DOCTORAL THESIS

Ultrasonic mid-air haptic technology in context of science communication

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

in the

Department of Informatics
School of Engineering and Informatics

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Dedicated to my dear child

You have not yet been born when I have written this letter. I haven't even known who your mother will be. All I knew was that, I would like you to develop a sense of curiosity about the world you live in. I do not expect you to read my doctoral dissertation. All I wish – if you stumble upon this volume – is that you will find inspiration from my own curiosity. If you live your life with an open mind, you will always be free, no matter what constraints life might throw at you. There are multiple ways to learn about the world: science, religion, art, or philosophy. Neither of these ways are right or wrong. They are different ways of contributing to the human experience. Yet, you have to be cautious. Value can only be derived of these paths, if they are treated with respect and kept in balance. The excerpts below helped me in appreciating the diversity of seeking knowledge, and I hope they will help you too.

> "We must cultivate all three intelligences for our overall health. If you have developed critical intelligence but neglected emotional intelligence, then you may not be sensitive to the suffering of others. If you have developed emotional intelligence but neglected spiritual intelligence, then you may lose hope after seeing the world's suffering. If you have developed spiritual intelligence but neglected critical intelligence, then you may fall victim to the abuse of a cult." – Haemin Sunim

> "Only once before in our history was there the promise of a brilliant scientific civilisation. Beneficiary of the Ionian Awakening, it had its citadel at the Library of Alexandria, where 2,000 years ago the best minds of antiquity established the foundations for the systematic study of mathematics, physics, biology, astronomy, literature, geography and medicine. What prevented them from taking root and flourishing? Why instead did the West slumber through a thousand years of darkness until Columbus and Copernicus and their contemporaries rediscovered the work done in Alexandria? Science and learning in general were the preserve of a privileged few. New findings were not explained or popularised. Science never captured the imagination of the multitude. There was no counterbalance to stagnation, to pessimism, to the most abject surrenders to mysticism. When, at long last, the mob came to burn the Library down, there was nobody to stop them." – Carl Sagan

My dear child, I encourage you to ask questions, carefully inspect arguments before believing or rejecting them, and actively seek new knowledge.

Much love, Dad

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In the first instance, I would like to thank my parents and other family members, alongside close friends. Mum, Dad, thank you for studying with me side by side, helping and encouraging me at all stages of my education. Thank you for supporting my ambitions as a science graduate, whether it be financially, through advice, daily conversations, the mind blowing food packages, or casual time spent together, which all gave me energy to become who I am. I'm just as grateful for your love and support Mama, Vera, and the Veres family.

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I must also lift my hat in front of one of the most influential people in my studies – Prof Kathy Romer. Thank you Kathy for believing and encouraging me since the first year of my undergraduate degree, and for opening up countless new doors. Without Kathy, I might not have ever thought of tactile graphics displays, selected a Masters project in science communication, or learnt to distinguish between commercial and academic thinking.

More importantly, I might not have met David, Tim, Linn, and Chloe - my personal heroes, who sacrificed more than anybody can ask for, just to make my dream come through. Thank you Grapheel team for creating a shared vision, which was a fantastic adventure into access to science, only possible because of your exceptional talents, empathy, and dedication. Last but not least, my heartfelt gratitude goes to all staff and students in the School of Mathematical and Physical Sciences, who taught me many curious tricks of nature. Yet, during the four years of my studies, you taught me one lesson that stands out more than all the others: the wonders of science behoove all those who desire it, regardless their abilities or interests.

DECLARATION

I, Daniel Hajas, hereby declare that this thesis has not been and will not be, submitted in whole or in part to another university for the award of any other degree.

Brighton,
April 24, 2021

Daniel Hajas

The following list quantifies the estimated contributions of collaborators in the respective chapters, and identifies my peer reviewed publications. More detailed description of my own contributions are provided in the associated "Contributions to thesis" sections.

Chapter 5: Hajas, D. (70%), Ablart, D. (10%), Schneider, O. (10%), Obrist, M. (10%) (2020). *"I can feel it moving: Science Communicators Talking About the Potential of Mid-Air Haptics"*. Frontiers in Computer Science, 2:534974.

Chapter 6: Hajas, D. (80%), Schneider, O. (10%), Obrist, M. (10%) (2020). *"Beyond learning outcomes: How do we Feel about Touching Subatomic Particles?"*. Unpublished.

Chapter 7: Trotta, R. (35%), Hajas, D. (35%), Camargo-Molina, E. (10%), Cobden, R. (10%), Maggioni, E. (5%), Obrist, M. (5%) (2020). *"Communicating Cosmology with Multisensory Metaphorical Experiences"*. Journal of Science Communication, 19:1.

Chapter 8: O'Conaill, B. (30%), Provan, J. (20%), Schubel, J. (20%), Hajas, D. (20%), Obrist, M. (5%), Corenthy, L. (5%) (2020). *"Improving Immersive Experiences for Visitors with Sensory Impairments to the Aquarium of the Pacific"*, in Proceedings of ACM CHI '20 Extended Abstracts, Honolulu, HI, USA.

Chapter 9: Hajas, D. (70%), Pittera, D. (15%), Nasce, A. (5%), Georgiou, O. (5%), Obrist, M. (5%) (2020). *"Mid-Air Haptic Rendering of 2D Geometric Shapes with a Dynamic Tactile Pointer"*. IEEE Transactions on Haptics, 13:4 (806-817).

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by Daniel Hajas

SUMMARY

This dissertation charts opportunities and challenges of engaging people with learning about science through the use of mid-air haptic technology. To that end, research has been carried out at the intersection of three multidisciplinary fields: Science Communication, Haptics, and Human-Computer Interaction.

For science communication to be effective, different tools are required for different audiences. For example, when a child pours cold milk into hot tea and sips a warm beverage, we can raise awareness of the haptic experience; triggering interest and facilitating learning about thermal equilibrium. Not every scientific concept may be explained through changing temperature, and not everybody likes tea, but the principle of haptic experience facilitated public engagement with science remains a valid basis to examine.

Science communicators seek new technological solutions and innovative modalities of communication, some of which include haptic technology and touch interaction. Ultrasonic mid-air haptic technology is a novel tool, which enables the creation of programable, invisible, cutaneous tactile sensations on an airborne interface between humans and the digital world. Mid-air haptic sensations may bring many benefits when used in science communication, but these have not yet been systematically studied.

Thus, the overall research question of this thesis addresses – How can engagement between science and society be supported by mid-air haptic technology? The research approach has been based on both qualitative and quantitative methods seen in HCI and haptics, such as psychophysical pilot studies, or eliciting experiences through interviews. Five projects form part of this thesis, in which both empirical research and practical work has been carried out. Multiple audience types, as building blocks of society, were studied in the individual projects, which investigated the effectiveness of the technology across three major aspects: leveraging the spectrum of haptic interaction, creating multisensory experiences of engaging with science in ecologically valid environments, and conveying specifically intended scientific information.

Mid-air haptics, in its current technological state, is most effective in facilitating the engagement between science and society in forms of entertainment and art, i.e. the Enjoyment dimension of the *AEIOU* framework of science communication. Yet, using novel methods of rendering haptic sensations, recognition of mid-air haptic shapes is comparable to recognition of other forms of tactile geometry, making communication of specific scientific information an achievable goal.

Based on the synthesised results, this thesis also recommends three areas of research relevant to science communication facilitated by the haptic experience. Specifically, future studies may address predictive modelling of shifting attitude towards science as a result of haptic experiences; developing methodological approaches to evaluating multisensory science communication; and investigating the assistive technology capabilities of mid-air haptics with regards to the knowledge transfer of scientific content.

In summary, this dissertation makes a two-fold contribution to the fields of haptics and science communication. Firstly, a contribution is made by characterising ultrasonic mid-air haptic technology in the context of public engagement with science objectives, and the needs of different audiences. Secondly, this thesis contributes new knowledge by developing and verifying a more effective method of rendering mid-air haptic sensations, capable of conveying information relevant to scientific concepts.

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Background

Chapter 1

Introduction

"Science and technology do not solve every problem. But without science and technology, no problem can be solved" – Teller (1991) at a public talk.

1.1 Research context

In this section, I introduce my personal motivation for becoming a doctoral researcher, the scope of my research, and the impact I hope it will have on the research community and the public.

1.1.1 Motivation

During my undergraduate degree, I studied physics. I always wanted to understand the fundamental building blocks and laws of nature, where we as human species have evolved. However, by the end of the degree, it became even more important to communicate what science is, and what it offers to those who are not actively involved in science. The remark cited at the beginning of this chapter, made by the Hungarian born, American physicist Edward Teller is a concise and precise reason why I chose to research science communication. In particular, my research interest was attracted towards the challenge of communicating "invisible", and abstract concepts conceived in modern science.

Most of us have no problem with comprehending the explanations of an apple falling from a tree, an ice cube melting in sunshine, or a plank floating on the surface of water. We are able to perceive the weight or temperature of objects, see them float in everyday situations. More often than not, we also trust our sensory experiences. However, the scientific discoveries of the past 150 years bombarded society with an increasing number of imperceptible phenomena. Elementary particles, electromagnetic fields, quantum effects, dark matter, dark energy, the Higgs' Boson, gravitational waves, genetic code, radioactivity and the list goes on. Some of these concepts will have very little or no effect at all on society, but some others will most likely transform humanity. One common feature of these discoveries is that they are hidden from the human sensory organs, thereby depriving us from direct sensory experiences of these phenomena. Such a barrier might hinder scientific and technological advancement of society. After-all, why would anyone believe scientists' claims about things that do not exist, at least not to our senses? More crucially, why would anybody nurture a prospering scientific culture, supporting research, if the methods used by scientist to reinforce their claims remains a mystery? If people sensed dark matter, or experienced a quantum effect, building and preserving a flourishing scientific culture would perhaps face less challenges.

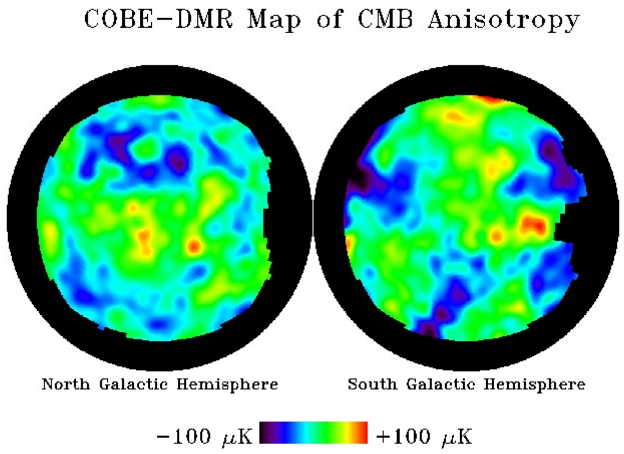

Figure 1.1: This false-colour image shows tiny variations in the intensity of the cosmic microwave background measured in four years of observations by the Differential Microwave Radiometers on NASA's Cosmic Background Explorer (COBE). The cosmic microwave background is widely believed to be a remnant of the Big Bang; the blue and red spots correspond to regions of greater or lesser density in the early Universe. These "fossilised" relics record the distribution of matter and energy in the early Universe before the matter became organised into stars and galaxies. Figure and caption reprinted from (National Aeronautical and Space Administration, 2020).

