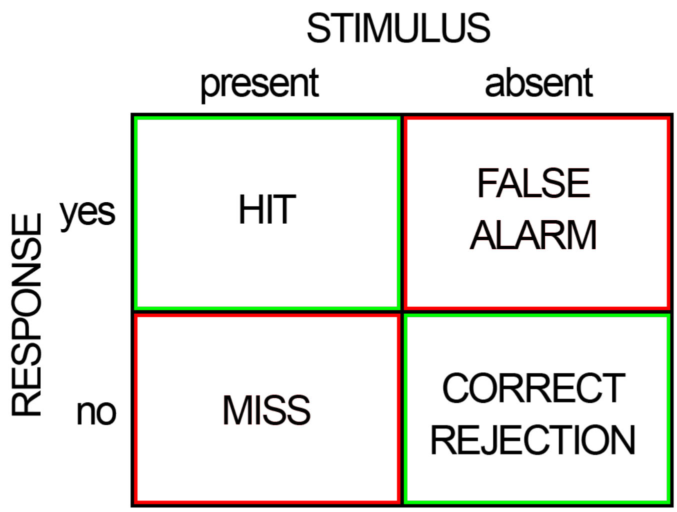


Figure 3.3: SDT method generates four possible values depending on the answers of the observer: 1) hit, 2) miss, 3) false alarm, and 4) correct rejection.

there is no signal (aeroplane but it was a bird).

Generally, the SDT theory assumes the existence of sensory and decision processes and tries to find out the parameter characterizing those processes. The first parameter is the *d'* that describe the sensitivity of the sensory process, or the separation between the signal distribution and the noise distribution (the separation between the green and red curve in Figure 3.4), and the β *index* that describes the bias or response criterion of the decision process.

The *d'* index is based on the *difference* between the percentage of hits and the percentage of false alarms. The β index instead, is based on the *ratio* between percentages of hits and false alarms. Therefore, the *d'* index refers to the accuracy of the system, and the β index refers to the criterion chose by the observer to be more prone to detect or ignore the signal. In our example, the *d'* describes how well an observer could discriminate between an aeroplane or a bird in the sky. The β index describe how much the observer would rather say "aeroplane" in comparison to "bird". If the observer was a medical doctor, we could interpret the *d'* as the skills of the doctor to detect a tumour in a patient based on the information collected. The β index would be the personal tendency of the doctor in case of noisy information (e.g., functional and structural imaging) to decide that what he/she sees is a tumour rather than not (Figure 3.4 exemplifies this concept).

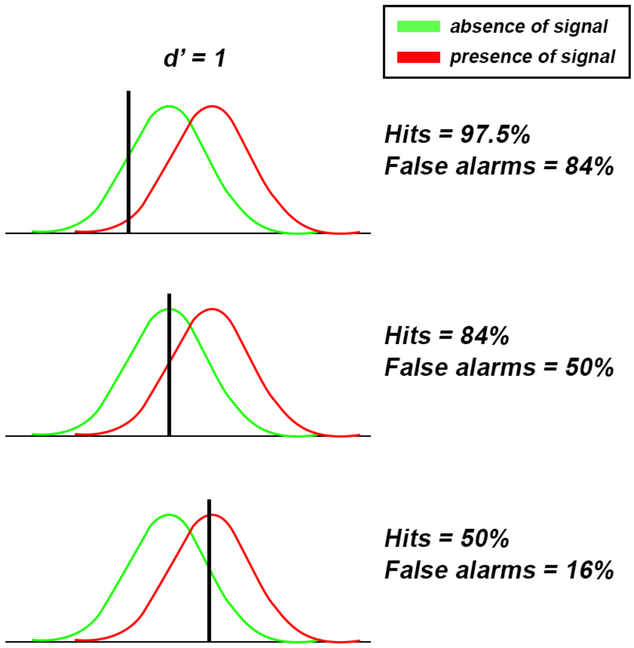


Figure 3.4: Visualisation of the *d'* index and the criterion. Two distributions are shown: in green, the probability distribution of a signal to be absent (noise), in red, the probability distribution of a signal to be present. Depending on the criterion chosen (vertical line), an observer will detect many signals but also many false alarms (top), many hits and high false alarms (centre), high hits and low false alarms (bottom).

Therefore, the SDT theory refuses the concept that the observer's answers on a psychophysical task depend only on the observer's sensory sensitivity. Instead, it prefers a vision where the answers depend not only on the sensory sensitivity but also on a post-perceptive decision criterion adopted by the observer. Further, this criterion depends on personal inclination to risk, mood, and several other factors.

The full range of an observer's decisions can be described by the *Receiver Operating Characteristic* (ROC) curves (Figure 3.5). The ROC curves capture the sensitivity (*d'*) through the bow in the curve. Moving along the bow captures the criterion (β index). For example, take the *d'*=1 curve; in this case, the criterion is very low (a point located towards the upper right part of the *d'*=1 curve), both, the number of hits and false alarms will be high. We would call this choice, a strict criterion. On the contrary, if the observer set a high criterion (a point located towards the bottom-left part of the *d'*=1 curve), then the number of hits and false alarms will be low. We would call this choice, a lax criterion. As indicated in Figure 3.5 right, the higher the

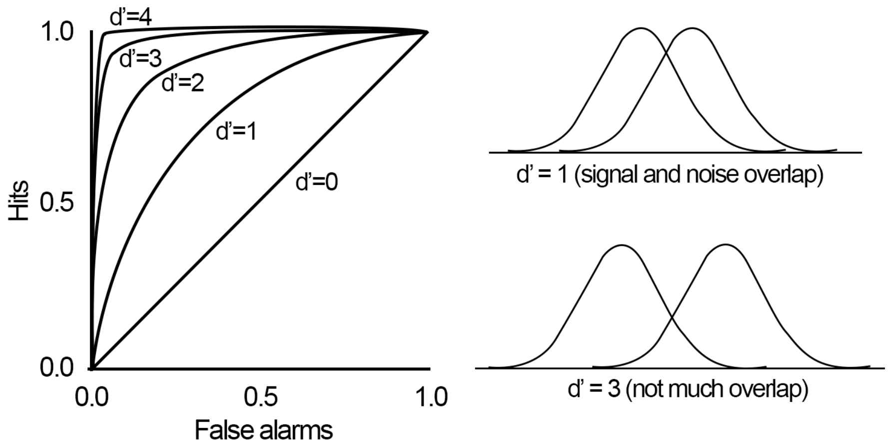


Figure 3.5: Left: the ROC curves graph showing the full range of an observer's possible decisions. The ROC curves capture the sensitivity (d') through the bow in the curve. Moving along the bow captures the criterion (β index). Right: the higher the *d'* index, the more separable the curves of noise and signal will be.

d' index, the more separable the curves of noise and signal will be. That is, to higher levels of system sensitivity, correspond higher probabilities of catching the signal (hits). Finally, it is interesting to note that for any choice of criterion with $d' \neq 0$, the hit rate will be always larger than the false alarm rate.

3.8 The psychometric function

The perception process cannot be described by specific values. Indeed, these values can vary across people and depend on several factors. That is why we tend to describe it by using probability functions, the psychometric functions. A psychometric function describe the relationship between a property of the physical stimulus and the observer's percept, expressed as answers to yes/no tasks, forced-choice responses, etc. Figure 3.6 shows one of the most famous psychometric function, the sigmoidal curve. This curve is described by the relation of the intensity of a stimulus on the x-axis, and by the probability that a subject will detect a stimulus with a certain intensity (the proportion of "yes" responses or the percentage of correct responses) on the y-axis. Different functions can be modelled from a psychophysics study (e.g., probit, logit, Naka-Rushton function, etc.). Psychophysics functions can be defined by three concepts: 1) the slope, 2) the X-intercept, and 3) the goodness of fit. Let's

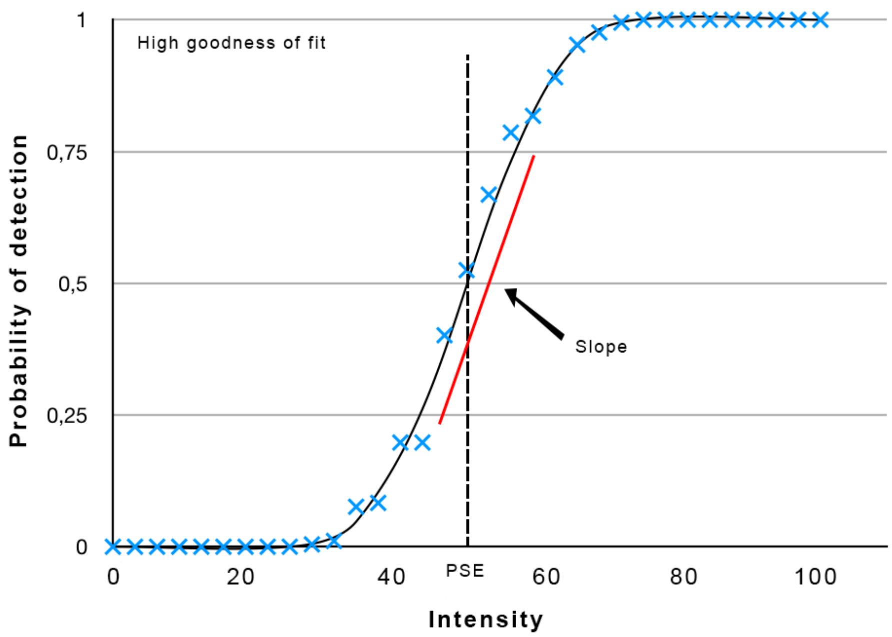


Figure 3.6: Example of a possible psychometric function, a sigmoidal function. On the x-axis, the stimulus intensity. On the y-axis, the probability that a subject detect a stimulus with a certain intensity. On the figure are highlighted the slope, PSE, and goodness of fit of the curve.

take as example a task where an observer needs to detect if a light is brighter than other ones.

The *slope* of a psychometric function, tell us how sensitive the observer is to the changes of stimulations (on the x-axis). Flat curves means the observer is not good at discriminating between the different brightness of the lights, and that the tested stimuli (the lights) are too hard to discriminate between each other. Curves that present a sudden change from one point to another one of the y-axis, indicate that the observer can detect easily a difference between the lights. Our chosen stimuli, are discriminated too easily. What we want to obtain is an incremental slope as the one in Figure 3.6, where there is a progressive increment from the different easy to detect (left values on the x-axis) to the zone of uncertainty (mean values) to again, values easy to discriminate (right values on the x-axis).

The *X-intercept*, tell us the observer's bias (or PSE, the stimulus quantity that is associated with the 50% value of the y-axis). That is, the X-intercept, tell us what is the point where two lights of different brightness will be perceived as equal. It might be that for a certain observer this value corresponds to the centre value on the x-axis (no bias) or to one of the extreme values on the x-axis (liberal or conservative bias).

The *goodness of fit* can be defined as the correlation *r* between the data points (our observers' responses) and the function (the chosen psychometric function). The more the data points lie on the psychometric function, the more the goodness of fit is good. In other words, the goodness of fit, describe how good our function fit the data. If we obtain a good goodness of fit, then we can be confident that the extracted parameters from the psychometric function, such as absolute thresholds, differential thresholds or JNDs, and PSEs, approximate well the phenomenon investigated.

3.9 Tactile psychophysics

Sensitivity is the ability to discriminate between two stimuli at a certain location (differential threshold). The differential thresholds tell us the maximum closeness possible between two pressure points before the subject perceives them as a single stimulus. The tongue, fingertips and lips are the most sensitive parts of our body [22, 186]. Knowing that the sensitivity varies from part to part of the body, it has important implications for the development of haptic interfaces. For instance, it informs us on the possibility to perceive shapes at a certain location. If thresholds vary across a location, designers and programmers might want to adapt the system spatial resolution to match the human one. Following the spatial acuity of a certain body location, researchers could avoid reproducing a tactile stimulation in its entirety still obtaining a convincing effect (see Section 5 on tactile illusions), avoiding providing useless information. Similarly, there are other psychophysical properties of our sensory system that can influence our perception of external stimuli. In the next sections, we will present the main studies that investigated thresholds across the body for different tactile properties.

3.9.1 Tactile thresholds

Recall from Section 2.2 that in the glabrous skin we have four important tactile receptors. Each one of these receptors is associated with a specific tactile channel. A channel is a functional/structural pathway where the information rising from a receptor is passed to the CNS. These channels are called NP-I (for RA-I receptor), NP-II (for SA-II receptor), NP-III (for SA-I receptor), and PC (for RA-II receptor, the Pacinian corpuscles). When we experience a certain tactile stimulation, our mechanoreceptors encode this stimulation as a spatio-temporal pattern, trigging certain neural afferent nerves. This activity is highly reproducible as long as the stimulation is invariant [95]. What changes is the way each mechanoreceptor encode this spatio-temporal pattern [118].

Thresholds for the detection of vibration changes depending on the spectrum of frequencies. The detection curve can be described as mediated by a set of different and partially overlapping sensory channels known as *information-processing channels*. Originally, it was hypothesised that two sensory channels were codifying the tactile information, separating low- and high-frequency information [164, 238, 242]. Capraro et al. [25] hypothesised three sensory channels. As previously described, now we know there are four channels to mediate the tactile information [16]: PC, NP-I, NP-II, NP-III. These channels are frequency-sensitive (see Figure 3.7, left). Different studies were aimed to assess their specific sensitivity [16, 17, 74, 239]. Figure 3.7, right, shows the resulting curve from the four overlapping sensory channels. The curve can be described as being composed by three segments. The first, between 0.4 Hz and 3 Hz, is a low-frequency curve which appears frequency insensitive. The second is a mid-frequency curve that appears as frequency-dependent. Finally, the last part of the curve is a U-shaped curve that seems to describe the Pacinian corpuscles sensitivity and ranges from 40 Hz to 500 Hz. Overall, it emerges how oscillations of higher frequencies require lower stimulus amplitude to be perceived.

Further, Bolanowski et al. [16] investigated the influence of the area of the contactor on the vibro-tactile thresholds. They noticed that the SA-II are not influenced by the tactor size. That is, the SA-II channel does not present spatial summation. With spatial summation, we intend that effect for which at equal frequency and amplitude of the stimulation, the stimulus conveyed through a greater contact surface is perceived as stronger. This effect seems specific to the PC channel [16, 237, 242].

Regarding a possible presence of temporal summation (i.e., a change in thresholds due to the stimulus duration), only the PC channel seems to exhibit this effect. The temporal summation characteristic of the PC channel seems to be dependent on the spatial summation effect [242].

A fundamental study on absolute thresholds for pressure across different body parts was carried by Weinstein in 1968 [248]. In Figure 3.8 are shown the different thresholds obtained by his study in males subjects. Overall, the face is the most sensitive area compared with the other parts of the body.

Tactile sensitivity may also vary for gender and age. If it is true that male and female have no difference in tactile thresholds when young, it seems that ageing brings a deterioration of the tactile acuity that is higher for men than women in all the four tactile channels (> 65 years old) [72]. Other studies found a difference in the thresholds between males and females [248], but it might be that the difference can be explained by the different size of the hand. A smaller hand has a higher sensitivity due to the equal number of receptors in the skin, concentrated in a smaller area

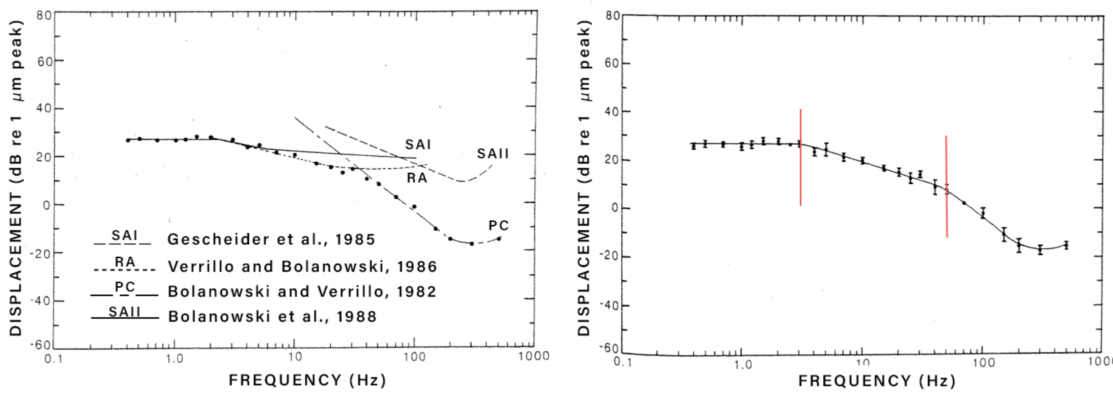


Figure 3.7: Adapted from Bolanowski et al., 1988 [16]. Left, the four different curves describing the four tactile sensory channels sensitivity for vibrations on the thenar eminence. Right, the curve resulting from the overlapping of the four channels. To be noted how higher frequencies (x-axis) of vibrations are perceived using smaller stimulus amplitude (y-axis).

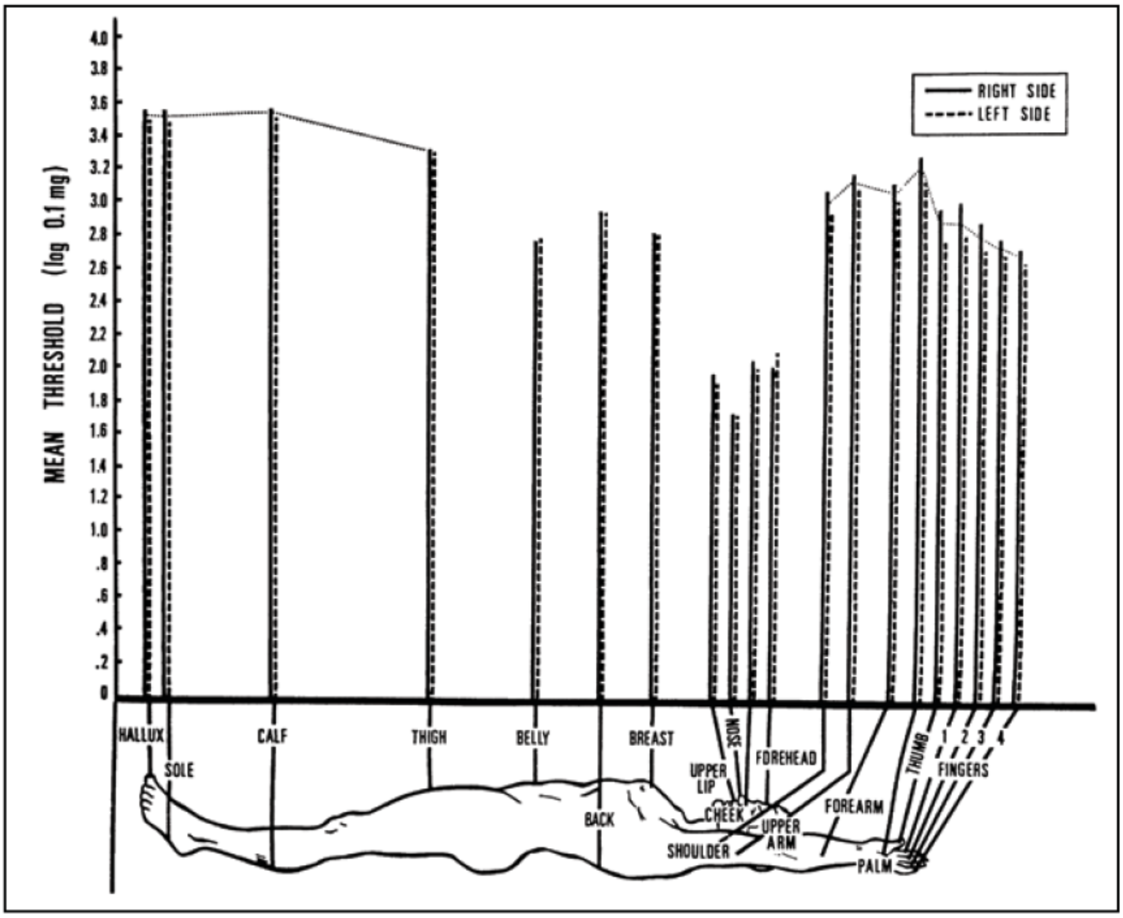


Figure 3.8: From Weinstein, 1968 [248]. The graph shows the different absolute thresholds for pressure in males across different body parts.

(higher receptors' density).

As anticipated, ageing is a crucial factor for tactile sensitivity. Overall, all the channels have an increased threshold with ageing, but it is more substantial in the PC channel (Pacinian corpuscles for high-frequency vibrations). Specifically to the PC channel, this might be due because of the spatial summation property prerogative of this channel. The functionality of the PC channel depends on the integration of neural activity over numerous receptors. If these receptors are diminished or deteriorated the effect on thresholds levels will be stronger compared to the other tactile channels (that do not exhibit spatial summation). In general, the loss of tactile sensitivity can be traced to the reduction in the tactile receptors' density. In favour of this hypothesis, Stuart et al. reported how tactile thresholds decrease with ageing in different body parts but not in the fingertips, where the density of tactile receptors is higher [224]. Changes in shape (and functionality) of the receptors might

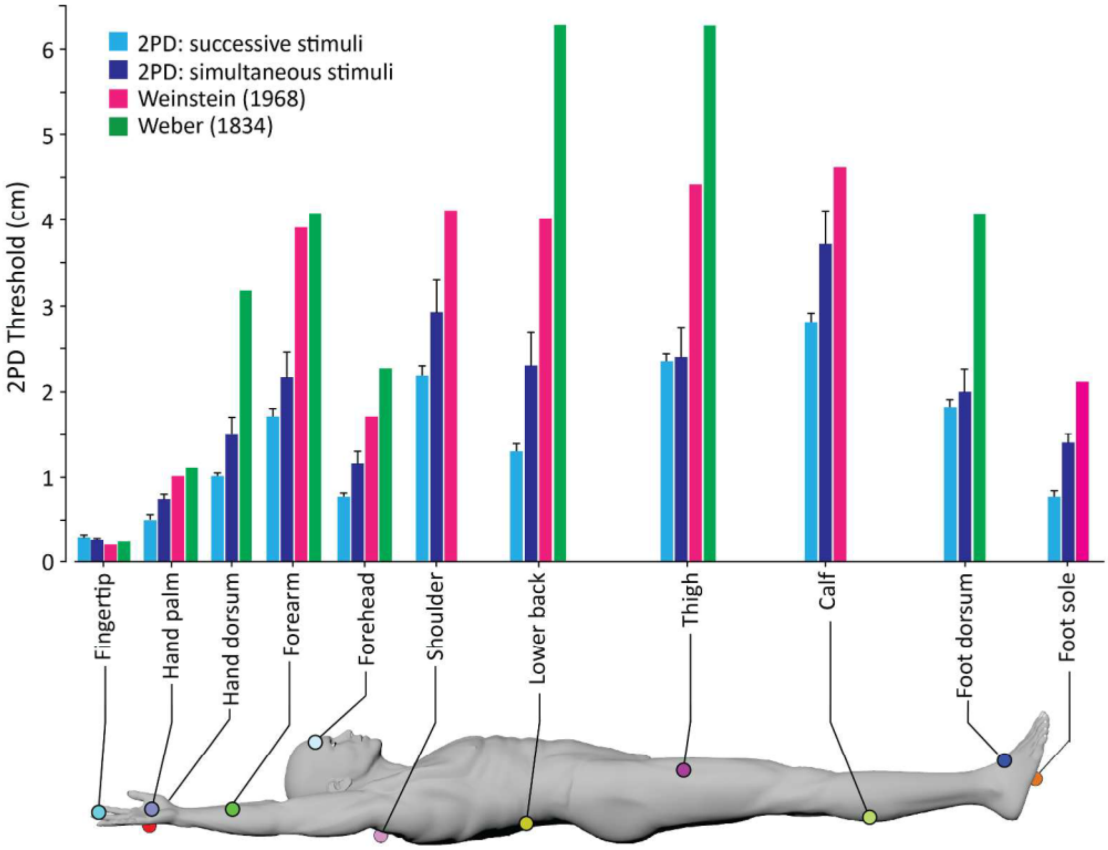


Figure 3.9: From Mancini et al. [157]. The graph shows the different spatial acuity thresholds across 4 different studies. Weber and Weinstein studies used simultaneous multiple stimulation.

be another cause responsible for the impoverishment of tactile sensitivity [72]. These hypotheses do not exclude other factors like the reduction of skin compliance and changes in the nervous system functioning with ageing. Gescheider et al. showed how the temporal summation effect goes into detriment with ageing [71]. Younger subjects present lower thresholds associated with the increasing of stimulus duration. Finally, absolute thresholds are influenced by other factors like the menstrual cycle, skin moisture, alcohol and tobacco consumption, and the presence of diseases such as bulimia/anorexia nervosa [92].

3.9.2 Spatial acuity

For spatial acuity, we intend the ability of a subject to discriminate two different tactile stimuli as such. In other words, is the minimum amount of difference between two stimuli (e.g., in intensity, weight, frequency, etc.) that a subject needs to be able to discriminate between the two stimuli. Usually, spatial acuity is tested using a calliper with blunt ends. The experiment starts with the two ends of the caliper opened at a certain discriminable distance. Then, this distance is reduced until the observer is not able to discriminate the two stimuli. As illustrated in Section 2.4, Figure 2.7, different areas of our body has a different topographic representation in the CNS due to differences in receptors' density. Indeed, many studies aimed to investigate differential thresholds in different parts of the body are in line with the Penfield sensorial homunculus. Figure 3.9 shows the results from two iconic studies by Weber [247] and Weinstein [248], and a more recent study by Mancini et al. [157]. With some variations depending on the study, this illustration clearly shows how the fingertips, the palm, and the foot sole are the most sensitive parts of the body. On the contrary, the lower back, the thigh, and the calf present the higher differential thresholds. The different threshold levels across the body can be explained by the difference in the receptive fields of the cortical neurons representing a certain area. Neurons with smaller receptive fields will lead to smaller differential threshold levels; when two stimuli occur at a small distance, they will activate separate neurons that will bring a separate percept [80].

3.9.3 Temporal acuity

For temporal acuity, we mean the shortest time interval between the onset of two tactile stimuli that allows an observer to perceive two different stimuli. In terms of strictly measuring temporal acuity, there are only a few studies. The first is a study by Gescheider in 1966 [70]. He investigated the difference between the tactile and auditory perception of successive brief stimuli. In this work, he reported that the tactile acuity between two successive stimuli delivered on the ring and index finger of the same hand, or the same location on the index finger, is equal to 10 ms. When the bilateral index fingers were stimulated, thresholds raised to 12.5 ms. From this same research, emerged that thresholds are influenced by the stimulus strength.

In particular, the first stimulus suppresses neural activity produced by the second stimulus if its strength is considerably higher, and vice-versa, if the strength of the second stimulus is considerably higher, the first stimulus is suppressed. Another confirmation that temporal thresholds depend on the somatotopic distance comes from Kuroki et al. Somatotopic distance is defined as the distance between two different locations as encoded in the cortical topography. In their study, Kuroki et al. demonstrated how temporal thresholds were lower when stimuli appeared on the same location (same-site condition) [136]. Thresholds tended to increase with the increasing distance of the stimulated location (see Figure 3.10).

Successive studies, tried to investigate other aspect related to the temporal acuity of the tactile sense, e.g., the temporal order perception (i.e., how much time must occur to perceive which stimulation came first), or temporal interval judgement (i.e., how long was the interval between the first and the second stimulation).

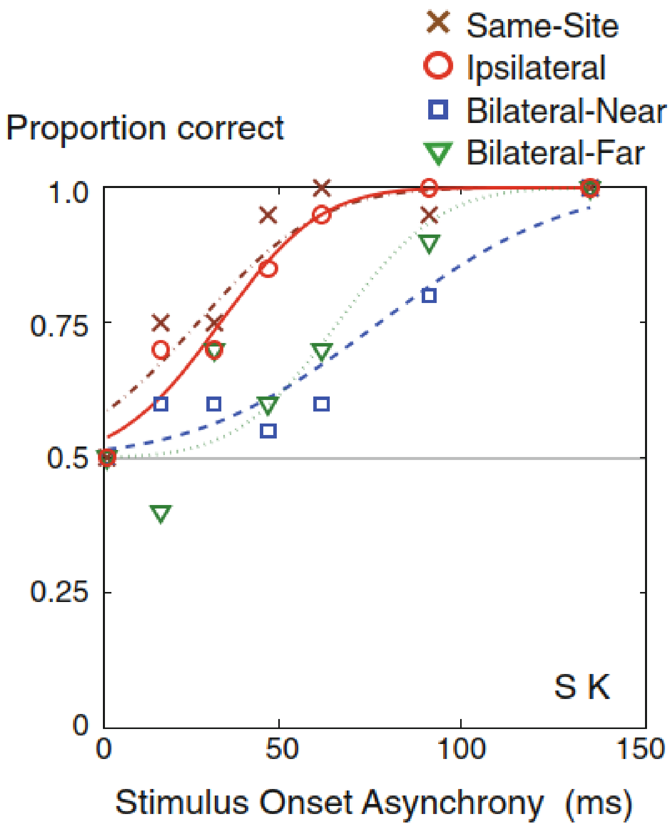


Figure 3.10: From Kuroki et al. [136]. Variation of tactile temporal thresholds with varying the stimuli location.

3.10 Summary

The Weber-Fechnerian methods were the first methods used to estimate human absolute thresholds and differential thresholds. The classical techniques are the method of limits, the method of adjustments, and the method of constant stimuli. Each one of them has both, advantages and disadvantages. Choosing the "right" methods it is often matter of a trade-off between time and precision. While classical psychophysics offers some precise estimates points (values) indicative of a threshold, modern methods, like the SDT offer a framework in which the threshold is seen as a distribution of probabilities. A system, in our case, the human tactile system, will have a certain sensitivity (*d'*) and an observer will select a criterion to discriminate between the target signal and the background noise, which will be always present, inside (in the form of neural noise) and outside the system. In this way, the quantity of stimulation needed to be separated from the background noise will be variable depending on several factors (e.g., mood, previous experiences, personality, etc.).

As we discussed in the previous chapter, the sense of touch is not an absolute sense. Its functioning depends on age, gender, it presents individual differences, can depend on the actual state of attention, mood, stress, training, temperature, etc. It is not merely passive, but there is an active (haptic) part of it that is responsible for the awareness of our movement and the extraction of objects features. Tactile receptors are responsible for encoding the information we receive from the external world and carry it to our CNS. The final percept will depend on a series of events and neural activity which we try to measure using classical or modern psychophysical methods.

When designing for tactile interactions, we must think of the target location, the spatial resolution of that location, what are the thresholds of that specific part of the body. In Chapter 6, 7, and 8, we present three studies aimed to understand the perceptive properties of our sense of touch when stimulated by an ultrasonic mid-air haptic device (see Chapter 4, Section 4.3.4). Specifically, the first study investigates the absolute thresholds of our left hand and arm. The second one analyses the optimal sampling strategies to use when stimulating through ultrasonic mid-air technology and the relationship between sampling rate and shape size. The third one, informs on some possible optimal parameters to facilitate the perception of 2D basic shapes on the hand, through a mid-air haptic device. Finally, the following two psychophysical studies (Chapter 9, and 10), investigate the apparent tactile motion phenomenon (see Chapter 5, Section 5.1), both, with contact and mid-air haptics. In these studies, we provide the optimal parameters to design a smooth sense of motion that extends from one hand to the other hand.

In the next chapter, we will introduce the main devices we can exploit to stimulate our sense of touch.

Chapter 4

Touch and technology

We have different methods that we can use to stimulate the sense of touch. We can exploit the skin deformation, stretch, or friction. We can use vibrations, electric stimulation, or temperature. Generally, we need a tool that is capable of making our tactile mechanoreceptors sending signals towards our brain (*firing*). To do that, we need to make use of some sort of external skin perturbators: the haptic devices. We can think at the tactile interaction as an exchange of input and output between the machine and the user. Following this view, we can describe a continuum from actuators, that only provide output to the user and more complex technology such as the haptic systems, where the communication happens bidirectionally from the machine to the user and vice-versa. Further, we can divide haptic systems in contact and contactless, or mid-air haptic.

4.1 Actuators

We refer to actuators for those devices that deliver an output on the human skin. Actuators deliver tactile feedback stimulating the mechanoreceptors in the skin (see Chapter 2, Section 2.2). These devices are only capable of sending a tactile stimulation, but they do not respond to the user's status.

4.1.1 Vibrating motors

A first kind of actuators are the vibrating motors (Figure 4.1). They provide relatively small-amplitude vibrations in a linear or a rotary sense. They can be applied directly onto the skin or by using a structure, and they can work in a single unit or in arrays. An example of this type of actuators can be found in classic game controllers, or mobile phones. In particular, this kind of motors are called *Direct Current motors* (DC motors) because they convert direct current energy into mechanical energy through the rotation. DC motors are inexpensive, but they have a poor temporal resolution, as it takes time to start and stop the rotational mass. Another kind of vibrating motors are the *voice coils*. Voice coils are coils of wire which sit into a magnetic field. When the current is switched on and off, this causes the coil to move. They can be very fast and accurate and it is possible to control frequency and amplitude separately. An example of these motors can be found in speakers.

Figure 4.1: An illustration of a simple vibrating motor. The ending part on the right rotate, producing vibrations.

4.1.2 Linear motors

As we saw in the previous subsection, vibrating motors move in a rotatory way. Linear motors, instead, move in and out along a linear plane. Usually, a motor converts rotational energy to linear energy by means of a screw or a gear. They can be composed of one or more pins usually disposed in arrays that actuate independently, in contact with the skin. These kinds of actuators are simple and versatile, allowing a series of different tactile sensation (e.g., vibrations, pressure, shapes, etc.). One of the main drawbacks is their cost and the cumbersomeness of the pins depending on the specific application. Apart from industrial applications where some robotic arm has to lift and moves objects, we can find this kind of actuators in Braille displays, for instance.

4.1.3 Piezoelectric actuators

Piezoelectric actuators are transducers that convert electrical energy into a mechanical displacement. Different materials show piezoelectric properties, but normally, is used a piezoelectric ceramic layer (or a series of layers) that expands when voltage is applied to it. Using multiple layers can amplify the effect. Piezoelectric actuators have large forces even with small motion. The main advantage is that they can be small (around 0.2 mm to 1 mm thick), they are inexpensive, they have fast response time, and they consume little energy. However, they can be hard to control (small displacements require accurate amplification) and they require high operating voltages.

4.1.4 Dielectric elastomers

Dielectric elastomers transform electric energy into mechanical work through a dielectric polymer film between two electrodes. When voltage is applied, the two electrodes at the opposite sides of the elastic film attract each other. This makes the elastic film to contract and expand its area. The stretch of the film is controlled by the voltage applied to the electrodes. These actuators require less power compared to vibrating motors and piezoelectric actuators.

4.2 Contact haptic systems

Haptic technology, or haptics, is a technology which exploits the characteristic of the sense of touch in its wider meaning (i.e., passive and active touch). Haptics can convey forces, vibrations, or motion onto a user's body. These, can confer realism to virtual objects in virtual reality (VR) enhancing the user experience through a sense of embodiment and presence (see Section 5.4.2). Additionally, they can enhance teleoperation environments (i.e., operation of a system or machine at a distance) by adding tactile sensors and actuators to mimic tactile sensation to and from the remote machine. Unlike actuators, haptic systems offer a bidirectional communication that goes from the user to the machine, and from the machine to the user. Over the last 20 years, numerous haptic devices have been developed. Haptipedia, a taxonomy of haptic devices conceived in the last 30 years [207], helps to navigate through the history of haptic technology. In this section, we will revise the main haptic systems delivering haptic feedback while directly in contact with the users' skin.

4.2.1 World-grounded devices

The most traditional haptic devices are the so-called *world-grounded haptic interfaces*. Grounded because the device requires an anchor to provide users with resistance or exert force against the user. Examples of these kinds of devices are the Butterfly Haptic Maglev 200 System, the Haption Virtuose 6D, the Sensable PHANTOM Premium, the Quanser 3-DOF Planar Pantograph, the Force Dimension Omega.3, and the Motek HapticMaster (Figure 4.2). Usually, these devices convey kinesthetic feedback or force-feedback. Typically, the user interacts in the virtual world by grasping a held tool and receiving feedback through it. In receiving force-feedback, it is possible to choose to control the device by impedance or admittance control. Impedance control devices apply forces between the target position and the actual position of the handle. Hence, they resist (impede) movement to controlled directions. Admittance control devices allow (admit) users' movement while applying force. We can imagine them as pushing a finger through a viscous substance while applying larger forces than impedance devices.

Figure 4.2: Examples of grounded devices. From top, from the left: the Butterfly Haptic Maglev 200 System, the Haption Virtuose 6D, the Sensable PHANTOM Premium. Bottom row from left: the Quanser 3-DOF Planar Pantograph, the Force Dimension Omega.3, and the Motek HapticMaster.

4.2.2 Body-grounded devices

Another set of haptic devices are those grounded on the body. These devices are also called *wearables*. Because they are located on the body, wearable technology introduces limitations in terms of power. These devices need to be miniaturised and power efficient. Further, their effect is limited to the part of the body where they reside. However, they allow users to move freely in the real world, removing workspace limitations. Typically, wearable devices convey passive information. Hence, they simplify the complexity needed for the world-grounded devices. Wearable devices can also take the form of exoskeletons. In this case, they can convey kinaesthetic information. In 2017, Pacchierotti et al. [176] tried to better define the differences among wearable devices. Within their taxonomy, they differentiate between systems with lower levels of wearability and those with higher levels of wearability. Systems less wearable are those whose ground is located at distance from the contact/interaction area (see Figure 4.3a). In this case, when the user will interact with an object, a force will be displayed on the contact area. At the same time, another undesired force will be exerted on the ground location. Higher wearability systems are those that are grounded as much as possible close to the contact area (see Figure 4.3b). In this way, the undesired forces arising from the haptic interaction will be limited to the same location of the interaction.

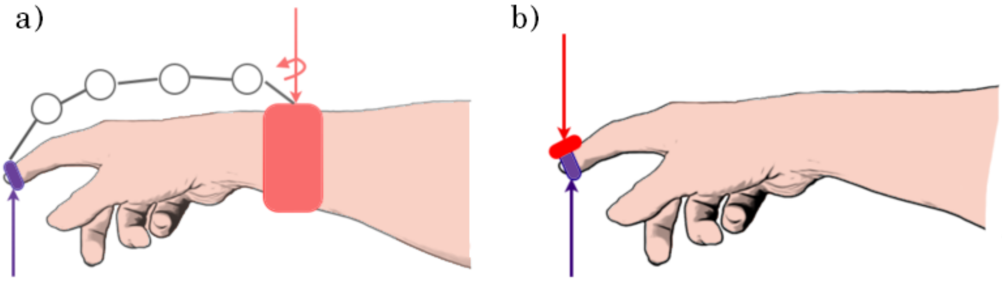


Figure 4.3: Adapted from [176]. a) Example of wearable device with low levels of wearability. Here, the ground (red rectangle) is located far from the interaction area (blue rectangle). b) Example of wearable device with high levels of wearability. Here, ground and action area overlap.

Optimally, a wearable device would minimise cumbersomeness and unwanted forces. Therefore, the more the ground will be close to the area of action, the higher it will be wearable and comfortable. At the point when ground and interaction area match, the information rendered by the device will be entirely cutaneous (e.g., in fingertips mounted devices).

Among the realm of wearable devices, we can distinguish the aforementioned exoskeletons, devices mounted on the fingertips, conveying haptic cutaneous feedback through normal indentation (moving platforms, pin-arrays, pneumatic systems), lateral skin stretch, relative tangential motion and vibration, and whole hand devices operating through kinaesthetic stimuli and vibration.

There are numerous amounts of studies on grounded haptic devices and wearables devices; it is out of the scope of this section to present the entirety of these systems and their detail. We refer to [37, 41, 175, 176] for an extensive review on haptic devices.

4.3 Mid-air haptic systems

Work on the sense of touch across disciplines provides a valuable basis on its functional and neurological understanding. These advancements together with the exploration of novel interaction techniques have also led to the development of new haptic systems. The most recent cutting edge haptic interactions happen through touchless interfaces: the mid-air haptic systems.

The main advantage of mid-air haptics is that users do not need any attachments on their body. The action becomes more ecological, simulating the way we normally interact with the surrounding environment. On the contrary, cumbersome devices on the skin can limit the tactile sensation and bias the tactile experience. In the next sections, we will present the main mid-air haptic technologies.

4.3.1 Mid-air tactile laser

Mid-air laser technology is based on the principle of the thermoelastic effect (indirect laser radiation) (Figure 4.4). In their study, Lee et al. [143] demonstrated how it is possible to convey a tactile sensation through a laser beam on a finger covered with an elastic material. The laser beam changes the material shape (thermoelastic effect), providing the user with tactile feedback. This technique has some advantages: it has a fine spatial resolution (9 mm), it has an instantaneous speed (the light speed), it can travel virtually infinite distances, and has little diffusion or attenuation. Albeit it represents an interesting media, this technology is not of easy application, for several reasons. It is not absolute mid-air (an elastic material needs to be applied on the target location and the tactile sensation is given by the change of shape of that material), it is not highly reusable (the material needs to be substituted after several usages). Finally, lasers could be dangerous if directed towards sensitive areas such as the eyes and the resulting tactile sensation is weak. Jun et al. proposed an alternative laser solution [120]. In their study they used a laser at low-power radiation, evoking thermoelastic effect directly on the user's skin, making it contracting and pain-free.

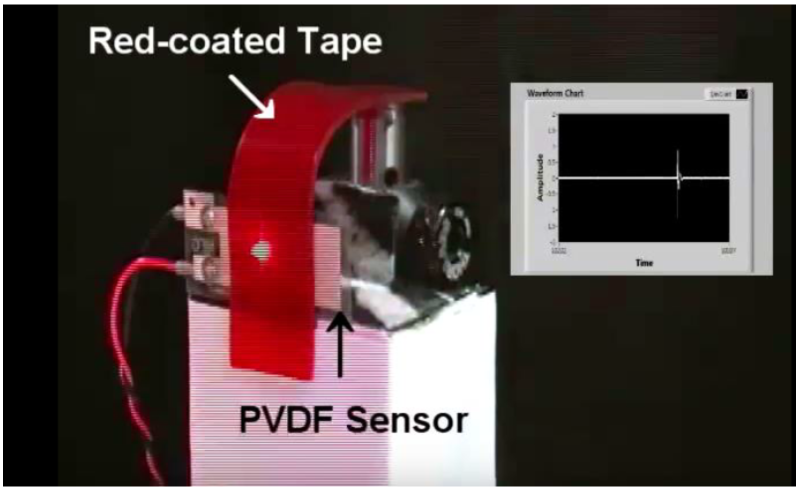


Figure 4.4: From [143]. This mid-air haptic device works by employing a laser beam that hits a thermoelastic material. This one, expanding, provides a tactile sensation on the user's skin. In the picture, the PVDF sensor was used to measure the force of the tactile stimulation.

4.3.2 Air-jet flow

Suzuki and Kobayashi [228] ideated a system that controls air-jets according to the position and orientation of the air receiver, which is held by the user (a tool similar to a spoon). At this point, the air impacts the receiver tool, making the user perceive pressure as a force. As for the laser beam technique, the medium (air) do not touch directly the body but a tool is still required to perceive the tactile stimulation. Unlike laser technology, instead, the jet flow is harmless for the whole body.

The AIREAL device can be thought of as an evolution of the air jet technique. Unlike standard jets of air, which are turbulent and dissipate quickly, vortex rings can maintain their energy and travel several meters to impart perceptible feedback at distance [84, 218].

This technology (Figure 4.5) has a discrete spatial resolution (10 cm), it can be felt on the whole body, and through clothes. An interesting scenario sees the possibility of sending cold or warm air within the vortex ring. Nevertheless, the temporal resolution of the devices is limited by the following generated vortices. The different vortices could interfere with each other. The air resistance represents another limitation, decreasing the vortex velocity causing delays.

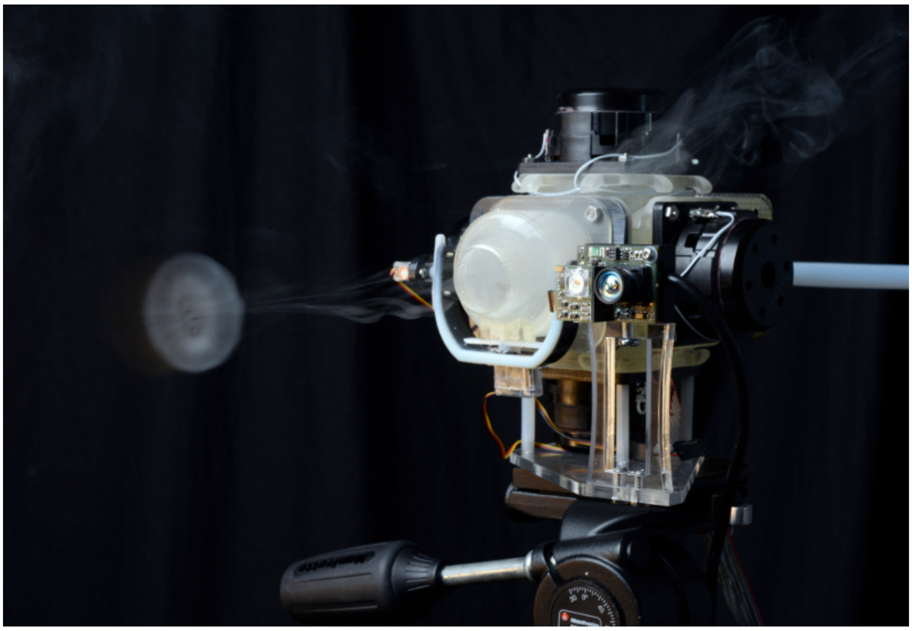


Figure 4.5: Adapted from [218]. The Aireal device exploit the use of toroidal air jets to deliver tactile stimulation at distance.

4.3.3 Electric arcs

In 2016 Spelmezan et al. presented yet another approach in the mid-air systems scenario [219]. Using the same principle of a Tesla coil, the authors could display electric arcs on the user's finger pad. As for the technology presented above, the electric arcs' device was capable of delivering one stimulus at the time. The electric arcs were 6 mm long and the area of skin stimulated small.

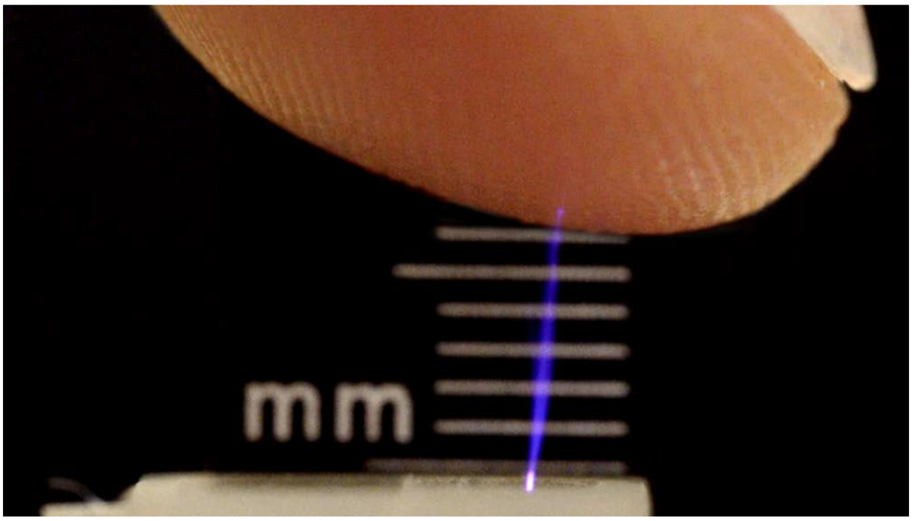


Figure 4.6: From [219]. The electric arcs were 6 mm long and the area of skin stimulated small.

4.3.4 Focused ultrasound

Ultrasound based systems represent cutting-edge technology in the mid-air haptics realm. These systems provide contactless tactile feedback in mid-air, they are non-invasive, they have a good spatial resolution (around 1 cm) [251], and they do not represent any risk of damage for structures and surrounding tissues [68]. Ultrasound has a long history that precedes the HCI's one. The first study employing ultrasound is dated back to 1927. Wood and Loom observed that a liquid can be atomized by a vibration device operated at 300 kHz. This process was called ultrasonic atomization [255]. In 1950, Fry et al. were one of the first to study the effect of ultrasound on the nerve fibres of the frog and the crayfish [60]. Later in 1977, Leonid et al. studied the tactile perception of focused ultrasound and the effects on the skin and deep receptor structures in humans [67]. They were using frequencies up to 2.67 MHz, and the participants' hand was studied underwater. Given the high frequencies used in the experiment, the tactile sensation was perceived at first as tactile sensation, then as temperature, and finally as pain. Another study of Dalecki et al. in 1995, investigated the tactile perception of ultrasound on the human arm and hand [39]. In this case, a Corprene® disk was affixed on the part of interest to maximize the radiation force delivered to the tissue. Only in 2001 Iwamoto, Maeda and Shinoda studied the feasibility of focused ultrasound for tactile feeling display. They illustrated how

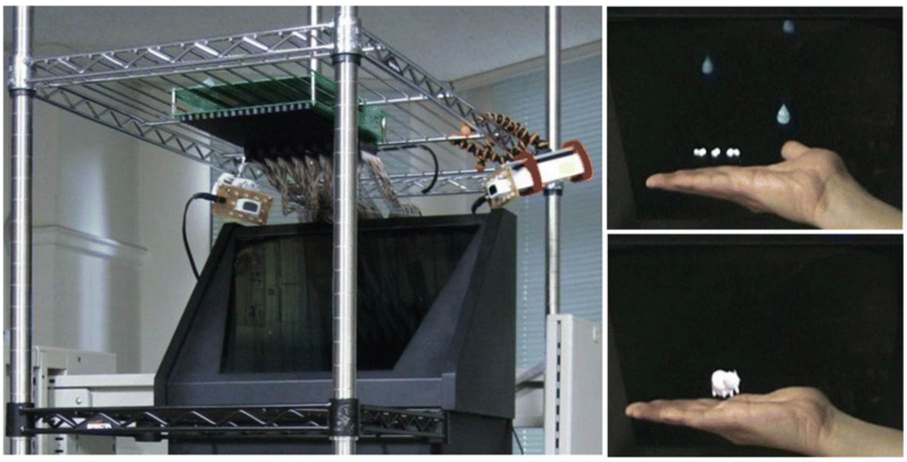


Figure 4.7: Adapted from [107]. The HoloVision display. This system mixes holographic images with an ultrasound haptic array, allowing seeing and touching objects in mid-air.

ultrasound from 1 MHz and 5 MHz can elicit a perceptible sensation through the direct stimulation of the nerves and by the radiation pressure force generated [112]. In line with what we know on the tactile receptors, they obtained the best results in the range of 30 Hz to 200-250 Hz, with a flat curve between 70 Hz and 100 Hz.

Researchers from the University of Tokyo, led by Takayuki Iwamoto presented their prototype in 2008. Their device was formed by a group of ultrasonic speakers placed in a concentric ring shape arranged into an array on a pad. Each transducer could be set to emit a different modulated ultrasound pulse, allowing each to create a pressure wave pushing through the air [113]. The year after they presented a tactile display (HoloVision) integrated with their ultrasound array (Figure 4.7) [107]. Finally, in 2013 a team headed by Subramanian, developed the Ultrahaptics device, a system composed of an array of ultrasound speakers capable of providing for the first time multiple focused points of tactile feedback in mid-air directly on to users' skin (Figure 4.8) [27]. This system works at an optimal distance of 20-30 cm, availing the phenomenon known as acoustic radiation pressure. Ultrasonic phased arrays focus sound waves coming from an array of ultrasonic transducers into a single location in space. In this focal region, the acoustic pressure almost instantly builds up and eventually becomes great enough to indent slightly the human skin and therefore stimulate the sense of touch. This focal region is thus equivalent to a tactile point. To convey a range of vibro-tactile haptic perception through this tactile point, one needs to modulate the tactile point either in wave amplitude [107] also

Figure 4.8: Ultrahaptics (now Ultraleap, since September 2019) ultrasonic device. A system composed of an array of ultrasound speakers capable of providing multiple tactile focused points in mid-air directly on to users' skin.

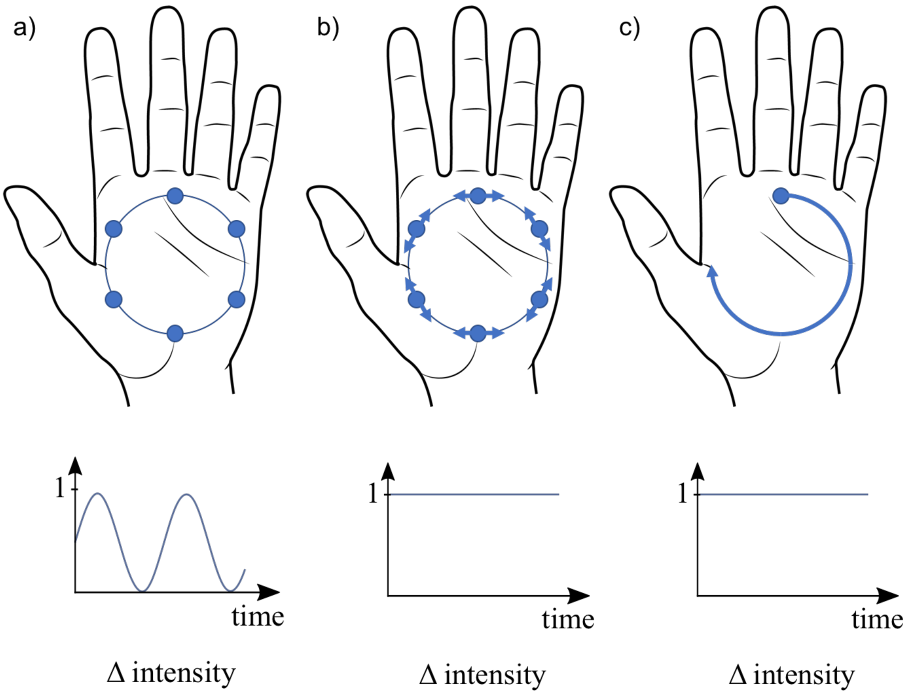


Figure 4.9: Mid-air tactile display can use three kinds of modulation techniques to produce a tactile pattern: (Left) Amplitude Modulation, (Middle) Lateral Modulation, (Right) Spatio-temporal Modulation. Each modulation technique varies the position and intensity of one or more mid-air tactile points differently over time.

referred to Amplitude Modulation (AM), or in its lateral position [229] also referred to Lateral Modulation (LM). Obrist et al. has shown that varying the modulation frequency varied the perception of tactile point strength among other aspects of its perception [171]. Another approach that constitutes an even more advanced modulation technique is to move the tactile point rapidly and repeatedly around a given path across the user's palm, hence producing a tactile pattern [127] referred to as Spatio-Temporal Modulation (STM), see Figure 4.9.

By electronically shifting the transducer phases one could focus the acoustic pressure to a point in space and use it to produce tactile stimuli on the user's hand. The force applied to the skin can reach 16 mN, for a contact area of 20 mm diameter [107]. More recently, with the use of 70 kHz (instead of 40 kHz) ultrasound transducers one could produce even smaller focused points [111]. As already mentioned, similar devices were used to create multiple focus points with different tactile properties [27], or mixed with other mid-air tactile display [173]. Further, it is possible to use an ultrasound board as an interface to pinch, twist and knead an object, the possibility of interaction by multiple users, and a low energy consumption, thus increasing the range of applications for HCI. Ultrasound phased arrays have therefore rapidly become a reliable and attractive technology for both researchers and developers interested in mid-air tactile applications.

Currently, the main disadvantage is the limited force exerted on the skin. However, it still allows the creation of a multitude of sensations. For instance, Obrist et al. provided a non-arbitrary map between emotions and haptic descriptions [172], Long et al. were able to render volumetric shapes using mid-air haptic technology [150]. Moreover, Carter et al. [27] employed ultrasound arrays as an input interface, allowing colour rendering, pinch-to-zoom interaction, and the possibility of interacting with a web application. Ablart et al., used mid-air touch to enhance users' experience while watching short films [1], and Vi et al. exploit mid-air touch to enhance users' experience during an art exhibition [240]. Further, Martinez et al. employed ultrasonic mid-air touch to mimic supernatural interactions [160]. Finally, in Chapter 8 we will present a study to enhance the users' performance in a recognition task of 2D shapes, in Chapter 10 we use mid-air touch to create an apparent tactile motion between the two non-interconnected hands, and finally in Chapter 11, we present an illusion of ownership in VR mediated by mid-air haptics.

4.4 Summary

In this chapter we introduced the main haptic devices developed in the last thirty years of research. This technology is the motor that activate our tactile receptors firing information to the brain. There are different devices: the tactile actuators, where the tactile information flow unidirectionally from the motors to the human skin, and the haptic systems that include the human response into the loop. The latest haptic technology available for researchers and designers is mid-air haptics that allows contactless interaction. Among these, the ultrasonic devices seem to be the most promising (and the only one commercially available) because of their relatively good spatial and temporal resolution. Besides, their characteristic of delivering tactile feedback in mid-air, makes their usage unobtrusive and attachments-free. This potentially allows users to freely interact in the environment without being aware of the device.

Although recent technologies have tried to target specific properties of the tactile sense, researchers and designers could exploit the perceptual organisation of our sense of touch by means of tactile illusions. Tactile illusions are a powerful tool that used symbiotically with haptic devices can increase or simplify the range of tactile sensations available to the user.

Chapter 5

Tactile illusions and embodiment

markbothTactile illusions and EmbodimentTactile illusions and embodiment

Perceptual illusions were primarily studied in the visual modality and their first descriptions dates as early as in the Greek and Roman literature [83]. Illusions are the result of misinterpretation of stimuli, neural processing, and anatomical properties of a specific sense. They can be found in different sensorial systems (i.e., vision, touch, hearing, taste, and smell), and they can be the product of multisensory processing (e.g., pseudo-haptics illusions, rubber hand illusion, etc.).

For the aim of this thesis, we will focus on the tactile illusions. As described in Chapter 2, our sense of touch is multifaceted, complex. It mixes cutaneous feedback (passive touch) and kinaesthetic feedback (active touch). Hence, reproducing all the tactile components seems an ambitious project and a hard one. Illusions can provide design shortcuts for creating convincing tactile experiences. Gallace and Spence in [64] provide an interesting reflection about the complexity of reproducing the tactile sense in general, and how its lack in VR environments makes the user frustrated because of the lack of realism and the impossibility of acting in the virtual world. Further, the authors describe how currently, most virtual systems have tried to reproduce the tactile sense exclusively on the hand, in particular on the surface of the fingers, which are the most sensitive parts of our body. Nevertheless, the goal of achieving realistic tactile sensation, potentially extending on the entire body, seems to appear less difficult than one might think. In support of this claim the authors cite the following scientific discoveries:

1. The skin sensors are not distributed equally on the whole body (see Section 2.2) and their receptive fields are wider in certain parts of the body. This translates into the possibility of applying a lower quantity of stimuli to be able to simulate the presence of an object in those less sensitive parts of the body.
2. The ability to be aware of a tactile stimulus disappears if more than three stimuli are presented simultaneously [65]. It is also possible that under certain conditions, the stimulus is recognized as a single pattern.

The researchers, drawing upon studies on haptic perception, suggested that probably it is not necessary to provide a complete and high-resolution tactile stimulation on the entire surface of the body in order to tactilely render an object in VR. Providing superfluous information would have no advantage, neither in terms of complexity nor in terms of bandwidth usage. This is in line with the concept of perceptual illusions to convey realistic experiences in VR. The idea of exploiting illusions to convey complex information, it is valid also outside a virtual environment.

5.1 Understanding tactile illusions

To date, many studies investigated and described more or less robust tactile illusions. The Müeller-Lyer illusion (Figure 5.1), is a phenomenon that was discovered first in the visual system and later, found also in the tactile system [246]. In this illusion, the line with the arrows pointing inwards appears longer than the line with the arrows pointing outwards. A possible explanation of the original visual illusion can reside in the way we perceive the image; in the illusion, the image would be erroneously perceived as 3D drawing, and our brain would decide to interpret the arrows as depth cues, making us see an erroneous length of the object based on

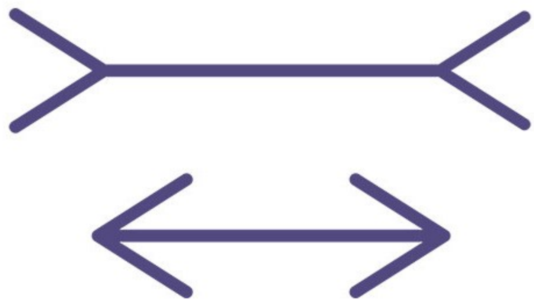


Figure 5.1: The Müeller-Lyer illusion. In the image, the first line appears longer compared to the second line. This illusion was first observed in the visual domain, and later studied also in its tactile version.

their distance from our point of view [82]. The haptic counterpart could be explained by the confusion theory [246]. Simply, the illusion would be explained by the mere confusion of the arrows' heads with their fins.

Another famous illusion is the Aristotle illusion. If we cross two fingers, and we touch an object (e.g., a pencil), we will perceive two objects. The illusion takes its name from the famous Greek philosopher and it might be explained by our prior knowledge of the world. In the everyday life when our fingers are touched at the same time, it is usually because we are in contact with two objects. A series of tactile illusions are capable of providing the user with an illusory sensation on movement. In particular, scientists individuated three main types of illusions of movement using a psychophysical approach [93, 100, 140] (see Figure 5.2): 1) the cutaneous rabbit illusion (or cutaneous saltation), 2) the haptic funnelling illusion, and 3) the apparent tactile motion (ATM) (more recent tactile illusions of movements are described in [103, 143, 165]).

In the cutaneous rabbit illusion, two vibro-tactile actuators are modulated in a timely fashion to create a third illusory perceptual sensation like that of "a rabbit hopping" in-between the two real actuators [69] (Figure 5.2A). In the haptic funnelling illusion, two actuators vibrate at different intensities, creating a third, intermediate perceptual point whose position is determined by the variation in intensity of the two vibrations [243] (Figure 5.2B). During the ATM illusion, two

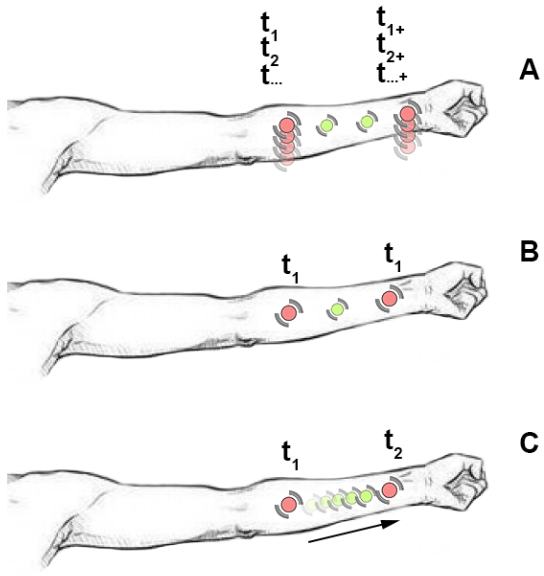


Figure 5.2: The main tactile illusions of movement. A) The cutaneous rabbit illusion, B) the funnelling illusions, and C) the apparent tactile motion (ATM). The red stimuli represent the physical actuators on the skin, the green stimuli represent the perceived illusory actuators. T_1-$T_{...}$ represent the temporal succession of stimuli.

actuators are activated while modulating the stimulus onset asynchrony (SOA) so that the user will perceive a feeling of movement between the two sites of stimulation (see Figure 5.2C) [131]. There are three possible scenarios: a) If the SOA is too long, then the two vibrations will be perceived as discrete and no illusion of movement will occur; b) if the SOA is too short, the two vibrations will be perceptually merged into a single one and no illusion of movement will occur; c) if the SOA is optimal, the two vibrations will be perceived as a movement. Goldreich proposed a Bayesian approach to explain spatio-temporal illusions based on low-speed priors (expectations) that can lead to underestimating spatial distances [79]. Specifically, the brain expects tactile stimuli to move slowly. This low-speed expectation would lead to an underestimation of the distance between two rapid sequential stimuli. Seen that the tactile stimuli are moving fast, but we expect them to be slow, they have to be closer in space to each other. This will make us perceive additional stimuli on the skin.

Another group of illusions deals with the body schema, like the rubber hand illusion (RHI) and its virtual counterpart, the virtual hand illusion (VHI), or the more general bodily illusions. These will be explained in more details in Subsections 5.3.1, 5.3.2, and 5.3.3. For the moment we can refer to Figure 5.3.

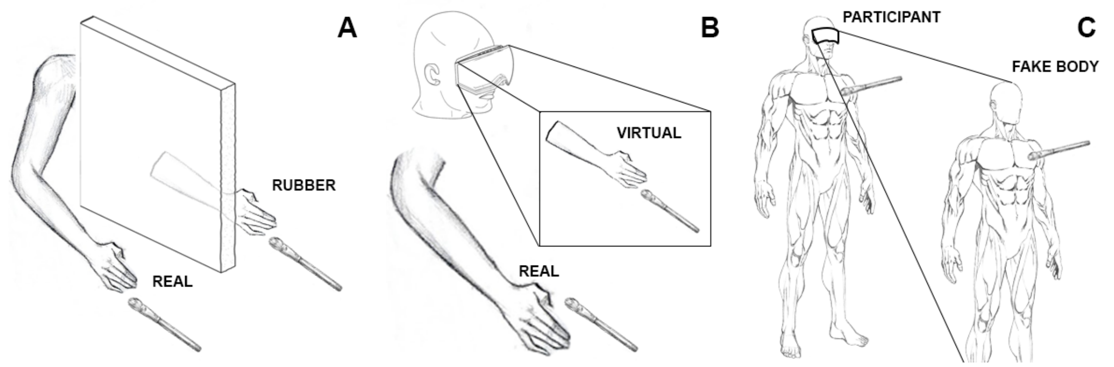


Figure 5.3: A) the rubber hand illusion, B) the virtual hand illusion, and C) full body illusion. All these illusions were first based on visuo-tactile integration.

Besides the mentioned illusions, many other tactile illusions were investigated. The interested reader could find a more extensive overview of tactile illusions in [23, 83, 93, 140].

All the above-mentioned illusions rely on visuo-tactile integration or more generally on multisensory integration. Gonzales-Franco and Lanier [81], the scientist who first used the words *virtual reality*, proposed three neuro-perceptive models to explain illusions in VR.

1) *Bottom-up multisensory processing*: our brain receives and combines bodily signals adapting them continuously based on the feedback received. When multiple sensory modalities provide congruent data, the brain is more likely to “believe” the information to be true. When they cannot be integrated, issues will arise (e.g., motion sickness). To tackle ambiguity in sensory information, the brain might seek higher probabilistic confidence in one interpretive state over the others (e.g., a sense will appear more reliable than another).

2) *Sensorimotor self-awareness frameworks:* these frameworks rely strongly on the comparison of internal representations of the actual, desired, and predicted states of the external world after a motor action has been executed. If the afferent sensory input matches the predicted state, then the brain is more likely to infer that the afferent input is correct.

3) *Top-down prediction manipulations:* discordant afferent inputs are recalibrated or suppressed in the brain to confirm a predicted state of the world. In other

words, the brain can "decide" that there is an error in measurement to reinforce a preference for a predicted outcome. Proprioceptive information can be manipulated in this way when reaching for objects in VR (e.g., haptic retargeting [9]). Nevertheless, the brain will reject an illusion when the discordance between afferent sensory inputs and the predicted/intended state become too extreme.

Finally, a recent paper that studied 1039 subjects, suggests that imaginative suggestibility (i.e., response to imaginative suggestions) can leads to the generation of subjectively real experience that could justify results in the RHI [152].

The last three illusions reported (i.e., RHI, VHI, and full body swap illusion) has been especially exploited to investigate the concept of embodiment. Numerous studies examined this paradigm and many variables were studied. In the next section, we introduce the concept of embodiment, and we discuss the main studies concerning it.

5.2 Defining the concept of embodiment

The definition of embodiment is not straightforward as one might think [77, 151]. On a general level, the sense of embodiment (SoE) can be considered as a set of beliefs that inform ourselves about being something, having a body and experiences. It is that process that sets boundaries between the self and the external world, differentiating ourselves from that external world. It can be referred to how we incorporate, biologically, the material and social world in which we live.

Carruthers defines the SoE as an offline representation of the body [38]. The offline body representation is what we know our body is usually, opposed to what our body looks like moment by moment. The SoE mainly consist of the feeling of being distinct from other objects and people [26]. The fact that everyone experiences the world in the first person, with one's perspective. The SoE is what makes us different from the rest, it is the perception of our physical boundaries, what make possible for us to recognize ourselves in the mirror. Longo et al. [151] approached the investigation of the SoE through a psychometric method. In their study, they exploit the RHI phenomenon. Participants (131) had to rate on a Likert scale (from -3 to +3) the grade of agreement on 27 statements. The statements were taken from previous studies on RHI. The authors found four main components through a principal component analysis (PCA): embodiment of the rubber hand, loss of own hand, movement, and affect. More specifically, they applied another PCA to the component "embodiment of the rubber hand". The new results individuated three more sub-components: ownership, location, and agency. In the experiment, *ownership* referred to the feeling of owning the rubber arm. *Location* explained the feeling of co-location between one own arm and the rubber one. *Agency* was explained as the feeling of being able to move the rubber arm.

De Vignemont [43] defines the SoE as that process that happens when some properties of an object are processed in the same way as they were properties of one's body. He further distinguishes three levels of embodiment: spatial, motor, and affective. For De Vignemont, there are also two different body representations: short-term and long-term body representations. That is why in a RHI study, the location of the rubber hand is embodied (short-term property), but not its texture (long-term property). Kilteni et al. [129] distinguish three sub-components of the SoE: self-location, sense of agency, and sense of body ownership. *Self-location* refers to that feeling of being inside a body and it coincides with Slater's *place illusion* [215]. *Sense of agency* is defined as having the feeling of being the cause of a motor action as a result of a motor intention. *Sense of ownership* refers to one's self-attribution of a body, the feeling of owning a body. How these three sub-components correlate between each other is still a matter of study. Authors conclude saying that to increase the SoE one must aim to increase their sub-components.

5.3 Extending our bodily boundaries

There are a plethora of studies that investigated the flexibility of our sense of embodiment. Probably the first scientist to discover a bodily illusion was Tastevin in 1937 [231]. While he was studying some aspects of the Aristotle illusion (see Section 5), he noticed that participants often attributed ownership towards a plastic finger protruding from underneath a cloth near their hand. Only many years later, Botvinick and Cohen investigated this phenomenon naming it "rubber hand illusion" [19].

Far from providing a full review of these studies, we will limit to report the main literature in the realm of bodily illusions (for a summary of the studies reported refer to 5.1).

5.3.1 The rubber and the virtual hand illusion

Studies on bodily illusions have their official start with the work of Botvinick and Cohen in 1998 [19]. In this original version of the RHI, participants sat on a chair with their left arm hidden behind a standing screen. A realistic left rubber arm model was placed in front of them. The researchers stroked participants' real and rubber arm at the same time with a brush (Figure 5.4), and they could see only the rubber arm being stimulated. After ten minutes, participants reported tactile sensations on the rubber arm. A further experiment confirmed also a distortion in the proprioceptive information. Both before and after the viewing period, the researchers asked participants to match with their right index finger the hypothesized location of their left index finger (the covered arm), at closed eyes. On average, after the illusion, this location resulted displaced rightward towards the rubber arm. Advances in VR and mixed reality technology have made it possible to study additional factors of the RHI [153, 201, 214, 258]. The reproduction of the RHI in VR is defined as virtual hand illusion (VHI). The procedure to elicit the illusion is the same. Participants wear an HMD and their arm is rendered as a virtual arm. The virtual arm is shifted with respect to the real one, and participants can see the tactile stimulation in VR through a HMD while feeling it on their real arm. After a while, the virtual arm will

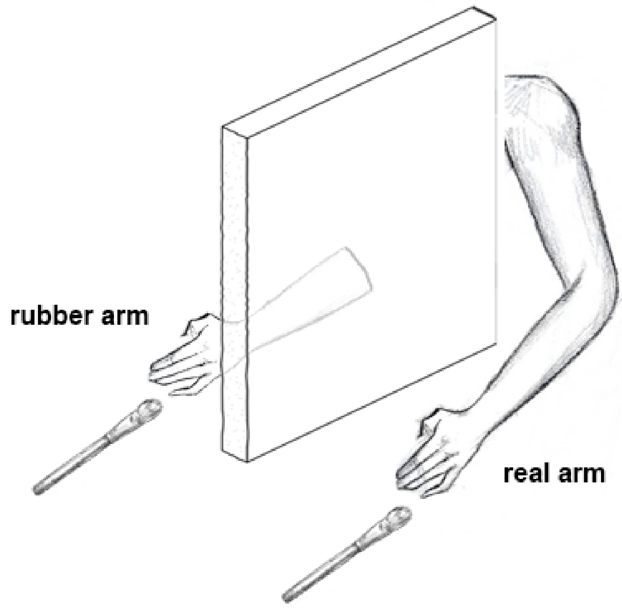


Figure 5.4: Participants left arm is hidden and a fake rubber arm is placed in front of them. The researcher stimulates the real and fake arm at the same time. After a while, participants will refer to feel the tactile stimulation as coming from the rubber arm.

be embodied.

In the classical RHI phenomenon the real and fake hands are stimulated by synchronous visuo-tactile stimulation. Later studies investigated how much visuo-tactile delay can be tolerated by participants in the asynchronous condition before the illusion breaks. In these studies, authors found that a delay of 300 ms between the stroking of the two hands (i.e., real and fake) reduced the effect of the illusion, and a delay of 500 ms broke the illusion [123, 211]. Regarding the maximum distance between the real and fake arm, it seems that distances greater than 30 cm reduces the strength of the illusion [147].

In one of the most famous variants of the RHI after the embodiment of the fake arm, subjects are confronted with a threatening event. In [49], the researchers threatened the rubber hand with a needle. Results showed an activation of those brain areas responsible for anxiety and interoceptive awareness (insula and anterior cingulate cortex) when a real limb is under threat. Suzuki et al. investigated the role of interoceptive information on the representation of our limbs in the space. Authors replicated the RHI by visually changing the shape of the hand according to participants' heartbeat [227]. By being able to induce the illusion, they demonstrated how not only exteroceptive information (visual and tactile feedback) but also internal feedback can influence the feeling of ownership towards a body part.

These results demonstrate that when the rubber arm is embodied in the body schema, our brain will treat it as a real part of the body. This could lead to hypothesize that when we incorporate an external object into our body schema, the rubber arm will have to adhere to certain properties that are commonly found for body parts.

Different authors investigated the importance of a fake arm position [35, 48, 102, 235]. They found that the illusion works only when the rubber arm is placed in an anatomically plausible posture. Perez-Marcos et al. examined if seeing a virtual arm disconnected from the rest of the body influences the strength of the illusion. Results showed that when participants were able to see the full body connected to the virtual arm, levels of ownership were greater [181]. The role of the hand's appearance was a concern of several studies. Armel and Ramachandran tested differences between the stimulation of a rubber hand versus a table. Skin conductance responses (SCR) were higher following a threatening stimulation on the anthropomorphic hand than on the table [8]. Similarly, Haans et al. investigated the extent to which RHI is influenced by visual discrepancies between the fake and participants' hand. Inhibition of the illusion was found for a non-human object (a white tabletop) in comparison to when a cosmetic prosthesis of a man's left hand was used. Tsakiris and Haggard showed lower levels of ownership when reproducing the RHI phenomenon using a stick instead of a rubber hand [235]. Lin et al. explored the role of graphics realism on levels of ownership towards a virtual arm, using different geometric hands' models [146]. They concluded that even if ownership was present for all the different hands' models, effects were stronger for the anthropomorphic ones. Unexpectedly, Ma et al. found how participants could embody non-corporeal objects such as a virtual balloon or a square [166]. They suggested that our body schema could be more flexible than previously thought.

The flexibility of body schema is further supported by studies that demonstrated how it is possible to induce a sensation of supernumerary arms. Several studies demonstrated how participants could perceive the feeling of having a third arm [87, 97]. A recent study, induced the feeling of a fourth arm through synchronous visuo-tactile and visuomotor stimulation [31]. Schwind et al. studied the effect of gender on the perception of avatar male and female hands in VR [205]. They demonstrated that, while males can accept female hands in their body schema having lower levels of embodiment only for non-human hands, females have lower ownership levels when trying to embody male hands. Preston and Newport were able to make participants feel as if their arm was impossibly long [187]. Another interesting study that challenges the stability of our body schema, is the one by Guterstam et al. In this study, the researchers made participants embody an invisible hand by stimulating synchronously their arm and an empty block of space [86].

The RHI has received interest also in the HCI field. Alonzo et al. carried a preliminary study in healthy subjects to investigate if a visuomotor stimulation could induce ownership towards a robotic arm. Participants wore a glove that allows for recording the fingers' movements. The same movements were sent and reproduced on the robotic arm. Authors reported higher levels of ownership towards the robotic arm in the visuomotor synchronous condition, compared to the visuomotor asynchronous condition [4]. In the same year, in a series of three experiments, Aldhous et al. replicated and extended the RHI phenomenon. The authors replaced the rubber arm with a static or digitally animated realistic picture of it. In another experiment, they replaced the rubber arm with a virtual image of it (virtual hand illusion). In both the experiments, they successfully reproduced the illusion. Further, they confirmed that in the visuo-tactile/visuomotor synchronous stimulation, levels of ownership towards the fake arm were higher [3]. Horiuchi et al. exploited an ultrasonic mid-air device to replicate the RHI phenomenon through a projected image on the rubber arm. Once again, they reported higher levels of embodiment for the visuo-tactile synchronous condition [104]. Further, they suggested that, when the screen used to hide the participants' arm was removed, a sensation of owning two arms was facilitated. Finally, Choi et al. explored the feeling of embodiment in virtual games in an immersive VR space. During the game, participants were allowed to move, and in the case where their body was rendered as a full-body, as opposite to a virtual cursor, levels of ownership were higher. Besides, they showed that even when introducing distortions in the tracking coordinates of the virtual hand, the level of embodiment was preserved [33].

5.3.2 More than just hands

Beyond inducing ownership towards a fake arm, researchers were able to extend the RHI illusion to other parts of the body.

For instance, Sforza et al. discovered that participants start recognising features of others' faces in the notion of self by synchronously touching participants and others' face [208]. This is particularly interesting because face plays a fundamental role in someone self-recognition and this process is rarely impaired (see the conspicuous incidence in the clinical population with prosopagnosia). Being able to *enface* other's people face provides yet another proof of the malleability of our body schema and self-representation. The same year, Paladino et al. demonstrated how brushing one's face while watching another person's face being touched, enhances the resemblance of one's face to the foreign face [177]. Further, observing synchronous stimulation elicited more positive affective reactions toward the other, indicating a social component of the illusion. Similarly, Ramachandran et al. by stroking with two hands the back of participants' head in synchrony with the back a mannequin's head were able to induce the illusion of transferring the tactile sensation from participants' head to the mannequin one [189].

In 2014 Michel et al. investigated the multisensory process giving rise of the RHI on the tongue. They chose this location because it is a part of the body that we rarely see. Indeed, the information coming from the tongue is usually proprioceptive and somatosensory. Because the vision has a strong influence over the experience of touch, authors wanted to test if an illusion of ownership towards an artificial tongue could be elicited [162]. Their study showed that participants could refer the tactile feedback as coming from a dummy tongue. Besides, when the tongue was visually stimulated with a beam of light, participants reported a tactile-like sensation or a thermal sensation.

Crea et al. transferred the RHI phenomenon to the lower limb [36]. Participants sat with their right leg hidden. A fake rubber leg was placed in front of them and stimulated synchronously with the real leg. As for the RHI, the rubber foot illusion requires synchronous visuo-tactile stimulation. In this study, the authors further investigated a synchronous incongruent condition. In this case, the stimulation could still be synchronous or asynchronous, but while the fake foot was stimulated using a brush, the real one was stimulated through two vibrators connected to the first two fingers of the foot (see Figure 5.5). The same year, Lenggenhager et al. tested healthy subjects and xenomelia patient. Xenomelia is a mental condition where a person does not accept one own limb. The researchers were able to reproduce the rubber foot illusion obtaining results comparable to the RHI. In doing that, they observed that xenomelia patients had stronger effects in the ownership of the fake foot, indicating a less structured body schema [144].

In 2016 Ekroll et al. demonstrated how participants can be tricked into believing they have a shorter finger when this is partially occluded by a semi-spherical ball. When participants saw their finger from the top view, the semi-spherical ball

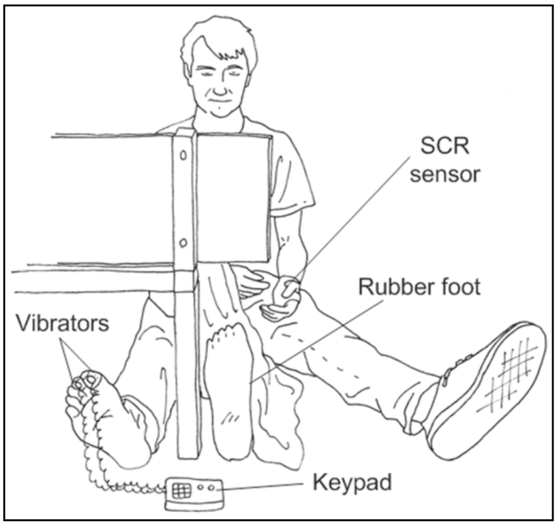


Figure 5.5: From [36]. Participants sat with their right leg hidden. A fake rubber leg was placed in front of them and stimulated synchronously with the real leg.

appeared to them as a complete sphere, therefore giving the feeling of having a shorter finger [50].

5.3.3 Full body illusions

It is relatively simple to investigate further instances of the RHI phenomenon by exploiting the use of VR technology. We described how scientists began to study the feeling of ownership towards a hand and how this paradigm was extended to other parts of the body. The missing piece is the research on full-body illusions or body swap illusions.

In 2007 Ehrsson provided first indirect evidence of the possibility of estranging a person from their own body. This illusion is called *out-of-body experience* (OBE). In his study, Ehrsson touched participants with two plastic rods on the chest whilst they were wearing a headset transmitting images from a camera located two meters behind participants' back. After two minutes of stimulation, participants referred the sensation of looking at their own body from the camera perspective [47]. Lenggenhager et al. reported a similar illusion. Their participants saw the backs of their bodies filmed from a distance of two meters and projected onto a three-dimensional HMD. Their back was tactilely stimulated, and they could see the same stimulation on their backs from a third-person perspective. After one minute of stimulation, participants had the feeling of observing their own body from behind [145]. These studies experimentally demonstrated the possibility of bending the body boundaries. The next year Petkova and Ehrsson reported a perceptual illusion of body-swapping [182]. This time, participants wore a headset displaying the images from the perspective of a mannequin located in front of them. A researcher synchronously or asynchronously stroked participant's and mannequin's abdomen with a brush for two minutes. Once again, the illusion of owning the mannequin body was reported only in the synchronous condition.

Further, studies investigated the rules and different possibilities for "foreign" bodies embodiment. Slater et al. studied the role of perspective in inducing ownership towards a different body [216]. Authors noted that a first-person perspective was sufficient to create an ownership illusion towards an external body even in the absence of synchronous stimulation. Normand et al. successfully induced the feeling of having a larger belly size [170]. Participants looked at an enlarged version of their belly while they were touching it through a probe. After a while, they reported the feeling of having a larger belly size. Farmer et al. investigated if it would be possible to embody a body of a different racial group. Authors demonstrated how it is possible to embody a body of a different skin colour [52]. Interestingly, scores for racial bias as measured by an implicit association task (IAT), were not predictive of the strength of the illusion. Instead, its strength was predicting levels of racial biases, with people reporting higher strength of illusion of embodiment towards a different skin colour showing lower racial biases. Another interesting study saw the illusion of ownership towards the body of a four years old child [11]. In this study, the authors concluded that not only an adult person could embody the body of a child, but that there might be behavioural correlation depending on the type of body in which the embodiment occurs. In the previous section (Section 5.3.1), we described an illusion of ownership towards an invisible hand [86]. Two years later, the same authors tested the possibility of inducing ownership towards a full invisible body [85]. In this study, participants wore a HMD that was allowing the view of their own body from first person, with the twist of having a transparent body. In practice, participants by looking downwards towards their chest could see just an empty space. Nevertheless, after synchronous stimulation of "the empty space" and their chest, participants referred the sensation of owning an invisible body. Furthermore, in a following experiment, they showed how the fact of owning a transparent body was correlating with reduced stress levels as measured by SCR following a stressful situation (participants were exposed in front of a public in the VE). Therefore, also in this study, it seems that the effect of owning a different body can correlate with other high-level processes other than just the perception of a different body.

Finally, a recent study demonstrated how it is possible to embody animal bodies. In particular, authors could induce a feeling of ownership towards the body of a cow or a coral using immersive virtual environments [2]. Interestingly, in subjects who experienced immersive virtual environments (in contrast to those who were only exposed to a video), there were long-lasting effects (1 week) regarding environmental involvement and awareness.

Authors	Title	Year	Summary
Botvinick M. and Cohen J.	Rubber hands 'feel' touch that eyes see	1998	The first study that explain the RHI
Armel K. C. et al.	Projecting sensations to external objects: evidence from skin conductance response	2003	RHI and skin conductance response for anthropomorphic and non objects
Ehrsson H. H et al.	That's my hand! Activity in premotor cortex reflects feeling of ownership of a limb	2004	RHI and neural correlates
Tsakiris M. and Haggard P.	The rubber hand illusion revisited: visuotactile integration and self-attribution	2005	RHI for anthropomorphic and non objects, bottom up and top down processes involved
Costatini M. and Haggard P.	The rubber hand illusion: Sensitivity and reference frame for body ownership	2007	RHI and importance of body position
Lloyd D. M.	Spatial limits on referred touch to an alien limb may reflect boundaries of visuo-tactile peripersonal space surrounding the hand	2007	RHI and spatial limits
Ehrsson H. H. et al.	Threatening a rubber hand that you feel is yours elicits a cortical anxiety response	2007	RHI and neural correlates
Ehrsson H. H.	The experimental induction of out-of-body experiences	2007	Out-of-body experience

Lenggenhager B. et al.	Video ergo sum: Manipulating bodily self-consciousness	2007	Full body illusion
Petkova V. I. and Ehrsson H. H.	If I were you: Perceptual illusion of body swapping	2008	Body swapping illusion
Shimada S. et al.	Rubber hand illusion under delayed visual feedback	2009	RHI and time variable
Ehrsson H. H.	How many arms make a pair? Perceptual illusion of having an additional limb	2009	RHI and additional limb
Sforza A. et al.	My face in yours: Visuo-tactile facial stimulation influences sense of identity	2010	Embodiment of a stranger's face
Slater M. et al.	First person experience of body transfer in virtual reality	2010	Role of perspective in inducing full body illusions
Holle H. et al.	Proprioceptive Drift without Illusions of Ownership for Rotated Hands in the 'Rubber Hand Illusion' Paradigm	2011	RHI and proprioceptive drift measure
Guterstam A. et al.	The illusion of owning a third arm	2011	RHI with a third arm
Ramachandran V. S. et al.	The phantom head	2011	Embodiment of a mannequin head
Norman J. M et al.	Multisensory stimulation can induce an illusion of larger belly size in immersive virtual reality	2011	Embodiment of a different body size

Perez-Marcos D. et al.	Is my hand connected to my body? The impact of body continuity and arm alignment on the virtual hand illusion	2012	RHI and body connection variable
Preston C. and Newport R.	How long is your arm? Using multisensory illusions to modify body image from the third-person perspective	2012	RHI with extra long arm
Farmer H. et al.	Beyond the colour of my skin: How skin colour affects the sense of body-ownership	2012	Embodiment of a different skin colour body
Suzuki K. et al.	Multisensory integration across exteroceptive and interoceptive domains modulates self-experience in the rubber-hand illusion	2013	RHI and interoceptive correlates
Guterstam A. et al.	The Invisible Hand Illusion: Multisensory Integration Leads to the Embodiment of a Discrete Volume of Empty Space	2013	RHI for an invisible hand
Banakou D.	Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes	2013	Embodiment of a body of different age
Kalckert A. and Ehrsson H. H.	The moving rubber hand illusion revisited: Comparing movements and visuo-tactile stimulation to induce illusory ownership	2014	RHI with visuo-tactile and motor variables

Alonzo M. D. et al.	Vibro-tactile feedback elicits embodiment of robotic hand in active motor task	2014	RHI with a robotic arm
Michel C. et al.	The Butcher's Tongue Illusion	2014	Embodiment of a fake tongue
Ma K. and Hommel B.	Body-ownership for actively operated non-corporeal objects	2015	RHI for non-corporeal objects
Crea S. et al.	The rubber foot illusion, Journal of NeuroEngineering and Rehabilitation	2015	Embodiment of a rubber foot
Guterstam A. et al.	Illusory ownership of an invisible body reduces autonomic and subjective social anxiety responses	2015	Embodiment of an invisible body
Lenggenhager B. et al.	Disturbed body integrity and the 'rubber foot illusion'	2015	Rubber foot illusion in neuropsychological patients
Lin L. and Jorg S.	Need a hand? How appearance affects the virtual hand illusion	2016	VHI and importance of visual appearance of the hand
Choi W. et al.	Multisensory Integration in the Virtual Hand Illusion with Active Movement	2016	VHI and hand tracking variable
Ekroll V. et al.	Illusory Visual Completion of an Object's Invisible Backside Can Make Your Finger Feel Shorter	2016	Embodiment of a shorter finger

Ahn S. J. G. et al.	Experiencing Nature: Embodying Animals in Immersive Virtual Environments Increases Inclusion of Nature in Self and Involvement With Nature	2016	Embodiment of an animal body
Schwind V. et al.	"These are not my hands!": Effect of gender on the perception of avatar hands in virtual reality	2017	VHI and gender effect
Aldhous J. et al.	The digital rubber hand illusion	2017	RHI with a digital hand
Horiuchi Y. et al.	Rubber hand illusion using invisible tactile stimulus	2017	RHI with an ultrasonic device
Chen W. Y. et al.	Body ownership and the four-hand illusion	2018	RHI with a fourth arm
Pittera D. et al.	I'm Sensing in the Rain: Spatial Incongruity in Visual-Tactile Mid-Air Stimulation Can Elicit Ownership in VR Users	2019	VHI with mid-air haptics

Table 5.1: Table of the cited experiment where the main topic is the study of the embodiment.

Taken together, the examples of perceptual tactile illusions presented in the prior sections demonstrate how flexible our body schema is and that it is possible to perturb it to include different body parts or even an entirely different body. From an HCI perspective, these findings on the creation of bodily illusions and embodiment, inspire the design of novel VR experiences involving the sense of touch, which can reinforce the embodiment.

By analysing the previous works on bodily illusions, it emerges a common factor that allowed to precisely control variables of interest and to render impossible scenarios: virtual reality. This technology helped different kind of researchers and scientists to create and recreate immersive worlds. VR is a key technology for the study of the embodiment, mental health, clinical therapies, training situations, simulations, etc.

5.4 Virtual reality: history and technology

The first multisensory experience in VR begins with Morton Heilig who conceived a machine for a "multisensory cinema experience", the "Sensorama" (Figure 5.6).

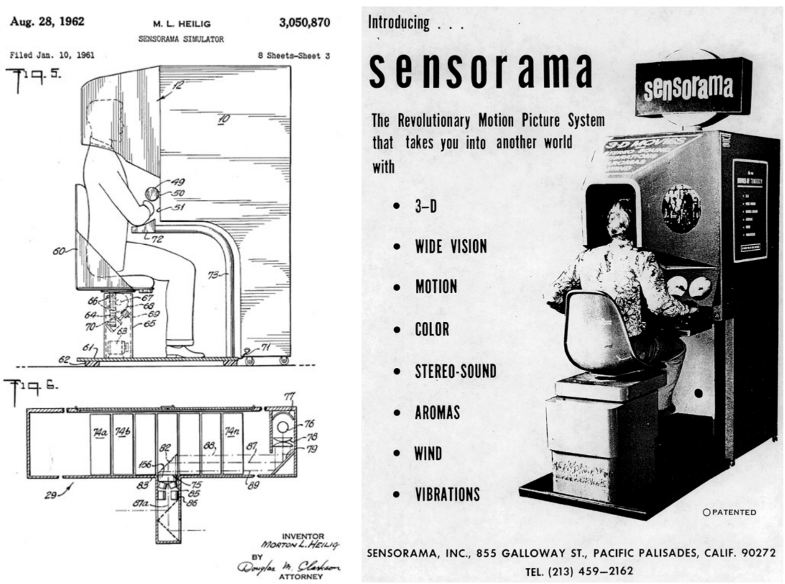


Figure 5.6: The sensorama of Morton Heilig. This machine was the first example of multisensory experience in VR.

This machine combined video projection, audio, wind, vibrations, and odours to make the user feeling completely immersed in the film (lasting a few minutes) rather than participating only as an external spectator. In 1960 Heilig patented an idea that many consider being the first example of Head-Mounted Display (HMD), a HMD stereoscopic television (although McCollum had patented the idea of a HMD in 1945) [132]. In 1961 Comeau and Bryan at the Philco Corporation built the "Headsight", the first modern HMD. It employed a magnetic tracking system and a single cathode-ray tube mounted on the helmet which showed the images on a monitor according to the measured head movements.

The first true example of virtual reality as we understand it today is to be attributed in the 1960s to Ivan Sutherland; he designed optical display glasses (Figure 5.7) connected to a position sensor and two miniaturized cathode tubes to transmit the image to the glasses in real-time. The position sensor sent the data to a computer that updated the view of the virtual environment in the glasses in real-time [226]. The allowed head movements were of 30°-40° up and down and about one meter laterally. This system was called "the sword of Damocles" due to the motion sensor hanging from the ceiling. Around the same time, Thomas A. Furness, a scientist at the Wright-Patterson airbase in Ohio, began working on aircraft cabin technology. The fighter jets were becoming so complex that the amount of information a pilot had to assimilate from the cockpit instruments and command communications had become unsustainable. The solution resided in a 3D cockpit that transmitted sensory information directly to the pilot's cockpit [61]. Today this instrumentation is used for night flight as 3D images can replace the pilot's direct view. The first virtual reality system was "the Aspen Movie Map" created in 1978 by Andy Lippman and a group of MIT researchers. The program consisted of a simulation of a walk in the city of Aspen, Colorado. The system used discs containing photographs of all the streets of Aspen, taken every three meters through the use of four cameras pointing in different directions mounted on a pickup truck. In this way, the user could move through the four directions (forward, backward, right, and left). Between the 60s and the 70s, Myron Krueger, among other computer scientists, created the VIDEOPLACE [135]. The computer had control of the interaction between the participant and the graphic objects on the screen. It could match the movement of an object with the

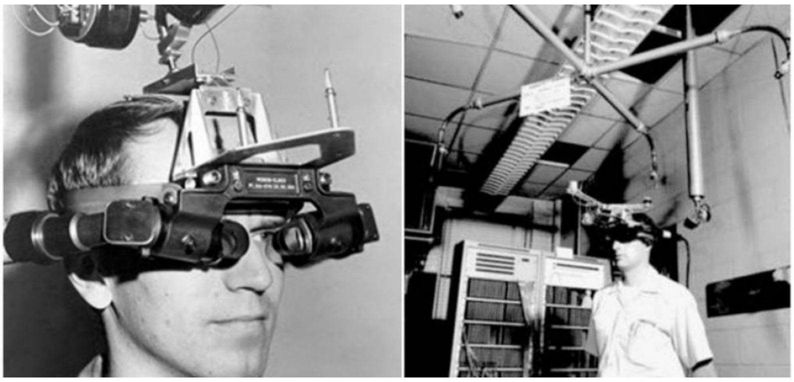


Figure 5.7: In the 1960s Sutherland ideated a first example of modern HMD. Left - optical display glasses and two miniaturized cathode tubes to transmit the image to the glasses in real time. Right - position sensors to update the view of the VE in real time.

participant's actions without necessarily considering the limits of physical reality. A series of simulations could be programmed based on each action and VIDEOPLACE offered more than 50 compositions and interactions, among these: critters, fractals, finger painting, digital drawing, replay, etc.

The first sensory glove, the "Sayre Glove", was developed by Tom Defanti and Daniel Sandin in 1977 during a project for the National Endowment for the Arts. The first device recognized for measuring hand position was developed and patented in 1983 by Dr Gary Grimes in the Bell laboratories: the "Grimes' Digital Data Entry Glove". This glove had sensors for bending fingers, tactile sensors on the fingertips, orientation sensors and sensors on the wrist. Finally, it is imperative to mention the "VPL Data Glove" by Zimmerman and Jaron Lanier, founder and CEO of VPL research in 1987. The Data Glove consists of a lightly coated Lycra glove covered by special optical fibres along the back of the fingers, with an inlet light and a photodiode at the other end. In this way, the bending of the fingers reduces the light transmitted by the optical fibres on the glove. The amount of light allowed to pass through the channels is analysed by a processor that is thus able to calculate the angle of finger bending [225]. To date, significant progress has been made concerning the graphic resolution, tracking of virtual reality systems, but the virtualization of other senses such as the tactile one has still to be improved.

5.4.1 Types of VR

The term "virtual reality" was used for the first time by Jaron Lanier in 1989 [221], by the at that time general director of VPL Research, a Californian company that deals with VR. With this term, we indicate a three-dimensional visual simulation of objects, spaces, and people generated and controlled employing a computer and integrated with other stimuli (tactile, acoustic, olfactory, muscular, etc.). These stimuli can be delivered to the user by wearing more or less sophisticated equipment (visors, gloves, helmets, keyboard, mouse, etc.). In this way, users can experience a surrogate of reality, whose limit theoretically coincides with human imagination.

It is possible to distinguish three types of virtual reality: immersive, semi-immersive, and non-immersive. The VR is considered immersive when it manages to create a sense of total absorption in the (VE) generated by the computer; usually this happens through the use of a helmet capable of isolating the user from the external reality, and by means of trackers, sensors that track the user's movements and transmit them to the computer adjusting the VE according to the user's movements. VR is considered semi-immersive when using a "cave", a projection chamber in which the VE is projected on its internal walls creating a sensation of immersion (Figure 5.8).

Figure 5.8: A VR cave. A projection chamber in which the virtual environment is projected on its internal walls, creating a sensation of immersion.

Finally, the VR is non-immersive when a simple monitor or video projector (instead of a helmet) is used to reproduce 3D images while still allowing a stereoscopic vision thanks to the use of special glasses. Usually, the user's interaction is allowed through a joystick.

VR is different from Augmented Reality (AR); it represents a three-dimensional interactive environment generated by a computer that allows the user to dive into a completely fictitious world. AR, instead, enriches the existing reality with virtual objects recreated by a computer.

5.4.2 Factors influencing VR experiences

Nowadays, VR found application in a great variety of cases; from therapies dedicated to the treatment of post-traumatic stress disorder (PTSD) to phobias (social or specific), eating and sexual disorders, and the study of schizophrenic behaviour [57]. Not limited to the clinical field, VR saw great success in the gaming and artistic industry, and in the education field. The use of VR allows the study of scenarios totally controlled by the researcher. This allows for finding more easily cause-effect links when studying human behaviour. For example, it has been proved that subjects with schizophrenic behaviour feel safer within a VE. Further, the neural correlates of a certain behaviour can be studied by integrating VR with imaging techniques like functional magnetic resonance imaging (fMRI).

To maximise the results when studying human behaviour in VR, users must come to behave as they would in reality. In other words, they must immerse themselves in the artificial environment, and experience what is called the phenomenon of presence. Generally, the term "presence" means the experience of being in a virtual environment [108, 217, 245, 252], but this term has not always been defined unanimously. Many researchers gave different definitions. Gibson defined presence as the feeling of being in an environment. Sheridan [210] distinguishes between presence (the feeling of being in an artificial world) and telepresence (the feeling of being in a remote, real place). Heeter [96] makes a distinction between three types of presence: personal, social and environmental. Schloerb [204] describes a subjective and objective presence. Lombard and Ditton [148] find a list of six possible applications of the term: social intensity, realism, transport, immersion, social actor within a medium, medium as a social actor. Witmer and Singer [252] defines presence as "the subjective feeling of being in one place or environment, even when one is physically in another". Similarly, Nicovich et al. [169] define presence as the subjective sensation of existence in an artificial environment that has been experienced. Sacau et al. [198] use the term "spatial presence", distinguishing between the physical, perceptive, and social dimensions. Finally, Slater [215] proposes that presence consists of two components: what he calls place illusion (PI), and the illusion that what is apparently happening, is really happening, plausibility illusion (PSI). The phenomenon of presence is not immutable. Studies aimed to individuate the factors that influence the presence are still in progress, but in the meantime, a series of data has emerged. Wallach et al. [245] divide these variables into three groups: technological, individual, and interaction variables. Contrary to what one might think, even when the virtual environment does not accurately or completely represent the real one, presence phenomenon can still be present. According to the authors, what seems to have more importance is the absence of conflicting elements with respect to the experience of everyday life [244]. As Casati and Pasquinelli pointed out [28]:

> "It is not the fidelity to the real model (the real world) that makes the artificial environment real, but the fidelity to the perceptive conditions involved in the mental construction of the perceived objects.[...] The credibility of a synthetic object depends on the adequacy of the reproduction of the relevant aspects of the perceptive system involved, and not on the realism of the reproduction of the stimulus".

There are other technological factors correlated with higher degrees of presence. These are vividness, defined as "the ability of a technology to produce a sensorially rich mediated environment" [221], coherence of sensory input and the presence of

Variable	Contribution
Form variables - This group includes the more objective	
Sensory outputs	
- Number of sensory outputs	Positive for higher numbers
- Consistency of sensory outputs	Positive when consistent
- Visual outputs, various dimensions:	Strong
– display size	Positive for larger proportion
– viewing distance	Positive for larger proportion
– quality of image	Positive for high quality
– depth cues	Positive
– camera techniques	Positive
- Audible outputs, various dimension	Strong
- Other sensory outputs (smell, touch, etc.)	Can be influential but usually less strong than audio or visual
- Body movement and force feedback	Positive when well done
Interactivity of medium	Positive
Visibility/obtrusiveness of medium	Negative
Interference from real world	Negative
Human contact	Positive
Content variables - Can be both objective and subjective	
Characters and storylines	Positive and negative
Media conventions	Usually negative
Nature of representation	Positive and negative
Media user variables - These are highly subjective and depend directly on the individual	
Willingness to suspend disbelief	Positive
Previous experience	Positive or negative

Table 5.2: Adapted from [122]. Factors influencing presence in VR.

multisensorial stimulation [64, 245]. In this case there must be coherence between the different sensory modalities, otherwise, we would obtain the opposite effect. The use of immersive technologies, such as HMD, increase the degree of presence. However, these technologies must respect the values of transparency and continuity. The first term expresses the lack of awareness of the same medium. The second term refers to the lack of interruption during the interaction. Interruptions can occur when the user becomes aware of the medium and the physical interface [230]. For this reason, mid-air haptics can be considered both, transparent and continuous, as it provides tactile stimulation while being invisible to the user allowing a continuous interaction in the VE.

Further, individual variables weight into the phenomenon of presence (e.g., empathy, imagination, tendencies to dissociation, locus of control, cognitive style, attachment and sensory processing, Big Five factors, levels of neuroticism, response to reward or punishment, search for strong sensations, etc.) together with cognitive abilities, level of anxiety, ethnicity and gender [245]. In this regard, a recent study proposes to explain the effect of the RHI illusion as related to the suggestibility of the subject [152].

Another factor influencing the level of presence is the possibility of moving in reality influencing the VE [245]. The free movement seems better than on-site movement, although current technologies have limitations in this sense. Cognitive and emotive meaning of VEs seem to play a role in inducing the sense of presence [245] among other factors that Kalawsky proposed (see Table 5.2) [122].

From the very beginning of VR research, it became clear that alone, sight and hearing were not sufficient to achieve a powerful immersion in that new artificial reality [13, 65]. Our sense of touch plays a fundamental role and it involves many parts of the body. In a study by Hoffman and colleagues, it has been shown that the introduction of tactile feedback increases the probability to perceive realistic VR objects [99]. Indeed, users will have some expectations regarding those objects: they will obey to the law of gravity, have a certain weight, consistency, etc.

The same authors in another experiment showed how biting a real chocolate bar, enhances the enjoyment of the experience in VR. Further, it also increases the level of presence, in comparison to the group that was asked only to imagine biting chocolate. Also, Sallnas et al. [200] conclude that the group with visuo-audio-haptic information had a better performance in a desktop VE collaborative task when compared with the visual-auditory information group.

5.5 Summary

In this chapter we presented the concept of tactile illusions, and we reflected on the possibility of using such illusions to help to tackle the complexity of rendering the sense of touch in a human-machine interaction. Then, we presented the main tactile illusions related to this thesis, from illusions of motion to rubber and virtual hand illusions. The latter are traditionally used to study the sense of embodiment. After defining the SoE, we presented how it is possible to modify our body schema to induce the illusion of owning different parts of the body until its entirety.

To do that, we make use of a technology now commonly available on the market: virtual reality. We present VR and described briefly its history. We then discussed the phenomenon of presence, or the feeling of behaving in a virtual scenario as if we would do in real life. We discussed how presence can be facilitated by the implementation of tactile feedback and in particular, by providing sensorial coherence, possibly in an almost "transparent" way. Mid-air haptic technology has the advantage of being potentially invisible to the interacting user and it allows for a continuous experience in VR. Finally, it emerged how the sense of touch is needed when thinking about VR applications. In the real world, we touch the floor with our feet when standing and walking, we feel the movement of our limb in the space, we touch objects around us, and we interact with them. When in a VE, graphic realism will help in making us believe what we see. Presence will raise, but it is not enough; if we cannot touch what we see or if we do not receive coherent information from our virtual interactions, the illusion of being somewhere else will fade.