The year preceding my doctoral studies, building on this initial motivation, I began exploring multimodal science communication projects. In my Master's dissertation, I chose to discuss the discovery, measurements, and implications of the Cosmic Microwave Background (CMB) radiation on cosmology for two reasons. Firstly, because the CMB's imperceptible nature makes its existence difficult to acknowledge. Even Penzias and Wilson (1965), the associated scientists of the discovery, found the mysterious signal difficult to comprehend without sound theoretical expectation, which was hypothesised by Dicke et al. (1965). Since the discovery, CMB became universally known and studied within the scientific community. However, despite serving as evidence for the widely known "Big Bang" model and the popular colourful visualisations (see Figure 1.1), we can assume that most people are unfamiliar with the term "Cosmic Microwave Background". Secondly, this choice of topic created a convenient transition to discussing multimodal science communication. It seemed there is potential for novel technologies to play a role in bridging the communication gap between science and society.

Clements et al. (2017) used digital fabrication techniques to create a, tangible model of the CMB map, as shown in Figure 1.2a. This was one of the projects using technology to produce a sensory probe (other than a visual illustration) for the purpose of communicating an abstract, imperceptible concept. Other projects, such as the Tactile Universe (Bonne et al.,

2018) or Madura (2017) also used 3D printing to create tactile visualisations of astronomical phenomena (as illustrated in Figure 1.2b). In addition, scientific concepts were also turned into an auditory experience. The LHCSound (Asquith et al., 2009) and Quantizer (Paradiso et al., 2016) projects also used state-of-the-art sound technology to create sonified representations of high-energy particle physics. My initial review of these motivating examples, incentivised this doctoral research. I grew curious of how the human sensory system creates a representation of our environment, what is the state of technology able to stimulate our senses, and how this knowledge could be used to communicate the secrets of nature. Specifically, I was curious to learn about the sense of touch, and the discipline of Human-Computer Interaction.

(a) The digitally fabricated model of CMB radiation with coins to show scale.

(b) A 3D printed tactile galaxy (M51, Whirlpool). A ruler is showed to demonstrate scale. Figure reprinted from (Tactile Universe, 2018).

Figure 1.2: Examples of digitally fabricated astrophysical concepts.

1.1.2 Scope

The contributions of this doctoral thesis are set in the intersecting research fields of haptics and Human-Computer Interaction (HCI). Within these two interdisciplinary fields, the area of research is focused on mid-air haptic technology, and multisensory HCI respectively. Knowledge from sensory perception, research methods of HCI, and literature from haptics is used to study the problem spaces of science communication.

In the evolution of computer science, assembly instructions were replaced by graphical user interface elements and jargon-free dialogues. Computers used to be the sole territory of trained engineers and computer operators. In 2020, even children are regular computer users. Technological advancements and the birth of a new discipline in the 1980s – Human-Computer Interaction – made this possible. The abstract, and complex internal processes of a computer's black box were impersonated, simplified, and more importantly lifted out from the black box and visualised on a screen. This enabled most people to associate objects on the human computer interface with metaphors from their familiar environment, and adopt the new knowledge.

Actively engaging with science is still an exclusive privilege of trained scientists. Yet if the abstract and complex concepts of imperceptible phenomena in natural sciences could be simplified, and made more perceivable, we might observe a boost in scientific culture too. If the visual paradigms of HCI were able to advance computer literacy in society, we may hypothesise that multisensory HCI might advance scientific literacy. Lifting imperceptible phenomena out of the black box of nature, through the creation of sensory metaphors with computer controlled simulations, we might be able to associate these with our everyday sensory experiences. Multisensory HCI focusing on science communication, or – *Human-Science Interaction* for short –

might mean that even people who are not highly trained will be able to appreciate and benefit from science. This thesis aims to discuss how this goal could be achieved.

Out of all the sensory channels, the sense of touch is a potentially fruitful research topic in context of science communication. The senses of vision and hearing have been extensively studied. Computer generated visualisations, soundscapes are thoroughly researched and used frequently to convey information or to entertain society. On the other hand, computerised interfaces for olfaction or gustation are hard to find. Although the physiology and anatomy of the senses of smell and taste are well studied; research on olfactory and gustatory perception, technological stimulation of chemical senses is yet to mature before its wide spread application. Somewhere between the two extremes lay haptics – the science of touch. Much is understood about how touch works, with much more to study. The arsenal of haptic technologies is vast, with a wide spectrum of applications emerging during the past decades, and completely new techniques added to the toolbox of haptic technology in the recent years. In addition to piezoelectric actuators and mechanical force feedback, it is now possible to computationally control ultrasound and create contactless tactile sensations, often referred to as mid-air haptics.

Producing airborne tangible simulations that are invisible and inaudible became possible with the invention of mid-air haptic technology. This may be an appealing property when communicating imperceptible concepts of science, since an apparently imperceptible phenomena to our eyes and ears suddenly becomes "real" to our sense of touch. It also means that augmenting the tactile sensation with matching visual and auditory stimuli may be done more easily, than augmenting fabricated tangible artefacts or wearable devices, in an augmented reality environment. The relatively high spacial and temporal resolution of ultrasonic mid-air haptics, alongside its programability may mean that the technology is capable of combining the benefits of multiple other haptic technologies in one tactile display. Its ability to render three-dimensional tactile sensations and movement, track hand gesture, remaining stable during tactile interaction may accommodate fundamental properties of natural phenomena, as well as requirements of interaction design. The sense of touch has also been shown to impact human emotions, behaviour and cognitive processes, including mid-air haptic technology mediated touch. This is very important, since emotional experiences and the affective domain of learning are a significant research topic in science communication. All of these arguments made the choice of research sub-scope fall on haptics, prioritising mid-air touch. Section 3.4.4 offers a more detailed comparison of mid-air haptics and other haptic technologies, discussing why airborne haptics may be a valuable tool in the hands of science communicators.

1.1.3 Project timeline, funding and impact

The research has been carried out between 2017 and 2020, in the Sussex Computer-Human Interaction laboratory at the University of Sussex, United Kingdom. Proceeding an initial literature review in 2017, I began working on the research presented in chapter 5 (January-April 2018). Followed by multiple unsuccessful submissions for peer review, I reanalysed the collected data, reframed the outcomes with a new collaborator (August '19 – February '20), which was accepted for publication in October 2020. The following year, I worked on three projects simultaneously, with varying degrees of attention, depending on the status of each individual project.

In May 2018, I started working on the content of chapter 9, but it was not completed until May 2019, when it was submitted for peer review, and later accepted for publication in January 2020. Between June '18 and July '19 I was involved in the collaboration discussed in chapter 7, working on experience design, implementation, and delivering two live events. The associated paper was submitted in December 2019, and accepted for publication in April 2020. During January-May 2019, I contributed to the work presented in chapter 8, which was accepted for publication in January 2020.

From October 2019 I started working on my last project, discussed in chapter 6, which has been terminated in September 2020. This project has not been submitted for peer review, since the onset of the COVID19 pandemic only allowed me to carry out a pilot study, and not a full scale experiment, as planned for the second half of the project. In 2020, I also spent significant time writing this thesis, and corresponding with co-authors and publishers about the fully revised version of accepted papers for publication.

The work was funded by Ultraleap Limited and the European Research Council (ERC starting grant SenseX). The company commercialised ultrasonic mid-air haptic technology in 2013. The academic programme at Ultraleap partners with multiple academics across the globe, sponsors PhD students to carry out research for the improvement of the technology, as well as its adaption in various application areas. A three months long research internship was going to constitute part of this doctoral programme (March-May 2020); however, this was suspended two weeks after its beginning, due to the global COVID19 pandemic. During October-December 2020, I was able to continue with the research placement at Ultraleap, but due to the six months delay, I was unable to incorporate these research outcomes within this thesis.

Given the commercial availability of mid-air haptic technology, I hope my contributions will have an impact on the research community and science communication practitioners alike. Researchers in the field of haptics and HCI may recognise informal science communication as a valuable application area to study and develop for, beyond the haptic technology studies conducted in science education. In the meantime, science communication researchers may want to study the effects of modern technology, published at HCI venues, in context of their sociology driven research questions. Two of the projects discussed in this thesis were published as practical insights, with public displays in the London Science Museum and the Aquarium of the Pacific (LA, USA). These practical contributions were created in the hope that they will impact the growth of multisensory public engagement, accommodating the needs of audiences with special needs, and catering for a range of audience attitudes.

1.2 Research statement

This doctoral thesis discusses the opportunities and challenges arising from the relationship between human tactile experiences, contactless haptic technology, and society's engagement with science. In the broadest sense, the overall research question addresses – *"How can engagement between science and society be supported by mid-air haptic technology?"* In this question, the keywords *"science, society, engagement"* are narrowed down, so that more specific studies may be carried out. Section 2.1 gives definitions of science and science communication, and how these terms should be interpreted in context of this dissertation. The emphasis is placed on the broad interpretation of science, including even disciplines such as mathematics or medicine, and on charting the informal to formal learning spectrum of science communication. The concept of society is operationalised in terms of *"publics"* and *"audiences"*, which are specific groups within society having well defined characteristics, further discussed in section 2.3. Thus, the individual chapters in this thesis study how mid-air haptics may support the needs of various publics, such as science communicators, specialists, as well as the needs of disengaged, attentive, and disabled audiences. Engagement is defined more specifically throughout chapter 2 in terms of the various models of public engagement, channels of communication, and the tools used by science communicators. In this regard, the thesis aims to discuss how mid-air haptics may engage audiences in both informal and formal learning environments, providing knowledge through practical projects and a discussion of their evaluation as well.

More specifically, the following research questions have been identified per project:

RQ1 (Ch. 5): Which features of mid-air haptics are identified as advantageous by *science communicators*, in context of public engagement and traditionally used tools of communication?

RQ2 (Ch. 6): How can we characterise the added experiential value of mid-air haptics for *disengaged publics*, compared to physical touch and audio-visual modalities of public engagement?

RQ3.1 (Ch. 7): How can we integrate mid-air haptic sensations in multisensory, live public engagement activities, for the *attentive public*?

RQ3.2 (Ch. 8): How can we integrate mid-air haptic sensations in multisensory, multimedia public engagement activities, for *sensory impaired audiences*?

RQ3.3 (Ch. 7 and Ch. 8): How can we evaluate the effectiveness of multisensory public engagement activities in informal learning environments?

RQ4 (Ch. 9): How can we apply mid-air haptic technology in formal learning environments, such that it is comparable to other technologies used for learning, by *vision impaired* learners and researchers?

1.3 Structure of thesis

Following from this introduction, in part I, I present a literature review on the disciplines of science communication and haptics. In chapter 2 I describe what science communication is, why communicating science is a concern, who are the audiences, how the communication happens, and where the opportunities are for improving science communication. In chapter 3, I introduce the anatomy and physiology of the human tactile sensory system, discuss the psychology of touch, provide an overview on haptic technology, and describe the focus of this doctoral thesis – mid-air haptic technology. Chapter 4 summarises the research methods I have been using to collect and analyse data throughout the doctoral programme.

Parts II to IV include a portfolio of projects, which forms the main contribution to this doctoral thesis. The shared theme of these chapters is the study of mid-air haptics mediated science communication from the perspective of different settings, different audiences, and their expectations.