In Chapter 11 we will present a study of four experiments aimed to explore the VHI phenomenon demonstrating that our brain can fill in the gap between spatially incongruent visual-tactile stimulations (gap between what we see and what we feel on the hand) maintaining the feeling of body ownership in situation other than perfectly, spatially matched stimulation. In particular, we exploit the advantages of an ultrasound mid-air haptic device (see Chapter 4, Section 4.3) and we recreate the VHI illusion varying the congruency of the stimulation (i.e., congruence and incongruence). We additionally test multiple incongruent visual-tactile stimulations to overcome the effect of the current limitation of the free-hands tracking systems (i.e., imprecise spatial tracking) on reported body ownership in VR. While the VHI has been studied before, it has not been explored using the emerging mid-air haptic technology (see [104] for an early paper on the RHI, but not in VR). Hence, the novelty of our study is the use of multiple mid-air tactile stimuli in VR, testing the occurrence of the VHI in congruent and incongruent conditions, and the use of new mid-air haptic technology.

Practice

Chapter 6

Study 1 - Understand Basic mid-air haptic perception[1]

In Chapter 2 we described the complex nature of our sense of touch, specifying the different properties of the mechanoreceptors in the skin. Since, the distribution of the tactile receptors is not uniform across the body and since that ultrasonic mid-air devices are a technology of recent implementation, in this first experiment we explored the tactile absolute thresholds (see Chapter 3) in the left hand and arm. This first step is needed if we want to develop new way of interaction using this technology. We need to establish an understanding of what people can perceive, so that we can make use of this information for the design of future interfaces (similar as we know today how to present auditory or visual stimuli).

Therefore, this initial study is part of the stage "Understand" and aims towards answering RQ1, trying to understand the psychophysics of touch related to mid-air haptics. The results of this study will provide the base for the following studies that focus on the palm.

[1] S.1 - Unpublished work

6.1 Introduction

As described in Chapter 4, mid-air haptics is the latest technology available to researchers and designers to deliver tactile feedback to the user without need for attachments on the skin. While various devices have been developed, ultrasonic mid-air haptic devices seem the most promising (see Chapter 4, Section 4.3). These devices seem to stimulate the Pacinian corpuscles (high-frequency vibration receptors) and to a minor degree the Meissner receptors (low-frequency vibrations receptors) [171, 251, 257]. To create tactile feedback, parameters such as frequency, intensity, duration, and direction can be manipulated to render different sensations [27].

Ultrasonic haptics has a lower spatial resolution compared to physical touch (1 cm of diameter [150]). However, it still allows the creation of a multitude of sensations. For instance, Long et al. were able to render volumetric shapes using mid-air haptic technology [150], Carter et al. [27] employed ultrasound arrays as an input interface, allowing colour rendering, pinch-to-zoom interaction, and the possibility of interacting with a web application. Moreover, Ablart et al., applied mid-air touch to enhance users' experience while they were watching short films [1], and Vi et al. applied mid-air touch to enhance users' experience during an art exhibition [240]. Finally, Obrist et al. provided a non-arbitrary map between emotions and haptic descriptions [172].

In these researches, authors focused solely on the palm of the hands. Hence, it raises the question if we can extend the ultrasonic tactile stimulation beyond the hand. After testing an ultrasonic device on different parts of the body (i.e., hands, feet, chest, abdomen, neck, back, calves, shins, thighs, buttocks, face) we confirmed that the feedback was perceivable mainly on glabrous skin where the presence of Pacinian and Meissner receptors is prevalent (see Chapter 2, Section 2.4). Hence, in this study, we systematically investigate the absolute thresholds on 20 locations across the left hand (palm and fingers) and arm.

6.2 Method

In this experiment, we calculate the absolute thresholds for ultrasonic mid-air haptic stimuli across the left hand and arm. In typical psychophysical methodology, the perception of stimuli at each location is repeated leading to high experimental times. To not strain participants and induce them to inaccurate answers, we limited the tested locations in the number of 20. The experiment lasted 60 minutes in total. We tested every phalanx of the left hand (faced upwards), the palm in two points (the centre and the upper part near the junction with the fingers), the centre of the wrist, the centre of the forearm, the centre of the biceps, and finally the shoulder in its central—medial part (see Figure 6.1). We chose to stimulate the left arm because there is no evidence of laterality for vibro-tactile absolute thresholds levels. The mid-air stimuli were focal points in the range of 5 Hz to 250 Hz. These frequencies were chosen because of the mechanoreceptors properties discussed in Chapter 2.

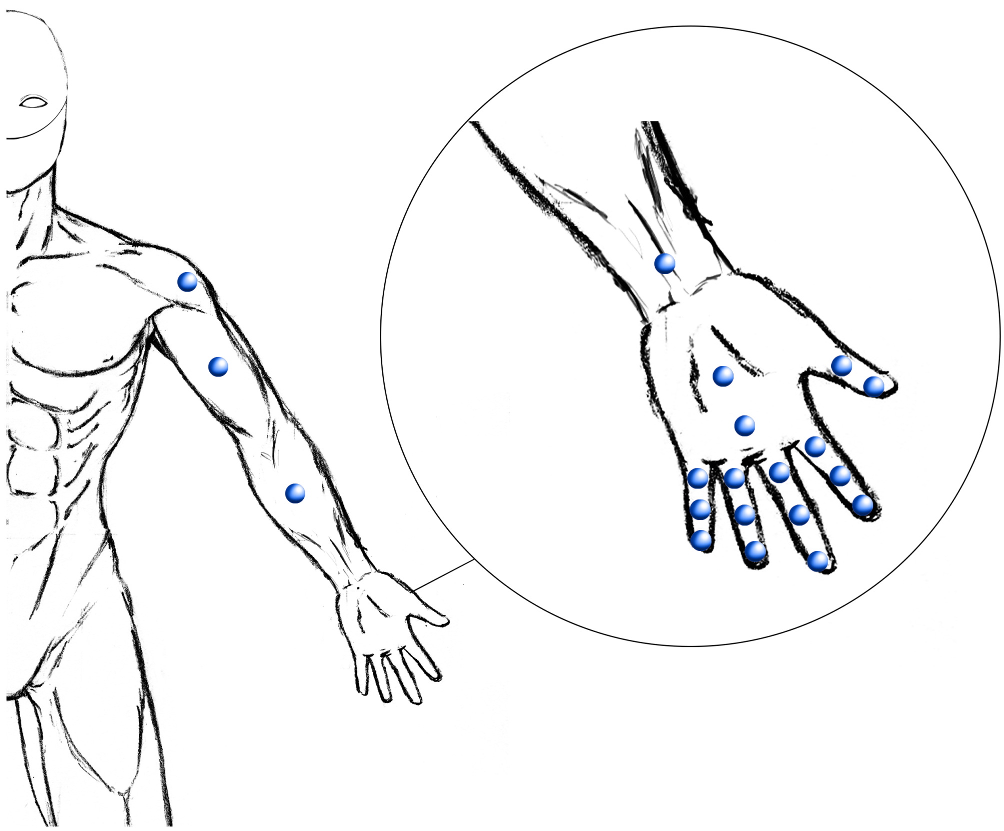


Figure 6.1: The 20 locations selected to test absolute thresholds for ultrasonic mid-air tactile stimuli.

In this experiment, participants sat comfortably on a chair with their hand facing upwards laying on a soft mould specifically created to avoid movements of the hand. Participants wore headphones playing white noise to cancel the noise from the haptic device and to receive automatic instructions. We used an Ultrahaptics mid-air haptic device to deliver tactile feedback to participants' left hand that was resting on top of the mould.

To control if the tactile feedback was delivered on the intended spot, we mounted a laser pointer on the ultrasonic board so that the pointing light was matching the tactile sensation on the skin at 20 cm of distance. This distance is the optimal working distance for the haptic device. The researcher changed manually the position of the device to focus on the intended 20 locations. Before starting the testing phase, the researcher was delivering a supraliminal stimulation to double-check with the participant that the tactile feedback was hitting the intended spot. To find the absolute thresholds we employed the 1-up-1-down adaptive staircase method with ascending and descending scales, repeated four times each. In practice, for each of the twenty locations participants were stimulated starting with very low frequencies (5 Hz, ascending scale) or very high frequency (250 Hz, descending scale). Each stimulus was preceded by a "beep" sound. After the stimulation, participants could hear a voice in the headphones asking if the stimulation was perceived or not. If not, the next stimulus was delivered, at a frequency 5 Hz higher. When participants were able to feel the tactile stimulus, the next stimulation was reduced by 5 Hz. The sequence was stopping after four inversions. Absolute thresholds are given by the average of the values of the last four inversions.

6.3 Participants

In this study, we recruited 21 participants (7 females, average age = 24). They had normal or glasses/lens corrected vision and no history of neurological or psychological disorders as captured through self—report. No subject had previous experience with the ultrasonic mid-air device as measured by a pre-test questionnaire.

6.4 Results

Figure 6.2 illustrates the calculated absolute thresholds for the mid-air stimulation on the chosen 20 locations (refer to Table 6.1 for the precise values). By looking at the figure it is evident that the most sensitive part is the palm near the phalanges (μ: 19.59 Hz, SD: 9.01). The biceps is the least sensitive (μ: 136.88 Hz, SD: 93.65). Further, only one subject could perceive the stimulation in this area.

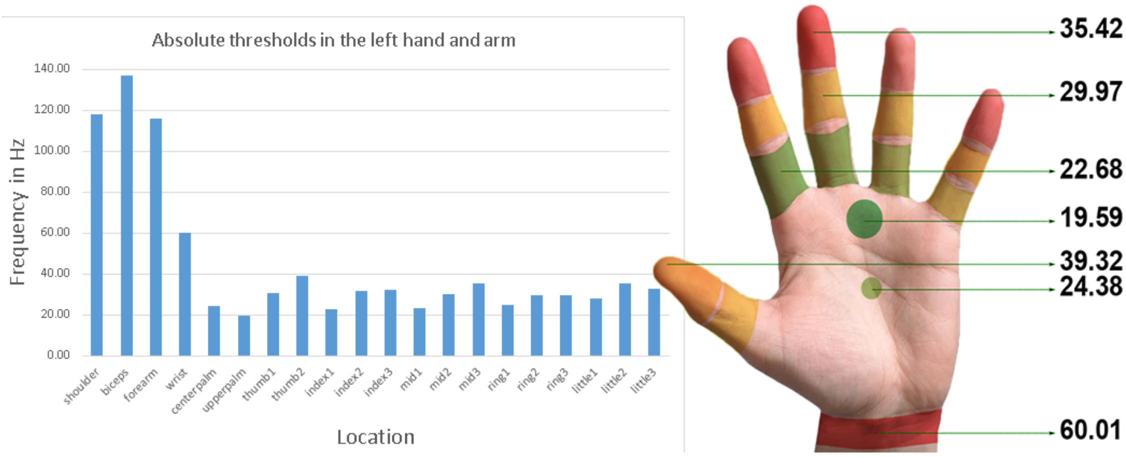


Figure 6.2: Absolute thresholds for the 20 test locations.

Focusing on the fingers, it appears there is a trend where the proximal phalanges (the ones near the palm) are the most sensitive, and the sensitivity reduces as we go towards the finger pads. In particular, the proximal phalanx of the index finger is the most sensitive, with a gradual increase of the thresholds as we move toward the pinkie finger. The thumb is the less sensitive finger, however, once again, the

Location	Hz	Location	Hz
palm (upper)	19.59	index1	22.68
mid1	23.32	palm (centre)	24.38
ring1	24.81	little1	28.30
ring3	29.72	ring2	29.75
mid2	29.97	thumb1	30.56
index2	31.49	index3	32.32
little3	32.67	mid3	35.42
little2	35.42	thumb2	39.32
wrist	60.01	forearm	115.98
shoulder	118.04	biceps	136.88

Table 6.1: Absolute thresholds in Hz for the 20 tested locations.

proximal phalanx is more sensitive than the distal one.

6.5 Conclusion

While this study aimed to expand the ultrasonic mid-air haptics psychophysical knowledge beyond the hand, an initial investigation revealed that, at the moment, the perception of this kind of technology is limited on the glabrous skin of our body. Hence, we proceeded with a systematic investigation of 20 locations on the palm, fingers, wrist, forearm, biceps, and shoulder. We provided a first knowledge on the absolute thresholds for ultrasonic mid-air touch providing a general picture on the distribution of the sensitiveness across the hand and arm. These results will help to inform designers and researchers for the development of future researches and applications.

CHAPTER 7

STUDY 2 - UNDERSTAND VARYING TECHNICAL PARAMETERS[1]

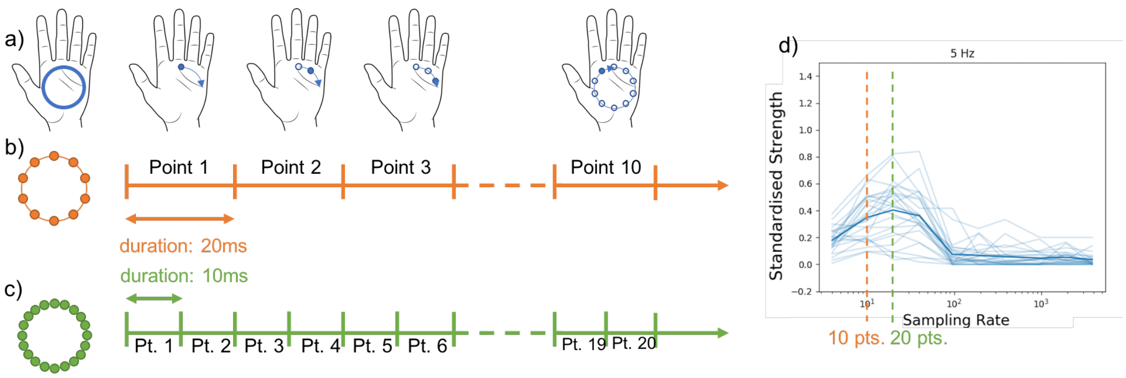


Figure 7.1: (a) A mid-air tactile pattern such as a circle is sampled into a set of successive positions, here 10. (b) Each sample point is presented during a given interval of time proportional to the total number of sample points. (c) Increasing the number of sample points will increase the rendering fidelity, but will also decrease the stimulation duration of each sample point. (d) Our study shows that changing the number of sample points affects the perceived strength of the pattern.

Mid-air tactile stimulation using ultrasound has been used in a variety of human-computer interfaces in the form of prototypes as well as products. When generating these tactile patterns with mid-air tactile ultrasonic

[1]Frier W., Pittera D., Ablart D., Obrist M., Subramanian S. "**Sampling strategy for ultrasonic mid-air haptics**". In *Proceedings of the CHI Conference on Human Factors in Computing Systems*, Glasgow, UK, 2019.

displays, the common approach has been to sample the patterns using the hardware update rate capabilities to their full extent.

In the current study, we show that the hardware update rate can impact perception. Specifically, in experiment 1, we show that the perceived strength of mid-air tactile pattern is related to the sampling rate of a pattern, especially for low draw frequencies (i.e. between 2 Hz and 10 Hz). The results show that for a high sampling rate (i.e., above 200 points), which is the common approach used in previous research, patterns with low draw frequency (i.e., under 20 Hz) could not be perceived by the user. However, using our approach, which is to lower the sampling rate, users could perceive a pattern with a draw frequency as low as 2 Hz. Fitting our results to a quadratic mixed model, we were able to determine the relationship between perceived strength and sampling rate, and further determine the optimal sample rate that generates the strongest subjective perception of tactile feedback.

In experiment 2, we repeated the same method varying the pattern sizes, that is, the diameter of a circular pattern displayed on a user's palm as seen in Figure 7.1. Combining these results with our first user study, we were able to determine the optimal sample rate for each combination pattern size and pattern draw frequency. Our results show that this optimal sample rate is proportional to the pattern size. In other words, for a given draw frequency, one should optimise the sample rate according to the distance between two consecutive samples.

Finally, we discuss the impact of our results on the design of tactile patterns and propose how our guidelines could be integrated within tactile feedback designer tools.

This study contributes to the stage "Understanding", RQ1, as it is still focused on using a psychophysical approach to better understand how we can design mid-air haptics that are optimally perceived by the users. Although the outcome of this research has important implications for design guidelines, we could not apply them in the following studies presented in this thesis due to the different nature of the stimuli used (simple focal points/lines vs. complex shapes) and because the outcome followed in time the other studies.

7.1 Experiment 1: sampling rate

There are various modulation methods and sampling strategies that can produce a mid-air tactile pattern using focused ultrasound. These methods and strategies predominantly depend on the available hardware being used. There has not been however any discussion on how sampling strategy affects the overall pattern perception. This section describes how we undertook to investigate the relation between sampling strategy and pattern perception. In particular, we focus on the pattern perceived strength relative to the pattern sampling rate.

7.1.1 Method

We hypothesized that the pattern sampling rate will affect the perceived strength. To test this, we run a magnitude estimation task [119]. In this task, participants had to estimate the perceived strength for patterns rendered with different sampling rates.

Participants were sitting comfortably on an office chair, which they were free to adjust to their liking. On the left of the participant, there was an acrylic box, roughly at their hip level. The box was 200 mm high and a mid-air tactile display UHEV1 from Ultrahaptics Ltd. was lying at the bottom of the box. An aperture was cut on

Figure 7.2: The setup for the user studies. Participants were perceiving the mid-air tactile pattern on their left palm while rating each pattern on a designated laptop.

the top box. Participants could rest their left hand over it while experiencing the different mid-air tactile patterns.

Before starting the experiment, an initial focal point was presented to the users' hand, so that they could align their palm with the array output. To avoid participants responses to be biased by surrounding noises, participants wore noise-cancelling headphones playing pink noise. On the desk, in front of the participants, a laptop was running the experimental protocol. Participants could read instructions from the laptop screen and input their strength estimates via a computer mouse. Figure 7.2 shows the overall set-up.

To test our hypothesis we used a set of patterns with various sampling rates. To avoid shape-related effects, all of these were variations on a circular pattern. All patterns were a 150 mm circumference circle (i.e. ≈ 24 mm centimetre radius), as it covers most of the palm of the participant (human palm width mostly varies between 75 mm and 95 mm [134]). Circles have also a clear periodic property and its intermediately positioned points can be easily made equally spaced, all of those limiting possible artefacts due to shape geometry.

In this experiment, we also wanted to test whether the sampling rate of the pattern will affect the sensations of different patterns equally. Therefore, we picked 6 different draw frequencies for the presentation of the pattern, as to cover different octaves and the sensitivity ranges of different mechanoreceptors [116]. An illustration of a circular pattern is depicted in Figure 7.1-a, while Figure 7.1-b&c show how the sampling rate affects the pattern spatio-temporal properties. The range of possible samples rates varied with the draw frequency. Due to this, we picked a total of 6 to 11 pattern sampling rates, depending on the draw frequency, which accounted for a total of 51 distinct patterns. Each pattern was repeated 3 times, making for a total of 153 stimuli in the experiment.

Each mid-air tactile pattern was presented to the participants left palm for 3 seconds. At the end of the stimulus, a numeric pad was displayed on the screen as well as an instruction inviting participants to enter their perceived strength estimates. Participants were asked to rate the perceived strength from 0 as the minimum (i.e. did not feel the pattern), to infinite, using whole numbers (i.e. no decimal) and to be as consistent as possible in their estimation throughout the experiment. Finally, participants were reminded to focus only on the pattern perceived strength and to omit any other qualitative evaluation from their rating (e.g., smoothness or simultaneousness). After participants validated their response, the next pattern was presented after a two seconds break until participants rated all stimuli. The patterns order were presented in a randomised order. The whole experiment lasted about 20 minutes.

7.1.2 Participants

In total 26 participants took part in the experiment (6 females, average age±SD: 29.3 ±5.2). Participants declared on the consent form that they did not have any sensory impairments related to their sense of touch.

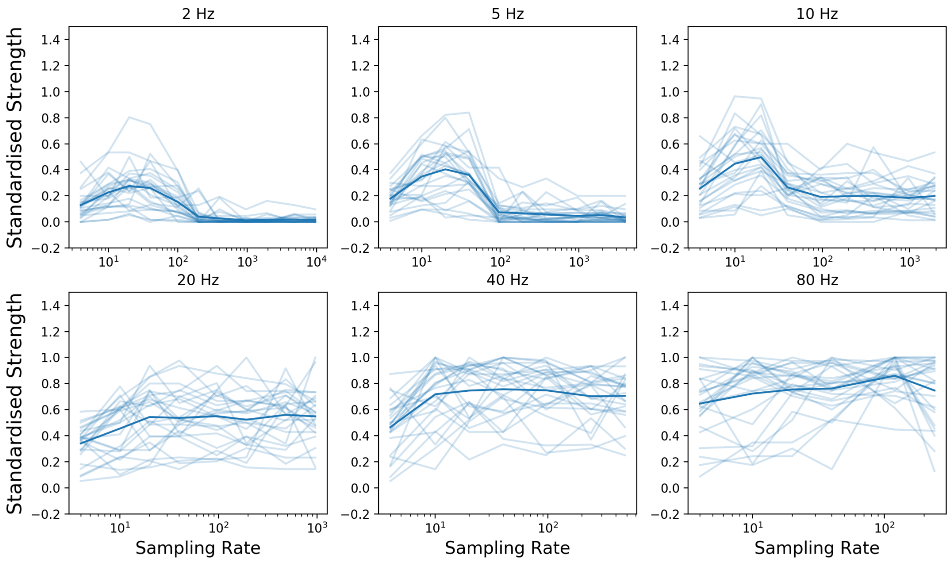


Figure 7.3: Standardised perceived strength as a function of number of sampling points, for a 150 mm circumference circle rendered at different frequencies. Light and bold curves represent participants responses and responses average, respectively.

7.1.3 Results

As participants were using different scales to estimate the pattern perceived strength, we first standardised participants' responses. We divided each participant estimate by their highest response [119, 223]. As we were interested in studying each pattern sensation separately, we further separated the data into 6 subsets, one for each pattern draw frequency. Post-processed participants perceived strength estimates are shown in Figure 7.3 as a function of pattern sampling rate. We invite the reader to note that the x-axis of the figure is logarithmically scaled as the pattern sampling rates spread across 4 orders of magnitude.

Each data subset was found to be unlikely to follow a normal distribution (Shapiro-Wilk, $p < .05$). Hence, we run a Friedman test on each data subset to test whether the perceived strength ratings were significantly different across sampling rate values. The Friedman test indicated significant differences between sampling rates groups for each draw frequency: $2\,\mathrm{Hz}(\chi^2(10) = 199.1, p < .001)$, $5\,\mathrm{Hz}(\chi^2(9) = 179.4, p < .001)$, $10\,\mathrm{Hz}(\chi^2(8) = 109.9, p < .001)$, $20\,\mathrm{Hz}(\chi^2(7) = 43.4, p < .001)$, $40\,\mathrm{Hz}(\chi^2(6) = 45.6, p < .001)$ and $80\,\mathrm{Hz}(\chi^2(5) = 15.26, p = .009)$.

To further determine whether the differences were significant across the whole range of sampling patterns, we run a pairwise Wilcoxon signed-rank test with Bonferroni correction to avoid type 1 error. For draw frequencies 20 Hz, 40 Hz and 80 Hz, the Wilcoxon test indicated significant differences only between 1 or 2 pairs of sampling rates. We, therefore, discarded those draw frequencies for the end of the data analysis. However, for draw frequencies of 2 Hz, 5 Hz and 10 Hz, the Wilcoxon test indicated significant differences for all sampling rate pairs, as long as the sampling rate was lower than 200, 96 and 48 points, respectively.

The fact that the upper sampling rate interval leads to no significant differences suggests that no specific behaviour could be extracted from that part of the data. Furthermore, the fact the corresponding perceived strength plateau around 0, suggest that the participants did not perceive those patterns. Those two points, motivated us to discard the data for the next step of the analysis and focus on the lower sampling

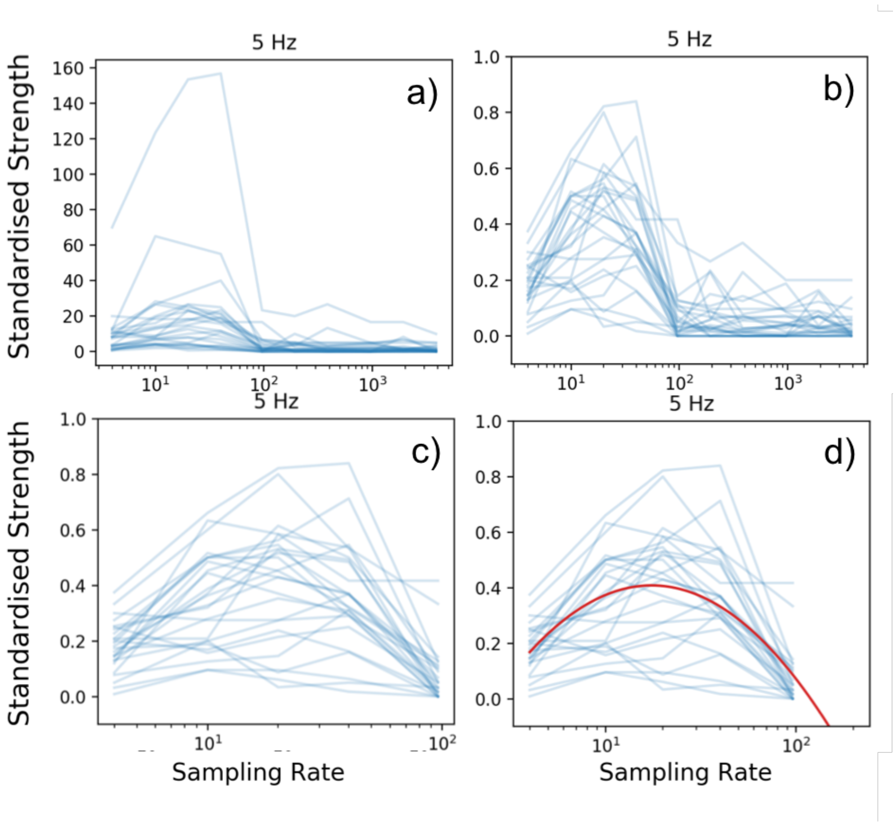


Figure 7.4: Data post-processing steps. (a) Raw data, (b) Standardised data, (c) Significant data, and (d) Fitted model.

	Quadratic Mixed Model		
Rate	R^2	*N. opt.*	*N. lim.*
2 Hz	0.68	22.4	236.6
5 Hz	0.72	17.5	119.2
10 Hz	0.62	15.8	149.4

Table 7.1: Quadratic mixed model results for frequency 2 Hz, 5 Hz and 10 Hz. Results include R^2, optimal sampling rate and sampling rate limit.

rate interval.

On the remaining data, which correspond to the left part of the curve on Figure 7.3, the reader can see that, the pattern perceived strength seems to follow a quadratic behaviour. Hence, we fit our data to a quadratic model. The model we used for regression can be seen in equation 7.1

$$\text{strength} = a \log_{10}^2(\text{sampling}) + b \log_{10}(\text{sampling}) + c \tag{7.1}$$

We remind the reader, that the model uses logarithmic values as the plots on Figure 7.3, where the quadratic behaviour can be observed, are using logarithmic xaxes. The model gave R^2 values of 0.68, 0.72 and 0.63 for the pattern draw frequency 2 Hz, 5 Hz and 10 Hz respectively.

We used the coefficient from the model to estimate the pattern sampling rate that was giving the highest perceived strength. We found that the optimal pattern sampling rate was 22.4, 17.5 and 15.8 points for draw frequency 2 Hz, 5 Hz and 10 Hz, respectively.

Finally, we estimated the sampling rate threshold that was leading to the pattern to be perceived or not. We found a threshold of 236.6, 119.2 and 149.4 points for pattern draw frequency 2 Hz, 5 Hz and 10 Hz, respectively. The post-processing step can be visualised in Figure 7.4 and the results of the data fitting are summarized in Table 7.1.

7.2 Experiment 2: sampling rate and pattern size

In experiment 1, we were able to determine a relation between pattern perceived strength and sampling rate. However, this relation parameters are varying with the pattern draw frequency. In this second experiment, we aim to determine whether these relation parameters vary as well when the pattern size changes.

7.2.1 Method

For this second experiment, we used the same protocol and set-up as in experiment 1. The new stimuli set was composed of 2 draw frequencies. We chose 0 Hz and 10 Hz, as they are the two boundary frequencies for which the effect of sampling strategy was observed in experiment 1. There were 11 and 9 pattern sampling rates for the two draw frequencies, 2 Hz and 10 Hz, respectively. We used 3 different pattern sizes, which were 100, 150 and 200 mm circumference. There was a total of 60 distinct patterns. Each pattern was repeated 3 times, making a total of 180 stimuli. This experiment lasted about 25 minutes.

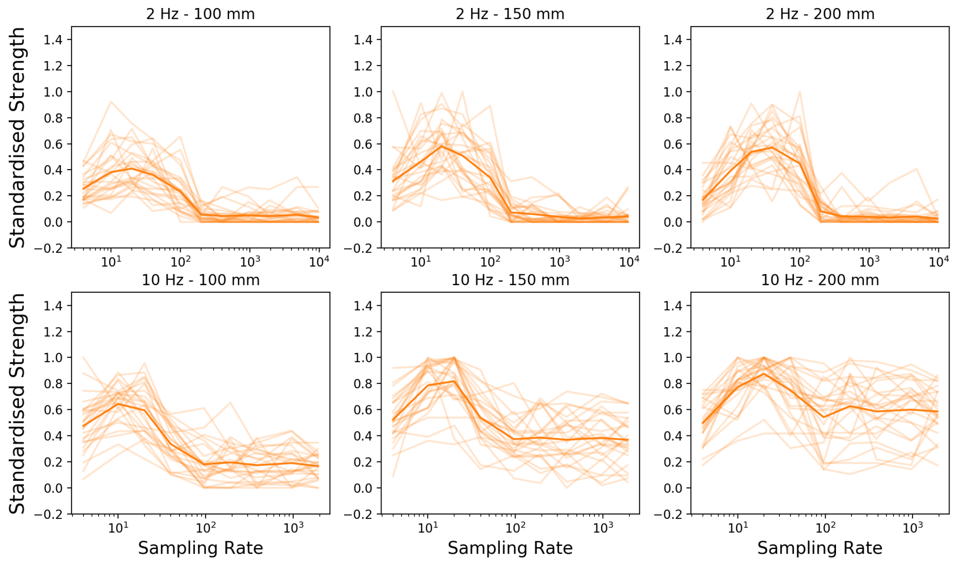


Figure 7.5: The standardised perceived strength as a function of the number of sampling points, for different frequencies and circle circumferences. Light curves represent participant responses and bold curves represent responses average.

7.2.2 Participants

For this second experiment we tested a total of 26 participants (4 females, average age±SD: 30±5.9). Participants declared on the consent form that they did not have any sensory impairments related to their sense of touch.

7.2.3 Results

The data collected were standardised as in the first experiment. We also separated the standardised responses into 6 subsets according to pattern draw frequency and pattern size. Figure 7.5 shows the resulting rating after standardisation for each data subset.

Each data subset was likely not normally distributed (Shapiro-Wilk, $p < .05$). Therefore, we run a Friedman test on each data set to test whether the perceived strength rating was significantly different across the corresponding number of sampling rate.

For patterns at 2 Hz, Friedman test indicates significant differences as $\chi^2(10) = 200.5, p < .001$, $\chi^2(10) = 212.3, p < .001$ and $\chi^2(10) = 208.9, p < .001$, for circumfer-

		Quadratic Mixed Model		
Rate	*Circum.*	R^2	*N. opt.*	*N. lim.*
2 Hz	0.10m	0.69	18.72	240.55
2 Hz	0.15m	0.60	20.95	241.76
2 Hz	0.20m	0.61	27.95	260.29
10 Hz	0.10m	0.67	10.77	92.09
10 Hz	0.15m	0.60	15.01	90.54
10 Hz	0.20m	0.60	20.30	84.52

Table 7.2: Quadratic mixed model results for frequency 2 Hz and 10 Hz across the different pattern sizes. Results include R^2, optimal sampling rate and sampling rate limit

ences 100 mm, 150 mm and 200 mm, respectively. For pattern at 10 Hz, Friedman test indicated significant differences as $\chi^2(8) = 138.1, p < .001$, $\chi^2(8) = 111.0, p < .001$ and $\chi^2(10) = 84.0, p < .001$, for circumferences 100 mm, 150 mm and 200 mm, respectively.

To further determine whether the differences were significant across the whole range of sampling pattern, we run a pairwise Wilcoxon signed-rank test with Bonferroni correction to avoid type 1 error on each data subset and thus determine which pair of pattern sampling rate were significantly different.

As in experiment 1, we found that the pairs of sampling rates were significantly different only for sampling rate below 200 and 96 points, for modulation 2 Hz and 10 Hz, respectively. Hence, for the same motivations as in experiment 1, we discarded the non-significant part of the data and run a quadratic mixed model on the significant part of the data.

The model indicate R^2 values of 0.70, 0.60 and 0.61 for the pattern draw frequency 2 Hz and circumference 100 mm, 150 mm and 200 mm, respectively. For pattern draw frequency of 10 Hz the model gave R^2 of 0.67, 0.60 and 0.60 for the patterns with circumference 100 mm, 150 mm and 200 mm, respectively.

We used the coefficients from the model to estimate the pattern sampling rate that was giving the highest perceived strength. We found that for 2 Hz draw frequency, the optimal sampling rate was 18.72, 20.95 and 27.95 points for circumference 100 mm, 150 mm and 200 mm respectively. We also found a sampling rate threshold of 240.55, 241.76 and 260.29 points for circumference 100, 150 and 200 mm respectively. For a draw frequency of 10 Hz, we found an optimal sampling rate of 10.77, 15.01 and 20.30 points for circumference 100 mm, 150 mm and 200 mm respectively. As for 2 Hz modulation, the perceived strength of pattern at 10 Hz plateau when the sampling rate is greater than a given number. Using the model parameters and the plateau values, we found that the sampling rate threshold was 92.09, 90.54 and 84.52 for circumference 100 mm, 150 mm and 200 mm respectively. The results of the data fitting are summarized in Table 7.2.

7.3 Discussion

In the current paper, we investigated a sampling strategy that maximised a pattern perceived strength. Using circular patterns rendered with different amounts of sampling points, we established a relationship between pattern sampling rate and pattern perceived strength. After discussing the user studies results, we will try to explain those same results using the psychophysical literature on the perception of touch. Finally, we will cover the implication of our work for tactile feedback designers.

7.3.1 User studies results

In the two user studies, we demonstrated that pattern sampling rate affects pattern perceived strength. However, significant effects were limited to patterns with draw-frequencies ranging from 2 Hz to 10 Hz. Although variability can be observed in user results magnitude, which could be accounted for users' subjective judgement, the overall trends are common across participants and can be modelled. Using a regression model, we fitted the pattern perceived strength to a quadratic function of the logarithm of the sampling rate (see equation 7.1).

From these regression functions, we identified an optimal sampling rate for patterns rendered at 10 Hz, of 10.77, 15.01 and 20.30 points for circumferences 100 mm, 150 mm and 200 mm respectively. By taking the ratio of the pattern circumference over the optimal sampling rates, we obtained an optimal distance between sample points of 9.7 mm ± 0.3. The low variation between optimal distances between sample points, designate this distance as an invariant for maximising pattern perceived strength across pattern sizes.

We found similar results with draw-frequency of 2 Hz, for which the optimal distance between samples points was on average equal to 6.5 mm ± 0.8. However, the optimal distances obtained are different across pattern draw frequency and despite our effort, we could not establish a clear relation between optimal distance and draw frequency.

Using the experiments results, we also found that the perceived strength plateaus when the pattern sampling rate is greater than a given threshold. This threshold is in average 245 ± 6.2 points and 89 ± 3.3 points for patterns at 2 Hz and 10 Hz, respectively. The low variation between threshold averages suggests the sampling rate threshold to be invariant across pattern sizes, although we could not establish the relation between threshold and pattern draw frequency.

Even though our experiment showed no effect of sampling rate on perceived strength for patterns at high frequency, we would like to point out that, when observed, the effect occurs only for sampling rate under 200 points. However, high-frequency patterns can not currently be rendered with sampling rates up to 200 points. For instance, the mid-air tactile display we used could render a pattern at 80 Hz with only 24 points at most. Technology will likely improve and allow rendering high-frequency patterns with a sampling rate of 200 points or more. Until then, we cannot completely rule out the effect of sampling rate on perceived strength in the case of high-frequency patterns.

Finally, on Figure 7.5, one may note that the maximum perceived strength varies with the pattern draw frequencies and sizes. However, this is in agreement with Frier et al., which claim that perceived strength varies with the tactile point speed (i.e., draw frequency times pattern circumference) . [58].

7.3.2 Psychophysical explanation

In an attempt to further understand the results reported in this study, we discuss here some hypotheses related to the psychophysics of the sense of touch. Testing these hypotheses is beyond the present scope of this paper, yet we believe it could be informative towards the reader.

Firstly recall that, for AM, different modulation frequencies are perceived with different strength, even though the amplitude of the stimulation remains the same, 200 Hz being the frequency perceived the strongest [73]. However, STM stimulation can no longer be described as a sinusoid like for AM and LM, but more like a pulse train with alternation between intervals of stimulation and non-stimulation. Using a Fourier expansion, this pulse train can be decomposed as a sum of sinusoidal signals, thus unveiling the presence of harmonics that are higher in frequency, with an amplitude depending on the pulse width. Decreasing the sampling rate may inadvertently increase the harmonic's amplitude close to 200 Hz, and thereby increase the associated perceived strength.

Another hypothesis is related to skin viscoelastic properties. High sampling rate stimulation leads to stimulation durations being too short for the skin deformation to reach the required mechanoreceptors' depth. At first, this hypothesis might seem unlikely since higher frequency patterns yield to tactile perception nonetheless. However, by definition, the rate at which the stimulation is repeated at a single location is much faster for high draw frequencies than for low draw frequencies. Therefore, it is plausible that at high frequencies the skin indentation builds up as the pattern is repeated over and over again whereas at low frequencies the elastic skin relaxes entirely between stimulation intervals.

Until now, mid-air haptics was relying on stimulating RA and PC mechanoreceptors that are sensitive to vibrations higher in frequency than the one involved in this study [116]. However, one could note that as the tactile points move across the skin surface, different groups of SA1 mechanoreceptors might be stimulated. Indeed, SA1 mechanoreceptors are mostly sensitive to the stimulus onset and offset (i.e., transient stimulus). Therefore, as the mid-air stimulus moves from one position to another, the stimulus is offset at the old position and onset at the new position. However, when a sampling rate is too high the sample position difference is lower than SA1 receptive field [236], and do not lead to this transient behaviour and therefore to tactile perception.

Ultimately, using a mechano-transduction model as the one presented by Saal et al. [197], one could test some of these hypotheses. Although, such models only predict stimulus detection, but will not determine optimal stimulation.

7.4 Conclusion

With this study we demonstrate that higher sampling rate does not always improve tactile perception and quite often the old cliché is true: less is more (see Section 12.5). Such design insights can be hugely beneficial to haptic engineers, developers and designers. Using the general trend found in the user-study results, we have therefore proposed ways and relationships for such parameters and variations to be hidden behind easy-to-use software packages.

We would like to emphasise that since the tactile perception of frequency follows a Weber-law, the range 2-10 Hz is half as wide as the range 10-200 Hz. Hence, increasing by 50% the range of discriminable frequency one could now apply to mid-air tactile patterns. We also would like to remind our readers, that in our study, we consider low frequency any frequency less than or equal to 10 Hz. However, our study focusing only on circular patterns, the 10 Hz frequency threshold might vary for other patterns, and hence ask the reader to interpret the values of this study carefully when applied to different shapes.

Then, we would like to invite feedback designers to adjust the sampling rate of a given mid-air tactile pattern, whenever it is possible, to maximise its perceived strength. We also remind designers that this optimal sampling rate is proportional to the pattern size. Hence, when scaling a given pattern, the sampling rate should be scaled accordingly.

Until now, we explored the absolute tactile thresholds for ultrasonic mid-air haptics in Chapter 6 and investigated the optimal sampling strategy to improve tactile perception. In the following chapter, we will present a study that probes the optimal parameters to make users perceive simple 2D geometric shapes.

CHAPTER 8

STUDY 3 - UNDERSTAND PERCEPTION OF MID-AIR SHAPES[1]

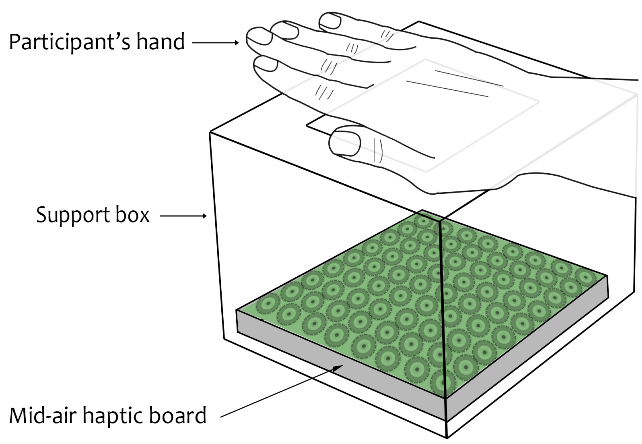


Figure 8.1: Experimental set-up. An ultrasonic array is positioned inside an acrylic box. On top of the box there is an opening that allows participants' hand, specifically the palm, to be stimulated with mid-air touch.

An important challenge that affects ultrasonic mid-air haptics, in contrast to physical touch, is that we lose certain exploratory procedures such as contour following. This makes the task of perceiving geometric properties

[1]Hajas D., Pittera D., Nasce A., Georgiou O., Obrist M. "**Mid-Air Haptic Rendering of 2D Geometric Shapes with a Dynamic Tactile Pointer**". In *IEEE Transaction on Haptics*, 2019 - under review, response to first round of review submitted.

and shape identification more difficult. Meanwhile, the growing interest in mid-air haptics and their application to various new areas requires an improved understanding of how we perceive specific haptic stimuli, such as icons and control dials in mid-air. We address this challenge by investigating static and dynamic methods of displaying 2D geometric shapes in mid-air.

We display a circle, a square, and a triangle in either a static or dynamic condition, using ultrasonic mid-air haptics. In the static condition, the shapes are presented as a full outline in mid-air, while in the dynamic condition, a tactile pointer is moved around the perimeter of the shapes. We measure participants' accuracy and confidence of identifying shapes in two controlled experiments ($n_1 = 34, n_2 = 25$). Results reveal that in the dynamic condition people recognise shapes significantly more accurately, and with higher confidence. We also find that representing polygons as a set of individually drawn haptic strokes, with a short pause at the corners, drastically enhances shape recognition accuracy. This paper contributes both novel scientific insights about the tactile perception of 2D shapes, and also provides design guidelines for improved mid-air haptic interfaces and haptic visualisations. Both of these contributions are discussed within the context of two application areas (automotive and education) from a haptics and HCI perspective. Specifically, we provide parameter recommendations for optimal shape recognition renderings that could be used for novel assistive technologies that enhance teaching of geometry and mathematics for visually impaired students, or for the rendering of haptic icons and controls in novel gesture controlled car user interfaces [90]. In both cases, a more accurate and confident identification of the communicated haptic shapes can significantly improve their effectiveness and thus future adoption rate of mid-air haptic interfaces. Our research supports the design of mid-air haptic user interfaces in application scenarios such as in-car interactions or assistive technology in education.

This study concludes the effort of investigating the perceptual side of the ultrasonic mid-air haptic technology and falls into RQ1, under the "Understanding" stage. This research happened before the outcome of the study previously presented

(Chapter 7). Therefore, we do not know if applying the principles highlighted in the previous chapter (optimal sampling strategy) will lead to different results.

8.1 Experimental design

To investigate the main research question on how accurately and confidently people can identify 2D shapes in mid-air, when displayed with a dynamic tactile pointer instead of a static outline, we defined the following two hypotheses:

H.1 Shapes will be correctly recognised on significantly more occasions in the dynamic condition than in the static condition.

H.2 Shapes will be correctly recognised with significantly more confidence in the dynamic condition than in the static condition.

Evaluating our hypotheses, we performed a user study, involving two controlled experiments and two pilot studies. Both experiment 1 and experiment 2 investigated the primary hypotheses (H.1 and H.2), as described in sections 8.2 and 8.4. However, in experiment 2, we modified the dynamic stimuli to also evaluate a new hypothesis (H.3, see section 8.3), conceived after the analysis of experiment 1. Namely, in experiment 2, the stimuli used for the dynamic condition were changed from a continuous loop to an interrupted loop, which means that the tactile pointer paused its movement for 300 ms and 467 ms at the corners of the square and triangle respectively. To find the optimal pause times in the movement of the tactile pointer for the different shapes, we ran an additional pilot study, involving two parts, as described in section 8.3. An overview of all the experimental conditions and variables studied is shown in Figure 8.2.

8.2 Experiment 1: Single-stroke shapes

In experiment 1, we tested hypotheses H.1 and H.2 by taking measurements of the dependent variables in the static and dynamic conditions. Importantly, the dynamic

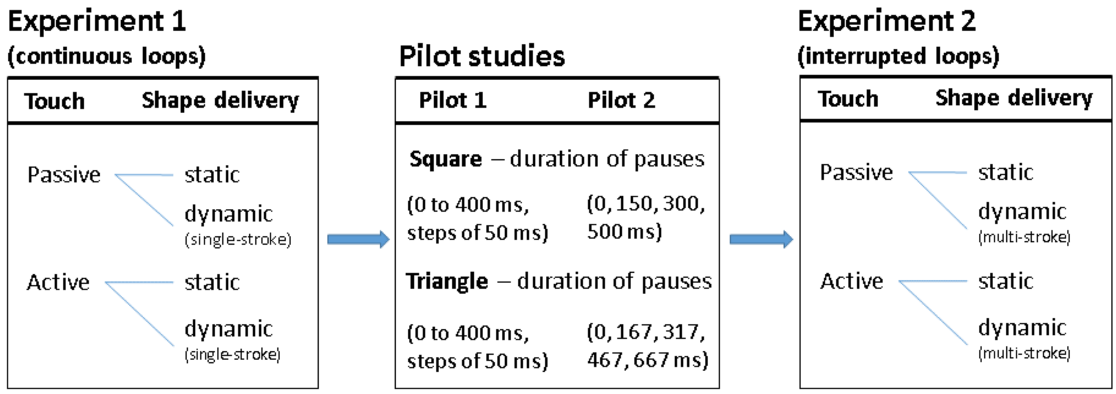


Figure 8.2: Summary of the two main experiments including two in-between pilot studies to determine optimal parameters for experiment 2.

tactile pointer was moved around the displayed shape giving no emphasis to any corners, as if drawn using a single continuous (brush) stroke.

8.2.1 Method

8.2.1.1 Participants

Participants were selected from the public and aged 18 to 50 years. We set an upper age limit to account for the potential decline of tactile acuity with age [196]. In experiment 1, we recruited 34 participants (f=20, m=14), with a mean age of 27.21 ± 5.79 years. 30 participants were right-handed, two left-handed, and two reported non-dominant hand. On a scale from 1 to 7, where 1 meant "no experience at all", and 7 meant "regular user for at least one year", participants' experience with the haptic interface was a mean of 2.00 ± 1.42. Participants declared on the consent form that they did not have any sensory impairment related to their sense of touch.

8.2.1.2 Materials

In this section, we describe the stimuli and device used, as well as the experimental task.

Stimuli Originally, we considered eight shapes to test our hypothesis on. These were a: circle, square, right-angle triangle, plus-cross, ellipse, rectangle, equilateral

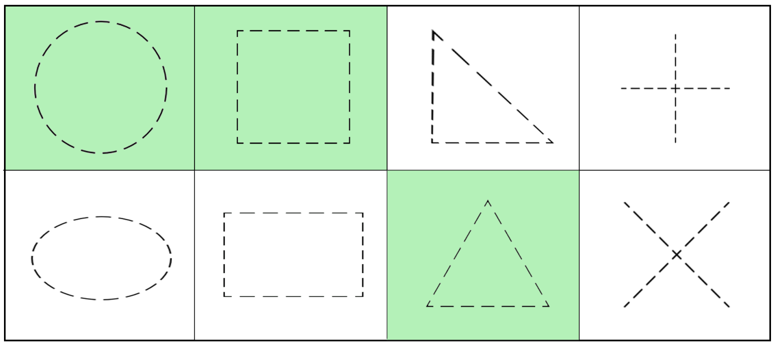


Figure 8.3: Overview on the original set of shapes considered in the study design phase. The final selection of three shapes used in our experiments are highlighted in green.

triangle and x-cross (see Figure 8.3). However, for simplification, we decided to limit the study to only three shapes: a circle, square and an upright equilateral triangle, as often seen in literature (e.g. [121, 232]). Using only three prototypical geometric patterns [232], we wanted to eliminate any potential confounding variables due to similarities of shape geometry.

The method of rendering static and dynamic haptic shapes differ both perceptually and in the way that they are generated. The static condition employed spatio-temporal modulation (STM) [127], where a single focus of constant amplitude (intensity = 1) is rapidly moved round the shape perimeter. The rotation frequency causes the human skin to vibrate at the same frequency (and its harmonics [32]) along the entire path trajectory, resulting in the perception of a static tactile sensation analogous to pressing a cookie cutter against the palm. The dynamic condition employed amplitude modulation (AM) [27, 107], where a single focus of oscillating amplitude intensity between 0 and 1, is slowly moved round the shape perimeter. The oscillating frequency causes the human skin to vibrate at the same frequency (and its harmonics [32]) but only at the focus, resulting in the perception of a dynamic tactile sensation, analogous to a pointy object or brush drawing shapes on the palm.

To study the effect of the independent variable, i.e. the mode of display (static vs dynamic) on the three chosen shapes (circle, square, triangle), we prepared a total of six tactile stimuli. The parameters were kept constant across all samples. We chose the size of the shapes (6 cm diameter/side length) to fit an average adult palm (anthropometric mean of palm length: 10.56 cm ± 0.46 cm) [30]. We chose 70 Hz for the STM rotational frequency, as it is near the optimal $5\,\mathrm{m\,s^{-1}}$ to $10\,\mathrm{m\,s^{-1}}$ draw speed, for path lengths given by the static shape outlines [58]. For consistency, we chose 70 Hz as the AM oscillation frequency, even though the optimal value for a point like stimulus is near 200 Hz. We used anti-clockwise pointer movements which is the default setting in the experimental device. The rate of drawing the shapes in the dynamic condition was chosen to be 0.5 Hz such that the movement feels natural, i.e., as if a finger drew on the palm. The pointer itself had a diameter of 0.8 cm, corresponding to the wavelength of the ultrasonic carrier, and simulating the size of a fingertip. The centre of the shapes coincided with the origin of the haptic interface's coordinate system, but vertically translated by 15 cm above the surface of the device (see Figure 8.1).

Device We used a mid-air haptic device manufactured by Ultrahaptics Ltd, which generates the tactile sensation using 256 ultrasound transducers. In order to fix participants hand at the same height and position area where the stimuli are displayed, we placed the device within a hand-support cavity. Participants were instructed to rest their hand on top of the support, over an $\sim 10 \times 10$ cm opening, as shown in Figure 8.1. To create the stimuli, we used the Ultrahaptics Sensation Core Library (SCL). The SCL includes a Python scripting interface, which allows developers to design sensations by constructing a graph of inter-connected operations (path geometry, transforms, animation, rendering etc.), known as "blocks". The sensations were prepared in advance, such that a Python script can call and display the stimuli on the haptic interface. The script was responsible for logging data, and randomising the order of stimuli.

Task The experimental task was simple: "Tell the researcher the shape you felt, and how confident you are in your answer". We evaluated our hypotheses in two conditions: (1) passive, and (2) active touch as part of the same experiment. In the active condition, participants were allowed to move their hand to explore the stimuli. In passive touch, participants were instructed to keep their hand still.

Prior to displaying the sequence of shapes, participants were given a chance to familiarise themselves with the area and tactile sensation of the stimuli. A matrix of 3×3 focal points were projected on the palm sequentially, from top left to bottom right, with the central point coinciding with the centre of the shapes. This was followed by displaying the three shapes in both conditions for 6 s, but without disclosing what the shapes are. Although we did not set a maximum number of times the familiarisation could be repeated, none of the participants did the familiarisation session more than twice.

After the familiarisation stage, participants were shown the first stimulus and asked to announce what shape they felt. At the moment of announcement the stimulus was terminated. Participants were told that their options are limited to "circle", "square" or "triangle". In experiment 1, we also emphasised, that a "I don't know" response is also allowed. Before moving to the next stimulus, the confidence rating was asked and recorded. This task was repeated 24 times in a randomised order, with each of the three dynamic, and three static stimuli repeated four times, in both of the active and passive conditions. We measured two dependent variables: the *accuracy* of the named shape, and participants' *confidence* in the perceived shape. Accuracy (a dichotomous variable) simply indicated whether the shape was correctly perceived or not. The confidence rating was a self-report scale, from 1 to 7, where 1 meant "not sure at all" and 7 meant "most certain".

8.2.1.3 Procedure

Upon arrival to the experimental space, participants were introduced to the experimental procedure, and informed consents were obtained. We started collecting demographic data, then participants were instructed to place their right hand above the haptic interface. We carried out a within subject experiment, where The active vs. passive conditions were counter balanced.

We strived to keep the experimental setup as controlled as possible by keeping the room temperature comfortably warm (~ 21°), to prevent participants from having cold hands and reduced skin sensitivity. Ambient white noise was setup to prevent any audible clues from the haptic device. In the active touch condition, participants were asked to fix their sight on the wall in front of them to avoid speculative guesses of the felt shape, based on the visual inspection of their moving hand. Between the active and passive touch conditions, a 30 s break was allowed. Participants were given a sponge ball to fidget with, and refresh their hand muscles, skin and joints.

At the end of the experimentation, we asked participants two qualitative questions: (1) "*Q1: Would you say either the static or the dynamic condition was easier for you to discriminate the shapes in?*"; and (2) "*Q3: What strategies did you use, if any, to try to understand the shape?*". We kept written notes on the responses, but did not collect qualitative data systematically in experiment 1. The entire procedure took 30 minutes per participant, who received a £5 Amazon voucher for their time.

8.2.2 Results

For the analyses we use *R* (v3.5.2) statistical software. For ease of reading, we grouped the report according to passive and active touch conditions.

8.2.2.1 Passive touch – accuracy metrics

A McNemar's test showed a statistically significant difference ($p < 0.001$) in accuracy across the static and dynamic conditions. We also analysed data with respect to individual classes (i.e. circle, triangle and square). Figure 8.4 shows the confusion matrices for both the static and the dynamic conditions, but excluding the "I don't know" answers. The overall accuracy for the static condition was 50.6% and for the dynamic condition was 56.7%. In both conditions, the matrices show a high level of confusion in participants' answers. In particular, the circle and the square shapes are the most confused. For example, excluding "I don't know" answers, 38% answers of square when the stimuli was a circle, or 33% answers of circle when the stimuli was a square in the static condition, with occasional mistakes in recognising the triangle. This is also supported by the subjective reports of users: *P9: "You could not feel whether it was supposed to be a circle or a square because the shape filled up all the space, and because you couldn't feel the edges."*.

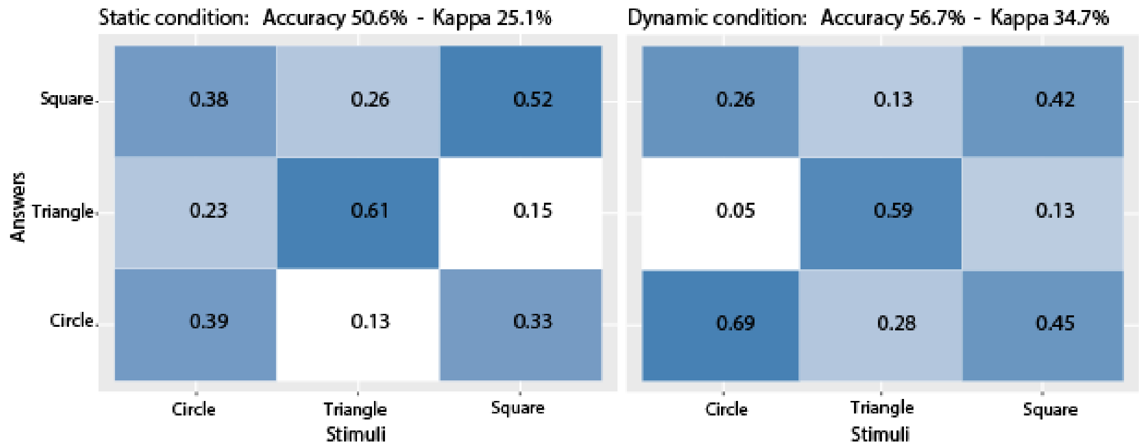


Figure 8.4: Confusion matrix for the passive static (left) and passive dynamic (right) conditions, expressed as percentage.

8.2.2.2 Passive touch – confidence levels

Figure 8.5 illustrates the box plot of confidence level for both static and dynamic conditions. The sample deviates from a normal distribution as assessed by the Shapiro-Wilk's test ($p < 0.05$). Therefore, we ran a Wilcoxon signed-rank analysis to test differences between the confidence levels in static and dynamic conditions. The test resulted statistically significant ($V = 4794, p < .001$). Participants are more confident in their choices when feeling shapes dynamically drawn (median = 5), than in the static condition (median = 3).

8.2.2.3 Passive touch – qualitative results

We also found coherent responses to the two qualitative questions asked. In the passive condition, without exception every participant said that comprehending the shape, when drawn in the dynamic condition was easier. Some only expressed a milder difference: *P15: "It's easier because it feels clearer, whereas the 'cookie cutter' case is more blurry."*; while others expressed a stronger disliking of the static condition: *P7: "Oh, not again the muddy."*, or *P33: "It's very difficult to grasp when it's*

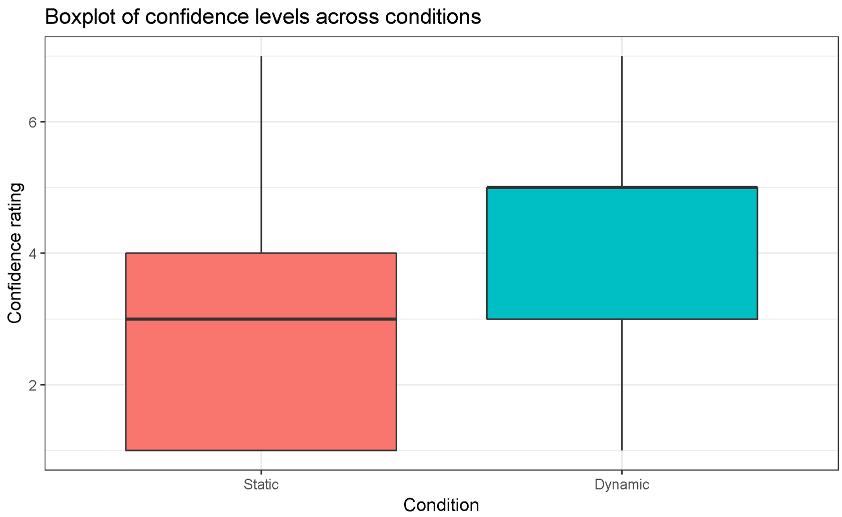


Figure 8.5: Box plot of confidence levels across the passive static (red), and passive dynamic (green) conditions.

a full blast. It just feels like air.”. Multiple participants described the static shapes as too “muddy”, “blurry”, or “fuzzy” to tell what shape it is. In the dynamic condition, we observed people reporting the use of typically two different strategies. First, focusing on curvature characteristics: *P27: “The circle felt like a smooth curve, whereas with triangle and square you could feel the corners.”*. Second, observing the dynamics of the moving point" *P26: “It slows down around the corners.”*. Multiple participants also referred to the “mental eye” as means of reconstructing the shape they felt.

8.2.2.4 Active touch – accuracy metrics

McNemar’s test did not find significant differences between active static and active dynamic stimuli ($p = 0.22$). As for passive touch, we also analysed data with respect to individual shapes and created confusion matrices (see Figure 8.6). The overall accuracy for the static condition was 57.3%, and for the dynamic condition was 52.7%. Similarly to the passive touch, both conditions brought participants to a high level of confusion in the active condition too.

8.2.2.5 Active touch – confidence levels

As in passive touch, from the box plot shown in Figure 8.7, it appears that reported confidence levels are higher for the dynamic condition. This is confirmed by a

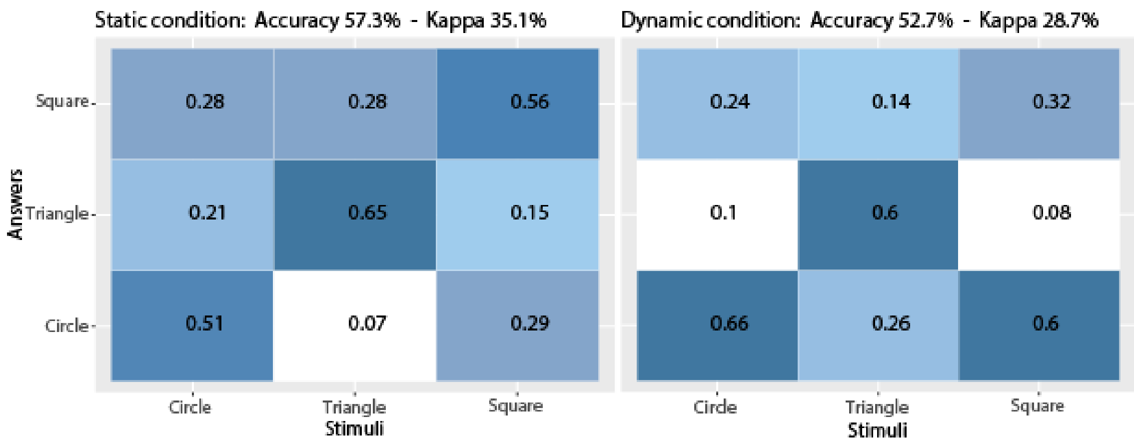


Figure 8.6: Confusion matrix for the active static (left) and active dynamic (right) conditions, expressed as percentage.

Wilcoxon signed-rank analysis ($V = 10591, p < .001$). The median scores are 3 and 4, for the static and dynamic conditions respectively.

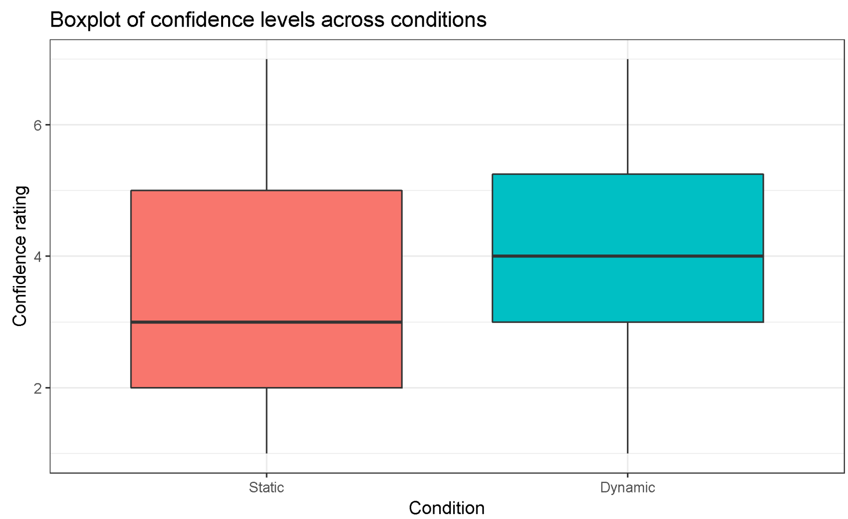


Figure 8.7: Box plot of confidence levels across the active static (red), and active dynamic (green) conditions.

8.2.2.6 Active touch – qualitative results

In the active touch condition, the coherency of qualitative data broke down, depending on the strategies people followed. Some people found the active dynamic condition still easier, if they tracked the tactile pointer: *P32: "The moving point was even easier, as you could almost place your hand on it and follow"*. However, the majority of people reported the static condition to be slightly easier to recognise shapes, adapting the strategy of tilting their hand, or focusing on points of stimulation on their palm.

8.2.3 Summary

In summary, our results show that participants are significantly more accurate in recognising shapes, when these are displayed in the dynamic condition (56.7%) vs. a static representation (50.6%), but only when their hand is fixed in space. Hence, for passive touch we can verify H.1 to be true even though the difference is not large. Reported confidence levels are also significantly higher in the dynamic condition, for both passive and active conditions. Hence, H.2 is also true. The qualitative data also revealed commonly used descriptors referring to the clarity of sensations, which we explore further in experiment 2.

8.3 Pilot Studies: Increasing recognisability

The results of experiment 1, backed up with qualitative reports, suggested that participants could not discriminate well between shapes, even in the dynamic condition. In particular, people were repeatedly confusing circles and squares. In order to address this, we devised a second experiment that would test an additional hypothesis:

H.3 In the dynamic condition, displaying shapes as a collection of discrete haptic strokes in form of an interrupted loop, instead of a continuous loop, will further improve the accuracy of shape recognition.

8.3.1 Parametrisation and chunking of haptic output

We motivated this hypothesis based on the literature discussing unistroke I/O and cognitive chunking. Considering visual chunking representations, such as a study performed by Dake et al. [259], it is known that a single continuous line may form a chunk, which represents a straight line, a curve, or a circle. For polygons, it's expected that the number of edges, and angles are perceived independently as single strokes, but grouped into the appropriate chunk. For example, a group of three strokes form a chunk representing a triangle. Chunking in HCI was discussed by Buxton [24] through multiple scenarios, in search for methods of accelerating the transition between novice and expert users of a computer interface. Buxton concludes that "*The key is gesture-based phrasing to chunk the dialogue into units meaningful to the application. – This desired one-to-one correspondence between concept and gesture leads towards interfaces which are more compatible with the user's model.*" [24]. He suggests that this principle is desirable for any application, from terminal commands to input-output interfaces, hence it is worth investigating in cases of novel haptic output devices. Goldberg & Richardson [78] designed a unistroke alphabet to find equivalents of touch typing with the use of a stylus. Such touch input system enables the transition from novice to expert user by means of increased input speed, while also enables higher accuracy interpretation for the recognition system. Robust tools, such as the $ 1 Recognizer [253] enabled non-experts to incorporate gesture recognition in their UI. However, it also opened up new research topics, such as how gesture articulation speeds affect recognition accuracy. In other words, what parameters of the input contribute to successful recognition by the system. With the evolution of haptic output devices, researching unistroke related parameters, in context of human recognition abilities becomes an interesting research topic. For instance, Hoshi [105] used ultrasonic mid-air haptics to transmit gesture based touch input to dynamically drawn, unistroke like haptic letters on the palm. An accuracy of 44% recognition was demonstrated, but no drawing parameters were discussed or evaluated.

To test hypothesis H.3, we altered the stimuli used for the dynamic condition, such that it is composed of a collection of discrete haptic strokes. In experiment 2, the tactile pointer paused its movement when it reached an angle, while in experiment 1, the tactile pointer moved without interruption around the perimeter of the shapes. However, the duration of interruption (referred to as "pause") remained a question. To determine the optimal duration of the pause, making the largest impact on recognisability, we ran two pilot studies as described below. In the first pilot, we wanted to find out the answer to the question: "*Does recognisability of the shape increase with the increase in duration of pauses at the angles?*". The second pilot was responsible for optimising the duration parameter, by determining the model for correlating duration and recognisability, such as a linear or quadratic fitting model.

8.3.2 Pilot study 1

8.3.2.1 Method

Participants In the first pilot study we recruited nine participants (f=4, m=5, mean age 29.6 ± 4.8 years). All the qualifying criteria reported in experiment 1 was applicable in this pilot study too.

Materials We compared nine stimuli for potential candidates of displaying both a square and a triangle, in the dynamic condition. Participants were given two tasks, in the same setup as experiment 1. In task 1, we displayed four repetitions of nine squares drawn at the rate of 2 s, with increasingly long pauses of 0 ms to 400 ms, in steps of 50 ms, at the angles. We asked participants to rate *"How much does the shape you felt resemble a square, on a scale from 1 (not at all) to 7 (very much)?"*. In task 2, the same task was completed for the triangle.

Procedure The 36 stimuli were randomised. Participants were told what the shape was on the display, and they were given a print standardised instruction of the task, since it was crucial they report how much the sensation resembles a shape, and not their ability to recognise it. We measured performance in only the passive touch condition. The pilot took 20 minutes, and a short break was allowed between the two tasks. Task 1 and task 2 were counter balanced. No compensation was paid.

8.3.2.2 Results

Figure 8.8 plots the mean scores of participants' rating of recognisability for the different pause durations at the corners of the triangle (left) and square (right). The graphs show that increasing the pause increases participants' perception of feeling

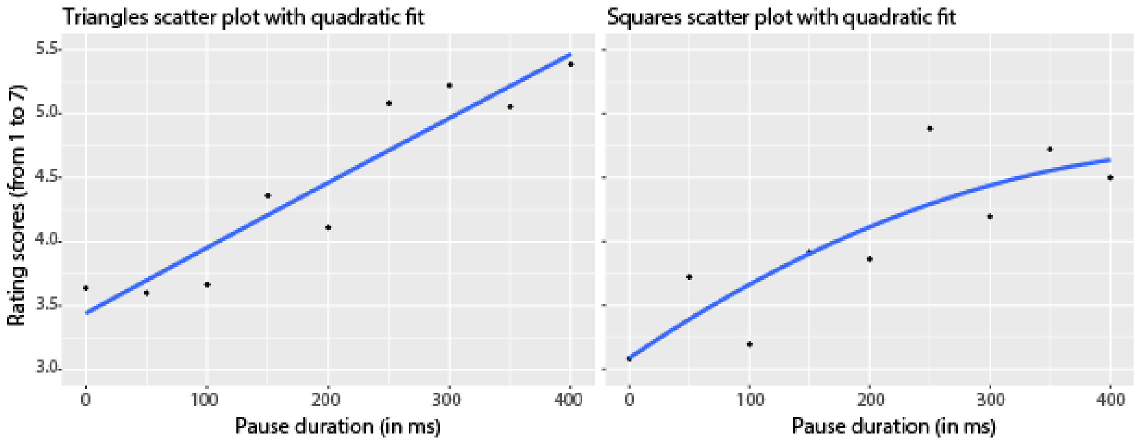


Figure 8.8: Scatter plot of recognisability: The mean scores of participants' rating (1-7) is plotted against the nine pause durations tested (ms) for the triangle (left) and square (right) in pilot study 1. A best fit curve is shown in blue.

a well resembled shape. We ran Wilcoxon tests to investigate differences across the various durations. From these analyses, we isolated three groups: 1) [0, 50, 100] ms; 2) [150, 200] ms; 3) [250, 300, 350, 400] ms, for both shapes. Although, the difference between instances of each group were not statistically significant ($p > 0.05$), the scores for the three groups are statistically significantly different.

The results confirm that, in the dynamic condition, there is a direct relation between the time spent at the corners, a kind of emphasis, and the participants' perceived sensation of a shape. However, from the graphs' in Figure 8.8, it is not clear if the trend would descend for longer pauses or continue increasing linearly. To investigate this, we ran a second pilot study.

8.3.3 Pilot study 2

8.3.3.1 Methods

Participants In pilot study 2, the pool of participants was identical to the group of participants taking part in the first pilot study.

Materials We reduced the variation of stimuli by decreasing the tested conditions of the pause duration. However, we increased the repetitions from four to ten, to obtain a cleaner dataset. In task 1, for squares we chose to test values of 0, 150, 300, and 500 ms. Another factor we accounted for in pilot study 2, is the difference between the draw speed of sides in triangles and squares. Since the overall rate of drawing and duration of pauses at corners were identical for both shapes, the speed at which sides are drawn differed. However, since pilot study 1 showed that there are intervals of pause durations at corners, at which no significant differences are observed, we chose to keep the draw speed of sides constant by varying the pause duration. Based on this speed, and the overall rate, we computed the equivalent duration of pauses in the triangle to be 167, 317, 467, and 667 ms respectively. For completeness, we also added the 0 ms baseline condition.

Procedure the procedure was identical to that used in pilot study 1, except the number of trials. Task 1 involved 10 repetitions of four variations on the square, and task 2 involved 10 repetitions of five variations on the triangle.

8.3.3.2 Results

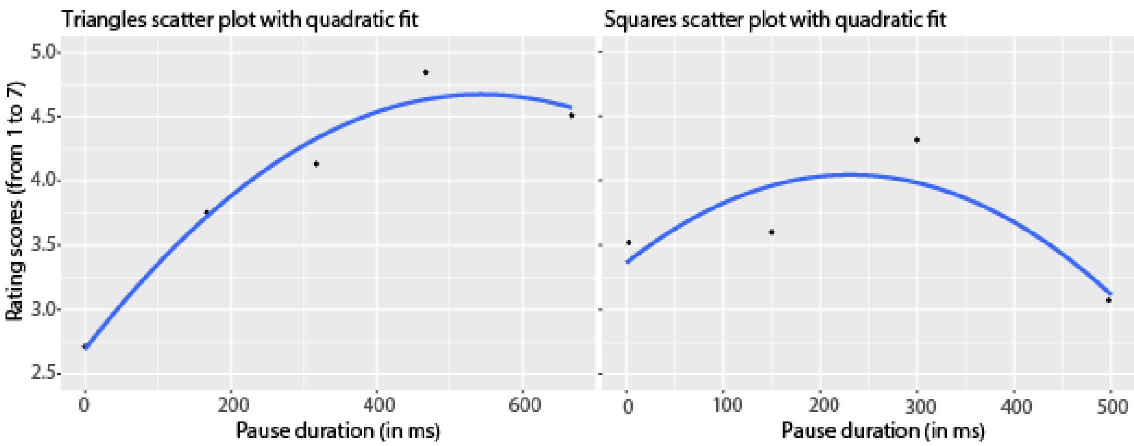


Figure 8.9: Scatter plot of recognisability: The mean scores of participants' rating (1-7) is plotted against the five/four pause durations tested (ms) for the triangle (left) and square (right) respectively, in pilot study 2. The best fit curve is shown in blue.

In case of the triangle, we see from Figure 8.9 that the best fit curve follows a quadratic trend, although it is less sharp than in the case of the square. The central values of 467 ms and 300 ms for the triangle and square respectively were statistically different from other values tested. We see that a too long pause may decrease performance. In case of the square, participants benefited from feeling the edges being drawn in identifying the shape [2]..

8.3.4 Summary

Two pilot studies were conducted to investigate the effect that corner pauses have on shape recognisability. The pauses caused interruptions in the way a dynamic tactile pointer displays a haptic shape. It was shown that different pause durations can have a noticeable impact on shape recognisability, and that the optimal pause durations differ from shape to shape. Although the results we obtained were indicative of the most appropriate duration to use (), it was not conclusive whether participants were going to be able to discriminate the shapes, once the stimuli were mixed, as in experiment 1. This was the objective of experiment 2.

8.4 Experiment 2: Multi-stroke shapes

This experiment studied all three hypotheses H.1, H.2 and H.3. We measured both participants' accuracy and their reported confidence levels for mid-air haptic shape recognisability, under the static and dynamic conditions for both passive and active exploration (see Figure 8.2). Importantly, we employ the modified dynamic condition where the dynamic tactile pointer experiences short pauses at the corners of the displayed shape, as if drawn using multiple (brush) strokes. The optimal pause durations were determined in the pilot studies described in the previous section.

8.4.1 Method

8.4.1.1 Participants

We recruited 25 participants (f=14, m=11), with a mean age of 30.24 ± 7.80 years. 22 participants were right-handed and 3 were left-handed. Their experience with the haptic interface was 2.08 ± 1.20. Nobody declared a disorder compromising their

[2]For a square drawn in 2 s, a 500 ms long pause at every corner means no time left to draw sides, i.e. the tactile pointer is repositioned from corner to corner in a discontinuous way.

tactile acuity. Participants of the pilot studies were excluded from taking part in this experiment.

8.4.1.2 Materials

The stimuli used in the static condition were identical to those used in experiment 1. In the dynamic condition, we exchanged the single-stroke stimuli with multi-stroke sensations. Based on the results of the two pilot studies, we chose 300 ms and 467 ms long pauses at the angles of the squares and triangles respectively. We expected that this method would help in distinguishing between circles and squares displayed in the dynamic condition.

8.4.1.3 Procedure

The task and procedure for experiment 2 followed the same protocol as in experiment 1, except two aspects. First, we did not allow for an "I don't know" answer when identifying the presented shape. We chose to make this change to feed the confusion matrix with more relevant data. The minimum confidence score accounted for the "I don't know" option. Secondly, we wanted to perform a more thorough qualitative analysis, hence, we audio-recorded the final five-minute interviews, and included a third question, asking participants *"Q2: Using 2-3 adjectives, how would you describe the clarity, or sharpness of the shapes you felt in each of the conditions?"*.

8.4.2 Results

8.4.2.1 Passive touch – accuracy metrics

As in experiment 1, we created confusion matrices for the two conditions, shown in Figure 8.10. The overall accuracy for the static condition was 51.7%, and for the dynamic condition was 83.0%. The values for the dynamic condition highlight how the shapes are better perceived with the introduction of multi-stroke shapes. Only 14% answers of square were given, where the shape was a circle; and only 9% answers of circle were given, where the shape was a square. This is a statistically different result and significant improvement compared to the results in experiment 1.

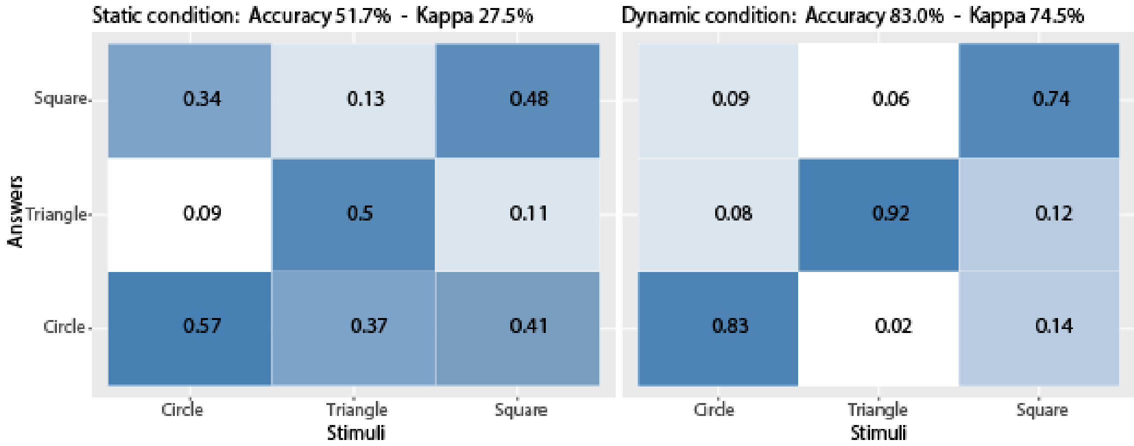


Figure 8.10: Confusion matrix for the passive static (left) and passive dynamic (right) conditions, expressed as percentage.

8.4.2.2 Passive touch – confidence levels

A Wilcoxon signed-rank analysis confirmed a significant difference ($V = 912, p < .001$) between confidence levels in the two conditions. Once again, participants are more confident in the dynamic condition (median = 5), than in the static condition (median = 3), as shown on the box plot in Figure 8.11.

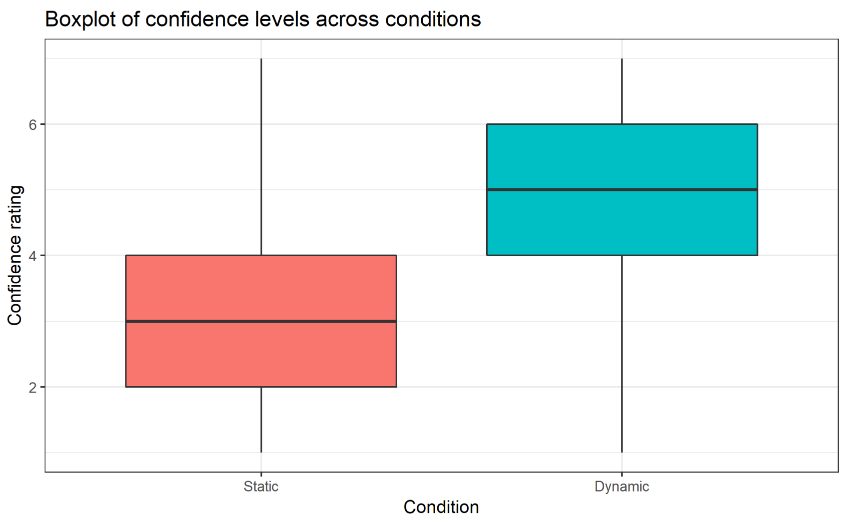


Figure 8.11: Box plot of confidence levels across the passive static (red), and passive dynamic (green) conditions, in experiment 2.

8.4.2.3 Active touch – accuracy metrics

Figure 8.12 shows the confusion matrices for both the active static and active dynamic conditions. The overall accuracy for the static condition was 57.3%, and for the dynamic condition was 84.7%. For the dynamic condition, the confusion matrix shows that the shapes were recognised with only marginal confusion.

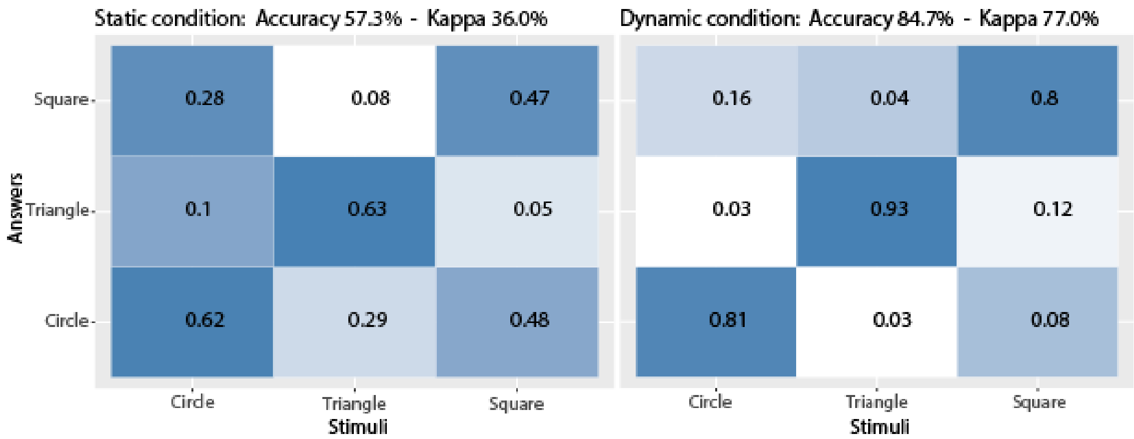


Figure 8.12: Confusion matrix for the active static (left) and active dynamic (right) conditions, expressed as percentage.

8.4.2.4 Active touch – confidence levels

In active touch, the reported confidence levels are again higher for the dynamic condition (Wilcoxon signed-rank test: $V = 2574, p < 0.001$). The median score for the confidence level rating is 4 for the static condition and 5 for the dynamic one (see Figure 8.13).

8.4.2.5 Qualitative results

In experiment 2, our aim was to quantify the observations on participants' comments from experiment 1 and systematically collect linguistic descriptors of the two types of stimuli. To do this, we transcribed all five minute interviews conducted at the end of the experiment. Relevant snippets of the transcripts were extracted, and grouped into three categories, coded as: (Q1) Preference, (Q2) Descriptor, and (Q3) Strategy. After the coding and extraction process, we further abstracted information relevant to the respective category.

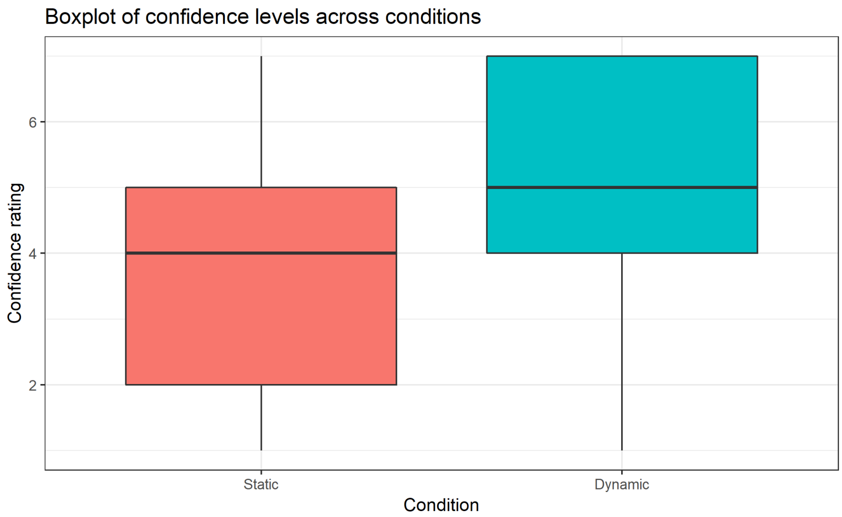


Figure 8.13: Box plot of confidence levels across the active static (red), and active dynamic (green) conditions, in experiment 2.

In Q1, we looked for how many people find either of the conditions easier based on their subjective reports, and how varied the spectrum of expressed difficulty is (from a little easier to a lot easier). We found that 22 of 25 participants reported that the dynamic condition was "easier". 3 participants said it depended on whether they explored actively or not. In the active touch they felt the static shapes were easier to recognise, though they still preferred the dynamic display mode when their hand was fixed. We also identified 11 positive, and 5 negative signifiers. Positive signifiers included adjectives, such as "definitely" (7 instances), or "much" (2 instances): *P9: "The moving one was definitely a lot easier."*. On the other hand, negative signifiers, such as "I think" (4 instances) or "perhaps" (1 instance) indicated a weaker preference: *P2: "I think the moving one was perhaps better."*.

In Q2, we abstracted a list of 28 adjectives, descriptive phrases associated with the individual conditions. We counted the frequency of these descriptors, and coded them according to three themes. The themes were divided into positive and negative attributes. For the themes, most frequent adjectives and frequency counts, see Table 8.1.

In Q3, we abstracted two key strategies. First, people who counted corners or edges in the passive dynamic condition, and people who moved their hand with the moving tactile pointer, in the active dynamic condition. In the former case, people

Valance	**Positive**	**Negative**
Theme	**Perceived quality of sensation**	
Total count (static)	4	13
Total count (dynamic)	12	3
Frequent descriptors (static)	– –	blow, wall of air (5) block (3)
Frequent descriptors (dynamic)	pencil/fingertip (3), smooth (1)	– –
Theme	**Perceived quality of shapes**	
Total count (static)	2	32
Total count (dynamic)	28	4
Frequent descriptors (static)	– –	fuzzy (7), blurry (3) unclear (5)
Frequent descriptors (dynamic)	clear (8), sharp (5), higher definition (4)	– –
Theme	**Perceived ability to recognise shapes**	
Total count (static)	3	20
Total count (dynamic)	17	1
Frequent descriptors (static)	– –	hard (10), indistinguishable (5)
Frequent descriptors (dynamic)	easy (10), makes mental image (3)	– –

Table 8.1: Descriptors of perceived quality of sensations, quality of shapes, and ability to recognise shapes.

reported that counting helped them create a mental picture of the shape: *P19: "I could see this almost like tracing something on my skin, so I could kind of mentally construct the shape"*. In the latter case, participants relied on whether the movement of tactile stimulus on their hand, matched the self-initiated, kinaesthetic movement.

8.4.3 Summary

We can claim H.3 to be true, since the results of experiment 2 show that displaying shapes as a collection of multiple strokes rather than a single stroke, can significantly improve accuracy of shape recognition. In particular, the overall accuracy for the passive touch in the dynamic condition increased from 56.7% to 83.0%; while the accuracy also increased in the active touch, dynamic condition, from 52.7% to 84.7%. We note that these ~30% improvements are both significant and important. We also see that in both passive and active touch, the median value of confidence is

5, which is significantly different from that in the static condition. In the active touch condition, the confidence increased compared to the results of experiment 1. The qualitative analysis also shows that people found static shapes more blurry or fuzzy, compared to dynamically drawn shapes, which were named as clear, or having a higher definition. The self-assessment of participants showed that recognising shapes in the dynamic condition is easy, while it is harder in the static condition.

8.5 Discussion

We investigated how accurately and confidently people can identify 2D shapes using mid-air haptic stimulation. Here we discuss how our work contributes novel insights to the haptics and HCI research communities. Then we reflect upon possible application scenarios that can benefit from our findings.

8.5.1 Mid-Air haptic shape recognition

We learnt three key lessons. First, in experiment 1 we showed that people can recognise significantly more accurately and confidently the tested shapes, when a dynamic tactile pointer traces the perimeter of the displayed shape, rather than presenting the shape as a full outline. In experiment 1, we also see that, while in passive touch the dynamic display mode performed 6.1% better on accuracy than static shapes, in the active exploration the dynamic condition performed just 4.6% less accurately overall. Although the results in active touch are not statistically different, this is in line with prior work [114]. There is more chance that a shape presented as a full outline is better understood while explored actively, than when passively felt. In contrast, if both the tactile pointer and the participant's hand is moving, this may conflict the creation of an accurate mental representation of shapes.

Secondly, experiment 2 showed that breaking down a shape into individual chunks (i.e. using multi-stroke brushes) can increase the accuracy of shape recognition by ~ 30%. The confusion between the shapes plummeted. This is in line with

H.3, based on chunking theory [259], and is supported by participant reports. Feeling a continuous loop led to a higher level of association with a circle, and feeling well distinguished numbers of corners, or edges enabled participants to make a link with either a triangle, or square: *P18: "Counting the corners, and if I didn't feel a corner and I felt a constant movement, then I thought it was a circle."*.

Thirdly, we obtained comparable results to those results cited in the literature. Gibson found a 72% accuracy of shape recognition, in a passive (rotation) touch condition. He also reported participants' recognition strategy to be "counting corners and points" [114]. The results by Kaczmarek et al. using an electro-tactile display are also a comparable 78.5% [121]. Ion et al. [109] also found vibro-tactile interfaces to perform ~20% less accurately on a shape recognition task, compared to a skin drag display. This is in line with the ~30% difference between accuracy of identifying dynamic and static shapes in our second experiment. Similarly, the qualitative reports of Ion et al. "clearer" skin drag stimulus vs. "blurry" vibro-tactile stimulus are matching our qualitative findings.

In addition, a relevant in-between step in our research were the two pilot studies. Those studies provided the optimal pause duration parameters for the specific size and draw speed of the tested shapes. These were experimentally deduced, however we also believe that this parameter can be defined precisely for a general geometry, as a function of other parameters, such as perimeter, number of sides, rate of drawing and so on. Reports of participants also clearly support the numerical findings. One participant said: *P9: "Having definitive pauses at the vertices, at the corners, meant that I could definitely feel four points. That must mean it's a square. I can definitely feel three points. That must mean it's a triangle. That helped immensely."*. Although we obtained an optimal pause duration for shape identification in a lab experiment, it did not consider any use case restrictions. For example, in some control interfaces such as automotive, time is of the essence and therefore a trade-off may exist between accuracy and sensation duration. This might be a good open research question for future investigation.

8.5.2 Application opportunities: two user scenarios

8.5.2.1 Scenario 1: Haptic controls in automotive systems

Imagine a driver wishing to turn the volume of the radio down, and increase the temperature in the car. It's an important interaction design task of in-car interaction to provide interfaces that do not require the driver to take their eyes of the road [90, 209]. One possibility is using gesture control interfaces, with integrated haptic feedback. Given that people can easily distinguish between simple shapes, such as a circle and triangle, it becomes possible to design a gesture control interface with added haptic feedback. Placing the hand in an interaction space, a haptic icon appears. If it's a circle, a rotating movement in either direction would increase or decrease the radio volume. Swiping movement brings up a new icon, for instance a triangle. In this case, rotating movement of the hand in either direction results in increasing or decreasing the inside temperature. Additionally, the 3 shapes studied: triangle, square and circle are the typical symbols one associates with play, stop, and record for music. Therefore, there is good motivation in using haptic shapes that have a close relationship with existing Human-Machine-Interface (HMI) icons. To evaluate the effectiveness and safety of such a system, we foresee an experiment which replicates our findings in a car simulator, and especially focuses on circumstances where users are subject to high cognitive demand, or potential risk.

8.5.2.2 Scenario 2: Geometry instruction for visually impaired students

Imagine a visually impaired student needs to learn trigonometry or other elementary geometry. Traditionally tactile graphics is embossed on paper, to aid the instruction. In certain scenarios, such as in rural areas, or a weekend before a school exam, the student requires remote help revising the concepts. In this case, through a voice call and the haptic interface, the tutor is able to assist, as illustrated in Figure 8.14. The teacher can also provide recorded materials, involving the explanations of geometric identities through the tactile pointer. If the tactile paper is acoustically transparent, the mid-air haptics can be used as an auxiliary tool, highlighting

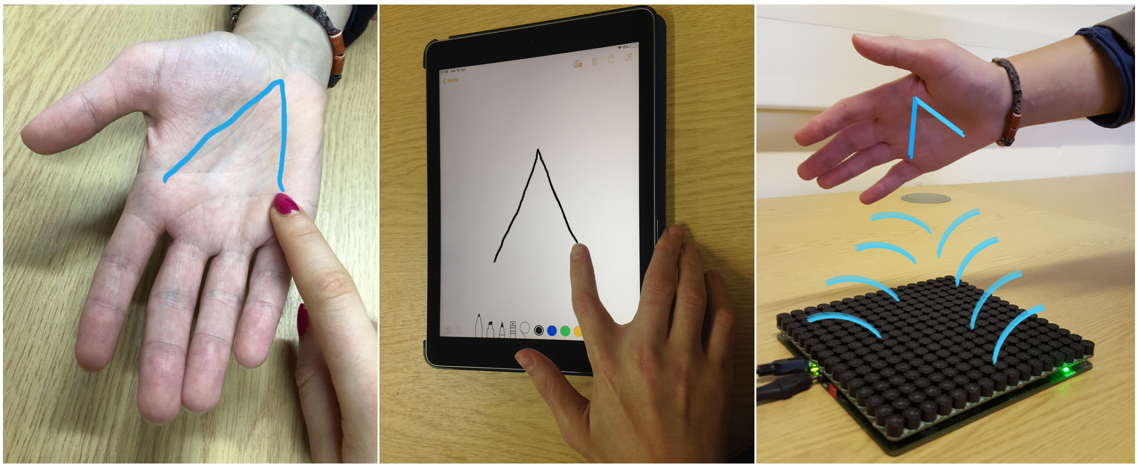


Figure 8.14: (left) A closeup photo of a finger, drawing a triangle into a palm; (middle) A person drawing a triangle on a tablet computer; and (right) A mid-air haptic kit stimulating a hand, in the pattern of a triangle.

the embossed features on the paper. The regions of interest are discussed through guided exploration using the tactile pointer. Providing appropriate input devices for content creation, the immediate tactile feedback is also possible, which is a critical requirement [18]. To evaluate the merit of such a system, we foresee an experiment, which studies tactile shape perception in mid-air vs. tactile graphics in novice users. One could also imagine that through the internet, e-learning could attain a new mid-air haptic dimension that could benefit both sighted and visually impaired/blind users.

8.5.3 Limitations and future work

One of the drawbacks of our method is the arbitrary choice of shape size. Recent work by Frier et al [59] suggests that the size of stimulus is affecting the perceived intensity of ultrasonic mid-air haptics. A potential solution is to personalise the size of the stimulus. Similarly, the arbitrary choice of rate at which the dynamic tactile pointer completed a loop needs to be tested to identify the optimal parameters. In physical touch it was shown that slower movement creates a sensation of curvature, while faster rates are perceived straighter [138]. This could contribute to confusions between a square and a circle when described with a continuously moving pointer. Further limitation of our study is the number of shapes tested. We have shown that displaying dynamic shapes is statistically better recognised if it's either a circle, square or equilateral triangle; however, we know little about how well people could distinguish between shapes, such as a circle and an oval, or a triangle in different orientations. Further, we cannot be sure if participants performance rate increment reflects a better performance in a shape discrimination task or if participants applied a vertex counting strategy. It might be that knowing the shapes they were asked to recognise, participants were focusing their attention on counting the vertices of the perceived shape. From the informal interviews after the study and from personal experience of the researchers the shape felt clearer with the discussed technique, it was still possible to perceive movement between the edges of the figure, and no explicit strategy seemed to be used. Although we did not detect such behaviour, we cannot completely dismiss it. Nevertheless, from an application point of view, the method we introduced in experiment 2 would be still useful to discriminate between shapes that are known to the user, regardless of the strategy used. In future work, we wish to optimise parameters, such as rate, orientation, size, or type of stimulus used as a tactile pointer; as well as conduct research to exclude possible secondary strategies used in the shape discrimination task as discussed above.

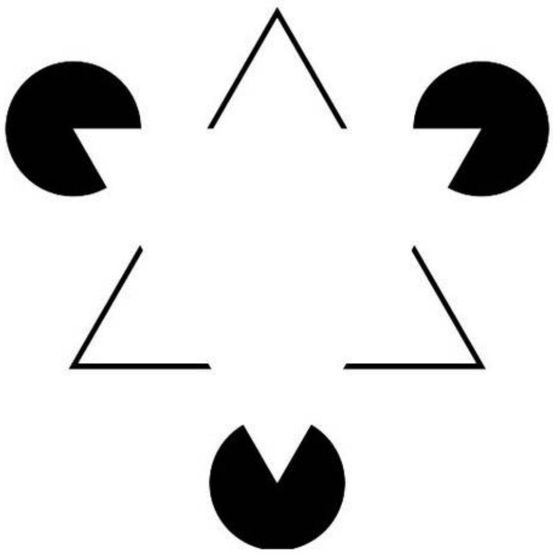


Figure 8.15: The Kanizsa triangle is a classic example used by the Gestalt psychologists to describe the law of closure. Even though the perimeter of the triangle does not exist, one can still perceive an equilateral triangle.

Finally, we could exploit tactile illusions in the attempt of increasing the shape recognition rate. For instance, we can imagine delivering mid-air focal points at the vertexes of a shape in an optimal timely fashion to convey a sensation of movement between the static points. Alternatively, we could haptically render only partial parts of the shape we want to convey delegating to the brain the task of completing the missing information and feeling the totality of such a shape, similar to what happens in the vision for the Kanizsa triangle (Figure 8.15).

8.6 Conclusion

Based on the work presented in this paper, we recommend using a dynamic tactile pointer, instead of rendering the full outline of the shape, when displaying two-dimensional geometric shapes with mid-air haptics. We also recommend to break down polygons into discrete sides, by interrupting the movement of the pointer at the angles. The optimal pause duration for a 6 cm side length square, displayed at a rate of 2 s, is 300 ms, and 467 ms for an equilateral triangle, at the same rate and side length parameters. According to these specifications, the accuracy of shape recognition is 83.0% and 84.7% in passive, and active touch respectively. These are comparable results to those found in the literature, studying raised pin arrays, electro-tactile or vibro-tactile displays, skin drag interfaces, and mid-air haptic displays creating 3D geometric shapes. These insights may play a crucial role in a plethora of application areas, such as mid-air haptics control design in an automotive context or as assistive technologies for visually impaired children, who are distance learners.

With this study it ends the "Understand" stage. In the next chapter we introduce the studies that will be part of the "Create" stage, aimed to demonstrate how mid-air haptics can be used to create a realistic illusion of movement between the two non-interconnected hands.

Chapter 9

Study 4 - Create Tactile illusion of movement[1]

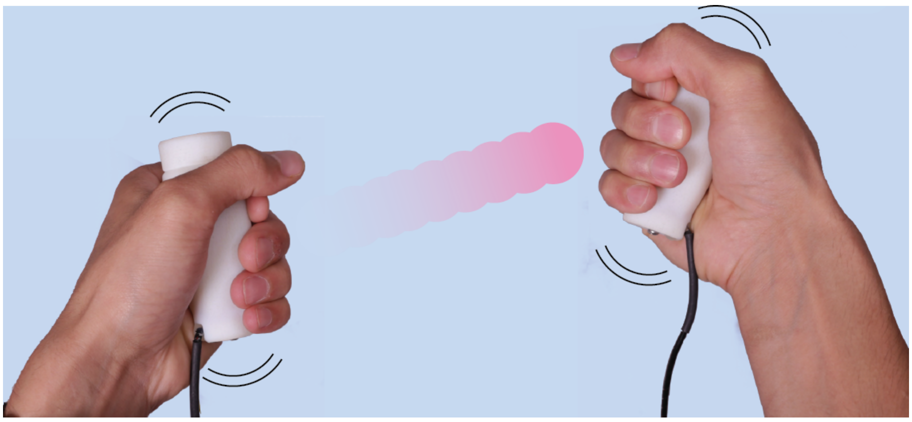


Figure 9.1: Illustration of the intermanual illusion of movement using the Hand-to-Hand vibrotactile device.

Touch constitutes a complex experience [14, 128]. The everyday action of touching an object is in fact a multifaceted task that consists of an awareness of both the object' substance and structural properties [142, 184, 192]. Due to this complexity, haptic experience designers and developers struggle in fully replicating the tactile sensation needed to achieve realistic and compelling experiences. Hence, tactile rendering in interactive technologies, including virtual

[1]Pittera D., Obrist M., Israr A. "**Hand-to-Hand: an intermanual illusion of movement**". In *Proceedings of the 19th ACM International Conference on Multimodal Interaction*, Glasgow, UK, 2017.

and augmented reality, is still limited. Research into tactile illusions provides a relatively simple, technically and computationally economical way of addressing the challenge [93].

Apparent tactile motion has been shown to occur across many contiguous part of the body, such as fingers, forearms, and back. A recent study demonstrated the possibility of eliciting the illusion of movement from one hand to the other when interconnected by a tablet. In this paper we explore inter-manual apparent tactile motion without any object between them. In a series of psychophysical experiments we determine the control space for generating smooth and consistent motion, using two vibrating handles which we refer to as the Hand-to-Hand vibro-tactile device. In a first experiment we investigated the occurrence of the phenomenon (i.e., movement illusion) and the generation of a perceptive model. In a second experiment, based on those results, we investigated the effect of hand postures on the illusion. Finally, in a third experiment we explored two visuo-tactile matching tasks in a multimodal VR setting. Our results can be applied in VR applications with inter-manual tactile interactions. The core idea behind tactile illusions is that a tactile sensation can be reproduced convincingly without the need to render every single aspect of the phenomenon [69, 131, 139].

In this paper, we focus particularly on the apparent tactile movement illusion (Figure 9.2) where two actuators are activated, and the stimulus-onset asynchrony (SOA) is modulated, so that the user will perceive a feeling of movement between two sites of stimulation. Here we present Hand-to-Hand (Figure 9.1), a vibro-tactile illusory movement between two hands. We investigated the possibility of an inter-manual illusion of movement without a device connecting the two hands (e.g., holding a tablet), but relying only on a handle held in each hand. In the first experiment, we investigated the feasibility of the illusion and determined the optimal parameters to evoke it. In the second experiment, the effect of postures on the users' perception is examined. Finally, we applied the developed perceptive model to assess users' multimodal integration between touch and vision in a VR setting. The contributions of this paper are threefold: (1) A systematic psychophysical investigation of the

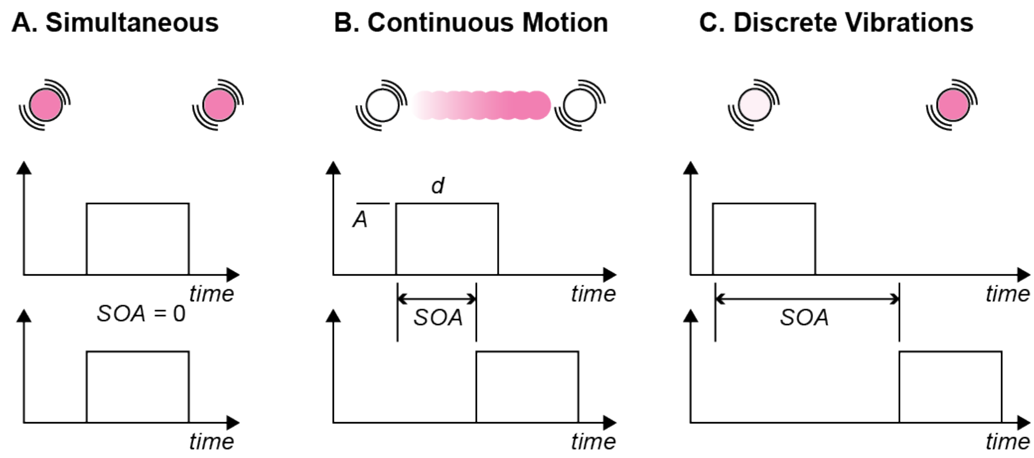


Figure 9.2: Representation of the tactile illusion of movement, showing the perceptive effect according to different stimulus onset asynchrony (SOA). If the SOA is too long, the perception will result in two discrete vibrations (right). If the SOA is too short, the perception will be merged in a single point (left). With an optimal SOA, a motion will be perceived (middle).

occurrence of the apparent tactile movement illusion on non-contiguous and not interconnected parts of the body, which allowed us to determine the parameters for establishing a perceptive model for tactile rendering. (2) Previous studies had shown that the temporal order judgment (TOJ) of a tactile stimuli's onset between two hands may vary according to different postures, in particular, varying the distance between the hands [212]. From the point of view of free-space user interactions, where a user is free to move the limbs in space, the perception of tactile stimuli with varying postures of the arms is important. Therefore, in the second experiment, we investigated different postures of the hands to assess the possible perceptual influence on the model previously established. (3) Lastly, we applied the model in a VR environment to examine the visuo-tactile integration. Overall, our results contribute to a richer understanding of multimodal integration, and will guide designers in their effort to design more immersive, realistic, and even more compelling tactile experiences when interacting with technology.

With this study we open stage two, "Create", aimed to answer RQ2. Here, we start the investigation of tactile illusion to tackle the complexity of reproducing the sense of touch with haptic devices. The following study will still follow a psychophysical approach to individuate the optimal parameter for conveying an illusion of movement between the two non-interconnected hands.