Part II explores the opportunities and challenges of mid-air haptic technology, from the perspective of informal science communication, studied in a controlled environment. Chapter 5 reports qualitative findings of recurring themes, from focus groups conducted with science communicators, studying their expectations of a novel tool of science communication. Chapter 6 builds on these findings, by conducting a more in-depth investigation about the affective domain of engaging with science, involving both science communicators and *"disengaged publics"*.

The chapters in part III present a set of practical projects, where mid-air haptics was integrated in public engagement events. These projects were carried out in the field, at informal science communication learning environments, to provide practical insights on multisensory science communication, as well as ecologically valid public feedback. Chapter 7 describes a multisensory dark matter experience, developed in collaboration with researchers at Imperial College London, and showcased in the London Science Museum on multiple occasions. This exhibition targeted *"attentive publics"*, evaluated through various recommended methods of evaluation in literature. Chapter 8 introduces a collaboration with Ultraleap Limited and the Aquarium of the Pacific to host a multisensory movie experience for a diverse audience in a commercial setting. This project reports on combined results of in-laboratory, controlled methods of evaluation, as well as feedback collected from sensory impaired members of the public.

Part IV shifts emphasis to the formal end of the science communication spectrum. This shift is accommodated by investigating the potential of mid-air haptics as an assistive tool in science instruction of vision impaired learners, and the accessibility of academic conferences for vision impaired researchers. Chapter 9 compares three methods of rendering, and reports on accuracy and confidence measurements of shape recognition. This study aimed at evaluating the potential suitability of mid-air haptics for displaying geometric information, with the objective to assess whether it could be comparable to shape recognition in tactile graphics. In the corresponding sections of this chapter, I write about studying rendering methods of simple, tactile, two-dimensional geometric shapes in mid-air, and its application in various learning environments. In scenario 1, I discuss how the findings based on user studies with the general public may be applied for teaching geometry for vision impaired students in secluded areas, opening up further topics in the discussion of this thesis. On the other hand, in scenario 2, I describe how the same findings may benefit the academic community attending scientific conferences, by means of applying mid-air haptics as a channel of accessibility. The end of this chapter includes a brief report of a work in progress, follow up study on shape recognition, which I carried out as part of my internship at Ultraleap Limited.

Part V ends the thesis with a discussion on what my research findings and practical work might imply. Individual sections are dedicated to discussions of the implications of my contributions, future research opportunities at the intersection of science communication and mid-air haptics, and the limitations of this thesis.

Chapter 2

Science communication – A literature review

"It has been said that astronomy is a humbling and character-building experience. To me, it underscores our responsibility to deal more kindly with one another, and to preserve and cherish the pale blue dot, the only home we've ever known." – Carl Sagan in "Pale blue dot" (1994) (Planetary Society, 2020).

In the previous chapter, I introduced my personal motivation of studying science communication in the wider perspective of human-computer interaction. I also briefly introduced keywords, such as science and society, but let us now review the literature on the topic of science communication in a more systematic manner.

2.1 Definitions of science communication

2.1.1 Defining science

What is science communication? To be able to understand what is science communication, we must first define what science is. The definition of science to be used in context of this doctoral thesis is not a universal definition, but rather a compromise of the numerous and varied definitions endorsed by different communities. The word *"scientia"* is the latin equivalent of *"knowledge"* (Webster New Collegiate Online Dictionary, 2020). In this respect, science is simply the act of acquiring knowledge. In 1998, the American Physical Society sent a definition of science to its peer societies for endorsement. The APS's Panel of Public Affairs adapted the statement *"Science is the systematic enterprise of gathering knowledge about the world and organising and condensing that knowledge into testable laws and theories"* (American Physical Society, 1999). Dictionaries, such as the New Short Oxford dictionary, or the Webster New Collegiate dictionary place emphasis on acquiring knowledge through the *"scientific method"*. The latter states that science is *" knowledge or a system of knowledge covering general truths or the operation of general laws especially as obtained and tested through scientific method"* (Webster New Collegiate Online Dictionary, 2020). Science in its purest sense is often thought of as the study of natural phenomena. However, in a more contemporary view, the definition is broader –

"science is a way of thinking, a sceptical way of interrogating the universe" (Sagan, 2020). Science may refer to *"pure science"* but also its applications, such as technology and medicine, as well as engineering – the link between scientific discovery and applications of knowledge (Burns et al., 2003). In this thesis, science implies Science, Technology, Engineering, Mathematics, and Medicine (STEMM) disciplines.

The definition of science communication is equally difficult to quantify. Bryant (2002) highlights that science communication is a process, stating that *"science communications are the processes by which the culture and knowledge of science are absorbed into the culture of the wider community"*. Burns et al. (2003) explains that science communication is not an off-shoot of communication studies, and it is more than just a way to encourage scientists to share their academic work with others. *"Science communication is defined as the use of appropriate skills, media, activities, and dialogue to produce one or more of the following personal responses to science: Awareness, Enjoyment, Interest, Opinion-forming, and Understanding"* (Burns et al., 2003). Some people use the phrase science communication when referring to its older interpretation, and the term *"Public Engagement"* when referring to the modern models of the discipline (Bultitude, 2011). *"Public Engagement with Science (PES) involves scientists and publics working together, and: allows people with varied backgrounds and scientific expertise to articulate and contribute their perspectives, ideas, knowledge, and values in response to scientific questions or science-related controversies."* (McCallie et al., 2009). In this thesis, I will use the terms science communication and public engagement interchangeably. Science communication is a multidisciplinary field of research and practice with its own observations, theories, and a growing community.

2.1.2 The spectrum of science communication

Learning about science – not learning to do science – can occur in both informal and formal environments. Communication of science may also be carried out at multiple levels. These levels are: Public Awareness of Science (PAS), Public Understanding of Science (PUS), Scientific Literacy (SL), and Scientific Culture (SC). one way to define PAS is – *"a set of positive attitudes toward science (and technology) that are evidenced by a series of skills and behavioural intentions"* (John K. et al., 1999). PAS is predominantly about attitudes toward science, and it may be regarded as a prerequisite – in fact, a fundamental component – of PUS and scientific literacy (Burns et al., 2003). In contrast, public understanding of science is typically characterised along three distinct dimensions. These are, depending on who you consult, conceptual, procedural, and affective understanding of science (Edgar, 1994). In order, these dimensions refer to an understanding of scientific content, the methods of inquiry, and the impact or value of science on social factors (Steve, 2001; PAISLEY, 1998). In the United Kingdom, PUS typically refers to all forms of science public engagement, such as science writing, museums, or public events.

Earlier definitions of scientific literacy were similar to those of PUS, and proposed categories of practical, civic, and cultural scientific literacy (Benjamin S. P., 1975). However, contemporary views assert that scientific literacy is a *"high priority for all citizens, helping them to be interested in and understand the world around them, to engage in the discourses of and about science,* *to be skeptical and questioning of claims made by others about scientific matters, to be able to identify questions, investigate and draw evidence-based conclusions, and to make informed decisions about the environment and their own health and well-being"* (Hacking et al., 2001). If we think about scientific literacy as an individual's character, we may think of scientific culture as the society's character of science. Scientific culture is – *"an integrated societal value system that appreciates and promotes science, per se, and widespread scientific literacy, as important pursuits"* (Burns et al., 2003). However, boundaries of PAS, PUS, SL, and SC are often blurred, and vary with cultural influence. For example, most European nations use the words *"scientific culture"* to describe a field known in the UK as *"public understanding of science"* and USA as *"scientific literacy"*.

2.1.3 The vowel analogy

The afore-mentioned levels at which science communication can occur are based on the personal, or public outcomes expected. Distilling the objectives of PAS, PUS, SL, and SC, the so called *"Vowel analogy"* emerges. Burns' definition of science communication, cited in the first paragraph, tells us that the aim of communicating science is to produce personal responses to science, such as Awareness, Enjoyment, Interest, Opinion forming, or Understanding. This is known as the AEIOU – or Vowel – analogy (Burns et al., 2003). But what do these terms mean?

"Awareness" in this context refers to familiarity with new aspects of science. *"Enjoyment"*, or other affective responses, emphasise the need for appreciating science as entertainment or art. *"Interest"* means a behaviour that is evidenced by voluntary involvement with science or its communication. Referring to *"opinions"*, the implication is the forming, reforming, or confirming of science-related attitudes. Last but not least, *"understanding"* stands for understanding of scientific content, processes, and science's value for society. These objectives highlight the necessity to consider the full human experience of learning about science, beyond a simple, one-way transfer of knowledge from scientists to the public, or teachers to learners. Science communication will not always cause an immediate increase in scientific literacy. In contrast, participants are expected to experience an increased interest in – or a change of attitude toward – science. This in turn may lead to enhanced scientific literacy or culture (Stocklmayer and Gilbert, 2002).

2.1.4 Informal to formal learning

The tools science communicators use to guide people may be either informal or formal. Examples of formal science communication – which, like formal learning – typically are well structured, compulsory, assessed, planned, and solitary (Wellington, 1991). Science education at schools and universities, academic conferences, or text books and distance education materials all count as formal science communication (Burns et al., 2003). Examples of informal science communication are more often voluntary, non-assessed, accidental, and social (Center for Advancement of Informal Science Education, 2020). Typical venues are the science museums, science shows at theatres, popular science books, or citizen science projects.

Although we distinguish between informal and formal science communication, science communication refers to the entire spectrum from public engagement to science instruction.

One argument supporting the spectral nature of informal to formal divide is Bloom's taxonomy for learning outcomes (Bloom et al., 1956). Even though Bloom's taxonomy, originally devised in 1956 and revised in 2001, is most famous for its cognitive domain, the author also prescribed a set of learning outcomes in an affective domain. The affective domain focuses on the attitudes, values, interests, and appreciation of learners. In this sense, it reflects the objectives of PAS, PUS, SL, and SC. The hierarchy includes outcomes of Receiving, Responding, Valuing, Organisation, and Characterisation. One might think of Bloom's affective hierarchy as an equivalent of the Vowel analogy of science communication. In this doctoral thesis, we refer to science communication as the entire spectrum of informal to formal approaches of growing scientific literacy in society.

2.1.5 Models of science communication

The process of science communication has been modelled in various ways. Earlier interpretations of PUS and SL (Benjamin S. P., 1975; Edgar, 1994) suggested that scientists know, and the public do not know. This is referred to as the *"deficit model"*. Communication in the deficit model implies a one-way transfer of knowledge. This is either depicted as the *"two stage"* representation (see Figure 2.1 [left]), or as the *"canonical"* representation (see Figure 2.2). In the canonical representation the scientists communicate through mediators, but it is still a one directional channel of communication. More recently, for example in the *"Science and Society"* report of the House of Lords in the UK (House of Lords, 2000), this requires active involvement of the public. This is referred to as the *"contextual"*, *"dialogue"*, or *"democratic"* model.