9.1 The Hand-to-Hand device

To facilitate the exploration of inter-manual tactile illusions of movement for non-contiguous parts of the body (hand to hand) we built a vibro-tactile device, we refer to as Hand-to-Hand. The device consists of two 3D printed handles (see Figure 9.3), each containing a voice coil actuator (www.moticont.com, model GVCM-019-032-02) sandwiched between two springs. The spring stiffness is selected such that the transfer function of the handle is similar to that of the human detection threshold functions [89]. The device is controlled through audio production software (www.puretata.com) and interfaced using UDP (User Datagram Protocol). This simple but effective framework allowed us to design a series of experiments where we precisely controlled the delivery of a tactile sensation (i.e., frequency, amplitude, SOA, ramp up/down of the signal) using integrated development environments (IDE) and game engines (Unity). In the third experiment, we attached an additional button to the top of each handle to allow participants to enter their responses.

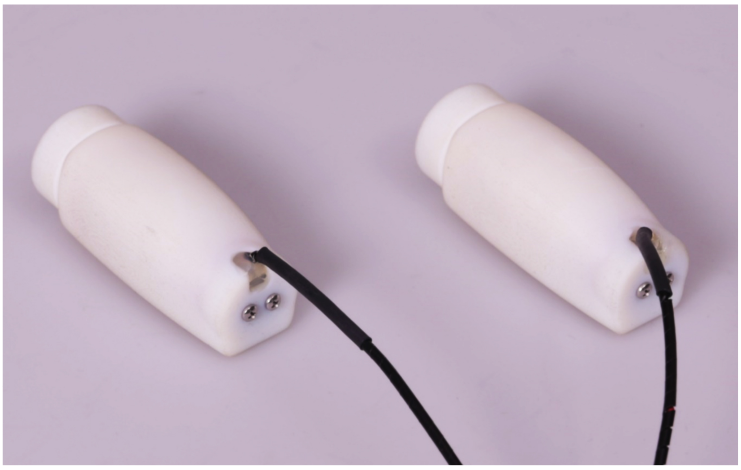


Figure 9.3: The Hand-to-Hand device consists of two 3D printed handles containing two voice coils sandwiched between springs and controlled by real-time software systems for interactive control.

9.2 Experiment 1: Finding the optimal parameters

The aim of this experiment was firstly to investigate whether the inter-manual illusion between the hands occurred when no objects were present between the hands, and secondly, if the illusion occurs, to determine optimal parameters to elicit a smooth illusion of movement. The experiment follows a psychophysical approach that establishes a mathematical model relation between the duration of the stimulation (***D***) and the temporal onsets (***SOA***).

9.2.1 Experimental setup

Participants sat on a chair with arm supports. To control the inter-manual distance we created a board to constrain the participants' hand movements. Two areas were marked on the board using foam strips, 2 cm tall, as boundaries (Figure 9.4).

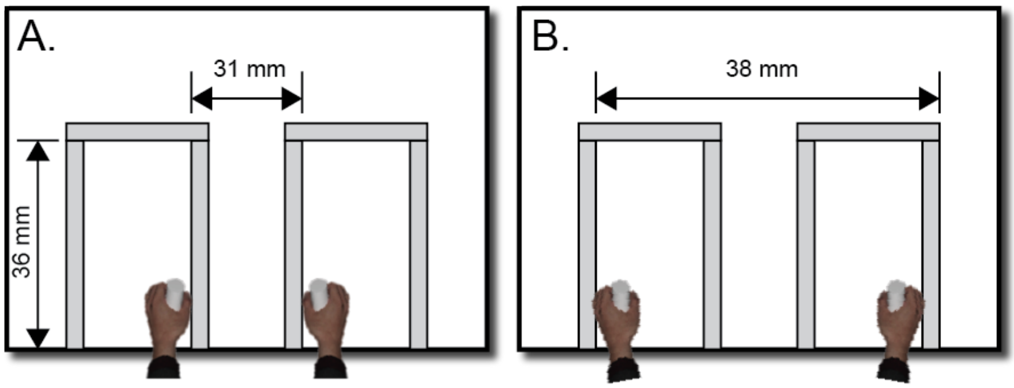


Figure 9.4: Experiment 1 set up: A) Regular hand posture. B) Wide hand posture.

9.2.2 Methods

Participants were provided with the Hand-to-Hand device (Figure 9.3). Before beginning the main experiment, participants had the opportunity to familiarize themselves with the stimuli. In a pilot study with another 10 participants, we determined that the frequency (70, 100 or 250 Hz) of stimulation did not influence the rating of the smoothness of the illusory motion, however, the duration settings (100 and 400 ms) varied subjective ratings on the smooth motion. Therefore, we set the test frequency at 70 Hz. The amplitude was set at 28 dB SL (dB above the detection threshold), to be sure participants could perceive the vibrations distinctly. In addition, we chose two durations (i.e., D = 100 and 400 ms) based on prior work [261]. For each duration we chose a different set of 7 temporal onset separations, SOA, equally divided as in [261]. For the 100 ms duration the SOAs ranged from 15 ms to 160 ms, and for the 400 ms duration SOAs ranged from 15 ms to 350 ms. These SOA ranges are required to reach a plausible effect of movement [261]. Every tactile stimulus was set to a linear ramp up and ramp down at a time equal to 20% of the stimulus duration [261].

Each duration and SOA was tested in two motion directions (left-to-right and right-to-left) and two postures. Participants' arms were comfortably leaning on the chair's arm supports, with the hands resting on the board at 31 cm distance for the regular posture (Figure 9.4A), and 38 cm for the wide posture (Figure 9.4B). For each duration and posture, participants were also tested in a control condition (SOA = 0, 12 times) to account for their random responses. In total, this experiment consisted of 180 trials, three repetitions of 2 duration, 2 direction, 2 posture 7 SOAs + 12 control conditions, divided in three blocks of 60 tactile stimuli.

Stimuli were presented in a randomized order one at the time, with at least 5 seconds gap to avoid tactile habituation. After the stimulus was presented, participants were verbally asked if the sensation of movement occurred. In the case of a negative response then the participant's rating was marked '0' and the next trial was presented. In the case of positive response, the same stimulus was repeated and participants were asked to verbally rate the smoothness of motion on a scale from 1 (discrete) to 7 (continuous). Each block was separated by a 2-minute break. Participants wore headphones to mask environmental and the device sounds. Moreover, a "beep" sound was played through the headphones before the beginning of every trial. Overall, the experiment lasted for 30 minutes.

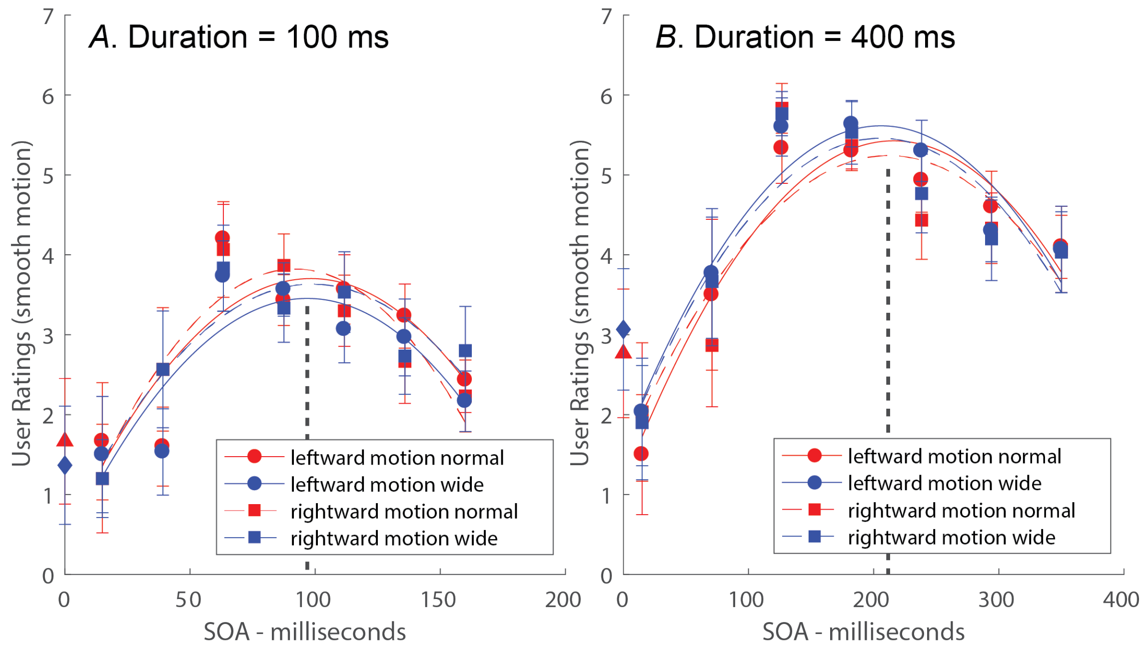


Figure 9.5: Plots of user ratings of the illusion of movement (y-axis) per SOAs (x-axis) at A) 100 ms and B) 400 ms.

9.2.3 Participants

The study was carried out in a single session with 10 participants (6 female, median = 24). They had normal or glasses/lens corrected vision and no history of neurological or psychological disorders. All participants were right-handed. Upon arrival, participants were asked to read the information sheet and sign a consent form, followed by a task explanation. All participants were compensated with US $10.

9.2.4 Results

To ensure that the rating scale was used appropriately, users' ratings (0, no motion, through 7, continuous motion) were averaged for the two durations across participants. At SOA = 0 (catch trials), the overall ratings were 1.68 and 3.2 for 100 ms and 400 ms, respectively. Figure 9.5 illustrates the average ratings as a function of SOA for the 2 durations, 2 directions, and 2 postures. The error bars show standard errors of the mean. Each plot was regressed with a best-fit quadratic trend, and the corresponding correlation coefficients are shown in Table 1. The two lowest parts of the curves correspond

to low SOAs (merged tactile perception) and to high SOAs (discrete tactile perception). The peaks of the curves correspond to the optimal values of SOAs and are reported in Table 1.

We checked the rating scores divided per stimulus' duration, and found that the data significantly deviates from a normal distribution. Therefore, we proceeded using a Friedman test. Results show a significant difference between the two durations, $\chi^2(1)$ =183.95, p<0.001. Looking at Figure 9.5, it is clear that the 400 ms duration (right) has a more powerful effect. That is, the illusion of movement is perceived strongly. The different SOA resulted significantly different as well, $\chi^2(6)$=143.59, p<0.001 for 100 ms, and $\chi^2(6)$=99.56, p<0.001 for 400 ms.

When analysing the direction of vibrations, we did not find an effect, $\chi^2(1)$=0.214, p=0.64 for 100 ms and $\chi^2(1)$=1.667, p=0.2 for 400 ms. The posture of the hands did not result in a significant difference, $\chi^2(1)$=0.44, p=0.51 for 100 ms and $\chi^2(1)$=0.68, p=0.41 for 400 ms. In conclusion, our results show that the duration and SOA are the only significant parameters with an effect on the illusion of movement, confirming previous works [261]. Fitting the peaks' data in Table 1 into a regression model, resulted in the following model:

$$y = 0.38x + 58.8, R^2 = .99 \tag{9.1}$$

where, x is representing the duration of the stimulus in milliseconds and y is the optimal SOA in milliseconds related to that specific duration.

Stimulus	Peak	R2
100 ms - regular posture, rightward motion	98.31	0.69
100 ms - regular posture, leftward motion	92.00	0.87
100 ms - wide posture, rightward motion	96.82	0.75
100 ms - wide posture, leftward motion	98.85	0.82
400 ms - regular posture, rightward motion	215.99	0.92
400 ms - regular posture, leftward motion	211.87	0.73
400 ms - wide posture, rightward motion	205.75	0.91
400 ms - wide posture, leftward motion	205.00	0.83

Table 9.1: The optimal values of SOA for the eight curves, along with the quadratic fit (R^2).

9.3 Experiment 2: Temporal order judgment

The illusion of movement is the result of an implicit temporal order judgment (TOJ) between the two stimuli perceived on the hands. The aim of this second experiment was to explore whether changing the posture of the arms (see Figure 9.6) influences the users perception and temporal judgment. In fact, prior works suggest that changing the posture of the arms could affect the temporal judgment of the two stimuli [212], and consequently could also affect the perception of the illusion of inter-manual movement. If an effect was observed, it would have been used to redefine the model established in experiment 1.

9.3.1 Pilot experiment: participants

To explore and choose the device's settings we conducted a pilot study with 12 participants (4 female, median = 24.5). They had normal or glasses/lens corrected vision and no history of neurological or psychological disorders. All participants were right-handed. Upon arrival, participants were asked to read the information sheet and sign a consent form, followed by a task explanation. All participants were compensated with US $10.

9.3.2 Experimental setup

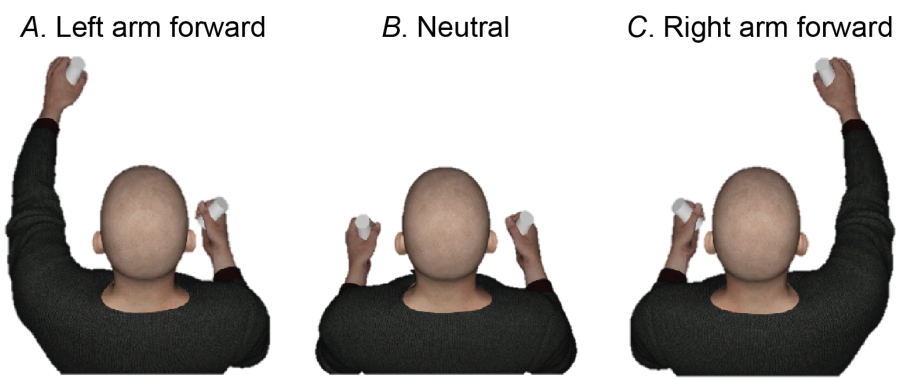


Figure 9.6: Experiment 2 set up including three different postures: left arm forward, neutral, right arm forward.

The experimental setting used for this pilot study was the same as in Experiment

1, with the difference being that participants were tested on a TOJ task. In other words, participants had to answer which of the two handles vibrated first. Since participants had to hold the two handles, we provided them with a 4 buttons foot pedal (Olympus America Inc., model RS31H) to enter their response.

9.3.3 Methods

For the tactile stimuli we used one frequency (70 Hz), two durations (100 and 400 ms) and a set of 11 SOAs (from -100 ms to a 100 ms in 20 ms increments). Positive SOA corresponded to the left handle vibrated first, and the negative SOA corresponded to the right handle vibrated first. The stimuli's ramp-up and -down time was kept at 20% of the stimulus duration. The amplitude of the signal frequency was 18 dB SL. Participants were required to switch posture of the arms in three possible ways (Figure 9.6): regular posture (as in Experiment 1), left arm completely extended in front of the shoulders and the right arm in neutral posture (condition left forward), or vice-versa (right forward).

We controlled the distance between participants' hands again using the board in Figure 9.4. A picture showing the testing posture appeared on the interface before the trial started. Participants had to press the central button of the pedal to play the stimulus. Stimuli could start from the left or from the right hand. After the stimulation, the participant had to indicate which hand they felt was stimulated first; pressing the left button on the pedal if the left handle vibrated first and vice-versa for the right side. After they answered, another posture followed and the entire procedure was repeated until the end of the block of 33 stimuli. Participants wore headphones to cover the environmental and the device noises. Each stimulus was repeated three times for a total of 198 trials (3 x 2 duration x 3 postures x 11 SOA). Overall, the experiment lasted for one hour.

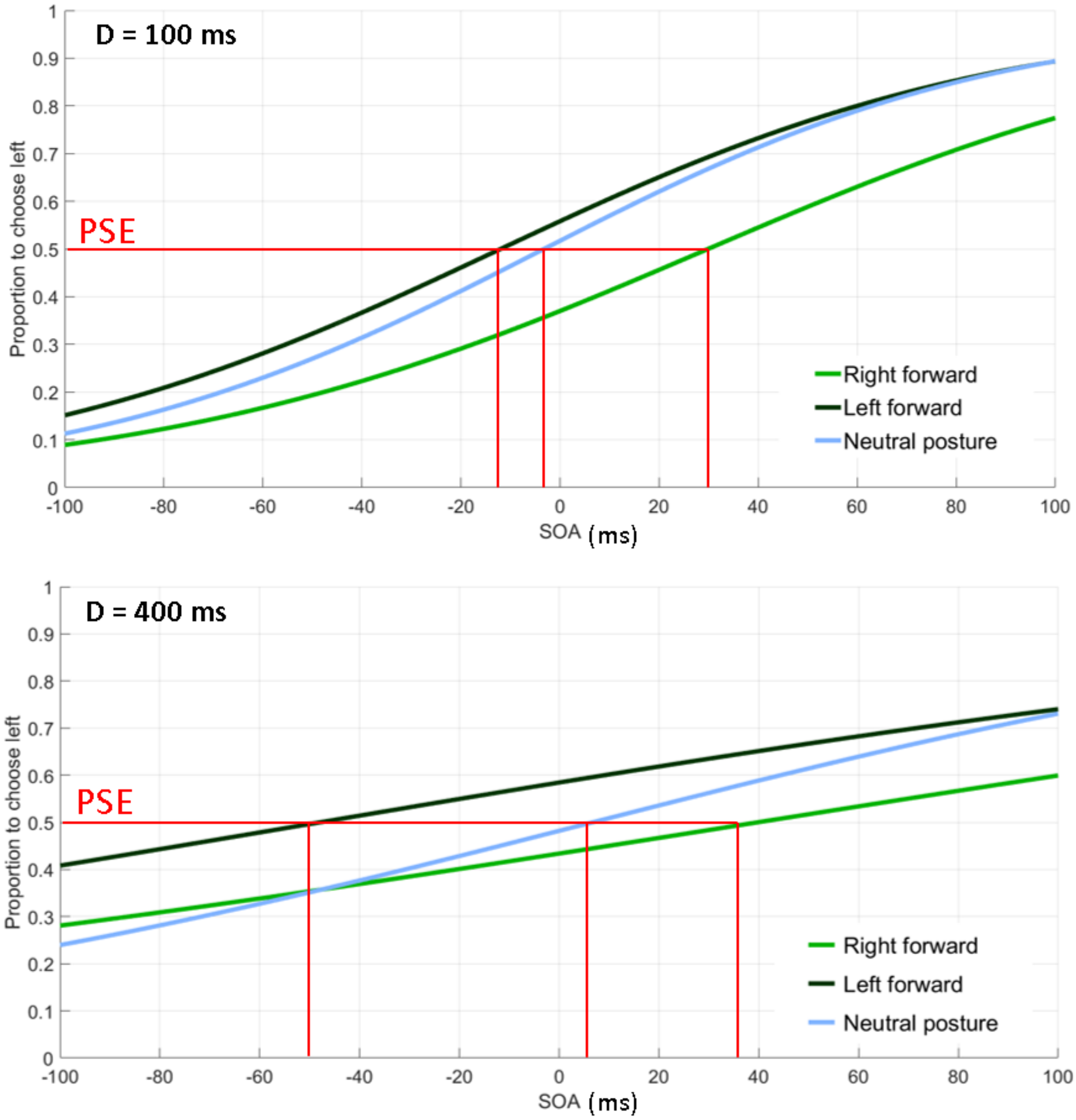


Figure 9.7: The three cumulative Gaussian functions for duration equal to 100 ms (top), and 400 ms (bottom). On the y-axis, the probability of choosing left as the first vibrating. On the x-axis, the SOAs: negative values correspond to the vibrations starting from right.

9.3.4 Results

Figure 9.7 shows the three psychophysics curves resulting from the data collection, for d = 100 ms and d = 400 ms. Each curve corresponds to a posture. The SOAs values appear on the x-axis: negative if the direction was going from right to left, positive when the vibrations were starting from the left handle. The probability of selecting the left handle as the first vibration is plotted on the y-axis. In a psychophysics curve, the point of subjective equality (PSE) indicates the point at which one can no longer perceive two stimuli as distinct. In our case, it is the point where participants could not feel which vibration was coming first, either the right or the left one. For d = 100 ms, the green curve appears shifted to the right. An ANOVA repeated measures showed a non-significant difference between the three postures ($F(2,20)=3.11$, $p=0.07$), although with a low p-value. For d = 400 ms, data were not following a normal distribution. We used a Friedman test to test differences between the three curves. The test did not show any significant difference between the three postures, ($\chi^2(2)=5.09$, $p=0.08$), and also in this case the p-value appeared low.

These results suggest that the posture did not clearly influence participant's performance in the TOJ task, but there might be a tendency in doing that. With the amplitude chosen participants reported uncertainty regarding the occurrence of both the vibrations, and this could explain the noisy distributions of data in Figure 9.7. Hence, we conducted another experiment with a higher amplitude equal to 28 dB SL to ensure a clear vibrotactile perception. We chose only one duration (100 ms) and repeated each stimulus 7 times instead of three to get more robust data.

9.3.5 Main experiment: participants

The experiment was carried out in a single session by 10 participants (8 female, median age = 22.5 years old). They had normal or glasses/lens corrected vision and no history of neurological or psychological disorders. All participants were right-handed. Upon arrival, participants were asked to read the information sheet and sign a consent form, followed by a task explanation. All participants were compensated with US $5.

9.3.6 Experimental setup

The experimental setting was same as in the pilot study (see Section 5.1.1).

9.3.7 Methods

For this experiment we followed the same procedure used in the pilot study (see Section 5.1.2) with the only difference being we had one vibration's duration (100 ms) at an amplitude of 28 dB SL. This experiment consisted of 33 stimuli repeated three times in three postures (99 trials). Participants wore headphones to cover the environmental and the device noises. Overall, the experiment lasted for 30 minutes.

9.3.8 Results

Figure 9.8 shows three psychophysics curves resulting from the data collection. Each curve corresponds to a posture. The SOAs values appear on the x-axis: negative values refer to the direction going from right to left, positive when the vibrations were starting from the left handle. The probability of selecting the left handle as the first vibration is plotted on the y-axis. In a psychophysics curve, the point of subjective equality (PSE) indicates the point at which one can no longer perceive two stimuli as distinct. In our case, it is the point where participants could not feel which vibration was coming first, either the right or the left one.

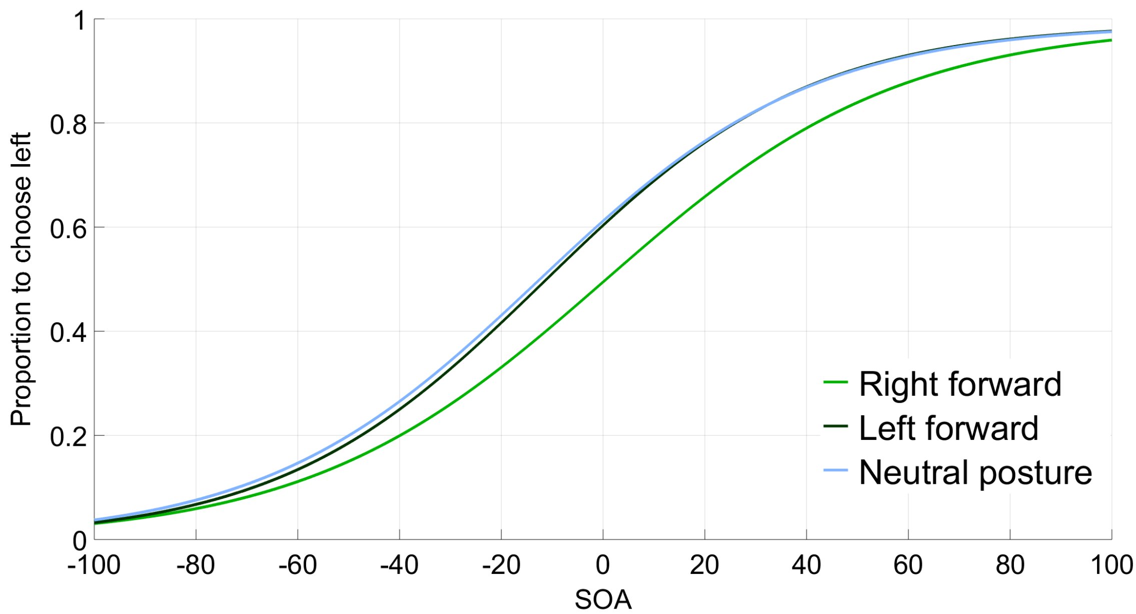


Figure 9.8: The three cumulative Gaussian functions. On the y-axis, the probability of choosing left as the first vibrating. On the x-axis, the SOAs: negative values correspond to the vibrations starting from right.

The three curves in Figure 9.8 appear to be very similar. Our data were following a normal distribution and no outliers were found. An ANOVA repeated measures performed on the 10 participants PSE data confirmed a non-significant difference between the three curves, $F(2,18)=2.595$, $p=0.102$. Therefore, our results suggest that the posture does not influence participant's performance in the TOJ task and thus has no crucial effect on the perception of the illusion of movement.

Looking at Figure 9.8 it is possible to infer that when the SOA was equal to 0, participants' answers were random, as expected. For very high SOAs instead, the probability of a correct answer (i.e., 'the left hand vibrated first when the left was vibrating first') was almost 100%, as indicated by the saturation of the curve on the value equal to 1. The threshold was set at 75% and computed pairing the three curves, and corresponded to a SOA equal to 66.4 ms.

9.4 Experiment 3: Multimodal interaction

With the two previous experiments we investigated the optimal parameters for the illusion of movement and defined a perceptive model that is not affected by the posture. In a final third experiment, we programmed an application that exploits the illusion of inter-manual movement in VR, using our established model. Moreover, we are interested in investigating the perceptual integration of visuo-tactile stimuli.

9.4.1 Experimental Setup

We created a virtual environment (VE) using Unity 3D to investigate the synchronization between tactile and visual stimuli. Participants wore an Oculus DK2 VR headset (960 x 1080 per eye, ca. 75 Hz, 100° FoW), and they could see in the VE two hands attached to a body, while sitting on a chair in front of a desk (see Figure 9.9). To navigate the VR interface, participants were provided with a pedal. The Hand-to-Hand device with the two buttons on the top allowed them to select the different settings of the interface and to skip to the next trial as follows.

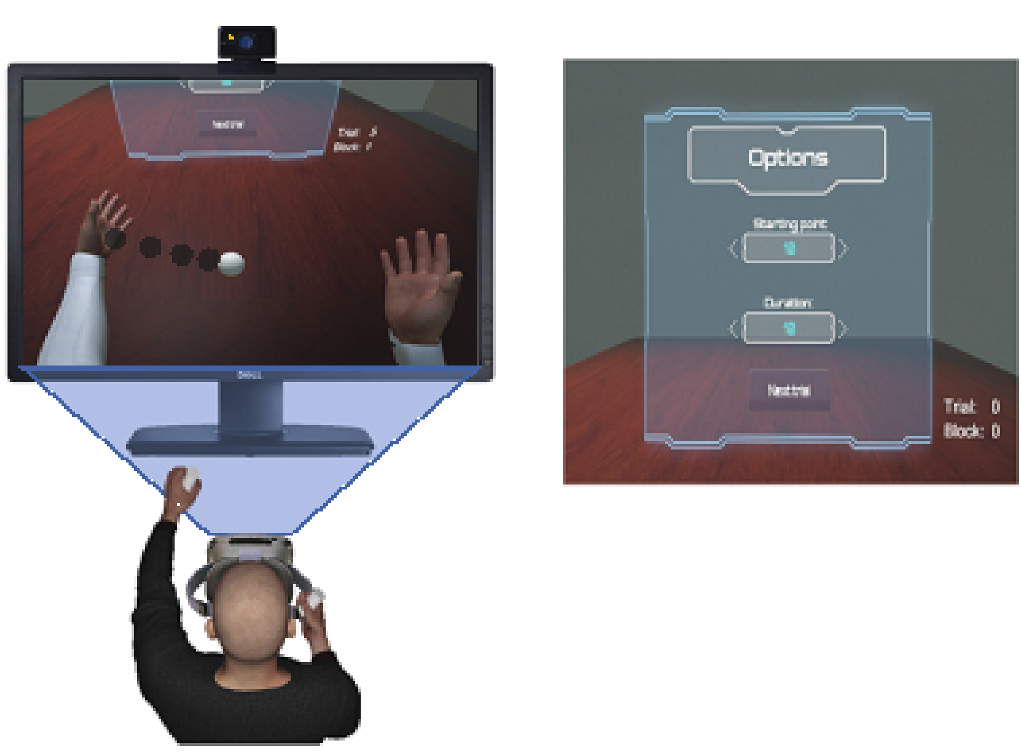


Figure 9.9: Experiment 3 setup. Participants wore an HMD for VR. In the VE they could see two hands, changing in posture according to the different parameters of the experiment, a body attached, and a white ball moving from one hand to the other at different speeds. (Right) The interface used in VR to complete the matching tasks.

9.4.2 Methods

During the experiment, the posture of the two hands was visually adjusted in the VE to create the four conditions: regular, wide, left forward and right forward posture (see Figure 9.9). In practice, at the beginning of the trial, participants could see the VE, and they had to adjust their arms' posture to match the ones in VR. The posture also appeared written on the screen in the VE to avoid misunderstanding. The visual stimulus was represented by a white ball moving from one hand to the other at five different speeds (2, 4.5, 7, 9.5 and 12 m/s for a total of 90, 120, 170, 250, 570 ms for the regular posture, and 110, 140, 200, 300 and 680 ms for the rest of the postures).

We controlled and counter-balanced the direction of the ball (left to right and right to left). At the beginning of every trial, an arrow was indicating the initial hand from which the ball would move from. The tactile stimulus was rendered through the two 3D printed vibro-tactile handles used in the previous experiments. This time, we added two buttons on the top of the handles, to allow participants to interact

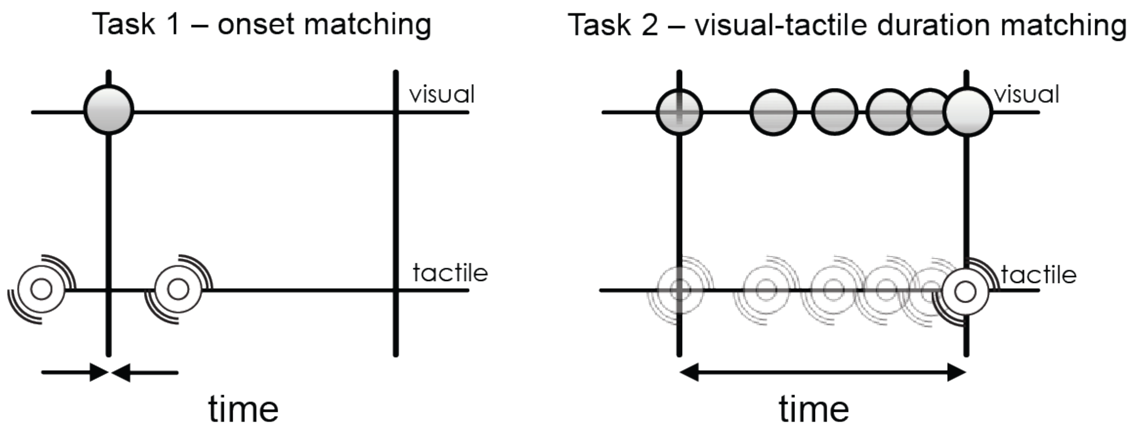


Figure 9.10: The two matching tasks used in Experiment 3. Task 1) Participants had to match the onset of the visual and tactile stimuli. Task 2) Participants had to match the duration of the visual and tactile stimuli.

with the VR interface fixed in front of the participants' point of view (see Figure 9.9).

To navigate, participants were provided with the same pedal as in experiment 2; pressing the central button to select the different options shown in Figure 9.9. They had the possibility of changing two settings: they could increase or reduce the delay of the onset time of the vibration on the first hand (starting point in Figure 9.10) and they could extend or shorten the total duration of the tactile event (duration in Figure 9.10), intended as the SOA plus the duration

of the two vibrations (including the time for the signal to rump up and down). Participants had to complete two tasks:

Task 1: the aim of the first task was to match the visual and the tactile cue onset (Figure 9.10 left). The visual cue (the white ball) was always visible for a fixed amount of time depending on the speed. Instead, the first vibration on the hand was randomly selected ± 50 ms respect to the visual cue. When the tactile stimulus appeared before the visual one, participants had to press the right button on the handle, increasing the stimulus delay by 5 ms. Conversely, if the first vibration was starting after the visual cue, participants had to press the left button on the handle, reducing the delay of the tactile cue by 5 ms. Every time that participants pressed one of the two buttons, the trial was restarted with the new values.

Task 2: The second task consisted of matching the total duration of the two events, the tactile and the visual one. Once participants completed task 1, they had to match the ending point of the two stimuli (Figure 9.10, right). When the ball was disappearing (once it reached the second hand), also the second vibration (on the second hand) had to disappear. If the tactile stimulus' duration (intended as the duration of the first vibration, plus the SOA, plus the second vibration) was shorter than the visual one, participants had to press the button on the right handle to extend the total tactile duration by 30 ms.

Vice-versa, if the total tactile duration was too long, participants had to press the button on the left handle, shortening the total duration by 30 ms. Also in this case, pressing a button meant restarting the stimulus from the first hand with the new values. The duration of the tactile stimulus was randomly selected between 100 ms and 400 ms, with the SOA changing in consequence of the duration's value, according to the model obtain from experiment 1 ($y = 0.38x + 58.8$).

This experiment consisted of two blocks of 60 randomized stimuli. For the tactile stimuli we used one frequency (70 Hz) and the duration and SOA were varying according to the model of experiment 1. The stimuli's ramp-up and -down time, was kept at 20% of the stimulus duration. The amplitude of the signal frequency was 28 dB SL.

We used the same board as from experiment 1 and 2 to control participants hands' distance (Figure 9.4). In total, participants had to complete two blocks of 40 trials in one hour.

9.4.3 Participants

The experiment was carried out in a single session by a new pool of 10 participants (6 female, median = 21). They had normal or glasses/lens corrected vision and no history of neurological or psychological disorders. All participants were right-handed. Upon arrival, participants were asked to read the information sheet and sign a consent form, followed by a task explanation. All participants were compensated with $10. Six participants could not complete the whole set of trials within the given time of 60 minutes. In total, we collected 692 trials out of 800.

9.4.4 Results

The data for Task 1 was negatively skewed, hence we normalized the data using the formula: lg10 (max value - value). We then analysed the data using a two-way ANOVA repeated measures test, with speed and posture as factors. The results show a non-significant effect neither of postures ($F(3,72) = 1.131$, $p = .342$) nor speed ($F(4,96) = .774$, $p = .545$). Their interaction was also not significant ($F(12,288) = .440$, $p = .946$). The data for Task 2 was also negatively skewed, hence, we normalized the data before proceeding with the analysis. We again performed a two-way ANOVA repeated measures test with speed and posture as factors.

The results indicate a significant main effect of speed, $F(4,96) = 8.585$, $p < .001$, and posture, $F(3,72) = 7.173$, $p < .001$. The pairwise comparisons between the visual minus tactile duration for specific speeds indicate that the visuo-tactile deltas' scores for the speed of 2 m/s and 4.5 m/s were different from all the other speeds ($p < .001$), meanwhile the other three speeds were not significantly different from each other ($p > 0.05$). The right forward posture was the only one to differ from the others ($p < .05$). The interaction between posture and speed was significant as well, $F(12,288) = 11.053$, $p < .001$. To further investigate this interaction, we analysed the simple effects. In particular, it appears that for speed equal to 4.5 m/s, in the right forward posture, the tactile cue need a shorter duration to be perceived as matching the visual cue ($p = 0.048$). The same is valid for speed equal to 7 m/s ($p = 0.019$).

Finally, for speed equal to 12 m/s, the posture right forward seems to significantly differ for all the other postures ($p < 0.001$). Figure 9.11 illustrates the linear fit of our data (the red lines) compared with the 1:1 uncompressed visuo-tactile relation (the black lines). For the regular posture (31 cm distance between the two hands) it appears that the tactile duration is compressed with respect to the visual one by a factor of approximately 1/4, meaning that even if the visual duration is increasing, the tactual duration is not increasing accordingly. This is especially true for the

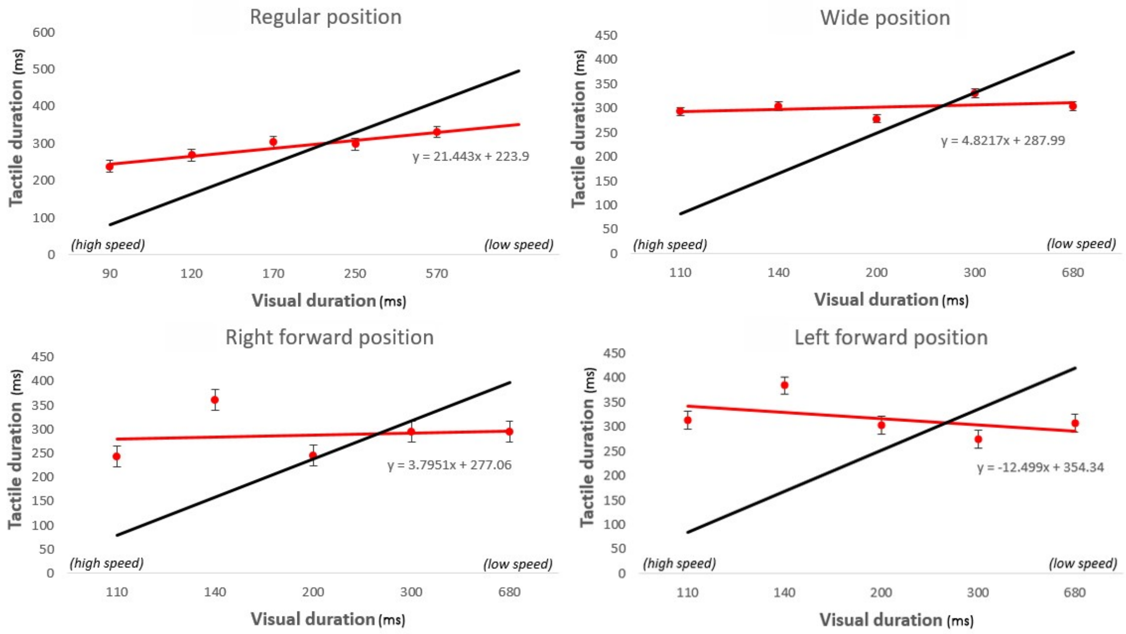


Figure 9.11: Linear fits of visual and tactile duration, divided per postures (regular, wide, right and left forward). The black line represents the 1:1 uncompressed visuo-tactile relation. The red line represents the linear fit of our data.

wide and right forward posture, where the red line appears to be almost flat. The left forward posture instead, indicates an inverse tendency: the slower the visual stimulus is (long visual duration), the shorter the tactile stimulus is perceived.

9.5 Discussion

Here, we investigated the occurrence of the tactile illusion of movement and its particularities as well as the effects of the postures of the hand, and when integrated in a virtual environment. With the first experiment we established that it is possible to elicit an illusion of movement using tactile stimuli delivered on two hands that are not interconnected by any means, such as a tablet used in prior research [261]. Based on that initial step, we then determined and described the optimal parameters to achieve a smooth tactile illusion of movement using a psychophysical approach.

We generated a perceptual model that expresses the relation between duration and SOA of the tactile stimuli: $y = 0.38x + 58.8$. This model, specifies the optimal parameters to use for achieving a smooth illusion of motion between the hands. In short, the most relevant variables impacting users' perception are duration and the stimulus-onset asynchrony (SOA) of the tactile stimuli, confirming previous results [261]. To understand whether the position of the users' arms (i.e., posture) influences the temporal perception of the two tactile stimuli, we used a temporal order judgment task (TOJ). This is important because judging the movement means ultimately recognizing which stimulus occur first and hence can guide design decisions in an interactive system based on touch.

Our results showed that the posture does not have any effect on the perception of movement, which is in contrast to prior findings presented by Shore [212]. The difference could be explained based on the use of different SOAs, which are also different to the work presented by Siyan [261]. In particular, the SOAs used in Shore, were 10 ms, 30 ms, 55 ms, 90 ms and 200 ms and no indication about the amplitude is provided, which might have a key role in the different results obtained. In fact, in our pilot study, where we used a lower amplitude of about 18 dB SL, the results had a different trend, near the significance level. Another difference was the modality of delivering the tactile stimuli, on the finger vs. through a vibro-tactile handle. We initially thought that the manual laterality of the participants could have had an effect on the outcome. Our participants were all right-handed, hence, it is hard to answer this question. It is known that crossing the hands has an impact on the TOJ of tactile stimuli [213, 256]. On the contrary, we found only one study investigating the effect of the hands' distance (not crossed) on a TOJ task [136], other than [212]. In Kuroki's study [136], authors demonstrated how the spatio-topic distance does not influence participants' performance in a simultaneity judgment task, similarly to our results.

In a final step, we programmed a virtual environment, where participants were able to perceive tactile stimuli integrated with visual stimuli in order to assess our perceptive model. In addition, we also investigate the visuo-tactile integration in a specific application context, relevant for exploiting tactile illusions and multimodal interaction. The results as summarized in the previous section do not allow clear conclusions. However, one could speculate that for slower velocities, the tactile cue is perceived before the visual one. What we know for certain is that there are no negative visuo-tactile duration deltas (visual delay minus tactile delay). In other words, the tactile stimulus is never happening after the visual cue, as the tactile perception is faster than the visual one. One possible explanation could be that the task used during the exposure phase resulted in an attentional bias towards the tactile modality. According to the 'law of prior entry', attending to one sensory modality speeds up the processing of stimuli in that modality [249], resulting in a change in the PSS (point of subjective simultaneity).

9.6 Limitations

This work is a first step into the analysis of the tactile illusion of movement without any object in between the two hands. Although our results are promising, we also need to acknowledge some limitations.

One limitation is that participants' hands were static in our experiments, which does not reflect users' behaviour in a virtual environment where they move around a space and interact with objects. In order to establish our perceptual model it was necessary to control the movement. However, future work can take users movement into account by creating a more interactive scenario, and consequently also extend our perceptive model. Moreover, future investigations of kinaesthetic cues only (with no visual feedback) can now be explored.

Another limitation are the sample sizes in our studies. With a larger number of participants some effects (e.g., posture in experiment 2) could become significant, although we consider that unlikely based on our repeated tests in preparation for our studies. Yet, it will be important that future work verifies our findings to strengthen our model and in particular considers any potential bias in the temporal order judgment task towards the right hand.

Finally, we are using a specific actuation technology and focusing on one specific type of illusion. Future work should consider other sensory illusions such as the phantom tactile sensation and sensory saltation, as well as explore the different types of illusions of movements (i.e., cutaneous rabbit illusion, the haptic funnelling, and the apparent tactile movement illusion) with other tactile devices and technologies entering the realm of virtual reality (e.g., mid-air touch [150]).

9.7 Conclusion

The findings from our three experiments demonstrate that eliciting a sense of illusory movement between two hands is not limited to situations when holding an object with both hands, or across two contiguous parts of the body. This work sets the stage for future investigations of tactile experiences exploiting tactile illusions. Findings with respect to the visuo-tactile integration require additional validation, however the findings are promising with respect to the temporal perception and consequently the design of applications in virtual environments and beyond.

In the following chapter, we take inspiration from the current study to explore the feasibility of the apparent illusion of movement when using mid-air haptic stimulation. Study 5 will make use of a similar methodology adding two different techniques to investigate what will give the best perception of movement between the two non-interconnected hands.

Chapter 10

Study 5 - Create Mid-air tactile illusion of movement[1]

Apparent tactile motion (ATM) has been shown to occur on many contiguous parts of the body, such as the fingers, forearms, and back. More recently, the illusion has also been elicited on non-contiguous parts of the body, such as between one hand and the other, either when the hands are interconnected or not interconnected by an object (e.g., when holding a tablet or not). In the previous chapter, we showed that it is possible to obtain ATM between non-interconnected hands by means of tactile actuators, here we explore the reproducibility of ATM between two free hands by employing mid-air tactile stimulation. We investigate the optimal parameters to generate a continuous and smooth motion using two arrays of ultrasound speakers. Having the ability to easily create different tactile patterns, we investigated the optimal values (in terms of frequency, duration, SOA, and direction) needed to render a smooth tactile sensation of movement. In the first experiment, we investigate the occurrence of the illusion when using a static focal point, and we define a perceptive model. In the second experiment, we examine the illusion using a dynamic focal point, defining a second perceptive model (see Fig. 10.1). Finally, we

[1]Pittera D., Ablart D., Obrist M. "**Creating an illusion of movement between the hands using mid-air touch**". In *IEEE Transaction on Haptics*, 2019.

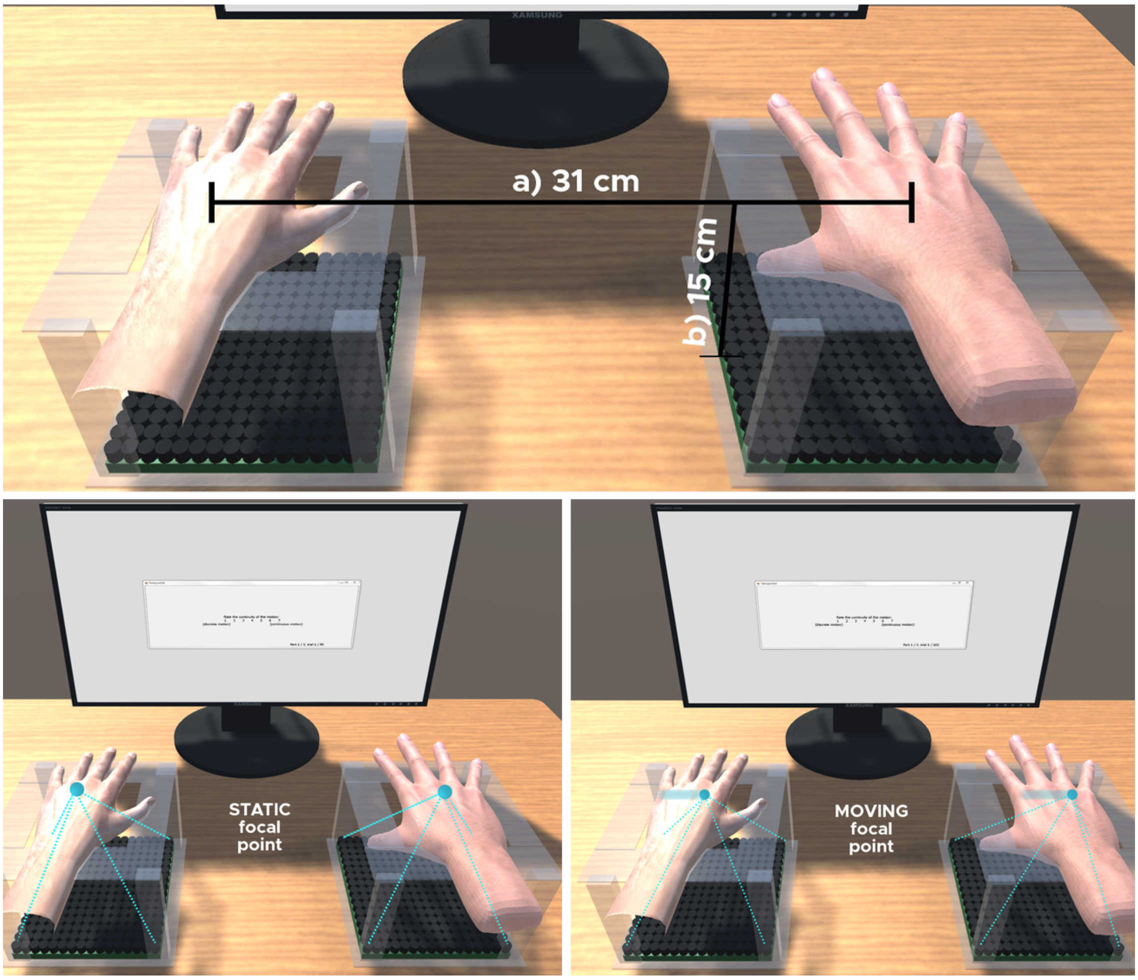


Figure 10.1: Experiments setting. TOP: For both experiments, a) the distance between the palm of the two hands was set at 31 cm, and b) the hands were resting on the two acrylic boxes at a distance of 15 cm above the two mid-air haptic devices. LEFT: In experiment 1, a static focal point was delivered to the centre of the distal part of each palm. RIGHT: In experiment 2, a dynamic focal point was delivered to the distal part of each palm.

compare the two perceptive models, one for each of the above techniques.

This investigation contributes to the basic understanding of mid-air tactile perception, allowing the representation of more complex scenarios that include tactile movement. With this investigation, we also aim to provide designers of tactile displays with an understanding of the optimal parameters for the design of a smooth tactile movement.

The current study is a follow-up of Study 4 (see Chapter 9) and is also part of the stage "Create", RQ2. Here, after starting the investigation of an illusion of movement obtained by using physical actuators, we try to shift the phenomenon using mid-air technology. To achieve this goal we used the procedure established in Study 4.

10.1 Setup and approach

The objective of this study is to investigate the reproducibility of ATM between two non-interconnected hands using mid-air tactile stimulation. Furthermore, we are interested in learning whether a static or dynamic focal point will provide the smoothest tactile motion sensation. In the following two sections, we present two studies that explore the optimal parameters needed for creating a smooth tactile transition from one hand to the other. In both experiments, we followed a psychophysical approach to determine the relationship between the mid-air stimuli and the resulting tactile perception (i.e., occurrence of ATM).

We used two mid-air haptic devices developed by Ultrahaptics Ltd. This device consists of an array of ultrasound speakers (16 x 16) that allows precise control of the tactile stimuli delivery (e.g., frequency, amplitude, SOA, ramp up/down of the signal, waveform, and duration) (see Fig. **??**). We programmed a graphical user interface (GUI) in C# to guide participants through the experiment. The ultrasonic haptic boards were controlled through a program written in C++ and connected to the GUI through the TCP/IP protocol. The boards were synchronized using high precision timers (ms order). The tactile focal points employed in the two experiments were designed using amplitude modulation (i.e., to create a 200 Hz focal point, the intensity of the point was alternating from 0% to 100%, 200 times per second). The intensity change followed a sinusoid curve to minimize the noise of the devices. In experiment 1, we projected a single static focal point onto the distal part of each palm. In experiment 2, the focal point moved along the distal part of each palm in a straight line, from the right to left or left to right, at different SOA values. We chose to project the tactile feedback onto the distal part of the palm because, especially for experiment 2, we needed a uniform (flat) area on which to display the focal point. In fact, if the dynamic mid-air point hit the skin at different heights, the perception could be non-uniform and hard to perceive.

Participants were sitting on a chair with their two arms leaning on arm supports and their palms downwards on two boxes (see Fig. 10.1). The boxes were acrylic structures, each containing a mid-air haptic device with a rectangular hole of 10 x 8 cm in the centre to allow the mid-air stimulation to reach the distal part of participants' palms. The distal part of the palm of each hand was aligned with the centre of the boxes' hole, where the mid-air stimulation was provided. The location of the stimulus delivery did not vary with the hand size; the hand was always hit at the centre of the distal part of the palm. The boxes were designed to keep users' hands at a constant distance of 15 cm above the ultrasound array, which is within the optimal working range of the device. The distance between the palms was kept at 31 cm as in [185]. Instructions were provided on a screen.

10.2 Experiment 1: Mid-air apparent motion: static point optimal parameters

The aim of this experiment was first to investigate whether ATM between the hands occurs when using a mid-air stimulation. If the illusion did occur, the second objective was to determine the optimal parameters to elicit a smooth illusion of movement to define a perceptive model. In this first experiment, we investigated the illusion using a single static focal point projected onto the distal part of participants' palms.

10.2.1 Methods

We first conducted a pilot experiment with seven participants (three females, age $\mu = 27.4$, SD ± 3.6) to determine the frequency and duration of the mid-air tactile stimulation. Based on previous studies [185, 260, 261], we tested three different frequencies (70 Hz, 100 Hz, and 250 Hz), and two durations (100 ms and 400 ms). While testing the smoothness of the motion in our pilot experiment (using the same study set-up as described above, see Fig. 10.1), the only pair of frequencies that was statistically similar was the 70 Hz and 100 Hz ($p > .5$). Hence, for the

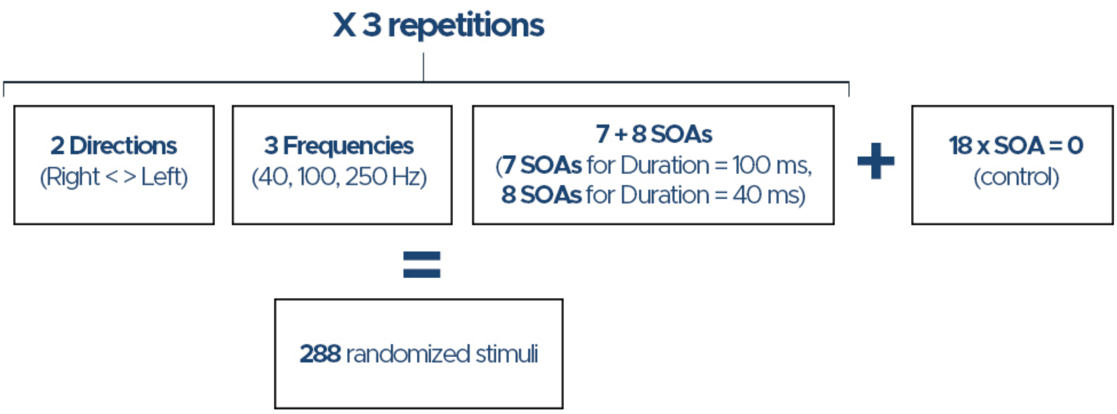


Figure 10.2: Experimental design for experiment 1. Every mid-air haptic stimulus was a combination of the four variables (i.e., duration, direction, frequency, SOA), and a control condition with SOA set at 0, for a total of 288 randomized stimuli. The picture is not representative of the order of presentation of the stimuli.

main experiment we selected only the 100 Hz and 250 Hz frequencies. In addition, knowing that mid-air touch perception is associated not only with the Pacinian corpuscles (receptors for high-frequency vibrations from 50 Hz to 10 kHz) but also with the Meissner corpuscles (receptors for low-frequency vibrations < 80 Hz) [171], we additionally tested the 40 Hz frequency, for a total of three frequencies (40 Hz, 100 Hz, and 250 Hz).

Based on the pilot study and accounting for the mechanoreceptors relevant for high and low-frequency vibrations, the experimental design for experiment 1 consisted of three blocks of 96 randomized mid-air tactile stimuli, for a total of 288 stimuli.

We chose two stimulus durations (i.e., 100 and 400 ms). For each duration, we chose a different set of SOAs, equally divided as in [185, 261]. For the 100 ms duration, the SOAs ranged from 15 ms to 190 ms for a total of eight intervals, and for the 400 ms duration, SOAs ranged from 15 ms to 350 ms, for a total of seven intervals. These different SOA ranges are required to reach a plausible effect of movement [185, 261]. For each duration, we also added an SOA = 0 as a control condition to account for random responses from participants. Every tactile stimulus was set to ramp up and down at a time equal to the 20% of the stimulus duration, as in [185, 261]. Therefore, every stimulus was a combination of duration (100 ms and

400 ms), SOA (the two different sets, plus the control SOA), frequency (40 Hz, 100 Hz, and 250 Hz) and direction (from left to right and vice-versa) (see Fig. 10.2 for an overview).

Before the testing phase began, participants had the opportunity to familiarize themselves with the mid-air tactile stimulation. A minimum of three pairs of stimuli were presented in a series to participants' palms while the researcher ensured that the user understood the experimental procedure. After this training phase, stimuli were presented one at a time, with at least a five-second gap to avoid tactile habituation. After the stimulus occurred, participants were guided by the GUI to report verbally if they felt a sensation of movement between the hands. In the case of a negative answer, the subsequent trial was presented. Instead, if a feeling of motion was reported, the participant was asked to indicate verbally the smoothness of the motion on a rating scale visible on the GUI, ranging from 1 (discrete motion) to 7 (continuous motion). Participant's answers were recorded on the computer by the researcher. Additionally, participants could ask to repeat the stimulation. Each block of 96 stimuli was separated by a two-minute break. Participants wore headphones to mask environmental and device noises. Moreover, a "beep" sound was played through the headphones before the beginning of each trial. Overall, the experiment lasted 45 minutes. All participants were compensated with a £7.5 voucher for participating in the experiment.

10.2.2 Participants

A total of 20 participants took part in the study (nine females, age $\mu = 26.8$, SD $\pm$ 7.7). They had normal or glasses/lens corrected vision and no history of neurological or psychological disorders. All participants were right-handed. Upon arrival, participants were asked to read the information sheet and sign a consent form before the task was explained to them.

10.2.3 Results

To ensure that the rating scale was used appropriately, we checked the ratings for the SOA = 0 (control trials). The overall ratings were respectively 0.39 and 0.12 for durations of 100 ms and 400 ms, meaning that participants did not feel movement when the tactile point was provided at the same time on the two hands. Users' ratings (1, discrete motion to 7, continuous motion) were averaged for the two durations across participants.

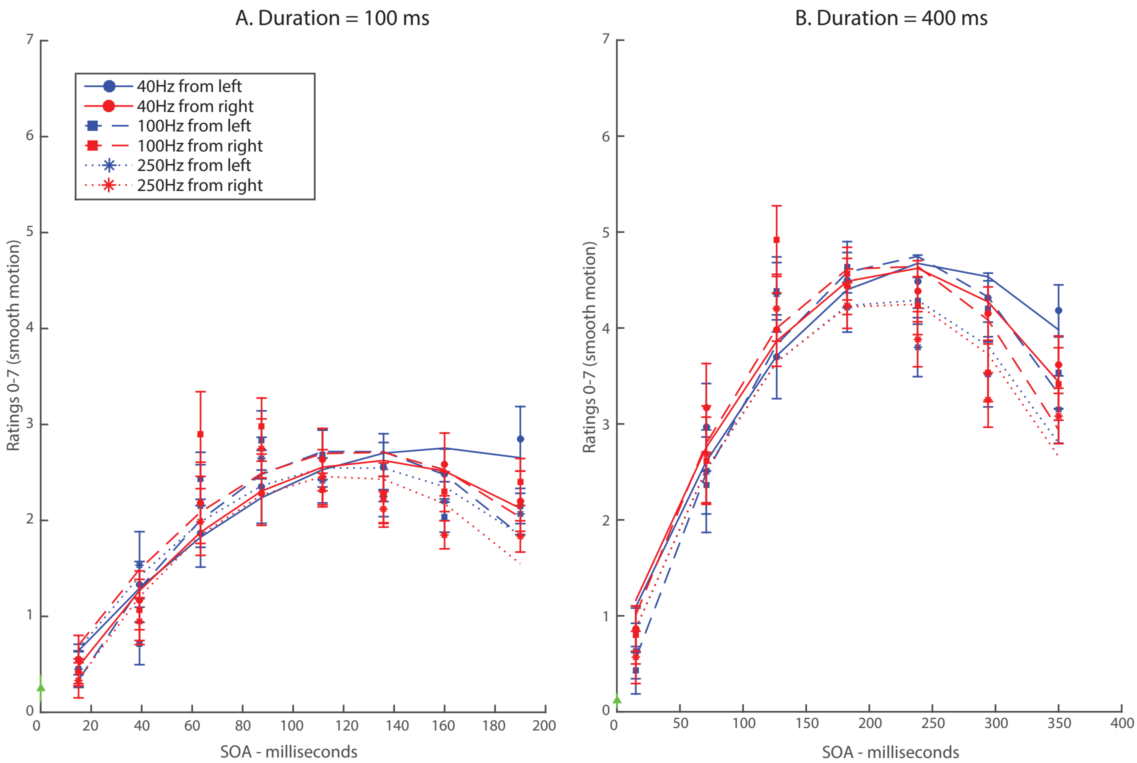


Figure 10.3: Plots of the ratings of the illusion of movement (x-axis) per SOAs (y-axis). The left graph shows the plot for 100 ms duration, and the right graph shows the plot for 400 ms duration. Dots and lines represent raw data and model fitting, respectively.

Fig. 10.3 illustrates the average ratings as a function of SOA for the two durations, the two directions, and the three frequencies, along with best-fit quadratic trends. The two lowest parts of the curves correspond to low SOAs (left part of the curves = merged tactile perception) and to high SOAs (right part of the curves = discrete tactile perception). The peaks of the curves are reported in Table 10.1, and they correspond to the optimal values of the SOAs needed to achieve a smooth sense of motion. On average, the optimal SOA value was found to be 177.21 ms.

Duration	Frequency	Direction	SOA peak (ms.)	R^2
100 ms	40 Hz	from left	158.57	.95
100 ms	40 Hz	from right	123.62	.83
100 ms	100 Hz	from left	123.32	.89
100 ms	100 Hz	from right	133.06	.94
100 ms	250 Hz	from left	125.33	.66
100 ms	250 Hz	from right	120.51	.86
400 ms	40 Hz	from left	247.45	.96
400 ms	40 Hz	from right	226.12	.95
400 ms	100 Hz	from left	216.27	.89
400 ms	100 Hz	from right	226.04	.96
400 ms	250 Hz	from left	213.09	.86
400 ms	250 Hz	from right	213.05	.90

Table 10.1: Optimal SOA values (in ms) and quadratic fit (R^2) for the different combinations of duration, frequency, and direction.

Fig.10.3 suggests non-linear trends of the rating scores. Moreover, comparing our results with previous research ([106, 261]), we can hypothesize that with very small and very large values of SOA, participants' ratings of the smoothness of motion will decrease. Therefore, a quadratic model seems more appropriate for describing our dataset. Using R software (v. 3.5.1) with the *nlme* package, we fit our data to a quadratic model accounting for individual differences between the subjects. "Subjects" represented our random variable (model 1). Our model, had a R^2 = .52, AIC[2] = 6541.12.

When inspecting Fig.10.3, there seems to be an interaction between the duration and SOA. Hence, we accounted for this interaction in our model. After fitting our dataset into a quadratic function, y = duration + SOA + SOA^2 + duration:SOA (model 2), the AIC decreased to 6386.93 (R^2 = .56). A likelihood ratio test between the two models suggested model 2 as more accurate in predicting our data, $p < .0001$. Therefore, our final model is:

[2]The Akaike information criterion (AIC) is a parameter used to compare different models, whereby the smaller the value between two models, the better the model fits the data (F. Korner-Nievergelt, T. Roth, S. von Felten, J. Gu´elat, B. Almasi, and P. Korner-Nievergelt (2015). "Chapter 11 - Model Selection and Multimodel Inference," in Bayesian Data Analysis in Ecology Using Linear Models with R, BUGS, and STAN, pp. 175-196.).

$$1) \quad y = 0.47 - 5 * 10^{-4} * dur + 2 * 10^{-2} * SOA - 9 * 10^{-5} * SOA^2 + 4 * 10^{-5} * dur : SOA$$

where the colon (:) represents an interaction. In this experiment we investigated the optimal parameters to achieve a smooth ATM between the two hands, employing a static point. In the next section, we will discuss the optimal parameters needed when using a dynamic point.

10.3 Experiment 2: Mid-air apparent motion: moving point optimal parameters

The aim of this second experiment was to investigate whether using a dynamic point instead of a static focal point on the palms would result in a smoother sensation of movement. For this experiment, we used again the same psychophysical approach used for experiment 1 (see Section 10.2.1).

10.3.1 Method

This second experiment consisted of 102 randomized tactile stimuli repeated three times, for a total of 306 stimuli. Participants received the same familiarization as in experiment 1 before proceeding to the study phase. An overview of the experimental design and conditions is shown in Fig. 10.2.

The procedure was the same as for experiment 1, with the key difference that the mid-air tactile stimulus was a dynamic focal tactile point instead of a static one. The focal point moved along a straight line from one hand to the other (see Fig. 10.1), being in contact with the participants' palm for a length of 4 cm, with a speed varying according to the duration of the stimulus. During the experiment, every stimulus was a combination of four variables: duration (100 ms and 400 ms), SOA (two different sets of eight and seven intervals, depending on the stimulus's duration, plus the control SOA), frequency (40 Hz, 100 Hz, and 250 Hz) and direction

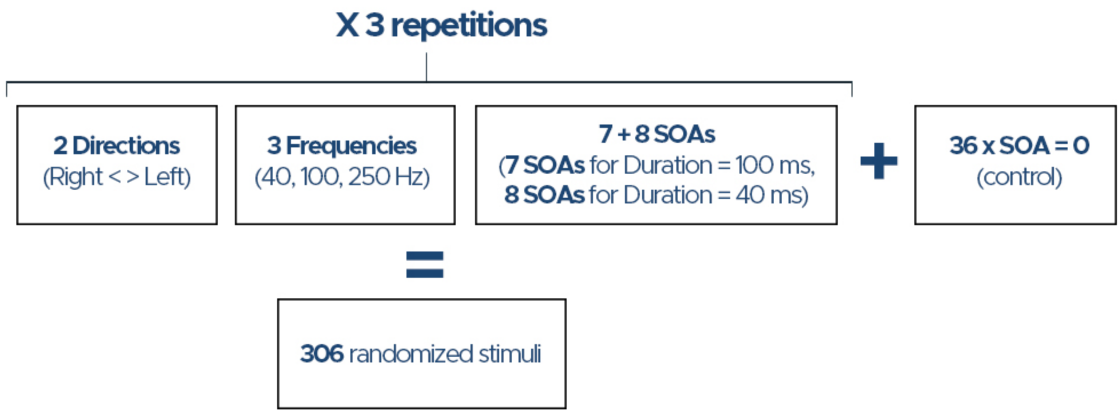


Figure 10.4: Experimental design for experiment 2. Every mid-air haptic stimulus was a combination of the four variables (i.e., duration, direction, frequency, and SOA), and a control condition with SOA set at 0, for a total of 306 randomized stimuli. The picture is not representative of the order of presentation of the stimuli.

(from left to right and vice-versa). Stimuli were presented one at a time, with at least a five-second gap to avoid tactile habituation. Each block was separated by a two-minute break. Participants wore headphones to mask environmental and device noises, and a "beep" sound was played through the headphones before the beginning of each trial. Overall, the experiment lasted 50 minutes. All participants were compensated with a £7.5 voucher for participating in the experiment.

10.3.2 Participants

A total of 20 participants took part in the study (nine females, age μ = 26, SD = ± 6.36). They had normal or glasses/lens corrected vision and no history of neurological or psychological disorders. All participants were right-handed. Upon arrival, participants were asked to read the information sheet and sign a consent form before the task was explained.

10.3.3 Results

To analyse the data, we followed the same procedure as in experiment 1. Fig. 10.5 illustrates the average ratings as a function of SOA for the two test durations, the two directions, and the three frequencies, along with best-fit quadratic trends. The two lowest parts of the curves correspond to low SOAs (merged tactile perception) and high SOAs (discrete tactile perception). The peaks of the curves correspond to the optimal values of the SOAs and are reported in Table 10.2.

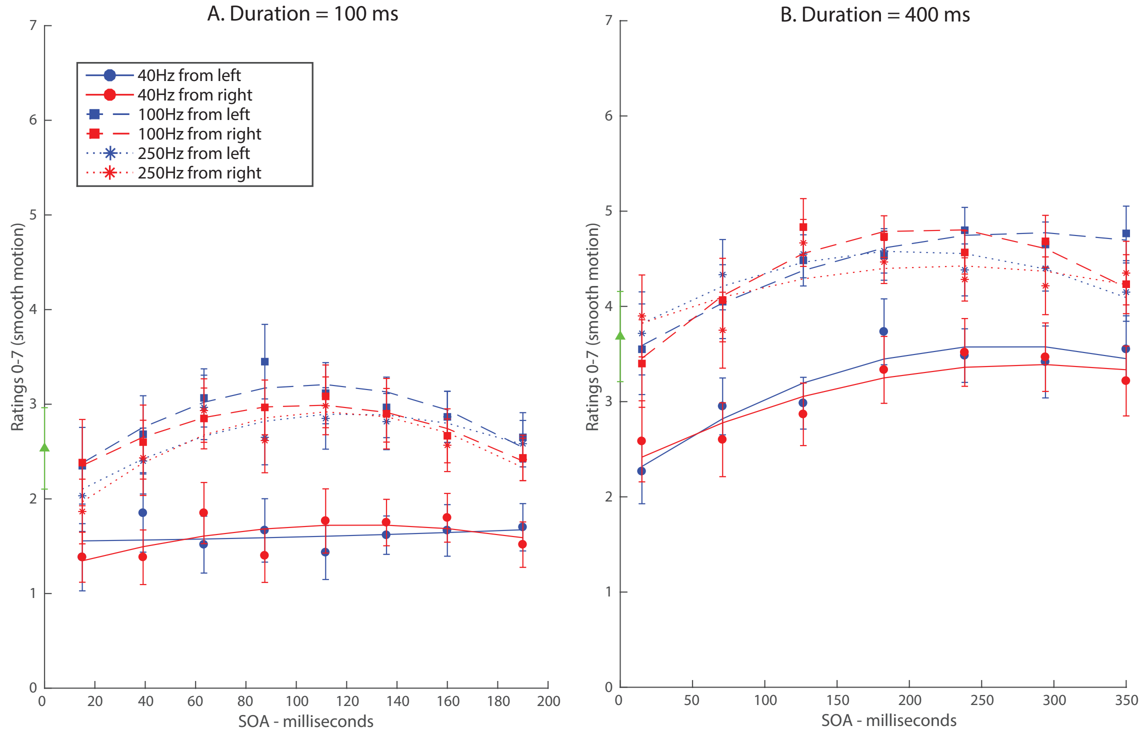


Figure 10.5: Plots of the ratings of the illusion of movement (x-axis) per SOA (y-axis). The left graph shows the plot for the 100 ms duration, and the right graph shows the plot for the 400 ms duration. Dots and lines represent raw data and model fitting, respectively.

On average, the optimal SOA value was found to be 175.53. As in experiment 1, our hypothesis was that with very small and very large SOA values, participants' rating of the smoothness of the illusion of movement should decrease. Therefore, we fit a quadratic model to describe our dataset: y = duration + SOA + SOA^2 (model 1). Moreover, from Fig.10.5, the curve for the 40 Hz frequency seems to have obtained a lower rating compared to the other two frequency curves (i.e., the 100 and the 250 Hz). Indeed, during the study, some participants referred to not being sure of the perception of this frequency because it was "too weak" and "subtle". Therefore, in our model we treated the variable frequency as categorical and used the 40 Hz frequency as the baseline. Our model obtained a R2 = .45. Below, we report the equations for the 40 Hz, 100 Hz, and 250 Hz frequencies:

2) $y = .66 + 4 * 10^{-3} * dur + 6 * 10^{-3} * SOA - 1.2 * 10^{-5} * SOA^2$

3) $y = 1.2 + 4 * 10^{-3} * dur + 6 * 10^{-3} * SOA - 1.2 * 10^{-5} * SOA^2$

4) $y = 1.1 + 4 * 10^{-3} * dur + 6 * 10^{-3} * SOA - 1.2 * 10^{-5} * SOA^2$

These results are consistent with the shape of the curves shown in Figure 10.5 (see the intercept term), where the 100 and 250 Hz frequencies seem to overlap, with the 40 Hz frequency having the lowest rating scores. In fact, some participants mentioned uncertainty about perceiving this frequency or described it as very light and hard to perceive.

In summary, based on our two experiments, we have created a first-time insight into the use of mid-air haptics for creating a tactile illusion of movement, testing a static versus a dynamic focal point. Below, we first discuss the findings by comparing both stimulation approaches, and then we present a discussion comparing our results using mid-air touch with the use of physical touch in the creation of ATM. We conclude with a discussion on future investigations and opportunities for design.

Duration	Frequency	Direction	SOA peak (ms.)	R^2
100 ms	40 Hz	from left	58.49	.07
100 ms	40 Hz	from right	107.34	.83
100 ms	100 Hz	from left	121.75	.80
100 ms	100 Hz	from right	124.48	.40
100 ms	250 Hz	from left	104.20	.95
100 ms	250 Hz	from right	112.95	.82
400 ms	40 Hz	from left	266.78	.87
400 ms	40 Hz	from right	280.84	.96
400 ms	100 Hz	from left	200.79	.87
400 ms	100 Hz	from right	285.47	.85
400 ms	250 Hz	from left	214.88	.90
400 ms	250 Hz	from right	228.40	.45

Table 10.2: Optimal SOA values (in ms.) and quadratic fit (R^2) for the different combinations of duration, frequency, and direction.

10.4 Comparing static vs. dynamic mid-air focal points

In this section, we are interested in comparing results from experiment 1 (static point) with experiment 2 (dynamic point), to understand how the perception of ATM is affected by the two different approaches employed in this study.

Upon a preliminary inspection, the rating curves of experiment 1 and experiment 2 (see Fig. 10.3 and 10.5) appear different, with the curves of experiment 1 being sharper and having a clear peak for the optimal SOAs. Moreover, when the SOAs are too short or too long, participants' ratings clearly decrease. On the contrary, for experiment 2, it is harder to visualize the same trend.

We hypothesize that when a dynamic focal point is delivered to the hands (experiment 2), subjects will always perceive a certain amount of movement, that is, the perceptual information will be perceived as more confusing compared to a static focal point (experiment 1). In other words, in the dynamic focal point condition, the SOA seems to play a minor role in the delivery of the illusion of movement. This means that when we want to render a smooth sensation of movement using a dynamic focal point, the SOA is not as crucial as for a static focal point.

Next, to compare the results obtained from experiment 1 with those of experiment 2, we estimated the linear and quadratic terms for predicting smoothness ratings from SOA at each duration (100 ms and 400 ms) and frequency (40 Hz, 100 Hz, and 250 Hz) for each subject (20). Therefore, we extracted six linear and six quadratic terms for each subject. We checked the distribution of these data through a Shapiro-Wilk test. Then, we ran separate independent t-tests between the linear and quadratic terms of data from experiment 1 and 2 across duration and frequency. If the distribution of a certain set of data did not follow a normal distribution, we employed a Mann-Whitney U test for the comparison.

When compared across the two experiments (static vs. moving mid-air point), the linear and quadratic terms obtained from the quadratic fitting of the smoothness ratings led to statistical differences in all cases (all the p-values $< .001$). The linear and quadratic coefficient of data from experiment 2 were lower in all cases compared to those of experiment 1. This demonstrates that the curves from Fig. 10.5 (experiment 2) are indeed flatter than those from Fig. 10.3 (experiment 1). Further, it confirms that when we deliver a moving point to the hands, the SOA does not play a fundamental role, and participants tend to rate the smoothness of motion always in the same way. This could mean that the physical and illusory movement provided on the hands are conflated in participants' perception.

Further, we were interested in understanding if the smoothness of motion ratings for experiment 2 were higher than those of experiment 1. We calculated the peaks of the curves for the smoothness of motion ratings for each participant (N = 20), for each duration (100 ms and 400 ms), and at each frequency (40 Hz, 100 Hz, and 250 Hz). Similarly to the previous analyses, we used an independent t-test or a Mann-Whitney U test, depending on the shape of the data distribution. For the duration = 100 ms we did not obtain any significant results ($p. > .05$). On the contrary, for the duration = 400 ms, we found two statistical differences: between the 40 Hz frequencies ($p. = .01$, 40 Hz-exp1-mean = 4.8; 40 Hz-exp2-mean = 3.8) and between the 250 Hz frequencies ($p. = .05$, 250 Hz-exp1-mean = 4.4; 250 Hz-exp2-mean = 5.1).

In light of these results, we cannot say if experiment 2 achieved a higher illusion of movement. Indeed, as previously stated, the 40 Hz frequency in experiment 2 was not well perceived, hence the significant difference. Participants reported the 40 Hz frequency as "too low", "too subtle", or "too sparse." It might be that the skin sensitivity along the stimulated location was not uniform, and an already subtle frequency would result in a confused perception. For the 250 Hz, the p. value is borderline, and it does not allow for strong conclusions. As this is the first investigation of mid-air tactile stimuli for creating ATM, further studies are needed to validate our research.

10.5 Discussion

This study investigated, for the first time, the occurrence of ATM using mid-air haptic technology, comparing a static versus a dynamic tactile focal point. With experiment

1 we established that it is possible to elicit an illusion of movement between two unconnected hands by using a static focal point. We then determined and described the optimal parameters to achieve a smooth tactile illusion of movement using a psychophysical approach. We generated a perceptual model that expresses the relation between the duration and SOA of the tactile stimuli (model 1). This model specifies the optimal parameters to use for achieving a smooth illusion of motion between the hands. The most relevant variables impacting users' perception are the duration and the SOA of the tactile stimuli, confirming previous results ([185, 260, 261]). In experiment 2, we replicated experiment 1 using a dynamic focal point. We derived a perceptual model (model 2,3,4) for the optimal parameters to achieve a smooth illusion of movement.

To enrich our understanding of creating a tactile illusion of movement, we compared results from experiment 1 and experiment 2 with respect to their effectiveness in achieving a smooth sensation of movement. The results suggest that there is no difference in the perceived smoothness of motion, but using a moving point could inflate the rating of the illusory motion.

10.6 Limitations and future research

Our results indicate that mid-air touch represents a promising approach to deliver an illusion of motion. In this section, we discuss some limitations and challenges of employing mid-air tactile technology, and we provide ideas for future research.

The mid-air haptic device provides a subtle tactile feedback (like puffs of air, or a breeze [171]), and as shown in experiment 2, low frequencies might constitute a limitation. Previous research has shown that the waveform of a tactile stimulus can lower or increase the absolute tactile thresholds (e.g., sinusoidal vs. square) [155]. Future work could investigate ATM produced by delivering the tactile mid-air stimulus through a different waveform (e.g., square shape) to observe whether the effect of the illusion would be strengthened.

In this study, we investigated ATM using a device positioned statically on a desk

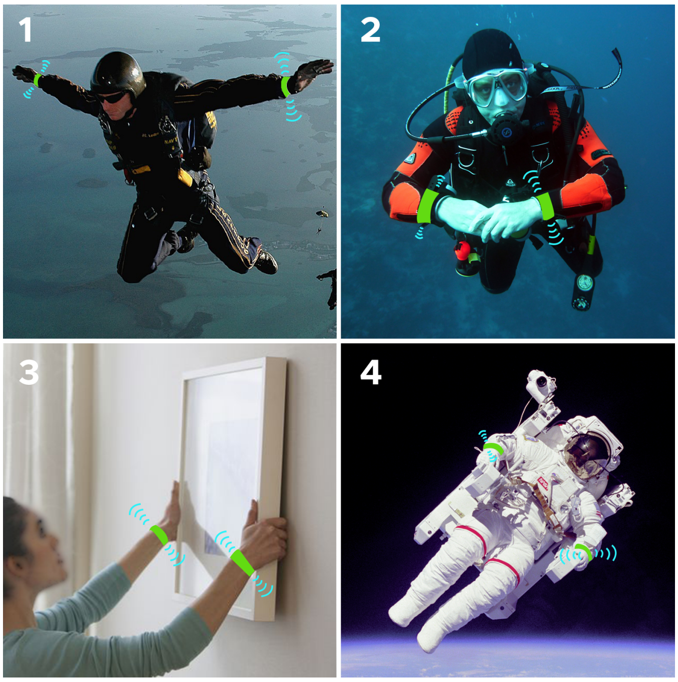


Figure 10.6: Example of applications where vision could be unreliable and ATM could provide alternative orientation information. 1) Skydiving: the environment could appear visually flat. 2) Underwater: humans can lose orientation underwater. 3) ATM could be used to provide information on balance (e.g., when hanging a picture on the wall, when the picture is straight, the motion will not be perceived anymore). 4) In space, humans can lose orientation.

to set the basis for understanding the phenomenon as mediated by mid-air touch. Future work could explore how this illusion of movement would change when the participant is free to move their hands in space.

Our findings and prior work [185, 261] have shown the occurrence of ATM between the hands. It would be interesting to test, with both mid-air and physical touch, the possibility of recreating an effect of movement between different parts of the body, for example, hands and feet, and to observe if the relationship between the durations and SOA of the tactile stimuli would change. Finally, other technologies could be used to explore ATM perception, such as wearable devices.

10.7 Conclusion

This study investigated, for the first time, the occurrence of ATM using a mid-air haptic device. We obtained the optimal parameters to achieve a smooth motion using a static versus a dynamic mid-air focal point. We provided a perceptual model for each approach used and then compared the results obtained from a static versus a dynamic point on the palms. These data suggest no difference between the two approaches, but the first (static point) might be preferable to achieve a cleaner sensation of motion.

Knowing the optimal parameters required to model a smooth sensation of movement can allow for new experiences in VR and non-VR environments. We can now feel the movement of the wind and the waves of the sea. In addition, the phenomenon of ATM could be used to provide directional information (e.g., as a tactile GPS) in cases where visual cues may be unreliable (e.g., in space, underwater, or when skydiving) or absent (e.g., in the dark or in the case of the visually impaired population). When in space, underwater, or free-falling in the sky, our vision may be unreliable and tactile motion could help to guide us towards our target. Furthermore, this sense of motion could provide hands-free information about the current position and balance of an object we are hanging or carrying (e.g., acting as a tactile bubble level) (Fig. 10.6).

We believe that this study provides a valuable insight into users' perception of mid-air tactile stimulation, and it will open a space for new immersive and realistic scenarios in gaming experiences in VR, AR, and traditional games. Next, we introduce our last study, for the "Apply" stage. In Study 6 while we apply an illusion of embodiment towards a virtual arm, we also create a virtual illusion of rain drops on the hand. Here, we demonstrate how our brain is capable to perceive visual-tactile congruence even when absent, to provide a more coherent version of the reality.

CHAPTER 11

STUDY 6 - APPLY TACTILE ILLUSION FOR EMBODIMENT IN VR[1]

Major virtual reality (VR) companies are trying to enhance the sense of immersion in virtual environments by implementing haptic feedback in their systems (e.g., Oculus Touch). It is known that tactile stimulation adds realism to a virtual environment and when users are not limited by wearing any attachments (e.g., gloves), it is even possible to create more immersive experiences. This means that when we try to convey haptic feedback through additional devices, such as hand-held controllers or haptic gloves, the users' presence could be disrupted. Therefore, it is important that we provide the user with a tactile medium that can be perceived as much as "invisibly" as possible, achieving a "perceptual illusion of non-mediation" [53, 148, 149, 159, 230]. In other words, users need to be unaware of the presence of the tactile device, while still being able to feel the stimulation generated from them.

Mid-air haptic technology provides contactless haptic feedback and offers the potential for creating such immersive VR experiences. However, one of the limitations

[1]Pittera D., Gatti E., Obrist M. "**I'm sensing in the rain: spatial incongruity in visual-tactile mid-air stimulation can elicit ownership in VR users**". In *Proceedings of the CHI Conference on Human Factors in Computing Systems*, Glasgow, UK, 2019.

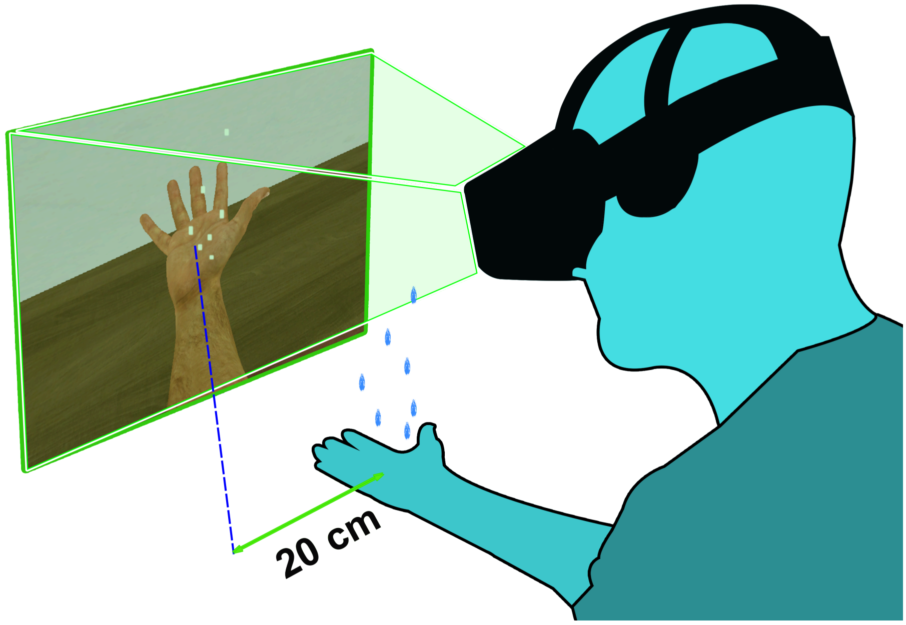


Figure 11.1: Illustration of the virtual hand illusion (VHI). A virtual arm is displayed in VR at the same height of the participant's hand. Both the virtual and the real arm receive synchronous tactile stimulation (e.g., raindrops simulated by mid-air touch). After few seconds, the participant will embody the virtual hand.

of mid-air haptics resides in the need for freehand tracking systems (e.g., Leap Motion) to deliver tactile feedback to the user's hand. These tracking systems are not accurate, limiting designers' capability of delivering spatially precise tactile stimulation.

In this paper, we investigate the illusion of falling raindrops that creates the illusion of real rain using mid-air tactile stimulation. To measure the illusion we exploit the phenomenon of the RHI in VR (referred to as VHI, see Fig. 11.1) using mid-air tactile stimulation. We use, not only the traditional congruent and incongruent visual-tactile stimulation approach, but for the first time exploiting mid-air touch in VR, we also use incongruent multiple stimulations. We demonstrate the occurrence of the illusion even during an incongruent visual-tactile condition, opening up new design explorations that help to overcome the effect of the current limitations of hand-free tracking systems (i.e., imprecise spatial tracking, thus, wrong tactile delivery on the hand). We hypothesize that mid-air touch is the right technology for this first time exploration, due to its controllability and requirement for no physical attachments in VR.

The contributions of this paper are: a) a systematic investigation of the reproducibility of the RHI in VR with real-time tracking and rendering of the human hand using mid-air tactile stimulation, b) demonstrating whether the illusion occurs with a multiple incongruent and multiple congruent stimulation approach, accounting for c) the relevance of the hand's posture (palm upward vs. palm downward) and d) demonstrating the importance of the stimulation type (tapping vs. stroking).

This is the last experimental study presented in the thesis and it falls under the "Apply" stage, aimed to answering if it is possible to convey the feeling of embodiment using mid-air haptics in VR (RQ3). While this research may seem unrelated to the previous studies investigating tactile illusions, also in this work we exploit a tactile illusion in a virtual context and replicating the illusion through mid-air technology. Further, we demonstrated the feasibility of embodying a virtual arm in our body schema.

11.0.1 The rubber hand illusion in VR

The RHI phenomenon has been widely studied since the late 90s. The key to achieving the illusion of ownership towards a fake arm is the visual-tactile congruency. That is when users can see the fake arm being stimulated, and they can feel the same stimulation at the same location and time on their own arm, they will be tricked to believe that the fake arm is actually their own. Following the first study by Botvinik et al. [19], many researchers investigated the key factors of this illusion. For instance, it has been demonstrated that a delay of 300 ms between the stroking of the two hands (i.e., real and fake) reduces the effect of the illusion, and a delay of 500 ms breaks the illusion [123, 211]. Kanayama et al. [125] used electroencephalography (EEG) activity in the gamma range to study the correlate of multimodal integration during the RHI using congruent and incongruent stimulation.

The advances in VR technology have made it possible to study new factors of the RHI illusion within psychology and other disciplines, including HCI [4, 104, 241]. VR technology allowed the study of additional variables of the RHI [153, 201, 214, 258].

The reproduction of the RHI in VR is defined as virtual hand illusion (VHI). The illusion is the same but is created in VR; participants wear an HMD and their arm is rendered as virtual arm. The virtual arm is shifted with respect to their physical arm. The researcher stimulates the participants' physical arm while they can see the physical stimulation through the HMD and feel it on their arm. After a while, participants will embody the virtual arm. Perez-Marcos et al. examined the results of seeing a body attached to a virtual arm [181]. Ma et al. investigated whether subjects can embody a non-corporeal object such as a virtual balloon or a square [166], and Lin et al. explored the role of graphics realism in the illusion, using different geometric hand models [146]. Choi et al. [33] studied the multisensory integration in the virtual hand illusion with active movement. Finally, Schwind et al. investigated the effect of visual realism on visual-haptic integration [206]. Successive researchers extended the VHI to the entire body [215], and studied the phenomenon of the body swap illusion (i.e., embodying another person's body) [7, 11, 156, 170, 182, 216]. Furthermore, other studies showed that people can embody a body with a different skin colour [52], a body of a different size [170], and a body of a different age [11].

Several studies explored the occurrence of the illusion for other parts of the body. For example, it has been shown that it is possible to achieve the embodiment of a fake foot (rubber foot illusion) [36, 144], and of an artificial tongue [162]. Moreover, Ramachandran et al. [189] showed that it is possible to embody a mannequin's head, and Ekroll et al. illustrated that people can be tricked into believing they have a shorter finger [50]. Finally, several researchers have demonstrated that it is possible to embody supernumerary hands [31, 87].

Taken together, these examples demonstrate how flexible our body schema is and that it is possible to perturb it to include different body parts or even an entirely different body. From an HCI perspective, these findings on the creation of bodily illusions and embodiment, provide inspiration for designing novel VR experiences involving the sense of touch, which can reinforce the embodiment. Here we explore to what extent mid-air haptics can be used to push the boundaries of the body ownership and recreate the RHI in VE.

11.0.2 Contribution of the present work to HCI

With our work we explore the VHI phenomenon demonstrating that our brain can fill in the gap between spatially incongruent visual-tactile stimulations (gap between what we see and what we feel on the hand) maintaining the feeling of body ownership in situation other than perfectly, spatially matching, stimulation. In particular, we exploit the advantages of an ultrasound mid-air haptic device, and we recreate the VHI illusion varying the congruency of the stimulation (i.e., congruence and incongruence). We additionally employ multiple incongruent visual-tactile stimulations to overcome the effect of the current limitation of the free-hands tracking systems (i.e., imprecise spatial tracking) on reported body ownership in VR. While the VHI has been studied before, it has not been explored using the emerging mid-air touch technology (see [104] for an early paper on the RHI, but not in VR). Hence, the novelty of our study is the use of multiple mid-air tactile stimuli in VR, testing the occurrence of the VHI in congruent and incongruent conditions. This has never been attempted before but offers interesting directions because it could solve the lack of precision of free-hand tracking devices.

Following, we 1) present a first experiment in VR that exploits the VHI using multiple incongruent visual-tactile stimuli. Then, we present two additional control experiments in which we 2) assess the influence of the hand's posture when participants are stimulated with a tapping stimulation (as in our VR study) by means of physical touch, and we 3) assess the influence of the hand's posture with a stroking stimulation.

11.1 Experiment 1: VHI mediated by mid-air haptics

With this experiment, we tested if the VHI can be mediated through mid-air tactile stimulation (comparing congruent and incongruent tactile stimulation) and if it is possible to maintain a sense of ownership toward a virtual arm even when

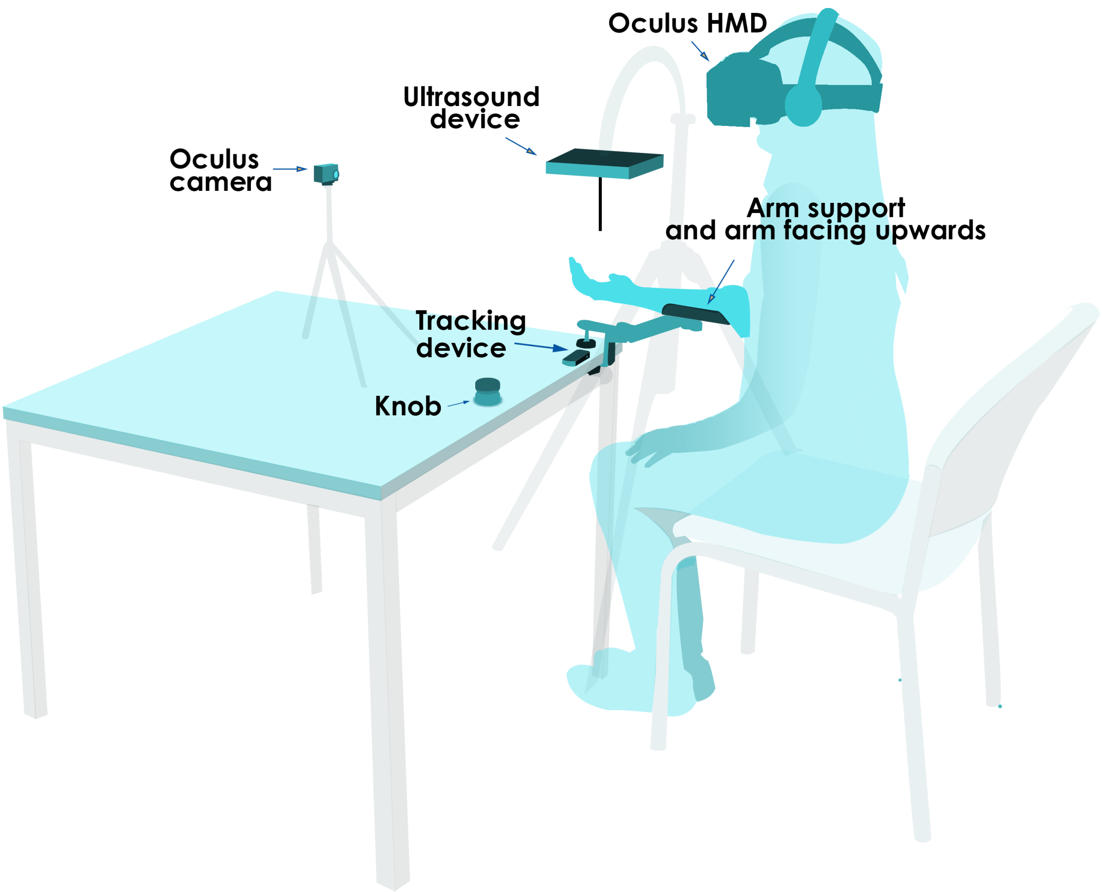


Figure 11.2: Set-up. The participant wore an HMD Oculus DK2 and sat on a chair with the arm resting on a support between the mid-air haptic device using ultrasound and the tracking system (Leap Motion). A knob was used to measure the proprioceptive drift.

using visual-tactile incongruent stimulation (multiple incongruent stimuli condition). These conditions have not been studied before, and it is interesting because it may allow the creation of an illusion overcoming the limitations of the current free-hand tracking systems.

11.1.1 VR and device set-up

We used the mid-air haptic device (by Ultrahaptics) to deliver tactile feedback to the participant's real hand using stimuli modulated at 200 Hz frequency. The VE consisted of a virtual version of the space where the study took place. Fig. 11.2 shows the set-up with the participant resting his/her arm facing upward on an arm support. Participants received a tactile stimulation on their palm from the top, mimicking raindrops. We used raindrops as the scenario for our experiment, taking inspiration

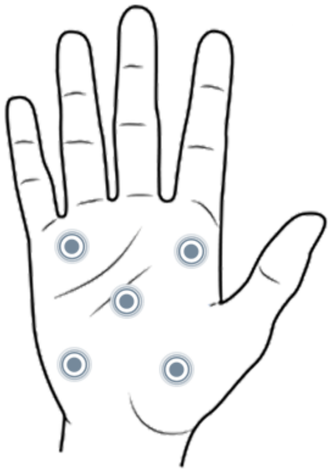


Figure 11.3: The five locations stimulated by the mid-air haptic device during the congruent and incongruent conditions.

from a work by Obrist et al., where users described the sensation of the mid-air haptic device as "dry rain" [171]. This hand posture is different from the one used in the standard RHI/VHI set up, where the hand is maintained facing down. We could not use a facing down posture to experience the raindrops, as the mid-air stimulation is best perceived on the glabrous (non-hairy) part of the hand [251], and also to simulate the natural movement of a raindrop. Participants experienced a virtual arm through an HMD (Oculus Rift DK2, field of view: 100 degrees with an estimated 960 x 1080 pixels per eye resolution, displayed at 60 to 75 Hz) that was real-time tracked by a hands-free tracking device by Leap Motion. Although we did not allow for movement during our experiment, the tracking device was necessary to render the arm in VR. The virtual arm was rendered by using the Leap Motion Core Asset for Unity 3D. This package comes with the UV maps for the 3D hands allowing matching participants' gender and skin colour.

Our experimental design, presented in the following sections, accounts for the difference in the set-up compared to the traditional VHI. Hence, we performed two control experiments to verify that the different hand's posture and stimulation type are not necessary for the illusion of ownership.

11.1.2 Study conditions

We investigated the VHI with the two traditional conditions: 1) a congruent visual-tactile stimulation, 2) an incongruent visual-tactile stimulation, and we additionally tested 3) a multiple incongruent stimulation condition, and 4) a multiple congruent stimulation condition.

1) **Congruent condition**: stimuli in VR were rendered visually by virtual drops of water falling one after the other, with a one-second interval, onto five locations on participants' virtual right hand (see Fig. 11.3). The mid-air tactile stimulation on the participants' real hand matched the location seen in VR.

2) **Incongruent condition**: the tactile stimulation on the participants' real hand did not match the location seen in VR. According to previous research [19], an incongruent visual-tactile stimulation breaks the illusion. We tested this condition delivering the tactile feedback (i.e., drops of water) randomly on a different location from that which participants could see in the VE.

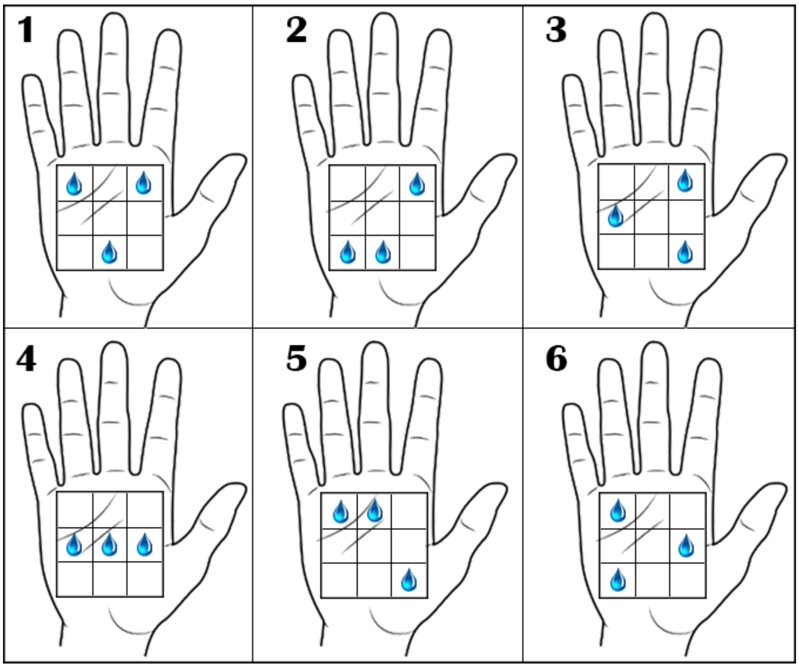


Figure 11.4: The six patterns used in the multiple incongruent and multiple congruent stimulation in VR. Each drop (rendered by a focal point) is approximately 1 cm of diameter, and at least 1 cm distant from the others, allowing the delivery of discrete mid-air tactile stimuli.

3) **Multiple incongruent stimuli**: this was one of the new conditions we in-

troduced in our study. We were interested to investigate whether the illusion can also occur using multiple incongruent stimuli enabled through the mid-air haptic device. Previous work established that a minimum of 1 cm distance between mid-air focal points is needed to ensure the discriminability of two tactile points [251]. The diameter of the focal point is also approximately 1 cm, hence, we divided the hand into a 3x3 grid (see Fig. 11.4). We delivered different patterns of three stimuli at a time, to make sure that all of our participants could have enough surface available on the palm to receive the stimulation, and so that the perception areas of the stimuli were not overlapping. Participants could see three drops of water in VR hitting the hand at the same time. The tactile stimulation on the real hand was rendered on three random incongruent locations.

4) **Multiple congruent stimuli**: as a control condition for the multiple incongruent stimulation, we also tested a multiple congruent stimuli condition. In this condition, we delivered three drops in VR visually congruent with three congruent tactile stimuli on the participant's real hand.

Overall, our investigation followed a repeated measures design with one factor at four levels (i.e., congruent, incongruent, multiple incongruent, and multiple congruent). The four conditions were randomized across participants. Participants were compensated with a £5 Amazon voucher.

11.1.3 Measures

To investigate the VHI illusion mediated through mid-air touch we gathered two established measures: a questionnaire for the subjective feeling of the illusion, and the proprioceptive drift measurement, an objective indicator of the illusion.

11.1.3.1 The questionnaire

We used the questionnaire originally used in Botvinick and Cohen [19] adapting the wording to take into account the difference in our set-up (e.g., the tactile stimulus was provided through drops of water in VR, rendered through mid-air tactile stimuli, instead of a brush). The questionnaire consisted of 9 items as shown in Table 11.1.

QUESTIONS
Q1. It seemed as if I were feeling the mid-air touch in the location where I saw the drop touching my virtual hand
Q2. It seemed as though the touch I felt was caused by the drops touching the virtual hand
Q3. I felt as if the virtual hand were my hand
Q4. It felt as if my (real) hand were drifting toward the left (toward the virtual hand)
Q5. It seemed as if I might have more than one left hand or arm
Q6. It seemed as if the touch I was feeling came from somewhere between my own hand and the virtual hand
Q7. It felt as if my (real) hand were turning "virtual", less consistent
Q8. It appeared (visually) as if the virtual hand were drifting toward the right (toward my real hand)
Q9. The virtual hand began to resemble my own (real hand, in term of shape, skin tone, freckles, hairs or some other visual feature)

Table 11.1: The 9-item questionnaire (from [19]). We adapted the wording to take into account the difference in our set-up (e.g., the tactile stimulus was provided through drops of water in VR, rendered through mid-air tactile stimuli, instead of a brush).

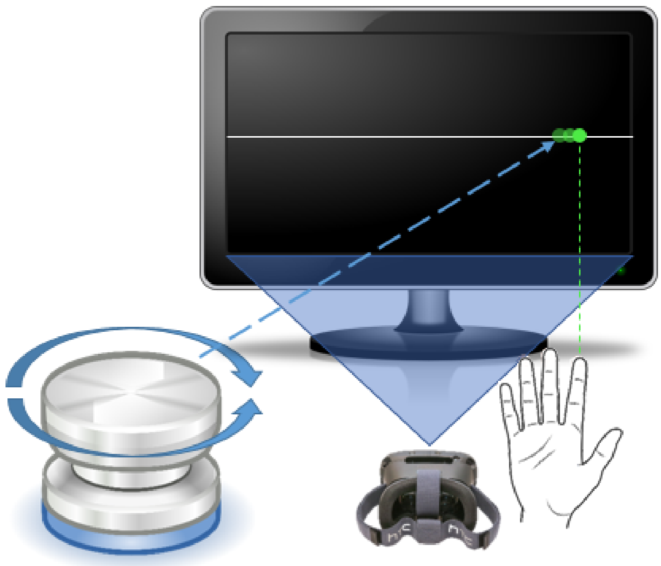


Figure 11.5: The proprioceptive measurement. Participants saw a black screen with an infinite white line and a cursor (green sphere) on it. By rotating the knob (left) they could move the cursor on the line until they felt the cursor position was matching their index finger.

The answers could vary on a Likert scale from 1 ("I strongly disagree") to 7 ("I strongly agree"). Q1 to Q3 measure the subjective illusion effect [19]. The remaining questions are considered as control questions.

11.1.3.2 Proprioceptive drift

The proprioceptive drift is a measure to determine the relative displacement of the perceived location of one's own hand toward the location of the fake hand after the stimulation, compared with a pre-stimulation baseline. To measure the proprioceptive drift we followed a similar approach to Suzuki et al. [227]. Before and after each stimulation, participants were shown a black background in VR, with an infinite white 3D line fronto-parallel to their right hand, where a cursor (a green ball) could be moved by the rotation of a knob (Fig. 11.5). Participants had to move the cursor with their left hand to match the perceived location of their index finger and press the knob to register the cursor coordinates. In all cases, the difference between the cursor's position in the pre and post-stimulation corresponded to the proprioceptive drift. A drift toward the virtual hand is considered an indicator of the illusion [19].

11.1.4 Methods

At the beginning of the study, participants sat on a chair. After putting on the HMD, participants had the possibility to explore the VE to familiarize themselves with the virtual set-up and the HMD. They were also invited to move their hand over the hand tracker system (Leap Motion), to experience the render of their hand in VR. The virtual hand was rendered but shifted about 20 cm to the left of the real hand location, to allow an appropriate mismatch for the proprioceptive drift measurement (following past procedures, see [35, 123, 158, 254]). Participants could see in VR their right arm from a first-person perspective. After this initial familiarization, the test phase started where the participants' right arm was guided onto an arm support at mid-way between the hand tracking device (Leap Motion) and the ultrasound array (see Fig. 11.2). The centre of the participants' palm matched the centre of the ultrasound array, allowing a real-time tracking of the hand. The mid-air device faced down toward the tracking device, with the subject's hand in between. The mid-air device was placed at 20 cm of distance above participants' hand, which is the optimal operative distance suggested for this device [27], and at the same time, allowed the hand tracking device to work smoothly. The chair was kept in a fixed position for every participant. In previous studies, the stimulation duration ranged from a minimum of 45 s to a maximum of 240 s [36, 40, 102, 124, 234]. As no specific explanation is provided in prior work, and given that the illusion occurred in all cases, we selected the middle value of 120 s. Participants experienced all four conditions in a randomized order (see the section Study Conditions). They were asked to focus exclusively on the palm of the hand, and to not move the right arm and hand (the one rendered in VR) to avoid receiving updated information regarding the position of their real hand. The proprioceptive drift was measured at the beginning and at the end of each condition. Additionally, at the end of each condition, participants completed the 9-item questionnaire illustrated in Table 11.1. The study consisted of four conditions for a total of 30 minutes. Participants wore headphones reproducing white noise to cover any environmental and device noises.