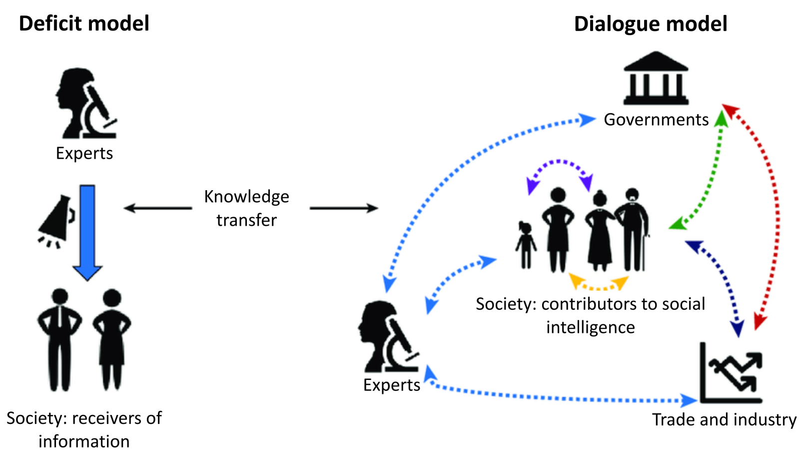

Figure 2.1: Representations of the deficit and dialogue models of science communication. In the deficit model, experts are directly communicating with the public. In the dialogue model more participants take part in a two-way communication. Figure adapted from (Courchamp et al., 2016).

A possible approach to depict the two-way, contextual model is via the *"mountain climbing"* analogy. The mountain climbing representation was originally used in the formal setting of education (Koballa et al., 1997). Imagine a mountainous landscape, where every mountain represents a school subject, and the altitude is the measure of how literate an individual is in that subject. Burns et al. (2003) extended this analogy to the informal setting of public engagement, as shown in Figure 2.3. PAS is thought of as becoming aware of a mountain range. Even if the

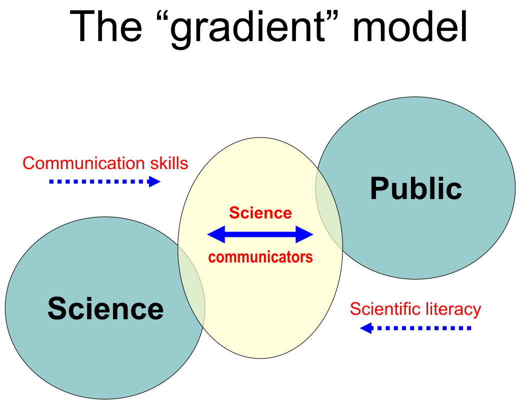

Figure 2.2: A representation of the canonical (or gradient) model of science communication. Scientist communicate with the public through the media. Science communicators must have skills in communication and be scientifically literate. Figure reprinted from (Claessens, 2021).

ascent on the slopes of PUS does not result in reaching the summit of scientific literacy in one field, it may help the climber become aware of other mountains. The next mountain the public climbs may even be easier, or more enjoyable. Scientific culture plays the role of the clouds surrounding the landscape. Science communicators can be thought of as the guides providing the skills to climbing, the tools, and the courage to do so (Burns et al., 2003).

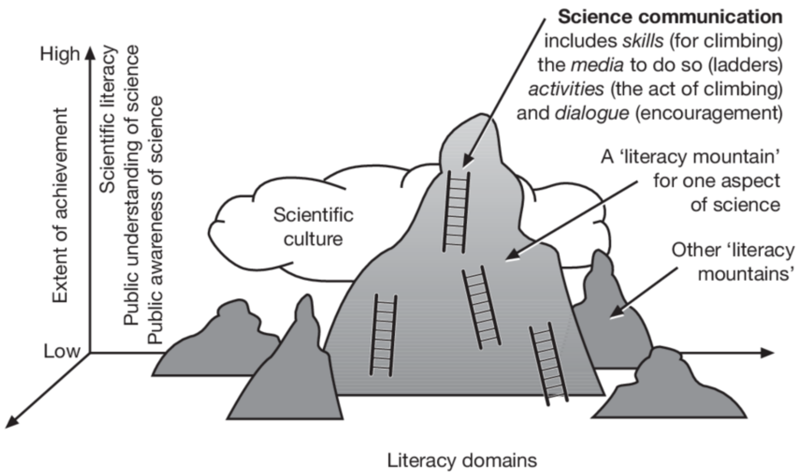

Figure 2.3: A representation of the mountain climbing model of science communication. The mountains are the domains of literacies, where the cloud illustrates scientific culture, and science communicators are the mountain guides. Communication is two-directional, as scientists at the summit are also able to climb downwards and meet the public. Figure reprinted from (Burns et al., 2003).

2.2 The purpose of science communication

Why should we communicate science? What makes science communication stand out from communicating other fields of interest with society? Perhaps nothing. There are numerous areas of interest, where people show a tendency for becoming literate. PAISLEY (1998) counted 44 areas of literacy based on topic specific journals in the late 90s. For example, computer literacy, film culture, or politics. However, science and technology is often portrayed as the force driving the frontiers of human civilisation, even if it comes with a degree of uncertainty (Ravetz, 1999).

2.2.1 Societal benefits

One argument we can make for communicating science is that the process benefits more participants than just the audience. The lay public gains by learning about science, but so do scientists, and society on the larger scale. While scientists may have the skills and facts at their disposal, it is the people who may be aware of problems in the local community, and have an interest in solving these (Burns et al., 2003). A recent example is of mutually aware local authorities and scientists who aim to resolve an agricultural and environmental challenge. As University of Sussex researchers put it – "drought and flood events are a major threat in sub-Saharan Africa (SSA) causing substantial losses of life, assets and livelihoods, and weakened national economic performance. Hazard, early warning and disaster risk preparedness actions can be effective in reducing these losses (as much as 20 times more effective than post-disaster relief). Here, advanced data analysis techniques used in astronomy are applied to facilitate improved hazard early warning models in Kenya" (Oliver, 2019). As we see in this example, it takes two stakeholders to respond to a local societal risk. In the dialogue model, science communication ought to facilitate making connections between local communities and science.

However, effective science communication is believed to have benefits at the personal level too. In 2010, Research Council UK published a list of individual motivators for scientists to engage with the public. Some of these motivators are: enhancing the scientist's research quality and its impact, inspiring the next generation of researchers, or influence and networking opportunities (Research Councils UK, 2010). From the public's point of view, according to Osborne (2000), four major factors play a role in institutional and strategic levels of greater scientific literacy. Firstly, the utilitarian argument. The people involved will gain technical skills and knowledge that will be useful to them in their wider lives. Secondly, the economic argument. Advanced societies require a technologically skilled workforce; science adds significantly to the overall output of a country. Thirdly, the cultural argument. Science represents a "shared heritage" and should be recognised as a wider part of our culture. Fourthly, the democratic argument. Science affects most major decisions in society, therefore it is important that publics are able to interpret basic scientific information (Osborne, 2000). Importantly, these arguments highlight the benefits of learning about science, and not how economic impact should be used to justify the need for basic science (Fabian, 2010).

2.2.2 Accountability, trust, and fear

Another argument for the need of public engagement is related to – not what people gain from learning about science, but – how people feel about it. Without society's support towards science, a fearful environment can emerge, resisting scientific progress (Benneworth, 2009). Some controversial subjects, such as nuclear energy, genetic modification, or high energy physics experiments can cause tangible fear responses in the public. An infamous case from 2008 is the fear that surrounded the launch of the Large Hadron Collider (LHC) in the European Organization for Nuclear Research (CERN). Law suits and protests were initiated to stop the high energy particle collision experiments, because of fear of generating harmful black holes (Courvoisier et al., 2013; Swiss Info, 2008).

A century before that, in 1925, American fundamentalism had its say against Darwin's theory of evolution. A teacher was prosecuted for illegally teaching evolution in school, which became known as the Scopes (monkey) trial (Holloway, 2016). The ban of teaching evolution was in place until 1968 in the USA, as a result of a conflict between religion and science on the matter of creation. Another example of societal fear is the "Chernobyl syndrome" and its debated effects on induced abortions. Studies in Greece, Sweden, Italy, Switzerland, and Denmark claimed increased induced abortions after the Chernobyl catastrophe, while studies in Norway, Hungary, Austria, and Finland did not report a change (Auvinen et al., 2001). The study by Auvinen et al. warns us that some of the studies, reporting increased induced abortions, may not be reliable enough to draw conclusions. Regardless, these examples illustrate that uninformed citizens may be subject to fear and scepticism towards science.

Fear, among other factors contributes to separation between science and society. Four cultural factors have been identified in particular: (1) the loss of expertise and authority of scientists; (2) a change in the nature of knowledge production; (3) improved communications and a proliferation of sources of information; and (4) the democratic deficit. The first of these four pressures are especially relevant to why science communication matters. Scientists need to remain accountable and trustworthy. Accountability is important because science is spending public funding, when financial aids are required to support other societal issues, such as migration or clean water reserves. Accountability and transparency may increase with the involvement of the public. Additionally, continued trust in science is necessary (Yearley, 2005). We are likely to face challenges that science is unable to solve on its own. Sustainable development is an example, where society as a whole must accommodate guidance from scientists to sustain Earth's ecosystems (Rockström et al., 2013). However, it was shown that public trust in science is declining, especially in controversial topics, such as climate change (Directorate-General for Communication, 2010). Communication about the processes of science, and the sources of scientific debate may relieve the pressure on scientists authority.

2.3 Science in the publics

We defined what science communication is, and argued why it is relevant. But, who do we communicate to? Will the message have an equal impact on everyone in society? Is the audience homogeneous or not? If not, what are the differences and how do we address these differences?

The main thread of this dissertation is running through how mid-air haptic technology can serve the expectations of multiple audiences, thus it is important to understand the diversity of the public.

2.3.1 The publics

Science communication research and practice often talks about its audience in plural, i.e. *"publics"* and not the public. The publics with their norms, customs, and social interactions constitute the society. Publics are typically characterised through their needs, interests, attitudes and levels of knowledge, but there are many ways to identify a segment of people. One useful categorisation relates to the dialogue model (see Figure 2.1 [right]). Four overlapping groups are identified. These are: (1) scientists in academia, industry, or government; (2) mediators, such as journalists, science communicators or teachers; (3) policy or decision makers in government or research councils; and (4) the lay public (Burns et al., 2003). In the coming chapters, this thesis will discuss three of the four groups; namely, science communicators or mediators (Ch. 5); specific audiences of the lay public through disengaged audiences (Ch. 6), and the attentive public (Ch. 7 and Ch. 8); as well as the disabled and expert audiences, scientists (Ch. 9). To begin with, we will mostly focus on specific audience segments and their needs within the lay public. We will review how the public is categorised as a function of attitude, how the border between public engagement and education blurs in context of communicating with the next generation of scientists, and how multisensory communication is used to serve the needs of people with disabilities.

2.3.2 Public attitudes: the disengaged, attentive, and expert publics

Audience segmentation is a thoroughly researched topic in science communication, where a frequent clustering method is based on people's attitude towards science. In 2000, the Office of Science and Technology (OST) and the Welcome Trust in the UK identified and labelled six groups of people, based on their expressed attitude in a survey. These labels are the *"confident believers, supporters, technophiles, concerned, not sure, and not for me"* (Office of Science & Technology and Wellcome Trust, 2001). A decade later, sponsored by the UK government, Ipsos MORI 2011 in partnership with the British Science Association identified the following clusters: *"concerned, indifferent, late adopters, confident engagers, distrustful engagers, and the disengaged sceptics"*. Surveys, workshops and public discussion groups were organised to collect the data.