11.1.5 Participants

For this study, we recruited 20 participants (9 females). Their mean $\pm$ SD age was 25.5 ± 7.9. They had normal or glasses/lens corrected vision and no history of neurological or psychological disorders.

11.1.6 Results

Here, we present the results of the study based on the combination of the subjective (questionnaire) and the objective (proprioceptive drift) measures.

Questionnaire: All the participants completed the 9-item questionnaire four times. Q1, Q2, and Q3 were likely not following a normal distribution (Shapiro-Wilk, $p < .05$). We ran a Friedman test on the calculated means of the answers given

	Descriptives for Q1 + Q2 + Q3		
Condition	*Mean rank*	*Mean*	*Std. Deviation*
Congruent	2.93	5.38	1.70
Incongruent	1.84	3.75	2.05
Multiple incongruent	2.81	4.98	1.74
Multiple congruent	2.43	4.77	1.60

Table 11.2: Descriptives for Q1 + Q2 + Q3. The higher the values, the more ownership was felt by the participants.

by the participants to Q1, Q2, and Q3, for the congruent, incongruent, multiple incongruent, and multiple congruent conditions. The Friedman test indicated a significant difference between groups, $\chi^2(3) = 32.2$, $p < .001$. A Wilcoxon signed-rank test was performed to further investigate the difference between groups. We used a Bonferroni adjustment for the Wilcoxon test's results to interpret the data and avoid a type I error. Hence, we divided the significance level of .05 by the number of tests made (six). Therefore, the new significance level was set at .05/6 = .008. Descriptive statistics of Q1, Q2, and Q3 are shown in Table 11.2.

The congruent and the incongruent condition were significantly different, $Z = -4.69$, $p < .001$, with the congruent condition being more able to convey the illusion of ownership. There was no difference between the congruent condition and the multiple congruent and incongruent conditions ($p > .008$). In addition, there was no significant difference between the multiple congruent and the multiple incongruent conditions ($p > .008$). Lastly, our two multiple stimulation conditions significantly differed from the incongruent condition, $p < .001$. Q4 to Q9 are traditionally considered control questions. As expected, their ratings did not show any significant differences, therefore, they will not be discussed further.

Proprioceptive drift: The Shapiro-Wilk test indicated our data to likely follow a normal-like distribution ($p > .05$). In our dataset, there were no outliers. Thus, we ran an ANOVA repeated measures to compare the averages of the results (proprioceptive displacement in cm) of our four conditions. Mauchly's test of sphericity indicated that the assumption of sphericity had not been violated, $\chi^2(9) = 8.903$, $p = .448$. The ANOVA highlighted a statistical difference between our four conditions, $F(3,76) =$

	Cong.	Incong.	M. incong.	M. cong.
Cong.	=	≠	=	=
Incong.	≠	=	≠	≠

Table 11.3: Pairwise comparisons for the four conditions: congruent, incongruent, multiple incongruent, and multiple congruent. "=", no difference between groups. "≠", difference between groups.

10.01, $p < .001$. To better investigate the differences between groups, we analysed the pairwise comparisons. Fig. 11.6 shows the box plot of the proprioceptive drift for the different conditions.

First, the congruent and the incongruent condition were statistically different ($p < .01$), with the congruent condition having higher scores as suggested by literature. As for the subjective feeling of ownership (questionnaire), the data for the proprioceptive drift highlighted no difference between the multiple congruent and the multiple incongruent conditions ($p > .05$). Interestingly, the congruent condition was not statistically different from the multiple incongruent ($p > .05$) and from the multiple congruent conditions ($p > .05$). The incongruent condition resulted to be statistically different from the multiple congruent condition ($p < .05$) and from the multiple incongruent condition ($p < .05$). See Table 11.3 for an overview of these results.

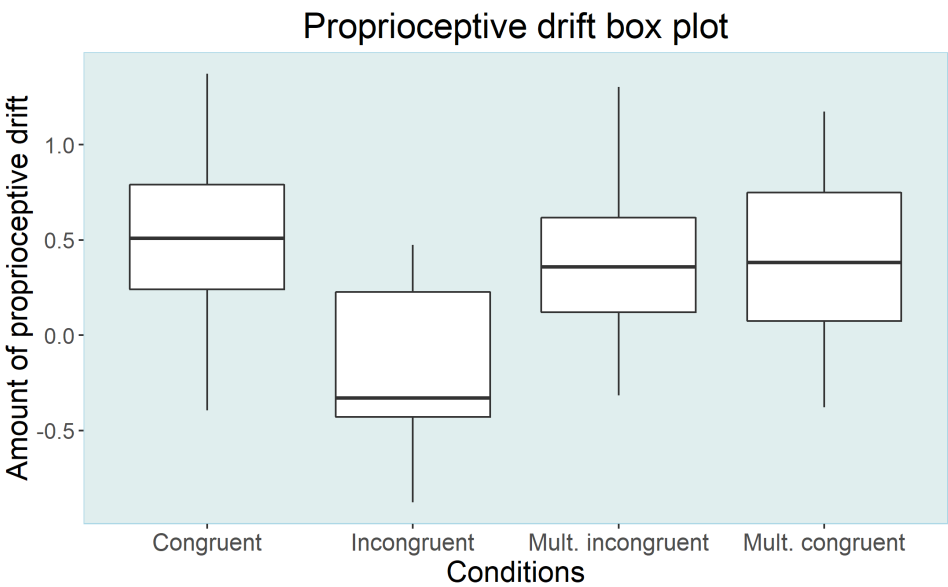


Figure 11.6: Box plot of the proprioceptive drift. The highest the values, the bigger the drift toward the virtual hand. In our scenario, 0.1 Unity units correspond to 1 cm.

11.2 Summary

As expected, results from the questionnaire indicated that the illusion of ownership toward the virtual arm is subjectively felt during the congruent condition. The same is true for the multiple congruent condition. However, the illusion also occurred in the multiple incongruent condition. This means that even when we deliver incongruent visual-tactile stimulation (i.e., participants see visual stimuli in one location, but they feel them on a different location) it is still possible to achieve an illusion of ownership of the virtual hand. These results are additionally confirmed by the proprioceptive measurements. Our data indicated that participants experienced the same amount of proprioceptive drift toward the virtual arm during the congruent, the multiple congruent and the multiple incongruent conditions.

Finally, we provide some hypotheses to justify why multiple incongruent stimuli felt as congruent. These hypotheses are: 1) Effect of temporal saliency: when the stimuli happen together we are not able to perceive the visual-tactile incongruence. 2) Spatial acuity: it decreases by increasing the number of stimuli. 3) Cognitive load: it is hard to focus the attention on the visual stimuli and their tactile effect, hence, we are not aware of the discrepancy.

Additionally, one may argue that the upward posture of the hand constricts the user to a more unnatural hand position in comparison with the downward posture. Hence, the user will receive more proprioceptive information (information regarding the position of the limbs across space) from tendons and muscles with the possible effect of reducing the strength of the illusion. Hence, we conducted two more studies (in what follows, control studies) exploiting the traditional RHI set-up, to assess the influence of the hands posture (downward vs. upward).

11.3 Experiment 2, RHI: tapping

With this first control experiment we aimed to assess the influence of the hand's posture when participants were stimulated by tapping stimulation (as in our VR study) by mean of physical touch.

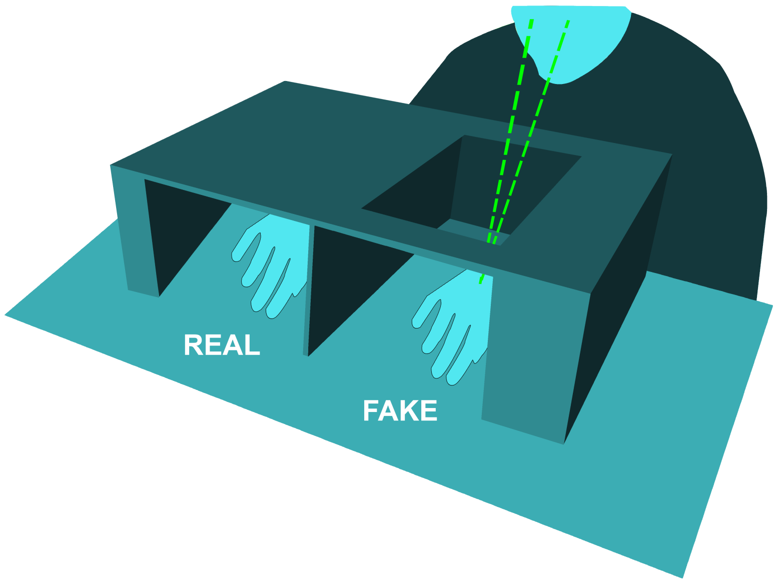


Figure 11.7: The RHI set-up. A cardboard box was built. The box had two entrances, one for the participant's right arm, and one for the fake arm. Once inside the structure, participants could see only the fake arm.

11.3.0.1 Conditions

We delivered tactile stimulation through two paint brushes (simulating the raindrop sensation in our mid-air stimulation in VR) with a diameter of 1 cm at the tip. The physical tactile stimulation was delivered on the real and on the rubber arm. The study was composed of four randomized conditions:

1. Palm down and synchronous stimulation.
2. Palm down and asynchronous stimulation.
3. Palm up and synchronous stimulation.
4. Palm up and asynchronous stimulation.

During each condition, the rubber hand was at a distance of 20 cm from the participant's hand. The stimulation was a tapping-like (non-continuous) stimulation lasting 120 seconds. The experiment lasted 30 min and participants received £5 Amazon voucher.

11.3.0.2 Methods

The behavioural measures obtained were the same as in our previous study: the questionnaire and the proprioceptive drift. We measured the proprioceptive drift before and after each condition. To do that, we built a cardboard box that had two entrances (see Fig. 11.7). The right entrance was for the participant's right arm; once in it, they were not able to see their real arm. The rubber arm was introduced in the left entrance. Furthermore, participants' right shoulder was covered with a black cloth. Before and after each condition, we asked participants to close their eyes and to mark over the cardboard box where they thought the position of their right index finger was. For a more accurate measurement, they repeated this process six times for each condition, three times before the stimulation, and three times after the stimulation. We calculated the averages of the three measurements before the stimulation and of the three after the stimulation. The difference between the averages of the pre- and post-stimulation was then used to assess the proprioceptive drift (in cm). As before, after each stimulation participants were asked to complete the 9-item questionnaire (see Table 11.1).

11.3.0.3 Participants

For this control experiment, we recruited 10 new participants (5 females). Their mean $\pm$ SD age was 21.8 $\pm$ 1. They had normal or glasses/lens corrected vision and no history of neurological or psychological disorders.

11.3.0.4 Results

Questionnaire: All the participants completed the 9-item questionnaire four times. Our data did not follow a normal-like distribution, therefore we proceeded with a Friedman test on the grouped Q1, Q2, and Q3, of our four conditions: palm down synchronous, palm down asynchronous, palm up synchronous, and palm up asynchronous. The Friedman test indicated a significant difference between groups, $\chi^2(3) = 38.8$, $p < .000$. A Wilcoxon signed-rank test was performed to further investigate the difference between groups. We employed a Bonferroni adjustment on the Wilcoxon tests results, in order to avoid a type I error. Hence, we divided the significance level of .05 by the number of tests made (six). Therefore, the new significance level was set at .05/6 = .008. Data showed a significant difference between the palm down synchronous vs. palm down asynchronous condition, Z = -3.67, p < .001. There was also a significant difference between the results for the palm up synchronous vs. the palm up asynchronous condition, Z =-4.01, p < .000. A comparison between the palm down synchronous and the palm up synchronous condition did not highlight any difference (p = .574).

	Descriptives for Q1 + Q2 + Q3		
Condition	*Mean rank*	*Mean*	*Std. Deviation*
Palm down sync	3.25	4.83	1.64
Palm down async	2.13	3.20	1.44
Palm up sync	3.05	4.67	1.86
Palm up async	1.57	2.57	1.13

Table 11.4: Descriptives for Q1 + Q2 + Q3. The higher the values, the more ownership (occurrence of the illusion) was felt by the participants.

Proprioceptive drift: We first checked the proprioceptive drift data for normality. The Shapiro-Wilk test indicated a normal-like distribution (p > .05). Thus, we ran a two-way repeated measures ANOVA to compare the averages of the results of the four conditions. While we found a significant difference between the synchronous and asynchronous conditions (p = .013), as expected we did not find a significant difference between the palm's postures (p = .73).

This first control experiment demonstrated that the hands' posture is not crucial to ensure a successful embodiment of the fake arm. Hence, our study results using the upward posture in the mid-air haptics VHI set-up are strengthened. In the next control experiment, we again tested the hands' posture, this time using a stroking-like tactile stimulation (as in the traditional RHI/VHI set-up).

11.4 Experiment 3, RHI: stroking

We now test the hands' posture with a stroking stimulation.

11.4.0.1 Conditions

This experiment was structured identically to the previous control experiment, however, instead of a tapping stimulation, we stimulated the real and the rubber hand with a stroking (continuous) stimulation.

11.4.0.2 Methods

The behavioural measures were the same as in the previous control experiment: the 9-item questionnaire and the proprioceptive drift measurement.

11.4.0.3 Participants

For this experiment, we recruited a new set of 10 participants (6 females). Their mean ± SD age was 22.3 ± 1.4. They had normal or glasses/lens corrected vision and no history of neurological or psychological disorders.

11.4.0.4 Results

Questionnaire: All the participants completed the 9-item questionnaire four times. The resulting data did not follow a normal distribution, therefore we proceeded with a Friedman test on Q1, Q2 and Q3 of the four conditions: palm down synchronous, palm down asynchronous, palm up synchronous, and palm up asynchronous. The Friedman test indicated a significant difference between groups, $\chi^2(3) = 52.9$, $p < .000$. A Wilcoxon signed-rank test was performed to further investigate the difference between groups. We applied a Bonferroni adjustment to the Wilcoxon tests results, in order to avoid a type I error. Hence, we divided the significance level of 0.05 by the number of tests made (six). Therefore, the new significance level was set at $.05/6 = .008$. Data showed a significant difference between the palm down synchronous vs. asynchronous condition, $Z = -4.38$, $p < .000$. We found the same result for the palm up synchronous vs. asynchronous condition, $Z =-4.32$, $p < .000$. A comparison between the palm up vs. palm down synchronous conditions did not highlight any significant difference ($p = .284$).

	Descriptives for Q1 + Q2 + Q3		
Condition	*Mean rank*	*Mean*	*Std. Deviation*
Palm down sync	3.38	6.10	1.39
Palm down async	1.75	3.10	1.66
Palm up sync	3.20	5.93	1.59
Palm up async	1.67	3.33	1.90

Table 11.5: Descriptives for Q1 + Q2 + Q3. The highest the values, the more ownership was felt by the participants.

Proprioceptive drift: We checked the proprioceptive drifts' data for normality. The Shapiro-Wilk test indicated a normal-like distribution ($p > .05$). Thus, we ran a two-way repeated measures ANOVA to compare the averages of the results of the four conditions. We found a significant difference between the synchronous and asynchronous conditions ($p = .025$). There was no difference between the palm's postures ($p = .31$).

This second control experiment re-confirmed that the hands' posture is not affecting the RHI, even when we use a stroking-like stimulation. Thus, our findings using mid-air tactile stimulation in VR are strengthened.

11.5 Discussion

Our main experiment in VR demonstrated how multiple visual-tactile incongruent stimulations were perceived as a congruent experience by the user. This can contribute to the design of even more realistic and immersive experiences in VR. Below we provide a final discussion on the findings and their relevance for HCI.

11.5.1 VHI mediated through mid-air touch

We investigated the virtual hand illusion introducing five variants to the traditional paradigm. Such variants regarded 1) the posture of the hand (palm upward vs. downward), 2) the stimulation type (tapping vs. stroking), 3) the number of incongruent stimuli delivered simultaneously during the stimulation (in the condition where multiple spatially incongruous/congruous taps were delivered to the virtual hand), 4) the use of a mid-air haptic device to deliver the tactile feedback. Our results indicated a subjective feeling of ownership toward the virtual arm during spatially congruent visual-tactile stimulation (see [19]), regardless of the number of the stimuli delivered simultaneously on the hand. Interesting, multiple spatially incongruent stimuli were also able to induce feeling of ownership in the users. In other words, it is possible to elicit body ownership toward a virtual arm even when there is a gap between what we see in VR and what we feel in reality, as long as the stimulation happens in multiple location simultaneously.

To test the influence of the new variants which we introduced in our set-up compared to the traditional RHI/VHI, we performed two additional control experiments, accounting for two different hand postures (upward vs. downward) and two different stimulation type (tapping vs. stroking). The results from the subjective reports and from the objective measurement did not highlight any influence of hand posture or stimulation type on the occurrence of the illusion, which took place as described in literature in cases where the palm was facing downward and the tactile stimulation was delivered by stroking.

11.5.2 Design potential for multiple incongruent stimulation

We envision three design scenarios that exemplify the benefit from the visual-tactile incongruence stimulation and highlight potentials for future research.

Scenario 1: We can imagine an AR/VR interface (e.g., computer desktop) where the user can select the icons receiving tactile feedback. The free-hand tracking system does not allow a precise matching between the visual and the tactile cues. Therefore, when touching the edges of the virtual icons on the interface, one could receive the tactile feedback on the wrong location on the hands with respect to what he is looking at in the VR/AR environment. This is a situation where multiple incongruent tactile points (the edges of the virtual icons' shape) are displayed visually in a certain location but rendered tactilely on a different one. Nevertheless, our design could provide a solution, since that users would be able to feel the multiple incongruent stimulation as congruent. In this way, we can provide the user with an understandable and realistic tactile percept, even in an incongruent visual-tactile stimulation. We still do not know if our paradigm could be applied on the fingertips; future research needs to investigate tactile perception of multiple incongruent stimulation on the fingertips in which the density of tactile receptors varies.

Scenario 2: Similarly, our paradigm could be applied to those applications where the system (e.g., VR or AR) would need to render a perfect reproduction of the real environment to allow physical social interaction. For instance, one of the last VR social networks, Facebook Spaces, shows how multiple people from different locations can join together in a shared virtual space. Each of the users is represented in the VE through an avatar simulating their body presence. These avatars are obviously different from the bodies of the users. This means we do not have a one to one representation of the users' body. In other words, if one of the users in the VE would like to express something via touch to another virtual user, both of the users will have to deal with a non-perfect visual-tactile correspondence. Our study indicates that even if the users A and B will see the tactile stimulus happening on a certain spot (on the virtual avatar) and they will feel it on another (on their real body), the experience will be perceived as congruent. Future work can expand this knowledge towards an exploration of multiple incongruent stimulation at different body parts (e.g., fingertips, shoulders, torso, etc.).

Scenario 3: In the famous film "Singing in the rain", Gene Kelly is dancing and singing in the rain. What few knows, is that after that scene, Gene endured a 103 F (39° Celsius) fever. Based on our work, we can imagine people watching this film scene in a cinema or home cinema setting, feeling the sensation of being under the rain, without getting wet or sick. In fact, mid-air haptics can provide the sensation of "dry rain" [171]. For such complex scenario, further insights into the tactile perception of mid-air haptics and the creation of illusions is required. However, as shown by prior work (see [1]), there is the potential to design more immersive and emotionally engaging film experiences through the use of mid-air haptic technology.

In summary, all the three design scenarios will benefit from the "invisibility" of the mid-air haptic device, which provides attachment-free interactions strengthening the immersion in the fictional environment (see [53]). Furthermore, we can imagine a wall consisting of ultrasonic arrays that will surround the user providing a 360° free-hands multi-user interaction room that will deliver tactile stimulation as desired without the user being aware of the stimulation medium. In this way, the tactile stimulation could follow the natural movement of the user and allow scalability beyond the user's hands.

11.5.3 Limitations and future works

Although this work presents a first of its kind investigation into the use of mid-air tactile stimulation to investigate the occurrence of body ownership during a visual-tactile incongruence, we also need to acknowledge some limitations.

While the technology opens up new possibilities for HCI designers, the range of perceivability of the tactile stimulus on the body is still limited, following the Pacinian mechanoreceptors distribution on the body. We focused our research on the hand but the occurrence of the illusion at other parts of the body still remains to be explored, once the technical limitations will be overcome. Regarding the optimal operative distance from the skin (15 cm), different researchers are looking for ways to extend the performance of transducer arrays. One promising way is the use of acoustic meta-materials: classic materials (like paper, plastic, wood) micro-engineered to have specific acoustic properties, that have already been used in combination with the device employed in this paper [161]. Moreover, our design could be tested with other mid-air devices. This will help in establishing a solid foundation for creating full-body immersive experiences in VR.

We started the investigation of the visual-tactile incongruence using three stimuli on the hand to make a clean setup and a first exploration of the VHI with multiple incongruent visual-tactile mid-air stimulation. Future work could explore further the phenomenon of the VHI using a different number of stimuli to establish a model of our perception under visual-tactile incongruence. Although in this case, one would have to keep in mind the nature of the mid-air tactile stimulation, which has a lower and not precisely defined spatial resolution compared to physical touch (e.g., the mid-air focal point is maximally perceived at the centre of its focus, and less on the boundaries).

Finally, it would also be interesting to study the time variable, investigating if it is possible to achieve the same results with time asynchrony. Moreover, in our set-up, we used the mid-air technology statically, under controlled variables, with less confounding variables. Future studies could investigate similar effects while users are free to move across space.

11.6 Conclusion

The findings from our three experiments demonstrate that it is possible to convey a sense of embodiment by using ultrasonic mid-air haptic technology. In this study, we systematically studied the occurrence of the virtual hand illusion by introducing new variables such as a multiple mid-air tactile stimulation, a different hand's posture, and a mid-air tapping stimulation. With two additional studies exploiting the traditional rubber hand illusion phenomenon, we controlled the hand's posture and tapping like stimulation, confirming those variables does not play a key role in the occurrence of the illusion. This work demonstrate how researchers and designer in HCI can rely on the brain ability to match small visuo-tactile gaps when a free-hands tracking device might result inaccurate.

CHAPTER 12

DISCUSSION AND IMPLICATIONS FOR DESIGN

The findings of the individual papers presented in this thesis have been discussed in detail in the previous six chapters. Here, we will discuss the implications of our results for the HCI field. We highlight three main contributions: 1) in the "Understanding" stage, we aim to answer RQ1, broadening the perceptual understanding of ultrasonic mid-air haptic technology, 2) to answer RQ2, in the "Create" stage, we create an illusion of motion with contact and non-contact (mid-air) haptic technology, and 3) in the "Apply" stage, to tackle RQ3, we demonstrate how using tactile illusions mediated by mid-air haptic technology can convey a sense of embodiment in VR (see Table 12.1 for a reminder of the research questions).

Research Question	
RQ1	How do we perceive ultrasonic mid-air haptic technology? What are the psychophysical properties of mid-air haptics?
RQ2	How can we create realistic haptic and specifically mid-air haptic sensations applying principles of tactile illusions?
RQ3	Using tactile illusions, can we convey the feeling of embodiment using mid-air haptics in VR?

Table 12.1: The three research questions of this thesis.

12.1 Inspiration for the design of mid-air haptics experiences

When we think of using new haptic technology, the first step is to know how the user will perceive it. In the first three studies presented in this thesis, we provide grounding knowledge that future haptic designers can use to create new experiences and upon which future researchers can expand. Due to the novelty of mid-air haptic technology, much is unknown of its psychophysical properties. The first research question was, therefore, **How do we perceive ultrasonic mid-air haptic technology, and what are the psychophysical properties of mid-air haptics?**.

Previous authors have discussed how ultrasonic mid-air haptic devices possibly stimulate only the Pacinian corpuscles and to a small degree, the Meissner receptors [171]. These mechanoreceptors are those responsible for decoding vibrations at high and low frequency (see Chapter 2, Section 2.2). Our first exploration seems to agree with this hypothesis. Before focusing on the hand and arm, we explored the perception of ultrasonic mid-air touch on the whole body. The only locations where the stimulation was perceivable were those in which the Pacinian corpuscles are diffused, glabrous skin. Furthermore, we studied absolute thresholds at 20 locations across the left hand and arm, providing an initial map for absolute thresholds. These first results indicate that the palm might be the most sensitive area for mid-air haptic stimuli and that the absolute thresholds vary depending on the area of stimulation on the hand. Therefore, when designing for tactile interactions, one may want to consider the variable nature of our perception to adapt the tactile stimulation and create an optimal tactile sensation on the hand.

Another question is related to the way we can use a haptic device to optimally convey a tactile sensation in terms of perceivability. For visual and sound stimuli, a higher update rate corresponds to better outcomes (e.g., avoiding motion blur) [45]. One may be inclined to think that the same will apply to tactile stimuli. In Study 2, we demonstrated that the sense of touch does not work in the same way as for vision or hearing, and we provide information on the optimal sampling rate to use to render shapes with mid-air haptic technology. This means that HCI designers will have a better idea of how to design their tactile experiences in a way that the user's sense of touch is optimally triggered to feel the intended stimulus.

Finally, as stated in Chapter 4, Section 4.3, mid-air haptic stimuli have the disadvantage of not having clear physical boundaries. Their output appears like a circle fading outwards from the centre. This means that when delivering a certain shape through ultrasonic mid-air haptics, the user might be puzzled about the actual shape perceived. Considering the potentiality of using mid-air haptics for monosensorial applications in which the user has only his/her sense of touch available, it is crucial to find a way the user can correctly interpret the stimulus delivered. Study 3 sets the first step in this direction. Relying on the concept of chunking from cognitive psychology [62], we hypothesised that facilitating this chunking process for the tactile stimulus will improve users' recognition rates for simple shapes. Our results show that we were able to obtain an improvement of $\approx$30% on users' performance in a shape recognition task compared to the traditional method. This means that users were $\approx$83.5% accurate in discriminating a 2D shape delivered through ultrasonic mid-air haptics.

Taken altogether, these first three studies provide future designers with psychophysical methods that have been proven to deliver optimal tactile sensations with ultrasonic mid-air haptic technology. Having basic knowledge of the optimal frequencies to use, the sampling rate, and techniques to render mid-air haptic shapes will constitute an advantage when designing tactile experiences. We do not need to treat our skin as a uniform surface, but we do need to be aware of the different receptors populating it. We also need to be aware of how to use a certain haptic system and understand the best way to render an intended output. Hence, we need to functionally adapt the output of our haptic devices if we want to render compelling tactile sensations.

12.2 Tactile illusions reduce tactile complexity

In Chapter 2, we described the functioning of our sense of touch, both in its passive and active (haptic) components. We described tactile physiology and the way our central and peripheral nervous system is organised to transfer the tactile information from the mechanoreceptors in the skin to the somatosensory cortex in the brain.

The plethora of studies revolving around each of the specific components of touch and its final sensations (e.g., pressure, weight, temperature, texture, etc.) demonstrate how the nature of our sense of touch is extremely complex. However, scientists have thought of using tactile illusions to tackle this complexity [89, 110, 220]. Because of the advantages of using a tactile technology which is unobtrusive and potentially "transparent", we further questioned if and how it is possible to use mid-air haptic systems to convey tactile illusions. Hence, we defined our second research question as **"Can we use tactile illusions to perceive realistic tactile sensations? If yes, can we use mid-air haptics to convey these tactile illusions?"**

In Study 4 and 5, we provide further knowledge on the apparent tactile illusion (see Chapter 5, Section 5.1). We demonstrate for the first time how a smooth illusion of motion can be delivered between two non-interconnected hands. We first show this by using a contact haptic device. Later, in Study 5, we adapted and expanded the apparent tactile motion illusion by using an ultrasonic mid-air haptic device. For both studies, we provided perceptual models to render a smooth feeling of motion between the two hands. Now, not only we know that it is possible to use mid-air haptic stimulation to convey tactile illusions but have also expanded the illusory stimulation beyond the body. We can now envision new sensations extending around our body, moving from one side to the other, potentially transferring between more users (see, for example [88, 183]).

We believe that future haptic designers could use these perceptual models to deliver optimal tactile sensations to users by exploiting tactile illusions, continuing the recent trend in HCI. For example, recent work by Azmandian et al. illustrates how using perceptual illusions can be an effective way to overcome technological limitations or satisfy perceptual complexity. In this study, the authors enhance the sense of presence in the VE and successfully convey the feeling of moving an object in VR by exploiting visual dominance over the sense of touch. Meanwhile, Razzaque et al. have developed a new interactive locomotion technique for VEs by rotating the virtual scene with respect to the user [191]. Israr and Poupyrev have elaborated an algorithm derived from the psychophysical study of two tactile illusions to allow a wide variety of moving tactile sensations onto users' skin. Hanamitsu and Israr [89] were able to simulate a variety of tactile properties (i.e., texture, patterns, pull/push sensation, vibration) in VR by implementing a spring device in the haptic controller. For their part, Whitmire et al. [250] have designed a haptic controller that simulates arbitrary textures, shapes, or interactive elements by mimicking specific tactile attributes. As defined in [163], if we think of a continuum going from the *real environment* to the *virtual environment*, with the augmented/mixed reality environment in between the two, we believe that ultrasonic mid-air haptic systems are a suitable medium for conveying tactile information in both real and augmented/virtual environments, through screens or HMDs.

Finally, Study 4, in accordance with previous studies ([260]), provides interesting results regarding the multisensory effects of vision and touch in VR. We believe that these studies will stimulate further insights for future works (see Section 12.6) and serve as a basis from which to continue the exploration of tactile illusions to create new forms of realistic stimulation to use in multimedia and virtual reality environments.

12.3 Perceptual illusions as a methodology to study novel haptic interfaces

As described in the previous section, tactile illusions can reduce the complexity that designers and researchers need to convey to our sense of touch to provide a realistic tactile sensation. Further, in this thesis, we demonstrated how the same perceptual illusions could be exploited as a methodology to study novel haptic interfaces, such as mid-air haptic ultrasonic technology.

Study 6 is maybe the most representative example. A well known psychological phenomenon, the rubber hand illusion, was exploited to investigate the brain ability of integrating in a coherent way incongruent visual and tactile stimulations. This also inform us on the capability of the device used, regarding its psychophysical properties. For instance, we could indirectly infer the minimum amount of distance required between two mid-air focal points to be perceived as one (instead of two or more). In Study 6, three tactile stimuli were presented incongruently with respect to their visual counterparts. As shown in the results section, our brain was not able to detect this visual-tactile incongruence. Hence, it could be that three mid-air focal points presented on the hand may saturate the brain ability to discriminate between multiple points. A similar study could investigate if the same effect exists for two or more than three mid-air focal points. In this way we could avoid a two-point discrimination task test for assessing our system (the brain) spatial acuity for mid-air stimuli.

As previously explained in Chapter 7, some of the illusions explored in this work could serve as methodology to enhance the haptics sensations we can deliver with mid-air interfaces. For example, we could exploit results from the tactile illusion of movement from Study 5, to increase participants' ability of discriminating between different 2D shapes. Instead of delivering a one focal point moving along the perimeter of the intended shape, we could provide one mid-air tactile points at each shape vertexes, and by modulating their intensity in time, provide a perceptual illusion of movement between the point resulting in a continuous and recognisable shape. Alternatively, we could simulate only crucial parts of the shape we want to convey, and delegate to the brain the task of completing the shape perception (see Figure 8.15).

12.4 Feeling embodied in VR through mid-air haptics

The development of more economical and less cumbersome VR HMDs has allowed the everyday use of VR systems on a large scale. One of the requirements of virtual systems is that they must be immersive. This means that the final aim is for the user to be transported to a new reality where their actions will be effortless and natural, in line with the sensorial expectations encountered in reality. The SoE is what makes a user embody something that originally did not belong to his/her body schema, such as the avatar used in a VE. Seen that it is fundamental for the user to perceive visuo-tactile congruence, mid-air haptic devices seem to be an effective means of conveying tactile information without disrupting users' sense of presence. Based on what we discovered in the previous studies, Study 6 aimed to answer the third research question: **Using tactile illusions, can we convey the feeling of embodiment using mid-air haptics in VR?**

We demonstrate through the phenomenon of the virtual hand illusion that it is possible to convey embodiment mediated by ultrasonic mid-air touch. In line with previous work [19], we were able to elicit an illusion of ownership by using visuo-tactile congruence. In particular, our participants reported the sensation of owning the virtual (fake) hand we were rendering and stimulating in VR with virtual drops of water. The drops of water were tactilely felt through the use of a mid-air haptic device.

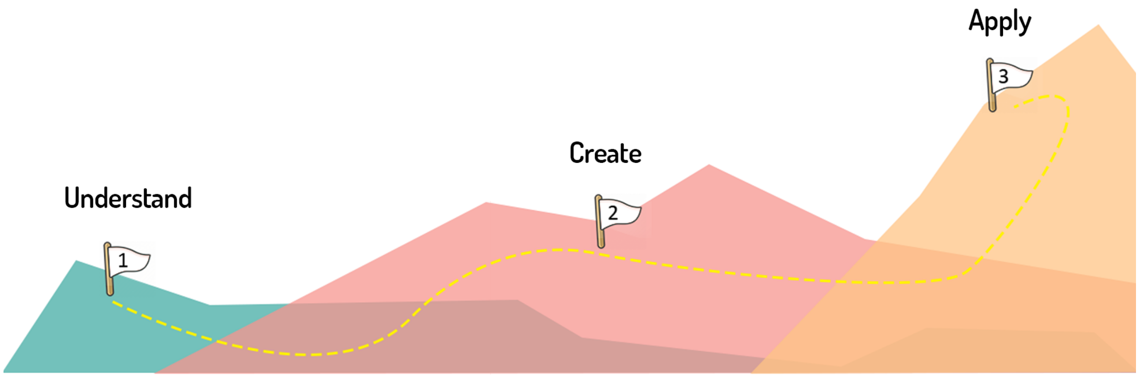
However, what is more interesting is that in our study we were able to convey the virtual hand illusion even in the presence of visuo-tactile incongruence. This, at first, might seem in opposition to previous work which has found that visuo-tactile incongruence is known to break the illusion of ownership [19, 101, 130]. However, we underline that here, in the case of visuo-tactile incongruence for tactile stimuli presented one at a time, our results do follow previous studies. It is only when we delivered multiple "visuo-tactilely" incongruent stimuli at the same time that we were able to obtain an illusion of ownership. It appears that, in this case, the brain can feel the gap and make the user still perceive the illusion of owning a foreign virtual hand (we propose a few hypotheses in Chapter 11). The fine details and limits of this "perceptual forgiveness" are still to be fully explored, but these first results indicate that our brain could fill in some gaps when some incongruence in the VE is provided. Besides, we demonstrate that mid-air haptic technology is indeed a potential tool that could favour embodiment in VR. Now, in addition to having perceivable and realistic tactile sensations across the body, the user will recognise the virtual body as his/her own: a body that will act and react according to the user's expectations.

12.5 Less is more

We report Figure 1.2 from Chapter 1. As illustrated, our first three studies are contained in the "Understand" stage, where we aim to contribute to the psychophysical knowledge of mid-air haptics. Study 1 serves as starting point for the exploration of mid-air haptics on the palm. Data from Study 1 makes researchers certain that mid-air haptic stimuli at certain frequencies are perceived by the subjects. In particular, Study 5 makes use of the results of Study 1 by applying the mid-air haptic feedback on the upper part of the palm, as this area appears to be the most sensitive.

Study 2 is suggesting that there is an optimal sampling rate to use when delivering mid-air haptic stimulations and that this sampling rate changes by changing the size of the stimulus. Although these results could not be applied in the following studies of this thesis as explained in Chapter 1, we believe these results provide important guidelines for researchers in the mid-air haptic field. Similarly, the purpose of Study 3 was to provide designers and researchers with optimal parameters to use when delivering "understandable-by-the-user" 2D shapes through ultrasonic mid-air haptic.

From this point forth, we move to creating illusions making use of mid-air haptics. Studies 4 and 5, fall into the "Create" stage. With these two studies we successfully demonstrate a tactile illusion of movement even in between not contiguous parts of the body. Study 4 starts investigating the phenomenon in traditional contact



Study	Theory chapters	Stage	Research Question
Study 1: Absolute thresholds for ultrasonic mid-air haptics Study 2: Sampling strategies for ultrasonic mid-air haptics Study 3: Strategies to render 2D shapes with ultrasonic mid-air haptics	Chapter 2 - The sense of touch Chapter 3 - Measuring tactile perception Chapter 4 - Touch and technology	Understand	RQ1: How do we perceive mid-air haptics? What are the psychophysical properties of mid-air haptics?
Study 4: Creating an illusion of movement with contact haptics Study 5: Creating an illusion of movement with ultrasonic mid-air haptics	Chapter 2 - The sense of touch Chapter 3 - Measuring tactile perception Chapter 4 - Touch and technology Chapter 5 - Illusions and embodiment	Create	RQ2: How can we create realistic haptic and specifically mid-air haptic sensations applying principles of tactile illusions?
Study 6: Illusion of embodiment in VR mediated by ultrasonic mid-air haptics	Chapter 2 - The sense of touch Chapter 4 - Touch and technology Chapter 5 - Illusions and embodiment	Apply	RQ3: Can we convey a sense of embodiment using mid-air haptics in VR?

Figure 1.2: Schemata of the studies presented in this thesis, how they link to the theory stages and research questions individuated.

touch, to be then applied in a mid-air touch scenario. As previously mentioned, Study 5 exploited results of Study 1. Finally, Study 6 is part of the "Apply" stage, where we demonstrate the flexibility of our body schema, and we apply an illusion of embodiment while we create a virtual illusion of rain drops on the hand. Here, we demonstrate how our brain is capable to perceive visual-tactile congruence even when absent, to provide a more coherent version of the reality. Study 1 was helpful to make sure participants could feel all the stimuli we delivered.

During the exploration of the proposed themes of this thesis, it seems that we can highlight a recurrent topic. It seems that when it comes to the sense of touch "less is more". If maybe not unexpected, in Study 1 it appears that, even if the ultrasonic device can reach very high frequencies (kHz order), our perception is tuned for frequencies in the range of around 50 - 250 Hz.

Similarly, in Study 2, we demonstrate how the optimal sampling strategy to adopt does not coincide with reaching the maximum capability of the device. Therefore, also in this case, less is more. We encourage tactile feedback designers working with mid-air tactile display to decrease the sampling rate whenever rendering tactile pattern with low frequency. Decreasing the sampling rate for a sensation that initially cannot be perceived, might suddenly unlock the said sensation. For instance, circular patterns as studied here, could not be perceived below 20 Hz with a high sampling rate. However, when the sampling rate was lowered, the same circular pattern could be perceived as low as 2 Hz. As no previous work exploring adjusting sampling strategy has been undertaken, we expect the possibility to render low-frequency patterns to be unveiled for most designers working with mid-air tactile display. Moreover, low-frequency patterns, operating at a much slower speed than usual pattern rendered with STM, are now expected to be perceived as moving points rather than complete shapes. Moving points, providing richer information (such as start & end locations, the direction of motion and rate of movement, all of which are masked at higher speeds), are better recognised than multi-points patterns. This has already been demonstrated for contact devices by Ion et al. [109] who used unistroke patterns.

In Study 3 we observed that the performance at a shape recognition task increases when we introduce some pauses at the angles of a 2D shape. Hence, we slow down the time of shape delivery, but we increase the shape recognisability. Although we cannot be sure if this applies to every 2D shape, in the three tested shapes we measured an increase of the performance of 30&, which is a good initial indication. As discussed in Section 8.5.3, it would be interesting exploring if it would be possible to provide only the vertexes of a shape, activated in timely-fashion, to render the sensation of a full displayed shape on the hand.

Study 4 and 5 shows how it is sufficient to deliver static stimuli (or quasi static stimuli in Study 4) to achieve a smooth sensation of movement. In Study 4 participants held in each hand a vibrating 3D printed handle. These handles were activated in an optimal timely-fashion to render an illusion of movement that was flowing from one hand to the other one. Although the movement of the motors inside the handles are in nature dynamic, the sensation on the hand is static. Only when we find the optimal SOA between the activation of the two handles, the user can feel an illusory sensation of motion. The same is true for Study 5. There, we exploit static mid-air control points, that, when activated in an optimal way, feels like a continuous motion. Further, it seems that for delivering an illusion of motion we should prefer static control points in contrast to moving control points.

Finally, in Study 6 results shows how even when we provide users with less visual-tactile congruence, it is still possible to achieve believable results, in our case a sensation of rain drops on the hand.

We believe that illusions are indeed part of a "less is more" approach and constitute a powerful tool in the hands of haptic researchers and designers to provide realistic information without having to fully reconstruct the complexity of a tactile stimulation.

12.6 Limitations and future work

Although every care has been taken to ensure the accuracy of the research here presented, no work is free from limitations, and we will discuss them in this section. Furthermore, we provide suggestions for future work, as illustrated in Figure 12.1.

Regarding our psychophysical studies, human perception is variable across different participants, and the studies presented will need more validation by future work. When applying psychophysical methods (e.g., in Study 1), we make a compromise between accuracy and time constraints. Indeed, as discussed in Chapter 3, there might be different methods from those used by the authors that could be more accurate. However, they would inevitably result in more time-consuming experiments. In these cases, one needs to decide if a longer experiment will compromise the user's attention and, therefore, their performance.

In Study 3, we presented a specific technique based on the segmentation of a whole shape into single lines (i.e., we introduce small pauses at the shapes' corners). This adjustment alone led to an increase of 30% in participants' accuracy. Whether focusing on different variables will increase participants' performance even more has still to be tested. At the same time, it would go beyond the scope of one PhD to take into account the full spectrum of variables (e.g., frequency, sampling rate, intensity, motion, direction, pauses, drawing methods, stimulus waveform, etc.). In our case, the intention was to start a first exploration on the topic, exploiting ultrasonic mid-air technology. Future work can build on this thesis and deepen our understanding of haptic shape recognition by exploring further variables (Figure 12.1). Another interesting variable to investigate further is the shape recognition time. In fact, it would be useful to compare the time recognition for mid-air haptics compared to visual and auditory stimuli. Considering applications for in-car interaction, this could be relevant to explore. Still, there might be situations in which the recognition time might not be an issue, for instance, in the case of data visualisation or science communication for visually impaired people.

Generally, we feel that more work is required to fully comprehend psychophysical behaviour in response to ultrasonic mid-air haptic technology. Further, body locations could be investigated and different tactile rendering techniques exploited.

As discussed in Chapter 9 and 10, our investigation was solely focused on the apparent tactile motion illusion. Further illusions could be investigated in future work to expand the set of tools available to designers to render a more engaging experience in multimedia environments and VR. Additionally, we could study the rendering of the apparent tactile motion while the user is moving (Figure 12.1) and between different body locations (Figure 12.1) to expand tactile interaction beyond the hands. In doing so, there might be an implicit limitation linked to the intensity of the mid-air haptic device employed. It is possible that this limitation could be overcome by future technological advancements or by experimenting with new variables, such as the stimulus waveform. Furthermore, it would be interesting to extend tactile illusions to more users (Figure 12.1). Other interesting information could be provided by a direct comparison between contact and mid-air haptic systems.

Finally, although an illusion of ownership of a virtual arm was successfully conveyed in Study 6, we did not directly study participants' presence in VR. We still

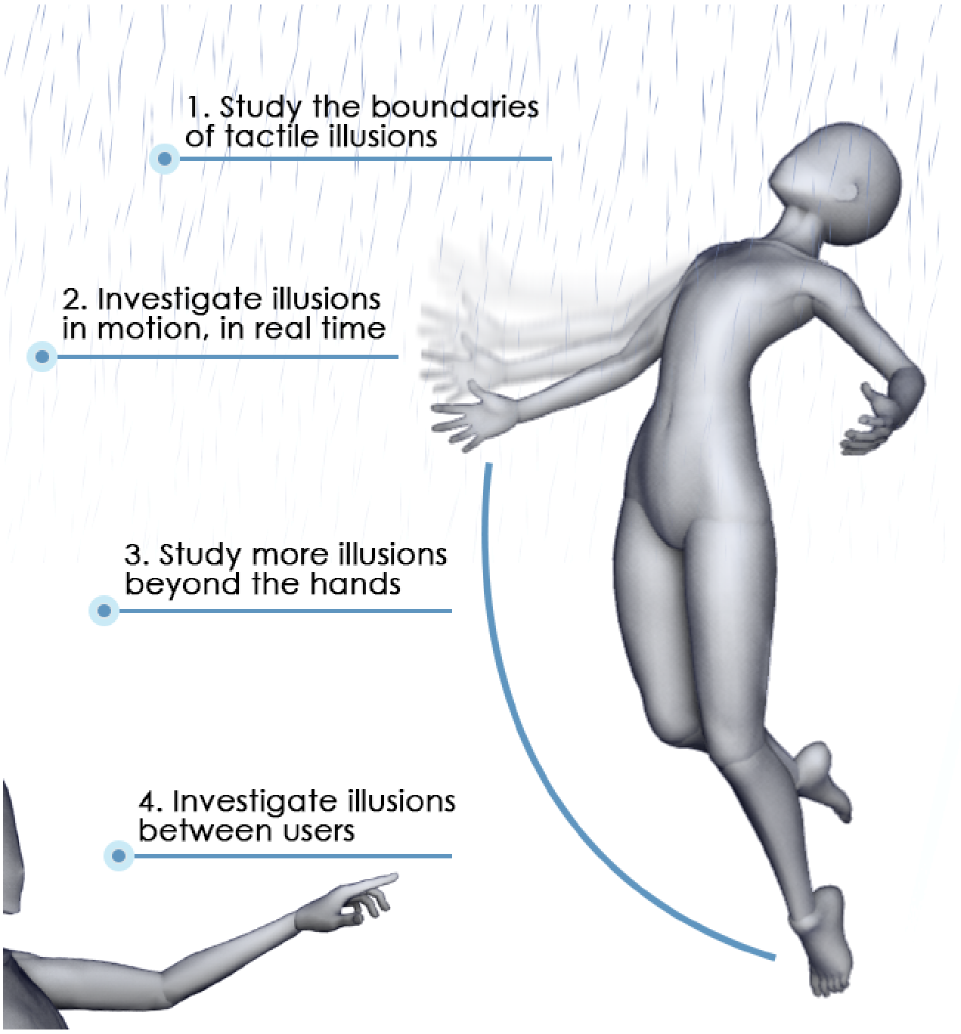


Figure 12.1: Inspiration for future work on the opportunities around mid-air haptics.

believe that if a user feels as if they are impersonating the virtual avatar, he/she will automatically feel more immersed in the virtual scenario, but further evidence needs to be collected. Moreover, concepts like immersion, presence, and embodiment, and the way we can measure them, are still in the process of being clearly defined, as discussed in Chapter 5, Section 5.2.

Although, as discussed, many aspects of our research still need to be taken forward, and more work is needed to strengthen and extend the results, we believe that this thesis contributes to the advancement of psychophysical knowledge of new ultrasonic mid-air haptic systems and to the use of tactile illusions to tackle the complexity of the sense of touch. We hope that this work will serve as an inspiration to designers and researchers in the field of HCI and related disciplines such as psychology and sensory science to continue to deepen psychophysical knowledge, investigate more tactile illusions employing mid-air haptic devices, and ultimately enable us to design novel and compelling interactive experiences and applications that extend the currently dominated audio-visual design space. The final aim could be that of having fine-tuned mid-air haptic widgets ready to be used in interactive scenarios. Let us imagine a developer creating a simple game in VR with Unity. When the developer instantiates an object in the VE, say a button, they will now have the possibility of dragging and dropping an already made haptic effect, say a haptic click effect, onto the object. In the same way, we can envision having several other types of mid-air haptic feedback ready to use for easy implementation in films, games, and multimedia experiences in general.

Chapter 13

Conclusions

This thesis started by giving an overview of the complexity of the sense of touch and how the current trend is that of implementing tactile sensations in new applications. Specifically, because the accessible prices and compact sizes of VR HMDs have made them suitable for the commercial market, there is a renewed interest in integrating tactile sensations in virtual environments. In Chapter 4, we illustrated the main haptic devices developed with the aim of providing realistic tactile feedback to the user. The latest technology is represented by mid-air (contactless) haptic devices. These seem particularly suitable for VR because they do not require any attachments on users' skin, being potentially "transparent", as discussed in Chapter 1. This means that when a user is immersed in a VE, the haptic device will not represent a distraction and will not be a reason for visuo-tactile incongruence, allowing for more natural and immersive interactions. Nevertheless, given the high complexity of our tactile system, the issue of delivering a realistic tactile sensation remains. To tackle this issue, some researches have suggested that we can exploit the organisation of the sense of touch to create tactile illusions.

Mid-air haptic technology is quite recent and an extensive understanding of its potential is still missing. We have reported on six studies. Study 1, 2, and 3 aimed to provide a better understanding of the user's perception of ultrasonic mid-air haptic systems. Study 4 and 5 present a successful rendering of an illusion of motion that extends beyond contiguous parts of the body, moving from one hand to the other. We demonstrate how mid-air haptic technology is equally suitable for conveying this illusion, providing a realistic sensation of continuous motion on the users' hands. We additionally provide perceptual models that VE developers could use to provide realistic tactile sensations. Finally, with Study 6, we demonstrate how it is possible to convey a feeling of embodiment using mid-air haptics, additionally showing how the user is not distracted by visuo-tactile incongruence.

To provide the users with the illusion that the virtual environment is real, it is fundamental that they act and react as if they were in the real world. To achieve these results, great advancements have been made in terms of graphics realism and compelling 3D sounds. We and many other researchers believe that the next implementation has to be the tactile system. Our sense of touch is the ultimate sense that informs us that what we see is real. Ultimately, we believe that what makes a user perceive a virtual environment as real resides in the details.

Note from the author:

"Last night I was playing a computer game. Some time had passed since my last car game, and I was wondering what it was that made this title so compelling and realistic. Then, I started to notice the lights reflecting on the body of my car, the warm glow of the sunset, the lights of the night, the dust on the bumpers. Later, I also noticed that hitting a traffic light (it is a game) caused its lights to turn off before it started to fly across the road. The way the damage looked on my car (a Lamborghini Huracan LP 610-4) and its behaviour when crashing into another interactable object were all in line to my expectations. Together, all these details constructed a realistic experience in my mind that eventually caused me to lose several hours of sleep (also due to the fact that I was procrastinating on the finishing of this thesis). In the same way, I believe that the studies presented here might contribute to fill some details still missing from our virtual experiences: those details that will engage the user in a virtual world that feels more realistic, because touching is believing. The ethical implications involved are, however, outside the scope of this thesis."

Bibliography

[1] D. Ablart, C. Velasco, and M. Obrist, *Integrating mid-air haptics into movie experiences*, in TVX 2017 - Proceedings of the 2017 ACM International Conference on Interactive Experiences for TV and Online Video, 2017, pp. 77–84.

[2] S. J. G. Ahn, J. Bostick, E. Ogle, K. L. Nowak, K. T. McGillicuddy, and J. N. Bailenson, *Experiencing Nature: Embodying Animals in Immersive Virtual Environments Increases Inclusion of Nature in Self and Involvement With Nature*, Journal of Computer-Mediated Communication, 21 (2016), pp. 399–419.

[3] J. Aldhous, R. Hetherington, and P. Turner, *The digital rubber hand illusion*, HCI 2017: Digital Make Believe - Proceedings of the 31st International BCS Human Computer Interaction Conference, HCI 2017, 2017-July (2017), pp. 1–5.

[4] M. D. Alonzo, C. Cipriani, and S. Member, *Vibrotactile feedback elicits embodiment of robotic hand in active motor task* *, International workshop of Human Friendly Robotics, 8 (2014), p. 2014.

[5] P. A. Andersen and K. Leibowitz, *The development and nature of the construct touch avoidance*, Environmental Psychology and Nonverbal Behavior, 3 (1978), pp. 89–106.

[6] Aristotle, *Metafisica*, Milano, 1993.

[7] O. Ariza, J. Freiwald, N. Laage, M. Feist, M. Salloum, G. Bruder, and F. Steinicke, *Inducing body-transfer illusions in VR by providing*

brief phases of visual-tactile stimulation, SUI 2016 - Proceedings of the 2016 Symposium on Spatial User Interaction, (2016), pp. 61–68.

[8] K. C. ARMEL AND V. S. RAMACHANDRAN, *Projecting sensations to external objects: evidence from skin conductance response.*, Proceedings. Biological sciences / The Royal Society, 270 (2003), pp. 1499–506.

[9] M. AZMANDIAN, M. HANCOCK, H. BENKO, E. OFEK, AND A. D. WILSON, *Haptic retargeting: Dynamic repurposing of passive haptics for enhanced virtual reality experiences*, in Conference on Human Factors in Computing Systems - Proceedings, no. May, New York, New York, USA, 2016, ACM Press, pp. 1968–1979.

[10] N. BAKALAR, *Sensory science: Partners in flavour*, Nature, 486 (2012), pp. S4–S5.

[11] D. BANAKOU, R. GROTEN, AND M. SLATER, *Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes*, Proceedings of the National Academy of Sciences of the United States of America, 110 (2013), pp. 12846–12851.

[12] C. BECKETT, B. MAUGHAN, M. RUTTER, J. CASTLE, E. COLVERT, C. GROOTHUES, J. KREPPNER, S. STEVENS, T. G. O'CONNOR, AND E. J. SONUGA-BARKE, *Do the effects of early severe deprivation on cognition persist into early adolescence? Findings from the English and Romanian adoptees study*, Child Development, 77 (2006), pp. 696–711.