Audience segmentation on national populations was also carried out by independent researchers, such as on the Swiss public by Schäfer et al. (2018). This time, survey questions addressed cognitive, affective, and behavioural components of attitude, with a special interest on the media consumption of participants. Four groups were identified and labelled as: *"Sciencephiles, Critically Interested, Passive Supporters, and the disengaged"*. Regardless of the labels we use, there is good evidence that publics are heterogeneous. In Shafer's words – "There are people with a strong interest for science, extensive knowledge, and a pronounced belief in its potential, who use a variety of sources either intensively, or with caution. There are other people with moderate levels of interest, trust, and knowledge and tempered perceptions of science, who use fewer sources. Yet another group of people exist, – who are not interested in science, do not know much about it, harbour critical views toward it, and encounter it – if at all" (Schäfer et al., 2018).

Considering the many objectives of science communication, and the diversity in society, the "*Who*" and "*How*" of public engagement must be matched with care. Creating the right personal responses, also depends on the target audience. In context of Public Awareness of Science, Jessy Shore elegantly described catering for three levels of awareness. Uninformed members of the public need to be made aware, the informed public needs to be intrigued, while the specialist public needs to be entertained (Shore, 1999). The uninformed or disengaged public do not know what they don't know, and do not actively seek scientific content. The objective is to make these people aware of a specific subject area, emphasise its impact on their lives, and make them aware that they can choose to learn more about the subject – further discussed in chapter 6. The informed, or critically interested public, know what they don't know, and actively make choices on when to expand their knowledge. Science communicators ought to engage these people in novel ways in a familiar context – the topic of chapter 7. The specialists, or attentive public, are often more knowledgeable then the science communicator on a given subject. The task here is to communicate a new perspective, to surprise, and to entertain – a topic we will further discuss in chapters 7 and 9.

2.3.3 Gateway to education: Engaging children and including audiences with disabilities

The interest based distinction is just one way of identifying audiences, and other demographic factors, such as age, gender, or ethnicity can often influence the method of science communication. The National Co-ordinating Centre for Public Engagement (NCCPE) in the UK gives guidance on communicating with, for example, community groups, family groups, underserved audiences, adults, students (NCCPE, 2020). It is important to find out the motivations of these demographic groups, where can they be found, and what matters to them. Two of the many special interest groups of publics are the children, and the underserved audiences, for instance people with disabilities.

Children have a pliable social identity and are receptive to changing their attitude towards science. The young audience is typically reached at events organised for family groups, such as science festivals, or at school outreach events. A big question is whether the outreach activity should be educational, emotionally engaging, or both (McCrory, 2010), and if both, then to what extent? Different stakeholders typically require different learning outcomes. Research councils and funding bodies want scientists to communicate their research, building up the science capital and recruit science undergraduates. Teachers want something that is related to the school syllabus and that is relatable by the children. Families often see science events as an opportunity for family bonding and social life outside the usual routine. Besides, a ten year old boy and a 14 year old girl might find different activities engaging, while another child might find the activity completely inaccessible. Therefore, designing science communication activities and using tools that are easily adaptable to multiple audiences and multiple expectations may make science mediators more successful.

Yet another factor in engaging with science, beyond the attitude and age groups within publics, is the physical abilities or disabilities of people. Visualisations are a popular choice of conveying scientific concepts, mostly through the use of analogies or metaphors that people are able to relate to. However, this approach does not satisfy the needs of people with visual impairments. For this reason, activities to make science more accessible, in particular astronomy, by using touch and sound were developed, mostly aimed at improving inclusivity (Arcand et al., 2017). For example, the "Tactile Universe" project created 3D models of galaxies, used to engage visually impaired children in astronomy (Bonne et al., 2018). Similarly, the "Tactile Collider" is aimed at visually impaired children to engage with the field of particle physics, and demonstrate particle colliders through the use of 3D sound and large scale tactile models (Dattaro, 2018). Other work in this area includes, for example, astronomical activities specifically intended for people with special needs (Ortiz-Gil et al., 2011), 3D tactile representations of Hubble space telescope images (Grice et al., 2015), of data from the X-ray Chandra Observatory (Arcand et al., 2019), of the Subaru telescope structure (Usuda-Sato et al., 2019), of the Eta Carinae nebula (Madura et al., 2015), and of cosmic microwave background radiation anisotropies (Clements et al., 2017). Sound has perhaps received less attention to date, but some sonification prototypes have been explored in astronomy (Casado et al., 2017; Lynch, 2017), as well as in high-energy particle physics (Paradiso et al., 2016; Asquith et al., 2009). In chapter 8 and chapter 9 we studied how mid-air haptic technology could serve sensory impaired audiences in either an informal or formal learning environment.

2.4 Channels of science communication

Despite being aware of a heterogeneous society, yet another challenge remains. Where and how can we reach the publics we identified?

2.4.1 Traditional journalism

A 2007 report prepared for the National Endowment for Science, Technology and the Arts, identified over 1500 initiatives of public engagement within the UK alone (Mesure, 2007). It is therefore a difficult task to classify activities as a certain type of engagement, but broadly speaking three mainstream channels of science communication are typically distinguished (Bultitude, 2011), the first of which is traditional journalism. This includes written articles, books (Weitkamp, 2010), podcasts and radio broadcasts (Redfern, 2009; Murcott, 2010), or television programmes (Mellor et al., 2011). The use of traditional media to communicate science has been studied extensively. Historically, the need for, and role of science journalists has changed internationally. In the late 18th century scientists themselves popularised their discoveries, for example through the Royal Institution's Christmas lectures (James, 2007). However, during the transition from enlightenment to development of field experts, in the 19th and 20th century scientists delegated the communication task to journalists (Broks, 2008). Despite the long interest in science, only 2.5% of printed news constitutes science, in contrast to 25% political, and 15% sport related news (Dimopoulos and Koulaidis, 2002). A large fraction of science news also focuses more on medical and health related advances (León, 2008). This is a trend reported on multiple accounts, and is believed to be a result of distinguishing between *"news"*, and *"news to use"* (Dunwoody, 2014), a distinction that is less outstanding in live public engagement events.

2.4.2 Live interactions and hands on activities

A more personal channel of public engagement is delivered through live events, and hands on activities. (Rowe and Frewer, 2005)) noted at least 100 different types of participation mechanisms, separate to other communication and consultation approaches. Few of the classic examples include public lectures, science centres and museums, sci-art, science cafes and festivals. Such activities involve a direct interaction between scientists and publics, where scientists are able to better control the content. The added benefit is that events enable two-way communication, and can involve partnering with other external organisations with complementary expertise (Bultitude, 2011). However, unlike journalism, face to face events are limited in audience reach (tens to thousands of people). Events are resource intensive, leading to low sustainability of activities. These can be criticised for only attracting audiences with a pre- existing interest (Bultitude, 2011). On the intersection of traditional media, and live events, online interactions emerged.

2.4.3 Online interactions and citizen science

In the 21st century, the role of science journalists goes through a shift once more. The plethora of user generated online content challenges traditional media channels and professional content creators (Dunwoody, 2014). Video portals, such as YouTube hosts a wide range of science content. It's been shown that content length, rate of delivery, social networks of the communicator, and regularity have an effect on popularity of science content. Professionally generated content does not have a monopoly in this respect (Welbourne and Grant, 2015). Blog posts, social media items are also gaining popularity as tools used by scientists to communicate themselves, but also to communicate with a wider audience (Bonetta, 2007; Puschmann, 2014). What counts as a science story, or when it is considered finished is a question to be answered. With hourly news cycles, and online news outlets, journalism also becomes a 24/7 occupation, with episodic instead of thematic coverage (Allan, 2011). This has the potential downside of reporting results, but neglecting the communication of the scientific process of discovery, the uncertainty element, and outliers of scientific results (Dunwoody, 2014).

Balancing these drawbacks, another form of participatory science communication gained momentum since the millennia. Citizen science communicates with the public by means of involving people in research. The concept of engaging amateur volunteers in data collection, or data processing is not new. In 1900, the Christmas Bird Count, became one of the earliest organised examples of citizen science projects (Silvertown, 2009). What is new, however, is the technological advancements which allow for online interaction between researchers and volunteers. The Zooniverse platform hosts over a hundred citizen science initiatives, and nearly two million volunteers (Zooniverse, 2020). Galaxy Zoo was one of the first projects motivating volunteers to take part in science research, contributing to a speedier data analysis method, as well as a feeling of scientific achievement by citizens (Raddick et al., 2009).

2.5 Improving science communication

What other ways are there? How can we take a step forward in the direction of improved science communication? We have seen the channels and tools that may be used by science communicators to reach a target public. But what can we do to improve on these tools to serve the AEIOU goals, and engage diverse audiences more effectively?

2.5.1 The role of metaphors and rhetorics

One of the branches of science communication research argues about the role of metaphors, rhetorical tools, humour, and storytelling in engaging with the public. Metaphor is a vital tool of science communicators. As (Kendall-Taylor and Haydon, 2016) put it *"An Explanatory Metaphor helps people organise information into a clearer picture in their minds?making them more productive and thoughtful consumers of scientific information"*. This notion of metaphors is based on cognitive processes, such as anchoring and objectification, which form part of Social Representations Theory (SRT). Another frequently discussed cognitive construct is the Mental Models Approach (MMA). Both SRT and MMA think of analogies as cognitive phenomena, to make sense of new concepts.

Besides metaphors, rhetoric tools are considered as another form of useful analogies, but as a linguistic construct instead of a cognitive phenomenon. (Schwarz-Plaschg, 2018) found four categories of rhetorical analogies, when people discussed nano-technology. These were: *"Acceptance-rejection, Anticipatory, Provocative, and Not-like"* analogies. People use references to previous knowledge to make an opinion on new, emerging technologies, and scientific discoveries. Informed opinion forming is essential in the democratic model of science communication, where public opinion may influence the priority of research and science investment (Gross, 1994; Schwarz-Plaschg, 2018).

2.5.2 The role of humour and storytelling

To use or not to use humour is still majorly undecided. The use of humour has been discussed in various teaching and learning settings. In the home, humour may help build trust between parents and children, whilst revising the school material. In schools, teachers may use humour to build a shared experience, ease tension in the classroom and make students more attentive (Lovorn, 2008). However, little is known about the true effects of laughter on learning, because the traditional views of education suggested that children should attend school to learn and not to be entertained. For a similar reason, there is a lack of extensive literature on the effects of humour on adults (Armstrong, 2002). Appropriate humour and laughter is often a good ice-breaker and may facilitate social interaction. However, inappropriate types of humour, such as ones based on stereotypes may be counter productive (Riesch, 2015). Laughter finds its way to science communication through stand-up comedy, where scientists become comedians, or through television programmes, such as The Big Bang Theory.

Although generally perceived well, the use of humour requires caution. On one hand it shows that scientists are also humans, but it risks scientists being viewed as unprofessional (Riesch, 2015). Comedy performances also lean towards the one-way model of science communication, where a passive audience is entertained but not engaged. Another contemporary approach to humanising science is through storytelling (Joubert et al., 2019). Through stories, students can relate more to either the concept, or the scientist. Even though recall might not be improved, humorous stories provide a hook, grab attention, and create excitement, and enjoyment amongst the audience (Frisch and Saunders, 2010). Using narratives allows for “emotification”, “personification”, and “fictionification”, which in turn contributes to mental processes at multiple levels, such as motivation, or transfer to long term memory (Dahlstrom, 2014). What comes next for science communication is in part to move away from bombarding the audience with facts, and instead, consciously tap in on their emotional engagement (Nisbet and Scheufele, 2009). Such hooks may be achieved through the constructs of metaphors, or stories. Emerging technologies, for instance social media, immersive digital media, and curated social interactions may also play a role in future improvements in science communication practice (Myllykoski, 2018). The importance of opening a gateway to learning – through affection, and serving community values – is increasingly recognised. The main body of this thesis will discuss how haptic technology can fit in this mindset.