[13] M. BERGAMASCO AND E. RUFFALDI, *Haptic Interfaces for Embodiment in Virtual Environments*, 20th years of IEEE RO-MAN, (2011).

[14] W. M. BERGMANN TIEST AND A. M. KAPPERS, *Analysis of haptic perception of materials by multidimensional scaling and physical measurements of roughness and compressibility*, Acta Psychologica, 121 (2006), pp. 1–20.

[15] &. S. R. BLAKE, R., R. SEKULER, AND R. BLAKE, *Perception*, McGraw-Hill, Boston, 2006.

[16] S. J. BOLANOWSKI, G. A. GESCHEIDER, R. T. VERRILLO, AND C. M. CHECKOSKY, *Four channels mediate the mechanical aspects of touch*, Journal of the Acoustical Society of America, 84 (1988), pp. 1680–1694.

[17] S. J. BOLANOWSKI AND R. T. VERRILLO, *Temperature and criterion effects in a somatosensory subsystem: A neurophysiological and psychophysical study*, Journal of Neurophysiology, 48 (1982), pp. 836–855.

[18] J. BORNSCHEIN, D. BORNSCHEIN, AND G. WEBER, *Comparing computer-based drawing methods for blind people with real-time tactile feedback*, in Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, CHI '18, ACM, 2018, pp. 115:1–115:13.

[19] M. BOTVINICK AND J. COHEN, *Rubber hands 'feel' touch that eyes see [8]*, Nature, 391 (1998), p. 756.

[20] J. P. BRESCIANI, K. DREWING, AND M. O. ERNST, *Human haptic perception and the design of haptic-enhanced virtual environments*, Springer Tracts in Advanced Robotics, 45 (2008), pp. 61–106.

[21] T. BROCHIER, M. HABIB, AND M. BROUCHON, *Covert Processing of Information in Hemianesthesia: A Case Report*, Cortex, 30 (1994), pp. 135–144.

[22] S. BURGESS, *A Study of Touch and Haptic Technologies*, (2013), pp. 1–15.

[23] H. E. BURTT, *Tactual illusions of movement*, Journal of Experimental Psychology, 2 (1917), pp. 371–385.

[24] W. A. S. BUXTON, *Human-computer interaction*, Morgan Kaufmann Publishers Inc., 1995, ch. Chunking and Phrasing and the Design of Human-computer Dialogues, pp. 494–499.

[25] A. J. CAPRARO, R. T. VERRILLO, AND J. J. ZWISLOCKI, *Psychophysical evidence for a triplex system of cutaneous mechanoreception*, Sensory Processes, 3 (1979), pp. 334–352.

[26] G. CARRUTHERS, *A model of the synchronic self*, Consciousness and Cognition, 16 (2007), pp. 533–550.

[27] T. CARTER, S. A. SEAH, B. LONG, B. DRINKWATER, AND S. SUBRAMANIAN, *UltraHaptics: Multi-point mid-air haptic feedback for touch surfaces*, UIST 2013 - Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology, (2013), pp. 505–514.

[28] R. CASATI AND E. PASQUINELLI, *Is the subjective feel of "presence" an uninteresting goal?*, Journal of Visual Languages and Computing, 16 (2005), pp. 428–441.

[29] J. S. CHAN AND F. N. NEWELL, *Behavioral evidence for task-dependent "what" versus "where" processing within and across modalities*, Perception & Psychophysics, 70 (2008), pp. 36–49.

[30] A. CHANDRA, *Analysis of hand anthropometric dimensions of male industrial workers of haryana state*, International Journal of Engineering, 5 (2011).

[31] W. Y. CHEN, H. C. HUANG, Y. T. LEE, AND C. LIANG, *Body ownership and the four-hand illusion*, Scientific Reports, 8 (2018), pp. 1–17.

[32] J. CHILLES, W. FRIER, A. ABDOUNI, M. GIORDANO, AND O. GEORGIOU, *Laser doppler vibrometry and fem simulations of ultrasonic mid-air haptics*, in 2019 IEEE World Haptics Conference (WHC), IEEE, 2019, pp. 259–264.

[33] W. CHOI, L. LI, S. SATOH, AND K. HACHIMURA, *Multisensory Integration in the Virtual Hand Illusion with Active Movement*, BioMed Research International, 2016 (2016).

[34] M. Cohen, J. Quintner, and S. van Rysewyk, *Reconsidering the International Association for the study of pain definition of pain*, Pain Reports, 3 (2018), p. e634.

[35] M. Costantini and P. Haggard, *The rubber hand illusion: Sensitivity and reference frame for body ownership*, Consciousness and Cognition, 16 (2007), pp. 229–240.

[36] S. Crea, M. D'Alonzo, N. Vitiello, and C. Cipriani, *The rubber foot illusion*, Journal of NeuroEngineering and Rehabilitation, 12 (2015), p. 77.

[37] H. Culbertson, S. B. Schorr, and A. M. Okamura, *Haptics: The Present and Future of Artificial Touch Sensation*, Annual Review of Control, Robotics, and Autonomous Systems, 1 (2018), pp. 385–409.

[38] G. Carruthers, *Types of body representation and the sense of embodiment*, Consciousness and Cognition, 17 (2008), pp. 1302–1316.

[39] D. Dalecki, S. Z. Child, C. H. Raeman, and E. L. Carstensen, *Tactile perception of ultrasound*, Journal of the Acoustical Society of America, 97 (1995), pp. 3165–3170.

[40] M. D'Alonzo and C. Cipriani, *Vibrotactile Sensory Substitution Elicits Feeling of Ownership of an Alien Hand*, PLoS ONE, 7 (2012).

[41] W. Dangxiao, G. Yuan, L. Shiyi, Z. Yuru, X. Weiliang, and X. Jing, *Haptic display for virtual reality: progress and challenges*, Virtual Reality & Intelligent Hardware, 1 (2019), p. 136.

[42] J. Dargahi and S. Najarian, *Human tactile perception as a standard for artificial tactile sensing–a review.*, The international journal of medical robotics + computer assisted surgery : MRCAS, 1 (2004), pp. 23–35.

[43] F. De Vignemont, *Embodiment, ownership and disownership*, Consciousness and Cognition, 20 (2011), pp. 82–93.

[44] A. R. DEWSBURY, *What the fetus feels*, British Medical Journal, 280 (1980), p. 481.

[45] P. DIDYK, E. EISEMANN, T. RITSCHEL, K. MYSZKOWSKI, AND H. P. SEIDEL, *Perceptually-motivated real-time temporal upsampling of 3D content for high-refresh-rate displays*, Computer Graphics Forum, 29 (2010), pp. 713–722.

[46] L. DUHN, *The importance of touch in the development of attachment*, Advances in Neonatal Care, 10 (2010), pp. 294–300.

[47] H. H. EHRSSON, *The experimental induction of out-of-body experiences*, Science, 317 (2007), p. 1048.

[48] H. H. EHRSSON, C. SPENCE, AND R. E. PASSINGHAM, *That's my hand! Activity in premotor cortex reflects feeling of ownership of a limb*, Science, 305 (2004), pp. 875–877.

[49] H. H. EHRSSON, K. WIECH, N. WEISKOPF, R. J. DOLAN, AND R. E. PASSINGHAM, *Threatening a rubber hand that you feel is yours elicits a cortical anxiety response*, Proceedings of the National Academy of Sciences of the United States of America, 104 (2007), pp. 9828–9833.

[50] V. EKROLL, B. SAYIM, R. VAN DER HALLEN, AND J. WAGEMANS, *Illusory Visual Completion of an Object's Invisible Backside Can Make Your Finger Feel Shorter.*, Current biology : CB, (2016), pp. 1–5.

[51] M. T. FAIRHURST, E. TRAVERS, V. HAYWARD, AND O. DEROY, *Confidence is higher in touch than in vision in cases of perceptual ambiguity*, Scientific Reports, 8 (2018).

[52] H. FARMER, A. TAJADURA-JIMÉNEZ, AND M. TSAKIRIS, *Beyond the colour of my skin: How skin colour affects the sense of body-ownership*, Consciousness and Cognition, 21 (2012), pp. 1242–1256.

[53] R. FARROW AND I. IACOVIDES, *Gaming and the limits of digital embodiment*, Philosophy and Technology, 27 (2014), pp. 221–233.

[54] T. FIELD AND M. DIEGO, *Vagal activity, early growth and emotional development*, Infant Behavior and Development, 31 (2008), pp. 361–373.

[55] T. FIELD, M. DIEGO, AND M. HERNANDEZ-REIF, *Massage therapy research*, Developmental Review, 27 (2007), pp. 75–89.

[56] T. FIELD, N. GRIZZLE, F. SCAFIDI, S. ABRAMS, S. RICHARDSON, C. KUHN, AND S. SCHANBERG, *Massage therapy for infants of depressed mothers*, Infant Behavior and Development, 19 (1996), pp. 107–112.

[57] D. FREEMAN, *Studying and treating schizophrenia using virtual reality: A new paradigm*, Schizophrenia Bulletin, 34 (2008), pp. 605–610.

[58] W. FRIER, D. ABLART, J. CHILLES, B. LONG, M. GIORDANO, M. OBRIST, AND S. SUBRAMANIAN, *Using spatiotemporal modulation to draw tactile patterns in mid-air*, in Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 10893 LNCS, 2018, pp. 270–281.

[59] W. FRIER, D. PITTERA, D. ABLART, M. OBRIST, AND S. SUBRAMANIAN, *Sampling strategy for ultrasonic mid-air haptics*, in Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, CHI '19, ACM, 2019, pp. 121:1–121:11.

[60] W. J. FRY, V. J. WULFF, D. TUCKER, AND F. J. FRY, *Physical Factors Involved in Ultrasonically Induced Changes in Living Systems: I. Identification of Non-Temperature Effects*, Journal of the Acoustical Society of America, 22 (1950), pp. 867–876.

[61] T. A. FURNESS, *The Super Cockpit and its Human Factors Challenges*, Proceedings of the Human Factors Society Annual Meeting, 30 (1986), pp. 48–52.

[62] M. G.A., *The Magical Number Seven, Plus or Minus Two Some Limits on Our Capacity for Processing Information*, Psychological Review, 101 (1955), pp. 343–352.

[63] G. GALILEI, *Il Saggiatore*, Roma, mascardi ed., 1623.

[64] A. GALLACE, M. K. NGO, J. SULAITIS, AND C. SPENCE, *Multisensory presence in virtual reality: Possibilities & limitations*, in Multiple Sensorial Media Advances and Applications: New Developments in MulSeMedia, IGI Global, 2011, pp. 1–38.

[65] A. GALLACE AND C. SPENCE, *The cognitive and neural correlates of "tactile consciousness": A multisensory perspective*, 2008.

[66] M. A. GARCÍA-PÉREZ, *Forced-choice staircases with fixed step sizes: Asymptotic and small-sample properties*, Vision Research, 38 (1998), pp. 1861–1881.

[67] L. R. GAVRILOV, G. V. GERSUNI, O. B. ILYINSKI, E. M. TSIRULNIKOV, AND E. E. SHCHEKANOV, *A study of reception with the use of focused ultrasound. I. Effects on the skin and deep receptor structures in man.*, Brain research, 135 (1977), pp. 265–77.

[68] L. R. GAVRILOV AND E. M. TSIRULNIKOV, *Focused ultrasound as a tool to input sensory information to humans (review)*, Acoustical Physics, 58 (2012), pp. 1–21.

[69] F. A. GELDARD AND C. E. SHERRICK, *The cutaneous "rabbit": A perceptual illusion*, Science, 178 (1972), pp. 178–179.

[70] G. A. GESCHEIDER, *Resolving of successive clicks by the ears and skin*, Journal of Experimental Psychology, 71 (1966), pp. 378–381.

[71] G. A. GESCHEIDER, E. J. BEILES, C. M. CHECKOSKY, S. J. BOLANOWSKI, AND R. T. VERRILLO, *The effects of aging on information-processing chan-*

nels in the sense of touch: II. Temporal summation in the p channel, Somatosensory & Motor Research, 11 (1994), pp. 359–365.

[72] G. A. GESCHEIDER, S. J. BOLANOWSKI, K. L. HALL, K. E. HOFFMAN, AND R. T. VERRILLO, *The effects of aging on information-processing channels in the sense of touch: I. Absolute sensitivity*, Somatosensory & Motor Research, 11 (1994), pp. 345–357.

[73] G. A. GESCHEIDER, S. J. BOLANOWSKI, AND R. T. VERRILLO, *Some characteristics of tactile channels*, Behavioural Brain Research, 148 (2004), pp. 35–40.

[74] G. A. GESCHEIDER, B. F. SKLAR, C. L. VAN DOREN, AND R. T. VERRILLO, *Vibrotactile forward masking: Psychophysical evidence for a triplex theory of cutaneous mechanoreception*, Journal of the Acoustical Society of America, 78 (1985), pp. 534–543.

[75] C. GIACHRITSIS, R. WRIGHT, AND A. WING, *The contribution of proprioceptive and cutaneous cues in weight perception: Early evidence for maximum-likelihood integration*, in Lecture Notes in Computer Science, A. M. L. Kappers, J. B. F. van Erp, W. M. Bergmann Tiest, and F. C. T. van der Helm, eds., vol. 6191 LNCS, Berlin, Heidelberg, 2010, Springer Berlin Heidelberg, pp. 11–16.

[76] J. J. GIBSON, *Psychological Review Observations on Active Touch '*, Psychological Review, 69 (1962), pp. 477–491.

[77] A. M. GLENBERG, *Embodiment as a unifying perspective for psychology*, Wiley Interdisciplinary Reviews: Cognitive Science, (2010).

[78] D. GOLDBERG AND C. RICHARDSON, *Touch-typing with a stylus*, in Proceedings of the INTERACT '93 and CHI '93 Conference on Human Factors in Computing Systems, CHI '93, ACM, 1993, pp. 80–87.

[79] D. GOLDREICH, *A Bayesian perceptual model replicates the cutaneous rabbit and other tactile spatiotemporal illusions*, PLoS ONE, 2 (2007), p. e333.

[80] E. B. GOLDSTEIN, *Sensation and perception*, Publications, SAGE, Pittsburgh, 2010.

[81] M. GONZALEZ-FRANCO AND J. LANIER, *Model of illusions and virtual reality*, Frontiers in Psychology, 8 (2017), pp. 1–8.

[82] R. L. GREGORY, *Visual illusions classified*, Trends in Cognitive Sciences, 1 (1997), pp. 190–194.

[83] M. GRUNWALD, *Human haptic perception: Basics and applications*, in Human Haptic Perception: Basics and Applications, vol. 9783764376, 2008, pp. 1–676.

[84] S. GUPTA, D. MORRIS, S. N. PATEL, AND D. TAN, *AirWave: Non-contact haptic feedback using air vortex rings*, UbiComp 2013 - Proceedings of the 2013 ACM International Joint Conference on Pervasive and Ubiquitous Computing, (2013), pp. 419–428.

[85] A. GUTERSTAM, Z. ABDULKARIM, AND H. H. EHRSSON, *Illusory ownership of an invisible body reduces autonomic and subjective social anxiety responses*, Scientific Reports, 5 (2015), p. 9831.

[86] A. GUTERSTAM, G. GENTILE, H. H. EHRSSON, AND H. HENRIK EHRSSON, *The Invisible Hand Illusion: Multisensory Integration Leads to the Embodiment of a Discrete Volume of Empty Space*, Journal of Cognitive Neuroscience, 25 (2013), pp. 1078–1099.

[87] A. GUTERSTAM, V. I. PETKOVA, AND H. H. EHRSSON, *The illusion of owning a third arm*, PLoS ONE, 6 (2011), p. e17208.

[88] T. HACHISU AND K. SUZUKI, *Representing Interpersonal Touch Directions by Tactile Apparent Motion using Smart Bracelets*, IEEE Transactions on Haptics, 12 (2019), pp. 1–1.

[89] N. HANAMITSU AND A. ISRAR, *Haplug : A Haptic Plug for Dynamic VR Interactions Haptic Plug*, 432 (2011), pp. 479–483.

[90] K. HARRINGTON, D. R. LARGE, G. E. BURNETT, AND O. GEORGIOU, *Exploring the use of mid-air ultrasonic feedback to enhance automotive user interfaces*, in Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, AutomotiveUI 2018, Toronto, ON, Canada, September 23-25, 2018, 2018, pp. 11–20.

[91] J. HARTCHER-O'BRIEN, C. LEVITAN, AND C. SPENCE, *Extending visual dominance over touch for input off the body*, Brain Research, 1362 (2010), pp. 48–55.

[92] C. HATZFELD, *Engineering Haptic Devices*, Springer Series on Touch and Haptic Systems, Springer London, London, 2014.

[93] V. HAYWARD, *A brief taxonomy of tactile illusions and demonstrations that can be done in a hardware store*, Brain Research Bulletin, 75 (2008), pp. 742–752.

[94] V. HAYWARD, O. R. ASTLEY, M. CRUZ-HERNANDEZ, D. GRANT, AND G. ROBLES-DE-LA-TORRE, *Haptic interfaces and devices*, Sensor Review, 24 (2004), pp. 16–29.

[95] V. HAYWARD, A. V. TEREKHOV, S. C. WONG, P. GEBOREK, F. BENGTSSON, AND H. JÖRNTELL, *Spatio-temporal skin strain distributions evoke low variability spike responses in cuneate neurons*, Journal of the Royal Society Interface, 11 (2014).

[96] C. HEETER, *Being There: The Subjective Experience of Presence*, Presence: Teleoperators and Virtual Environments, 1 (1992), pp. 262–271.

[97] H. HENRIK EHRSSON, *How many arms make a pair? Perceptual illusion of having an additional limb*, Perception, 38 (2009), pp. 310–312.

[98] E. HERRERA, N. REISSLAND, AND J. SHEPHERD, *Maternal touch and maternal child-directed speech: Effects of depressed mood in the postnatal period*, Journal of Affective Disorders, 81 (2004), pp. 29–39.

[99] H. G. HOFFMAN, A. HOLLANDER, K. SCHRODER, S. ROUSSEAU, AND T. FURNESS, *Physically touching and tasting virtual objects enhances the realism of virtual experiences*, Virtual Reality, 3 (1998), pp. 226–234.

[100] N. HOGAN, B. A. KAY, E. D. FASSE, AND F. A. MUSSA-IVALDI, *Haptic illusions: Experiments on human manipulation and perception of 'virtual objects'*, Cold Spring Harbor Symposia on Quantitative Biology, 55 (1990), pp. 925–931.

[101] J. HOHWY AND B. PATON, *Explaining away the body: Experiences of supernaturally caused touch and touch on non-hand objects within the rubber hand illusion*, PLoS ONE, 5 (2010).

[102] H. HOLLE, N. MCLATCHIE, S. MAURER, AND J. WARD, *Proprioceptive Drift without Illusions of Ownership for Rotated Hands in the 'Rubber Hand Illusion' Paradigm*, Cognitive Neuroscience, (2011), pp. 37–41.

[103] M. HOLLINS AND O. FAVOROV, *The tactile movement aftereffect*, Somatosensory & Motor Research, 11 (1994), pp. 153–162.

[104] Y. HORIUCHI, K. YOSHIDA, Y. MAKINO, AND H. SHINODA, *Rubber hand illusion using invisible tactile stimulus*, in 2017 IEEE World Haptics Conference, WHC 2017, no. June, IEEE, 6 2017, pp. 490–494.

[105] T. HOSHI, *Handwriting transmission system using noncontact tactile display*, Haptics Symposium 2012, HAPTICS 2012 - Proceedings, (2012).

[106] T. HOSHI, T. IWAMOTO, AND H. SHINODA, *Non-contact tactile sensation synthesized by ultrasound transducers*, Proceedings - 3rd Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, World Haptics 2009, (2009), pp. 256–260.

[107] T. HOSHI, M. TAKAHASHI, T. IWAMOTO, AND H. SHINODA, *Noncontact tactile display based on radiation pressure of airborne ultrasound*, IEEE Transactions on Haptics, 3 (2010), pp. 155–165.

[108] W. IJSSELSTEIJN, *Presence in the Past: what can we learn from Media History ?*, Being There: Concepts, effects and measurement of user presence in synthetic environments, (2003), p. 24.

[109] A. ION, E. WANG, AND P. BAUDISCH, *Skin drag displays: Dragging a physical tactor across the user's skin produces a stronger tactile stimulus than vibrotactile*, Conference on Human Factors in Computing Systems - Proceedings, 2015-April (2015), pp. 2501–2504.

[110] A. ISRAR AND I. POUPYREV, *Tactile Brush : Drawing on Skin with a Tactile Grid Display*, Proceedings of CHI'11, (2011), pp. 2019–2028.

[111] M. ITO, D. WAKUDA, S. INOUE, Y. MAKINO, AND H. SHINODA, *High Spatial Resolution Midair Tactile Display Using 70 kHz Ultrasound*, 2016, pp. 57–67.

[112] T. IWAMOTO, T. MAEDA, AND H. SHINODA, *Focused Ultrasound for Tactile Feeling Display*, ICAT 2001 Proceedings of the 11th International Conference on Artificial Reality and Telexistence, (2001), pp. 121 – 127.

[113] T. IWAMOTO, M. TATEZONO, AND H. SHINODA, *Non-contact method for producing tactile sensation using airborne ultrasound*, in Lecture Notes in Computer Science, vol. 5024 LNCS, Berlin, Heidelberg, 2008, Springer Berlin Heidelberg, pp. 504–513.

[114] J. J. GIBSON, *Observations on active touch*, Psychological review, 69 (1962), pp. 477–91.

[115] R. S. JOHANSSON, *Tactile sensibility in the human hand: receptive field characteristics of mechanoreceptive units in the glabrous skin area.*, The Journal of Physiology, 281 (1978), pp. 101–125.

[116] R. S. JOHANSSON AND J. R. FLANAGAN, *Coding and use of tactile signals from the fingertips in object manipulation tasks.*, Nature reviews. Neuroscience, 10 (2009), pp. 345–359.

[117] R. S. JOHANSSON AND A. B. VALLBO, *Tactile sensibility in the human hand: relative and absolute densities of four types of mechanoreceptive units in glabrous skin.*, The Journal of Physiology, 286 (1979), pp. 283–300.

[118] R. S. JOHANSSON AND B. VALLBO, *Tactile sensory coding in the glabrous skin of the human hand*, Trends in Neurosciences, 6 (1983), pp. 27–32.

[119] L. A. JONES AND H. Z. TAN, *Application of psychophysical techniques to haptic research*, IEEE Transactions on Haptics, 6 (2013), pp. 268–284.

[120] J. H. JUN, J. R. PARK, S. P. KIM, Y. M. BAE, J. Y. PARK, H. S. KIM, S. CHOI, S. J. JUNG, S. H. PARK, D. I. YEOM, G. I. JUNG, J. S. KIM, AND S. C. CHUNG, *Laser-induced thermoelastic effects can evoke tactile sensations*, Scientific Reports, 5 (2015).

[121] K. KACZMAREK, M. TYLER, AND P. BACH-Y RITA, *Pattern identification on a fingertip-scanned electrotactile display*, vol. 4, 01 1997, pp. 1694 – 1696 vol.4.

[122] R. S. KALAWSKY, *The Validity of Presence as a Reliable Human Performance Metric in Immersive Environments.*, Presence, (2000), pp. 1–16.

[123] A. KALCKERT AND H. H. EHRSSON, *The moving rubber hand illusion revisited: Comparing movements and visuotactile stimulation to induce illusory ownership*, Consciousness and Cognition, 26 (2014), pp. 117–132.

[124] M. KAMMERS, F. DE VIGNEMONT, L. VERHAGEN, AND H. DIJKERMAN, *The rubber hand illusion in action*, Neuropsychologia, 47 (2009), pp. 204–211.

[125] N. KANAYAMA, A. SATO, AND H. OHIRA, *Crossmodal effect with rubber hand illusion and gamma-band activity*, Psychophysiology, 44 (2007), pp. 392–402.

[126] E. KANDEL AND J. SCHWARTZ, *Principles of neural science, Fifth edition, compressed pdf*, 2013.

[127] B. KAPPUS AND B. LONG, *Spatiotemporal modulation for mid-air haptic feedback from an ultrasonic phased array*, 25th International Congress on Sound and Vibration 2018, ICSV 2018: Hiroshima Calling, 3 (2018), pp. 1669–1674.

[128] D. KATZ, *The world of touch*, Routledge, 1925.

[129] K. KILTENI, I. BERGSTROM, AND M. SLATER, *Drumming in immersive virtual reality: The body shapes the way we play*, IEEE Transactions on Visualization and Computer Graphics, 19 (2013), pp. 597–605.

[130] K. KILTENI, A. MASELLI, K. P. KORDING, AND M. SLATER, *Over my fake body: Body ownership illusions for studying the multisensory basis of own-body perception*, Frontiers in Human Neuroscience, 9 (2015).

[131] J. H. KIRMAN, *Tactile apparent movement: The effects of interstimulus onset interval and stimulus duration*, Perception & Psychophysics, 15 (1974), pp. 1–6.

[132] K. KIYOKAWA, *An introduction to head mounted displays for augmented reality*, in Emerging Technologies of Augmented Reality: Interfaces and Design, IGI Global, 1 2006, pp. 43–63.

[133] R. L. KLATZKY, S. J. LEDERMAN, AND C. REED, *There's More to Touch than Meets the Eye: The Salience of Object Characteristics with and without Vision*, Journal of Experimental Psychology: General, 116 (1987), pp. 299–302.

[134] S. KOMANDUR, P. W. JOHNSON, R. L. STORCH, AND M. G. YOST, *Relation between index finger width and hand width anthropometric measures*, Proceedings of the 31st Annual International Conference of the IEEE

Engineering in Medicine and Biology Society: Engineering the Future of Biomedicine, EMBC 2009, (2009), pp. 823–826.

[135] M. W. KRUEGER, T. GIONFRIDDO, AND K. HINRICHSEN, *VIDEOPLACE - an Artifical Reality.*, in Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '85, New York, New York, USA, 1985, ACM Press, pp. 35–43.

[136] S. KUROKI, J. WATANABE, N. KAWAKAMI, S. TACHI, AND S. NISHIDA, *Somatotopic dominance in tactile temporal processing*, Experimental Brain Research, 203 (2010), pp. 51–62.

[137] H. LAGERCRANTZ AND J.-P. CHANGEUX, *The emergence of human consciousness: from fetal to neonatal life.*, Pediatric research, 65 (2009), pp. 255–60.

[138] N. LANGFORD AND R. J. HALL, *Cutaneous perception of a track produced by a moving point across the skin*, Journal of experimental psychology, 97 (1973), pp. 59–63.

[139] E. C. LECHELT AND R. BORCHERT, *The interdependence of time and space in somesthesis: The Tau effect reexamined*, Bulletin of the Psychonomic Society, 10 (1977), pp. 191–193.

[140] S. J. LEDERMAN AND L. A. JONES, *Tactile and Haptic Illusions*, IEEE Transactions on Haptics, 4 (2011), pp. 273–294.

[141] S. J. LEDERMAN AND R. L. KLATZKY, *Hand Movements: A Window into Haptic Object REcognition*, Cognitive Psychology, 19 (1987), pp. 342–368.

[142] S. J. LEDERMAN AND R. L. KLATZKY, *Haptic perception: A tutorial*, Attention, Perception & Psychophysics, 71 (2009), pp. 1439–1459.

[143] H. LEE, J. S. KIM, J. Y. KIM, S. CHOI, J. H. JUN, J. R. PARK, A. H. KIM, H. B. OH, J. H. BAEK, S. J. YANG, H. S. KIM, AND S. C. CHUNG, *Mid-Air Tactile Stimulation Using Indirect Laser Radiation*, IEEE Transactions on Haptics, 9 (2016), pp. 574–585.

[144] B. LENGGENHAGER, L. HILTI, AND P. BRUGGER, *Disturbed body integrity and the 'rubber foot illusion'*, Neuropsychology, 29 (2015), pp. 205–211.

[145] B. LENGGENHAGER, T. TADI, T. METZINGER, AND O. BLANKE, *Video ergo sum: Manipulating bodily self-consciousness*, Science, 317 (2007), pp. 1096–1099.

[146] L. LIN AND S. JÖRG, *Need a hand? How appearance affects the virtual hand illusion*, Proceedings of the ACM Symposium on Applied Perception, SAP 2016, (2016), pp. 69–76.

[147] D. M. LLOYD, *Spatial limits on referred touch to an alien limb may reflect boundaries of visuo-tactile peripersonal space surrounding the hand*, Brain and Cognition, 64 (2007), pp. 104–109.

[148] M. LOMBARD AND T. DITTON, *At the Heart of It All: The Concept of Presence*, Journal of Computer-Mediated Communication, 3 (1997), pp. 0–0.

[149] M. LOMBARD, T. B. DITTON, D. CRANE, B. DAVIS, G. GIL-EGUI, K. HORVATH, AND J. ROSSMAN, *Measuring presence: A literature-based approach to the development of a standardized paper-and-pencil instrument*, Presence 2000: The Third International Workshop on Presence, (2000), p. 13.

[150] B. LONG, S. A. SEAH, T. CARTER, AND S. SUBRAMANIAN, *Rendering volumetric haptic shapes in mid-air using ultrasound*, ACM Transactions on Graphics, 33 (2014), pp. 1–10.

[151] M. R. LONGO, F. SCHÜÜR, M. P. KAMMERS, M. TSAKIRIS, AND P. HAGGARD, *What is embodiment? A psychometric approach*, Cognition, 107 (2008), pp. 978–998.

[152] P. LUSH, V. BOTAN, T. SCOTT, J. WARD, AND Z. DIENES, *Phenomenological control: response to imaginative suggestion predicts measures of mirror touch synaesthesia, vicarious pain and the rubber hand illusion.*, 1 (2019), pp. 1–78.

[153] K. Ma and B. Hommel, *The virtual-hand illusion: Effects of impact and threat on perceived ownership and affective resonance*, Frontiers in Psychology, 4 (2013), pp. 1–6.

[154] K. Maclean, *The impact of institutionalization on child development*, Development and Psychopathology, 15 (2003), pp. 853–884.

[155] K. E. MacLean, M. J. Enriquez, and T. Lim, *Morphing in periodic tactile signals*, Proceedings - 3rd Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, World Haptics 2009, (2009), pp. 178–183.

[156] L. Maister, M. Slater, M. V. Sanchez-Vives, and M. Tsakiris, *Changing bodies changes minds: Owning another body affects social cognition*, Trends in Cognitive Sciences, 19 (2015), pp. 6–12.

[157] F. Mancini, A. Bauleo, J. Cole, F. Lui, C. A. Porro, P. Haggard, and G. D. Iannetti, *Whole-body mapping of spatial acuity for pain and touch*, Annals of Neurology, 75 (2014), pp. 917–924.

[158] A. Marotta, M. Tinazzi, C. Cavedini, M. Zampini, and M. Fiorio, *Individual differences in the rubber hand illusion are related to sensory suggestibility*, PLoS ONE, 11 (2016), p. e0168489.

[159] T. Marsh, *Staying There: An Activity-Based Approach to Narrative Design and Evaluation as an Antidote to Virtual Corpsing*, in Being There: Concepts, Effects and Measurements of User Presence in Synthetic Environments, Ios Press, 2003, pp. 85–96.

[160] J. Martínez, D. Griffiths, V. Biscione, O. Georgiou, and T. Carter, *Touchless haptic feedback for supernatural VR experiences*, in 2018 IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2018, Tuebingen/Reutlingen, Germany, 18-22 March 2018, 2018, pp. 629–630.

[161] G. Memoli, M. Caleap, M. Asakawa, D. R. Sahoo, B. W. Drinkwater, and S. Subramanian, *Metamaterial bricks and quantization of meta-surfaces*, Nature Communications, 8 (2017), pp. 1–8.

[162] C. Michel, C. Velasco, A. Salgado-Montejo, and C. Spence, *The Butcher's Tongue Illusion*, Perception, 43 (2014), pp. 818–824.

[163] P. Milgram, H. Takemura, a. Utsumi, and F. Kishino, *Mixed Reality (MR) Reality-Virtuality (RV) Continuum*, Systems Research, 2351 (1994), pp. 282–292.

[164] S. R. Mills, M. Morioka, and M. J. Griffin, *Limitations of Vibrotactile Thresholds*, in Conference on Human Responses to Vibration, 2018.

[165] A. Moscatelli, M. Bianchi, A. Serio, A. Terekhov, V. Hayward, M. O. Ernst, and A. Bicchi, *The Change in Fingertip Contact Area as a Novel Proprioceptive Cue*, Current Biology, 26 (2016), pp. 1159–1163.

[166] K. Ma and B. Hommel, *Body-ownership for actively operated non-corporeal objects*, Consciousness and Cognition, 36 (2015), pp. 75–86.

[167] K. Myles and M. S. Binseel, *The Tactile Modality : A Review of Tactile Sensitivity and Human Tactile Interfaces*, Tech. Rep. May, 2007.

[168] B. A. Nardi, *Context and consciousness : activity theory and human-computer interaction*, MIT Press, 1996.

[169] S. G. Nicovich, G. W. Boller, and T. B. Cornwell, *Experienced Presence within Computer-Mediated Communications: Initial Explorations on the Effects of Gender with Respect to Empathy and Immersion*, Journal of Computer-Mediated Communication, 10 (2006), pp. 00–00.

[170] J. M. Normand, E. Giannopoulos, B. Spanlang, and M. Slater, *Multi-sensory stimulation can induce an illusion of larger belly size in immersive virtual reality*, PLoS ONE, 6 (2011).

[171] M. OBRIST, S. A. SEAH, AND S. SUBRAMANIAN, *Talking about tactile experiences*, in Conference on Human Factors in Computing Systems - Proceedings, New York, New York, USA, 4 2013, ACM Press, pp. 1659–1668.

[172] M. OBRIST, S. SUBRAMANIAN, E. GATTI, B. LONG, AND T. CARTER, *Emotions mediated through mid-air haptics*, Conference on Human Factors in Computing Systems - Proceedings, 2015-April (2015), pp. 2053–2062.

[173] Y. OCHIAI, K. KUMAGAI, T. HOSHI, S. HASEGAWA, AND Y. HAYASAKI, *Cross-Field Aerial Haptics : Rendering Haptic Feedback in Air with Light and Acoustic Fields*, Chi '16, (2016), pp. 3238–3247.

[174] R. OKAZAKI, H. KAJIMOTO, AND V. HAYWARD, *Vibrotactile stimulation can affect auditory loudness: A pilot study*, in Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), P. Isokoski and J. Springare, eds., vol. 7283 LNCS, Berlin, Heidelberg, 2012, Springer Berlin Heidelberg, pp. 103–108.

[175] M. A. OTADUY AND S. SUBRAMANIAN, *Haptic Technologies for Direct Touch in Virtual Reality*, (2016).

[176] C. PACCHIEROTTI, S. SINCLAIR, M. SOLAZZI, A. FRISOLI, V. HAYWARD, AND D. PRATTICHIZZO, *Wearable haptic systems for the fingertip and the hand: Taxonomy, review, and perspectives*, IEEE Transactions on Haptics, 10 (2017), pp. 580–600.

[177] M. P. PALADINO, M. MAZZUREGA, F. PAVANI, AND T. W. SCHUBERT, *Synchronous multisensory stimulation blurs self-other boundaries*, Psychological Science, 21 (2010), pp. 1202–1207.

[178] Y. W. PARK, K. M. BAEK, AND T. J. NAM, *The roles of touch during phone conversations: Long-distance couples' use of POKE in their homes*, Conference on Human Factors in Computing Systems - Proceedings, (2013), pp. 1679–1688.

[179] J. PECK AND T. L. CHILDERS, *Individual Differences in Haptic Information Processing: The "Need for Touch" Scale*, Journal of Consumer Research, 30 (2003), pp. 430–442.

[180] M. PELÁEZ-NOGUERAS, T. M. FIELD, Z. HOSSAIN, AND J. PICKENS, *Depressed mothers' touching increases infants' positive affect and attention in still-face interactions.*, Child development, 67 (1996), pp. 1780–1792.

[181] D. PEREZ-MARCOS, M. V. SANCHEZ-VIVES, AND M. SLATER, *Is my hand connected to my body? The impact of body continuity and arm alignment on the virtual hand illusion*, Cognitive Neurodynamics, 6 (2012), pp. 295–305.

[182] V. I. PETKOVA AND H. H. EHRSSON, *If I were you: Perceptual illusion of body swapping*, PLoS ONE, 3 (2008), p. e3832.

[183] E. PEZENT, A. ISRAR, M. SAMAD, S. ROBINSON, P. AGARWAL, H. BENKO, AND N. COLONNESE, *Tasbi: Multisensory Squeeze and Vibrotactile Wrist Haptics for Augmented and Virtual Reality*, 2019 IEEE World Haptics Conference (WHC), (2019), pp. 1–6.

[184] D. PICARD, C. DACREMONT, D. VALENTIN, AND A. E. E. GIBOREAU, *Perceptual dimensions of tactile textures*.

[185] D. PITTERA, M. OBRIST, AND A. ISRAR, *Hand-to-hand: an intermanual illusion of movement*, in Proceedings of the 19th ACM International Conference on Multimodal Interaction - ICMI 2017, 2017, pp. 73–81.

[186] J. C. POSNICK, A. G. ZIMBLER, AND J. A. GROSSMAN, *Normal cutaneous sensibility of the face* , Plast.Reconstr.Surg., 86 (1990), pp. 429–433.

[187] C. PRESTON AND R. NEWPOR, *How long is your arm? Using multisensory illusions to modify body image from the third person perspective*, Perception, 41 (2012), pp. 247–249.

[188] L. R. SQUIRE, D. BERG, F. E. BLOOM, S. D. LAC, A. GHOSH, AND N. C. SPITZER, *Fundamental Neuroscience (4th edition)*, 2010.

[189] V. S. RAMACHANDRAN, B. KRAUSE, AND L. K. CASE, *The phantom head*, Perception, 40 (2011), pp. 367–370.

[190] P. RAMSAMY, A. HAFFEGEE, R. JAMIESON, AND V. ALEXANDROV, *Using haptics to improve immersion in virtual environments*, in Computational Science – ICCS 2006, V. N. Alexandrov, G. D. van Albada, P. M. A. Sloot, and J. Dongarra, eds., Berlin, Heidelberg, 2006, Springer Berlin Heidelberg, pp. 603–609.

[191] S. RAZZAQUE, Z. KOHN, AND M. C. WHITTON, *Redirected Walking*, Proceedings of EUROGRAPHICS, (2001), pp. 289–294.

[192] C. REED, R. KLATZKY, AND S. LEDERMAN, *Haptic Integration of Object Properties: Texture, Hardness, and Planar Contour*, Journal of Experimental Psychology, (1989).

[193] C. L. REED, R. L. KLATZKY, AND E. HALGREN, *What vs. where in touch: An fMRI study*, NeuroImage, 25 (2005), pp. 718–726.

[194] G. RÉVÉSZ, *Psychology and art of the blind*, vol. 53, Longmans, Green and Co., 1950.

[195] T. ROSBURG, *Tactile ground surface indicators in public places*, in Human Haptic Perception: Basics and Applications, Birkhäuser Basel, Basel, 2008, pp. 491–499.

[196] I. RUTTEN, W. FRIER, L. VAN DEN BOGAERT, AND D. GEERTS, *Invisible touch: How identifiable are mid-air haptic shapes?*, in Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems, CHI EA '19, ACM, 2019, pp. LBW0283:1–LBW0283:6.

[197] H. P. SAAL, B. P. DELHAYE, B. C. RAYHAUN, AND S. J. BENSMAIA, *Simulating tactile signals from the whole hand with millisecond precision*, Proceedings of the National Academy of Sciences, 114 (2017).

[198] A. SACAU, J. LAARNI, AND T. HARTMANN, *Influence of individual factors on presence*, Computers in Human Behavior, 24 (2008), pp. 2255–2273.

[199] O. SACKS AND S. M. STEIN, *The Man Who Mistook His Wife for a Hat*, vol. 166, Gerald Duckworth, 1 1995.

[200] E.-L. SALLNÄS, K. RASSMUS-GRÖHN, AND C. SJÖSTRÖM, *Supporting Presence in Collaborative Environments by Haptic Force Feedback*, ACM Transactions on Computer-Human Interaction, 7 (2000), pp. 461–476.

[201] M. V. SANCHEZ-VIVES, B. SPANLANG, A. FRISOLI, M. BERGAMASCO, AND M. SLATER, *Virtual hand illusion induced by visuomotor correlations*, PLoS ONE, 5 (2010), pp. 1–6.

[202] A. H. SASNUR, P. A. SASNUR, AND R. S. M. GHAUS-UL, *Congenital insensitivity to pain and anhidrosis*, Indian Journal of Orthopaedics, 45 (2011), pp. 269–271.

[203] M. M. S. SCHALKA, M. S. N. P. CORRÊA, AND A. L. CIAMPONI, *Congenital insensitivity-to-pain with anhidrosis (CIPA): A case report with 4-year follow-up*, Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology, 101 (2006), pp. 769–773.

[204] D. W. SCHLOERB, *A Quantitative Measure of Telepresence*, Presence: Teleoperators and Virtual Environments, 4 (1995), pp. 64–80.

[205] V. SCHWIND, P. KNIERIM, C. TASCI, P. FRANCZAK, N. HAAS, AND N. HENZE, *"These are not my hands!": Effect of gender on the perception of avatar hands in virtual reality*, Conference on Human Factors in Computing Systems - Proceedings, 2017-May (2017), pp. 1577–1582.

[206] V. SCHWIND, L. LIN, M. DI, S. JÖRG, J. HILLIS, AND M. DI LUCA, *Touch with Foreign Hands: The Effect of Virtual Hand Appear-ance on Visual-Haptic Integration*, SAP, 18.

[207] H. Seifi, F. Fazlollahi, M. Oppermann, J. A. Sastrillo, J. Ip, A. Agrawal, G. Park, K. J. Kuchenbecker, and K. E. MacLean, *Haptipedia*, in CHI 2019, 2019, pp. 1–12.

[208] A. Sforza, I. Bufalari, P. Haggard, and S. M. Aglioti, *My face in yours: Visuo-tactile facial stimulation influences sense of identity*, Social Neuroscience, 5 (2010), pp. 148–162.

[209] G. Shakeri, J. H. Williamson, and S. A. Brewster, *Bimodal feedback for in-car mid-air gesture interaction*, in Proceedings of the 19th ACM International Conference on Multimodal Interaction, ICMI 2017, ACM, 2017, pp. 518–519.

[210] T. B. Sheridan, *Musings on Telepresence and Virtual Presence*, Presence: Teleoperators and Virtual Environments, 1 (1992), pp. 120–126.

[211] S. Shimada, K. Fukuda, and K. Hiraki, *Rubber hand illusion under delayed visual feedback*, PLoS ONE, 4 (2009), p. e6185.

[212] D. I. Shore, K. Gray, E. Spry, and C. Spence, *Spatial modulation of tactile temporal-order judgments*, Perception, 34 (2005), pp. 1251–1262.

[213] D. I. Shore, E. Spry, and C. Spence, *Confusing the mind by crossing the hands*, Cognitive Brain Research, 14 (2002), pp. 153–163.

[214] M. Slater, D. Perez-Marcos, H. H. Ehrsson, and M. V. Sanchez-Vives, *Towards a digital body: The virtual arm illusion*, Frontiers in Human Neuroscience, 2 (2008), p. 6.

[215] M. Slater, D. Perez-Marcos, H. H. Ehrsson, and M. V. Sanchez-Vives, *Inducing illusory ownership of a virtual body*, Frontiers in Neuroscience, 3 (2009), pp. 214–220.

[216] M. Slater, B. Spanlang, M. V. Sanchez-Vives, and O. Blanke, *First person experience of body transfer in virtual reality*, PLoS ONE, 5 (2010), pp. 1–9.

[217] M. SLATER, M. USOH, AND A. STEED, *Depth of presence in virtual environments*, Presence: Teleoperators and virtual environment, 3 (1994), pp. 130–144.

[218] R. SODHI, POUPYREV, M. GLISSON, AND A. ISRAR, *AIREAL: interactive tactile experiences in free air*, ACM Transactions on Graphics, 32 (2013), p. 134.

[219] D. SPELMEZAN, R. M. GONZÁLEZ, AND S. SUBRAMANIAN, *SkinHaptics: Ultrasound focused in the hand creates tactile sensations*, in IEEE Haptics Symposium, HAPTICS, vol. 2016-April, 2016, pp. 98–105.

[220] C. SPENCE, *In Touch with the Future*, Oxford Press, 2015.

[221] J. STEUER, *Defining Virtual Reality: Dimensions Determining Telepresence*, Journal of Communication, 42 (1992), pp. 73–93.

[222] V. STROBEL, *Pold87/academic-keyword-occurrence: First release*, (2018).

[223] P. STROHMEIER AND K. HORNBÆK, *Generating Haptic Textures with a Vibrotactile Actuator*, Proc. CHI '17, (2017).

[224] M. STUART, A. B. TURMAN, J. SHAW, N. WALSH, AND V. NGUYEN, *Effects of aging on vibration detection thresholds at various body regions.*, BMC geriatrics, 3 (2003), p. 1.

[225] D. J. STURMAN AND D. ZELTZER, *A Survey of Glove-based Input*, IEEE Computer Graphics and Applications, 14 (1994), pp. 30–39.

[226] I. E. SUTHERLAND, *A head-mounted three dimensional display*, in Proceedings of the December 9-11, 1968, fall joint computer conference, part I on - AFIPS '68 (Fall, part I), 1968, p. 757.

[227] K. SUZUKI, S. N. GARFINKEL, H. D. CRITCHLEY, AND A. K. SETH, *Multisensory integration across exteroceptive and interoceptive domains modulates*

self-experience in the rubber-hand illusion, Neuropsychologia, 51 (2013), pp. 2909–2917.

[228] Y. SUZUKI AND M. KOBAYASHI, *Air jet driven force feedback in virtual reality*, IEEE Computer Graphics and Applications, 25 (2005), pp. 44–47.

[229] R. TAKAHASHI, K. HASEGAWA, AND H. SHINODA, *Lateral Modulation of Midair Ultrasound Focus for Intensified Vibrotactile Stimuli*, Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 10894 LNCS (2018), pp. 276–288.

[230] A. TANG, F. BIOCCA, AND L. LIM, *Comparing Differences in Presence during Social Interaction in Augmented Reality versus Virtual Reality Environments : An Exploratory Study*, 7th Annual International Workshop on Presence, (2004), pp. 204–208.

[231] J. TASTEVIN, *En partant de l'expérience d'Aristote: Les déplacements artificiels des parties du corps ne sont pas suivis par le sentiment de ces parties ni pas les sensations qu'on peut y produire [Starting from Aristotle's illusion: The artificial displacements of pa*, L'Encephale, 1 (1937), pp. 57–84.

[232] A. THEUREL, S. FRILEUX, Y. HATWELL, AND E. GENTAZ, *The haptic recognition of geometrical shapes in congenitally blind and blindfolded adolescents: Is there a haptic prototype effect?*, in PloS one, 2012.

[233] E. I. TONY PRESCOTT, EHUD AHISSAR, *Scholarpedia of Touch*, 2016.

[234] M. TSAKIRIS, L. CARPENTER, D. JAMES, AND A. FOTOPOULOU, *Hands only illusion: Multisensory integration elicits sense of ownership for body parts but not for non-corporeal objects*, Experimental Brain Research, 204 (2010), pp. 343–352.

[235] M. TSAKIRIS AND P. HAGGARD, *The rubber hand illusion revisited: visuotactile integration and self-attribution.*, J Exp Psychol Hum Percept Perform, 31 (2005), pp. 80–91.

[236] A. B. VALLBO AND R. S. JOHANSSON, *Properties of cutaneous mechanoreceptors in the human hand related to touch sensation.*, Human neurobiology, 3 (1984), pp. 3–14.

[237] R. T. VERRILLO, *Effect of Contactor Area on the Vibrotactile Threshold*, The Journal of the Acoustical Society of America, 35 (1963), pp. 1962–1966.

[238] R. T. VERRILLO, *A duplex mechanism of mechanoreception*, Proc. First International Symposium on the Skin Sense, Thomas, Springfield, Illinois, 1968, (1968), pp. 139–159.

[239] R. T. VERRILLO AND S. J. BOLANOWSKI, *The effects of skin temperature on the psychophysical responses to vibration on glabrous and hairy skin*, Journal of the Acoustical Society of America, 80 (1986), pp. 528–532.

[240] C. T. VI, D. ABLART, E. GATTI, C. VELASCO, AND M. OBRIST, *Not just seeing, but also feeling art: Mid-air haptic experiences integrated in a multisensory art exhibition*, International Journal of Human Computer Studies, 108 (2017), pp. 1–14.

[241] D.-B. B. VO AND S. A. BREWSTER, *Touching the Invisible: Localizing Ultrasonic Haptic Cues*, Proceedings of World Haptics Conference 2015 - WHC '15, (2015), pp. 368–373.

[242] G. VON BÉKÉSY, *Über die Vibrationsempfindung*, S. Hirzel, 1939.

[243] G. VON BÉKÉSY, *Experiments in Hearing*, The Journal of the Acoustical Society of America, 88 (1960), p. 2905.

[244] H. S. WALLACH, M. P. SAFIR, AND M. BAR-ZVI, *Virtual reality cognitive behavior therapy for public speaking anxiety: A randomized clinical trial*, Behavior Modification, 33 (2009), pp. 314–338.

[245] H. S. WALLACH, M. P. SAFIR, R. SAMANA, I. ALMOG, AND R. HOREF, *How can presence in psychotherapy employing VR be increased? Chapter for inclusion in: Systems in health care using agents and virtual reality*, Studies in Computational Intelligence, 337 (2011), pp. 129–147.

[246] A. WATSON AND C. FRENCH, *Müller-Lyer haptic illusion and a confusion theory explanation*, 1966.

[247] E. H. WEBER, *Concerning touch, 1834.*, in Readings in the history of psychology., Appleton-Century-Crofts, East Norwalk, 2007, pp. 155–156.

[248] S. WEINSTEIN, *Intensive and extensive aspects of tactile sensitivity as a function of body part, sex and laterality*, in First International Symposium on Skin Senses, 1968, pp. 195–222.

[249] K. WEISS AND I. SCHARLAU, *Simultaneity and temporal order perception: Different sides of the same coin? Evidence from a visual prior-entry study*, The Quarterly Journal of Experimental Psychology, 64 (2011), pp. 394–416.

[250] E. WHITMIRE, H. BENKO, C. HOLZ, E. OFEK, AND M. SINCLAIR, *Haptic Revolver: Touch, Shear, Texture, and Shape Rendering on a Reconfgurable Virtual Reality Controller*.

[251] G. WILSON, T. CARTER, S. SUBRAMANIAN, AND S. BREWSTER, *Perception of ultrasonic haptic feedback on the hand: Localisation and apparent motion*, Conference on Human Factors in Computing Systems - Proceedings, (2014), pp. 1133–1142.

[252] B. G. WITMER AND M. J. SINGER, *Measuring Presence in Virtual Environments: A Presence Questionnaire*, Presence: Teleoperators and Virtual Environments, 7 (1998), pp. 225–240.

[253] J. O. WOBBROCK, A. D. WILSON, AND Y. LI, *Gestures without libraries, toolkits or training: A $1 recognizer for user interface prototypes*, in Proceedings

of the 20th Annual ACM Symposium on User Interface Software and Technology, UIST '07, ACM, 2007, pp. 159–168.

[254] A. WOLD, J. LIMANOWSKI, H. WALTER, AND F. BLANKENBURG, *Proprioceptive drift in the rubber hand illusion is intensified following 1 HzTMS of the left EBA*, Frontiers in Human Neuroscience, 8 (2014), p. 390.

[255] R. WOOD AND A. L. LOOMIS, *XXXVIII. The physical and biological effects of high-frequency sound-waves of great intensity* , The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 4 (1927), pp. 417–436.

[256] S. YAMAMOTO AND S. KITAZAWA, *Reversal of subjective temporal order due to arm crossing.*, Nature Neuroscience, 4 (2001), pp. 759–765.

[257] K. YOSHINO, K. HASEGAWA, AND H. SHINODA, *Measuring Visio-Tactile threshold for Visio-Tactile Projector*, in SICE Annual Conference 2012, 2012, pp. 1996–2000.

[258] Y. YUAN AND A. STEED, *Is the rubber hand illusion induced by immersive virtual reality?*, Proceedings - IEEE Virtual Reality, (2010), pp. 95–102.

[259] D. ZHANG, Y. DING, J. STEGALL, AND L. MO, *The effect of visual-chunking-representation accommodation on geometry testing for students with math disabilities*, Learning Disabilities Research & Practice, 27 (2012).

[260] S. ZHAO, A. ISRAR, M. FENNER, AND R. L. KLATZKY, *Intermanual Apparent Tactile Motion and Its Extension to 3D Interactions*, IEEE transactions on haptics, 10 (2017), pp. 555–566.

[261] S. ZHAO, A. ISRAR, AND R. KLATZKY, *Intermanual apparent tactile motion on handheld tablets*, IEEE World Haptics Conference, WHC 2015, (2015), pp. 241–247.