2.6 Summary

In this chapter, we have seen different models of science communication, its spectrum ranging from informal to formal interactions, and the levels at which communication may happen. We reviewed the societal benefits and purpose of public engagement in terms of accountability, trust, and fear response. We also saw that the public is highly heterogeneous, exhibiting diverse attitudes towards science, with different audiences having specific needs. We discussed how audiences can be reached through the channels of journalism, live events, and online interactions, touching on modes of communication, engagement, and public participation. We also considered the tools used by science communicators, such as stories, metaphors, or humour to engage their audiences, many of these angles on science communication provide overlapping research interests with human-computer interaction, and applications of haptic technology, which will be further explored in this thesis. Although before that, let us look at what we know about the human touch.

Chapter 3

The haptic sense and haptic technologies – A literature review

"One touch of nature makes the whole world kin" – William Shakespear (1609) in the third act of "Troilus and Cressida".

In the introduction of this thesis, I briefly argued why the sense of touch may be a more fruitful area of study than other senses in context of science communication. In particular, I noted how the invisible and inaudible tactile sensation created by mid-air haptics, and its effects on emotions, may serve the objectives of public engagement with science. However, before discussing the opportunities and challenges at the intersection of science communication and haptics, we need to review knowledge on human touch.

3.1 Anatomy and physiology of the human touch

There are two primary processes which make humans aware of their existence and environment: sensing and perception. Senses are biological detectors which collect and transfer information through the nervous system to the brain. Perception then organises the incoming information and creates meaning, often influenced by higher level processes, such as expectations, memories, or emotions. Humans are able to process some chemical signals through the olfactory and gustatory sensory systems, as well as a limited range of electromagnetic radiation through the optic system. In respect to the nature of signals, the sense of touch is most similar to the auditory sensory mechanism, both of which process mechanical information. Yet, the haptic or somatosensory system, in many regards has a unique structure and set of functional purposes, hence why this chapter begins with a brief overview on the anatomy and physiology of touch.

3.1.1 The touch organ and its neurology

Defining the sensory organ associated with touch is difficult; however, the majority of touch related afferent nerve fibres, i.e. those which transmit sensory input to the brain, are mostly distributed in the largest human organ – the skin (Gallace and Spence, 2010). Three main types of skin are distinguished: mucosal, glabrous, and hairy skin. The mucosal skin covers the internal surfaces of the body and are generally humid. The gums and the tongue are capable of vitally important sensorimotor functions, such as shape recognition or high tactile spacial resolution (Boven and Johnson, 1994). The glabrous (non-hairy) skin, such as the inner (volar) region of the hands has a rather thick superficial layer made of keratin, which is not innervated. However, the epidermis right under it, is living and has a special geometry, such that the papillae of the epidermal-dermal junction are twice as frequent as the print ridges (Hayward, 2018). In the hairy skin, such as the dorsal regions of the arm, each hair is associated with muscular and sensory fibres that innervate an organ called the hair follicle. The primary sensory role of hair is retained in the tactile hair (vibrissae) found on all therian mammals, except humans (Prescott and Dürr, 2015).

Humans evolved a higher concentration of mechanosensory receptors in the glabrous skin than in hairy skin or internal organs. We distinguish between slowly adapting (SA) and rapidly adapting (RA) mechanoreceptors, where SA type receptors are activated during the whole period of stimulation, while RA types respond only at the onset and offset of the stimulation (Hayward, 2018). The Pacini corpuscle (RA II) is the largest receptor found in the deeper regions of the subcutaneous tissues, opportunistically distributed and correlated with the presence of main nervous trunks, rather than functional skin surfaces. It is specific to vibrations, most sensitive to a stimulation frequency of about 250 Hz but continuing with decreasing sensitivity to 1000 Hz; able to detect vibrations of 0.1 micrometer at the skin's surface (Hayward, 2018). The Meissner corpuscle (RA I), found in the glabrous skin, also plays a role in detecting low frequency (< 80 Hz) vibration, by signalling the velocity of skin deformation, which controls the pressure between the touched object and the skin (Oey and Mellert, 2004). The receptors are tucked inside the dermal papillae, and thus in the superficial regions of the dermis, but nevertheless mechanically connected to the epidermis via a dense network of connective fibres (Hayward, 2018). Merkel complexes (SA I) have the smallest receptive field but are densely populated, and are mainly responsible for detecting skin indentation and very low frequency vibration (Oey and Mellert, 2004). In the hairy skin, these structures are associated with each hair. Ruffini endings (SA II) are detecting skin stretch, but are mainly found in joins, where they respond to the deformation of the join capsule, when the joint approaches the end of its useful range of movement. Recently, it has been suggested that its role in skin-mediated touch is minor, if not non-existent, since glabrous skin seems to contain very few of them (Hayward, 2018). Muscles are connected to the skeleton by tendons which also have mechanoreceptors called the Golgi organs. These respond to the stress to which they are subjected and report it to the central nervous system, which is thus informed of the effort applied by the muscles needed, to reach a static or dynamic equilibrium (Hayward, 2018). For a schematic illustration of mechanoreceptors in the skin, see Figure 3.1.

The hairy skin hosts a system of unmyelinated low threshold C-tactile (CT) mechanoreceptors (Loken et al., 2009). These receptors are particularly sensitive to light stroking touch and thus are thought to underlie an affective, or social, touch capacity. This hypothesis is supported by CT fibres projecting to the insula region, a gateway to the processing of reward, and not to the somatosensory cortices (Prescott and Dürr, 2015). The sensory system involved in perceiving the changes in skin temperature begins with free nerve endings found in the dermal and epidermal

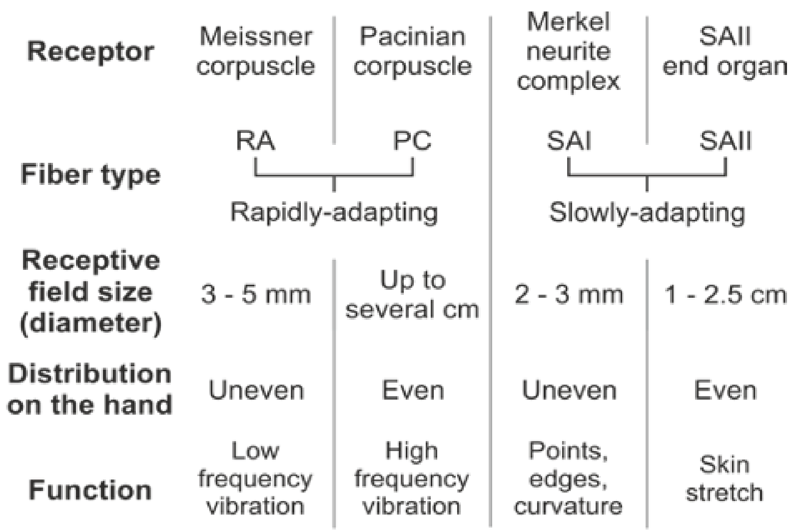

Figure 3.1: Four distinguished mechanoreceptors linked to fibre type, the receptive field size, the distribution on the hand, and their functions. Figure reprinted from (Obrist et al., 2013).

layers of skin that can be functionally classified as cold and warm thermoreceptors. Warm and cold receptors respond similarly to radiant and conducted thermal energy and are involved in the perception of innocuous (harmless) temperatures. several temperature-sensitive ion channels of the transient receptor potential (TRP) family have been identified as candidate temperature sensors, also being involved in chemesthesis. The skin also contains thermally sensitive receptors leading to pain sensation known as thermal nociceptors that respond to noxious or harmful temperatures. Afferent signals arising from cold thermoreceptors have been also shown to play a role in the perception of wetness, suggesting that thermal cues are used in conjunction with tactile inputs to perceive wetness (Jones, 2009).

Signals from these receptors are organised in somatotopic maps of the skin surface in the primary somatosensory cortex of the brain (SI) (Wilson and Moore, 2015). These maps are organised to match the topographic layout of the periphery, so that skin areas that have a higher density of receptors, greater receptor innervation, or that are functionally more important, have a proportionately larger representation in cortex (Hayward, 2018). The human sensory homunculus, first described by Penfield and Boldrey (1937) is probably the best known of these maps (Prescott and Dürr, 2015). As described in reviews by Gallace and Spence (2010) and Hayward (2018): Tactile information is transmitted from peripheral receptors distributed throughout the skin, via the dorsal column nuclei to the thalamic nuclei, and from there to SI. The somatosensory cortex, divided into two main areas of SI (primary) and SII (secondary), is located on both sides of the great parietal circumvolution, and a huge number of fibres project onto it. SI is divided into the four Brodmanareas: 1, 2, 3a and 3b, based on their neuronal architectures. Thalamic fibres terminate for the most part in 3a and 3b which are, in turn, connected to areas 1 and 2, portraying a hierarchical organisation where, like in the other sensory modalities, increasingly abstract representations are successively formed. Information from SI is then transferred to SII, where tactile information is integrated SII is connected with other higher order areas of the parietal cortex, with the insula, and indirectly to the premotor cortex. The awareness of touch results from the reciprocal interactions occurring between these structures, engaging emotions, motor responses, and cognitive functions in the process.

3.1.2 The functions of haptic sensing

Tactile sensing is a distributed sensory system, thus it is practically impossible to associate a single stimulus to an anatomical classification of the sources of information (Hayward, 2018). However, to understand the fundamentals and complexity of the haptic sense, it is useful to decompose and conceptualise the key subsystems of touch, by imagining the following scene. Sitting on the sofa Annie reaches out to lift a heavy, smooth surfaced mug, and drinks a hot sip of tea which flows down her throat. Feeling the hot, smooth surface of the mug is primarily transmitted through the cutaneous touch associated with the skin on the hand, responsible for detecting tactile, thermal, and pain signals. The network of mechanoreceptors in our skin detect change of pressure or vibration, thermoreceptors detect temperature deviations, and nerve fibres detect pain or pleasure signals (Prescott and Dürr, 2015). Lifting a heavy mug pulls down on the joints, muscles, and tendons in the arm, providing kinaesthetic signals through mechanoreceptors embedded in these tissues for the haptic sensory system, such as weight. The haptic sense has been described as a sensory-motor organ, where cutaneous sensing and kinaesthesia form an integrated feedback loop, that is to say cutaneous feedback is combined with motor functions during active movement (Krueger, 1982).

Sitting in a balanced position, perceiving body posture, and generally being self-aware of our body and reflexes is associated with proprioception. The specific postural configuration of internal organs, and the tactile sensation of the sofa touching the body contributes to proprioception, similarly to the vestibular system contributing to head position, movement and balance (Hayward, 2018). Drinking tea and sensing the flow of liquid inside the throat or the filling of stomach is associated with somatosensation, a term describing haptic sensations within the body. In this respect, somatosensory signals are detected by visceral nociceptors embedded in internal organs, although the term somatosensory system is also often used to refer to the overall haptic sense (Gallace and Spence, 2010).

All of these distributed haptic sensory subsystems combined together give humans the experience we refer to as touch – the ability to make physical contact with the world (Prescott and Dürr, 2015). For example, texture perception heavily relies on both cutaneous and kinaesthetic signals arising while rubbing a surface with a finger, just like reaching out to lift a mug relies on both proprioception and kinaesthesia (Lederman and Klatzky, 2009).

3.2 The psychology of touch

The psychology of touch is heavily influenced by four human factors: cognition, perception, affection, and behaviour. Just like the anatomy and physiology of touch can not be split into separate units, the factors of the psychology of touch are intertwined, dependent on each other. However, once more, it is useful to study human factors independently in context of haptic sensing, to understand their contributions to the overall psychology of touch. The general view on cognition is that it consists of the *"activity of symbolic representational systems – dealing* *with environmental information – serving functional or adaptive behavioural goals".* This view implies that representational systems must incorporate perceptual, affective, and behavioural knowledge (Paivio, 1990). Since integration of abstract, often imperceptible concepts of science with one's personal mental world, rely heavily on representational systems; this section will review some of the fundamental knowledge on all four of these factors.

3.2.1 Cognition

To understand the role of cognition in touch, I focus on three concepts: mental representations, dual coding theory, and cognitive load theory. In 1978, Palmer distinguished between the real world, the mental world, and the mental model in his analysis. According to this, the mental world is the representation of the real world, while the mental model is a set of mental representations, which feed the mental world (Paivio, 1990). Such mental representations can take forms of imagery, linguistic, or propositional representation (Palmer, 1978). In this approach, imagery representations are considered modality specific, while linguistic representations are characterised by a-modal nature (Paivio, 1990). Further distinction of representations and processes rely heavily on a structure vs. function relation. Representations are considered structural entities on which processes can operate, while processes refer to the activities in which functional meaning can be obtained from the structural information. However, there is no clear boundary between the two. for instance, when counting corners of a geometric shape, the functional operation yields information on structure of the representation (Paivio, 1990).

The theory of dual coding implies that imagery and verbal representational systems are structurally and functionally distinct, and that the theory is valid for all sensory modalities (Paivio, 1990). Functionally, imagery and verbal representations may be activated independently, but also trigger each other. Haptic representation is believed to fall under imagery encoding, but spreading to verbal encoding when familiar objects are explored via touch (Johnson et al., 1989; Lacey et al., 2007). As interaction with the environment is often cross-modal, interference of modality specific representations in context of DCT has been explored. In particular, whether multimodal or unimodal representations describe better our understanding of mental representations. Lacey et al. (2007) reported more evidence for cross-modal representations, than modality specific representations in a review.

Cognitive load theory also states that the processing of too much information may lead to cognitive overload, and introduce a split attention effect (Sweller, 1988, 1994). It has been shown that if the received information is presented in a mixed modality, for instance auditory and visual, this may reduce cognitive load (Yaghoub Mousavi et al., 1995). The novice vs. expert user distinction is understood to be another relevant factor. Zhou et al. (2007) showed that during surgical training, expert medical staff can benefit more from haptic feedback than novice users, who experience higher cognitive load during the task. Therefore, the integration of novel haptic technologies in public engagement with science settings poses uncertainties, when considering benefits of mixed modality representations, and limitations of cognitive overload of novice users.

3.2.2 Perception

One of the earliest perceptual abilities humans possess is the perception of 'self'. Infants are able to distinguish between self-touch and external touch, right after their birth, which helps in establishing self-awareness (Rochat and Hespos, 1997; Gallace and Spence, 2010). We can perform psychophysical studies on touch, similarly to other senses, to determine spacial and temporal tactile acuity on the skin. for instance using Weber's (1834-1978) two point discrimination test, the lips, tongue, and fingertips stand out as the locations on the body with the greatest sensitivity to touch. In each place we are typically able to distinguish points that are as little as 1-2mm apart (Weinstein, 1968). In contrast, at the middle of the back, two points several centimetres apart may be felt as a single stimulus (Hayward, 2018). Similar estimates can be made for other measures of sensitivity such as orientation (Keyson and Houtsma, 1995), pressure, point localisation (Wilson et al., 2014), and vibration detection (Oey and Mellert, 2004).

Beyond spacial and temporal resolutions of touch, it was questionable how the physical intensity of stimulation relates to the perceived magnitude (Chaudhuri, 2010). Weber found that there is a linear relation between the intensity of stimulus and the threshold of perceiving difference in magnitude. This means that an increased intensity will result in increased difference in thresholds too, applicable for all senses at varying gradients of constant values per sense (Chaudhuri, 2010). Fechner also provided a mathematical description between perceived magnitude and intensity of stimulation. According to this, the perceived intensity changes logarithmically with the physical intensity (Chaudhuri, 2010).

Haptic perception serves multiple purposes, some of which are shared with other sensory channels, such as impacting cognitive or affective processes. However, touch can also serve unique functions, such as manipulating objects of the physical world, and detecting information inaccessible to the other senses, for example wiping off a tear drop from the cheeks. When discussing perception through touch with respect to object manipulation or recognition, two of the key areas of study are: active vs. passive touch (Gibson, 1962), and exploratory procedures (Lederman and Klatzky, 2009). Gibson's "Observations of active touch" highlight the difference between receptive and exploratory senses. In his view, the skin of the hand, and the hand can be treated as separate sensing organs, but the sensory input from these combine to the information perceived during active touch (Gibson, 1962). Gibson's set of experiments show that when fingers are actively exploring shapes, the form recognition is significantly higher than in the case of passive touch. He explains it with the voluntary movement of the observer, as opposed to the stimulus being delivered by an external agent. Other researchers criticised Gibson's method, finding contradictory results and stating that passive form recognition is not inferior to the active mode in performance (S. Schwartz et al., 1975). However, the distinction between active exploration and passive touch is still acknowledged, since it makes a difference in metrics, such as recognition time (S. Schwartz et al., 1975; Heller, 1984; M Smith et al., 2009).

In context of active touch, J Lederman and Klatzky (1987) were indeed able to provide a taxonomy of purposeful hand movements, as well as analyse whether particular procedures were necessary or sufficient to determine object dimensions of interest. For example, the associations of lateral movement (texture), static touch (temperature), contour following (shape recognition), enclosure (object recognition), squeeze (compliance), or lifting (weight) were established. It is also known that during haptic encoding, with or without visual exploration, different object dimensions become more salient (Klatzky et al., 1987). Typically, the exploratory procedures are grouped into processes acquiring either material or geometric properties via touch.

3.2.3 Affection and behaviour

'I touch, therefore I am'. Tactile sensations are very particular in a way that the sense of touch is bi-directional. We can not touch, without being touched (Hayward et al., 2004), hence, it reminds us of our existence and amplifies the sense of embodiment (Hornecker, 2011), affecting emotions and behaviour too. There is also evidence that stimulating CT fibres, or the densely innervated genitals of both male and female, project to the insula region in the brain, indicating direct relationship between touch and affection (Prescott and Dürr, 2015). Affection can be broken up to the studies of feelings, mood, and emotions, which differ in duration. In controlled laboratory studies, we can best measure the impact of interfaces on the most immediate mode of affection – emotions.

Beetz et al. (2012) published a review on the effects of human-animal interaction (HAI), comparing these to known attributes of the oxytocin hormone. A major overlap between positive effects of HAI, and positive effects of oxytocin was noted, such as effects on social interaction (greater empathy and trust), learning, or mental health (reduced stress, anxiety, depression). Since pleasurable tactile interaction is a major contributor in oxytocin release, such as stroking dogs (Odendaal, 2000), the great extent of overlap suggested positive effects of touch on emotions. Applied to social robotics, Yohanan and MacLean (2012) used a haptic creature to analyse patterns of gestures used to communicate emotional expressions, as well as associating these with human intent. Five tentative categories were proposed, where intent and emotional state may overlap, including protective, comforting, restful, affectionate, and playful gestures. In context of human-human interaction (HHI), Hertenstein et al. (2006, 2009) reported that touch can communicate at least eight distinct emotions. Six of these – anger, fear, disgust (negative emotions) and gratitude, love, sympathy (positive emotions) – were accurately decoded by humans when their arms were touched by unacquainted partners (Hertenstein et al., 2006). These findings were extended by reports of accurately communicated happiness and sadness through touch, in a study including full body interaction (Hertenstein et al., 2009). In both cases, the mean accuracy rate of recognised emotion was between 50-70%, which is comparable to accuracy rates found in studying facial and vocal communication of emotions.

In addition to being critical for growth and development, communication and learning, touch also serves to comfort and give reassurance and self-esteem. A child's first emotional bonds are built from physical contact, laying the foundation for further emotional and intellectual development (Field, 2001). Harry Harlow's classic 1958 experiment with infant monkeys showed that touch was more important than nutritional care of mothers, and that touch deprived monkeys had difficulties in emotional development and mating (Harlow and Zimmerman, 1958). Another frequently cited case study, of children in Romanian orphanages during or after World War II, also showed negative effects of touch deprivation on social behaviour and emotional development (Settle, 1991). Several cross-cultural studies also confirmed that touched bar guests intend to give a larger tip (H Crusco and G Wetzel, 1984; Gueguen and Jacob, 2005). Similarly, touch can increase volunteering rates between students when trying to solve a mathematical problem (Gueguen, 2004), and in some cases even increase student's performance.

Such knowledge on the impact of touch, affection and behaviour may play a crucial role, when science communicators engage with publics. Creating positive experiences and shaping attitudes towards science, may benefit from tactile interactions in public engagement, where the psychology of touch feeds into the objectives of science communication. The afore-mentioned human factors of touch also serve as design guidelines and constraints of technological solutions, which stimulate the sense of touch. The next section reviews various types of haptic technology, discussing the way these work, and the application areas these may serve.

3.3 Haptic technologies

Historically, teleoperation is said to be the mother discipline of haptics (Hayward et al., 2004). Often, exoskeleton devices were used by operators to control a remote robotic arm, or other probe, which in turn would feed back the forces registered by its sensors to the user on the master side. The goal of such haptic interfaces is to gain insight and manipulate systems that are dangerous or inaccessible for human presence. Therefore the design of exoskeletons aim to couple the haptic feedback with the controller, which supports high fidelity anatomical movements of the operator (King et al., 2010; Bejczy and Salisbury Jr, 1980). However, these devices are neither wearable or portable (Pacchierotti et al., 2017), thereby limiting their application areas. As new application areas emerge, and the added value of touch to human-computer interaction is acknowledged, the horizon of haptic technology begins to expand. Adding the sense of touch to graphical user interfaces implies a more natural interaction between men and machine, by means of adding a physical dimension to visual information. Furthermore, as haptic technology evolves, new opportunities open up for integrating touch with computer simulated, virtual environments, making the human-computer interaction even more immersive.

3.3.1 From visualisation to physicalisation: haptic technology in context of HCI

One of the most straight-forward application areas of marrying the sense of touch with technology, is the ability to represent data in a physical form. To obtain information, a depiction of data and its meaning is necessary for humans. Such representations can be cast either in a two-dimensional (2D) surface, or in a three-dimensional (3D) tangible representation, where data is encoded as representation attributes, such as colour, shape, texture or hardness. Perhaps one of the most well known early works, of translating numerical data into geometric information is originating from Descartes' 1637 Discourse on geometry (Encyclopedia.com, 2020). Since the introduction of analytic geometry, visual representations of abstract information have been used to demystify data and reveal otherwise hidden patterns (Heer et al., 2005). Information visualisation seeks to augment human cognition by leveraging human visual capabilities to make sense of abstract information. Digital computer screens possess several strengths, including quick and dynamic frame-rate, detailed resolution, and their capability to immerse people within a virtual representation nearly indistinguishable from reality (Moere, 2008). However, screens are still considered as productivity tools for output information, but not calm computing interfaces which integrate with our environment, promoting more natural interaction.

We are just rediscovering that tactile interactions may increase usability and enjoyment of data representations (Hornecker, 2011). Yet, designing (and implementing) a tangible artefact that allows for abstract meaning to be gathered through physical form is not an obvious task (Challis and Edwards, 2001). Jansen et al. (2013) showed that physical representations of bar charts can be more effective than their 2D visual equivalents. This has inspired further research, which investigated physical representations from various aspects, such as memorability (Stusak et al., 2015) or low level prototyping of demographic data through haptics (Stusak and Aslan, 2014). Both of these studies presented findings in favour of physical representations. Other research has shown that haptic data visualisation provokes more emotional responses than visual charts (Follmer et al., 2013). Similarly to graphical user interfaces, shape changing, tangible user interfaces can have functional features, as well as features that hint possible uses, so called 'affordances'. Although the cost and technological barriers of producing shape changing displays only allows for research and not daily use, there is an emerging attempt to develop the vocabulary for dynamic, physical affordances (Follmer et al., 2013).

3.3.2 Types of contact haptic technology

This subsection reviews the ways different types of haptic technology render tactile output. For instance, tangible user interfaces render physicalised information, but mostly as a pseudo 3D representation, which is often displayed in a grounded haptic interface. On the other hand, wearable haptic technology and force feedback devices are capable of rendering truly 3D haptic representations. Still, these two types of haptic technologies differ, in that wearables typically simulate direct touch interaction, while force feedback devices make use of indirect touch.

Surface haptics and tangible user interfaces

More advanced material science and computational research is directed towards shape changing, and programable matter tangible user interfaces (TUI). TUI's afford pseudo 3D (sometimes called 2.5D), or truly 3D representations in physical space, through grounded devices, i.e. non-portable or wearable technology. Prototype tools have been developed using jamming particles to create programmable stiffness interfaces (Follmer et al., 2012). The evolution of various shape changing devices also led to researchers defining metrics, such as "shape resolution" (Roudaut et al., 2013) analogously to screen and touch resolution. Other work also tried to integrate flexible sensing technology with shape changing interfaces, and introduce soft-composite devices (Yao et al., 2013). Rasmussen et al. (2012) published a review on shape changing displays, which identified eight types of shape change and underlying transformations. In the same review, three open research questions on: purpose of shape change, design space of shape change, and the user experience of such interfaces were defined.

Wearable and handheld haptic technology

Development of wearable and handheld haptic interfaces also gained momentum recently, with application areas, such as multimedia, assisted navigation or entertainment (Pacchierotti et al., 2017). By definition, wearables are contact haptic devices, often applying skin stretch on the fingertips (Salada et al., 2018), or other vibro-tactile mechanisms built into portable equipment, such as bracelets, gloves or vests. For example, ”Grabity” is a finger mounted haptic device, which aims to simulate weight and other forces during grasping motion in a virtual reality setting through the use of voice coil actuators stretching the skin (Choi et al., 2017). Other examples include TouchVR (Trinitatova et al., 2019), which uses a DeltaTouch haptic display to convey multimodal tactile sensations, such as softness or slippage to the palm in a VR setting. PaCaPa is also intended for VR use, where size, shape, and stiffness are rendered through the handheld haptic device (Sun et al., 2019). Canetroller (Zhao et al., 2018) is a haptic cane controller that simulates white cane interactions, enabling people with visual impairments to navigate a virtual environment.

Force feedback devices

Another class of haptic technology – force feedback devices – mostly stimulate the kinaesthetic sense, by exerting forces on muscles, joints, and tendons (Hayward et al., 2004). Typically, force feedback haptic technology which is grounded, mediates haptic sensations indirectly via a pointer, but also enables mid-air interaction. For instance the “3D systems Phantom” product family uses a stylus to provide force feedback across six degrees of freedom (3D systems, 2020). The “Falcon” by Novint Technologies is a similarly popular commercial force feedback device, also used in research. Both of these technologies were used to study the added value of haptic feedback in education, for instance, as we will see in the next section.

In summary, there is a wealth of haptic technologies, ranging from grounded to wearable, stimulating cutaneous or the kinaesthetic sense, mediating direct or indirect touch; but all requiring contact between user and device. After looking at how contact haptics is used in engaging with science, we will close this chapter on reviewing contactless haptic technology.

3.3.3 The utility of haptic technology in engaging with science

In this subsection I review how tactile interaction has been used to engage and educate the public about scientific topics.

Tangible models

The utility of touch and three-dimensional (3D) modelling has already been recognised by many in the scientific community, especially in medicine and astronomy (Arcand et al., 2017). Visualisations of space are most often limited to a two-dimensional projection on the sky; however, the ability to expand this view to 3D models enabled astronomers to get deeper insights to phenomena, such as supernova explosions and their underlying physics. Augmenting 3D visualisations with tactile properties, most often by 3D printing tangible artefacts, is considered a step further, providing cognitive tools for experts and non-experts alike for comprehending imperceptible objects. For example, the “Tactile Universe” project created 3D models of galaxies, used to engage visually impaired children in astronomy (Bonne et al., 2018). Similarly, the “Tactile Collider” is aimed at visually impaired children to engage them with the field of particle physics, and demonstrate particle colliders through the use of tactile graphics, large scale tactile models, and 3D sound (Dattaro, 2018). Other work in this area includes, for example, astronomical activities specifically intended for people with special needs (Ortiz-Gil et al., 2011), 3D tactile representations of Hubble space telescope images (Grice et al., 2015), of data from the X-ray Chandra Observatory (Arcand et al., 2019), of the Subaru telescope structure (Usuda-Sato et al., 2019), of the Eta Carinae nebula (Madura et al., 2015), and of cosmic microwave background radiation anisotropies (Clements et al., 2017). Most of these static tangible artefacts, serve as manipulable 3D representations of structural information, providing insight into scale, or morphology of objects at the cosmological, or microscopic scale.

Haptic technology enhanced learning and engagement

Another popular method of adding the sense of touch to scientific subjects is through the application of haptic technology. In particular, grounded or handheld force feedback devices have been used widely, for training or demonstration purposes of more dynamic attributes, such as forces between physical bodies. As early as 1964, Project GROPE created a haptic display to render 6D force fields of interacting protein molecules for research chemists, making docking mechanisms easier to handle (Brooks et al., 1990). More recently, haptic enhanced learning mechanisms, such as the haptic bridge have been proposed in a study using HapKit, where elementary school children explored two different representations of mathematical functions (Davis et al., 2017). Jones et al. (2003) compared full haptic and no haptic conditions of observing nanoscale viruses, using a Phantom nanoManipulator, which controls an atomic force microscope over the world wide web. Minogue et al. (2016) looked at using the Novint Falcon force feedback system to implement haptic enhanced science simulations of phase change and intermolecular forces. The same device has been used to explore added benefits of haptic simulations, in context of the Coriolis effect for physics undergraduate students (Hamza Lup and Page, 2012), and conceptualising buoyancy at elementary education (Chen et al., 2014).

Similarly, force feedback devices have been used to focus on accessibility of science content for vision impaired learners, by incorporating the interaction modality of touch, just like using 3D printed models. Jones et al. (2006a) studied the use of a pen-like haptic device to teach cell morphology and function to vision impaired students. The same research group (Jones M. et al., 2006) also contrasted a highly sophisticated Phantom haptic device, a gaming joystick, and a computer mouse, asking legally blind students to interact with instructional content on viruses. Nam et al. (2012a) explored the usability of haptic user interfaces in form of a Novint Falcon device, whilst teaching molecular properties to teenage vision impaired children. Most of these studies investigated effects of haptic aided instruction on overall learning experience and content retention, in contrast to traditional instruction techniques, such as verbal or text based communication.

While access to information, cognitive workload and other learning outcome metrics were the centre of previously cited studies, reports also discuss hedonic benefits of haptics, such as increased engagement with science and more immersive experiences. However, there is little attention drawn in literature to the utility of touch in public engagement with science, such as the added value of haptics for creating interest, or fostering positive attitudes. Therefore, this thesis aims to study how haptic technology may benefit research and practice, in the discipline of science communication, going beyond the evaluation of touch in context of learning outcomes and cognitive processes. In particular, the focus of this thesis is on ultrasonic mid-air haptic technology, introduced in the next section. This technology is not only novel, but also lays somewhere between static tangible models stimulating the cutaneous subsystem, and force feedback devices, which are computerised and primarily stimulate the kinaesthetic subsystem. Mid-air haptics stimulates cutaneous touch, it is programmable, contactless, and invisible; of which all properties may be leveraged in technology enhanced science communication, such as recent sensory virtual reality experiences (Zec and Porter:, 2020; Stepanova et al., 2019).

3.4 Mid-air haptic technology

3.4.1 Types of mid-air haptic technology

We have seen a wide range of haptic technologies. A common feature of the devices reviewed in the previous section is that they require either direct, or indirect contact with the user. However, there exists another class of haptic technology, which is able to create tactile sensations in a contactless way. This is often referred to as mid-air haptics, or airborne haptics. Two main types of airborne tactile stimulation is distinguished: air-jet based, and acoustic radiation pressure based haptics (Arafsha et al., 2015).

Considering air-jet solutions, tactile sensations are delivered by either sending compressed air directly through focused nozzles (Suzuki et al., 2002), or by creating air vortices (Glezer, 1988). The latter method uses air vortices by controlling the pressure difference between the nozzle and the outside medium (Arafsha et al., 2015). This method allows the produced air vortices to reach further distances while preserving form and speed (Sodhi et al., 2013). A limitation of this type of airborne haptics is the low spatiotemporal resolution of tactile output.

In contrast, ultrasonic mid-air tactile stimulation can be used to create more focalised output. In this case, a phased array of ultrasonic transducers is used to create high pressure focal points, based on the concept of acoustic radiation force (Iwamoto et al., 2008; Hoshi et al., 2010; Carter et al., 2013). The pressure focal points reflect on the air-skin interface, applying a force that deforms the skin. The intensity of the focal point is modulated to create a vibratory stimulus, perceived by the mechanoreceptors. For a detailed description on ultrasonic haptics, see Appendix A.

One of the challenges of ultrasonic haptics is the audible artefacts created during the modulation and phasing of the ultrasonic carrier (Hoshi et al., 2010). Another is the energy loss in the medium, when carrier frequency is increased in an attempt to create more focalised tactile pixels (Iwamoto et al., 2009). Yet another challenge is to keep sound pressure levels at a safe range considering hearing, whilst increasing acoustic radiation pressure, in an attempt to create higher intensity sensations (Howard et al., 2005). Regardless of all the challenges, ultrasonic mid-air haptics conquers over air-jet solutions.

3.4.2 Research on the psychology of mid-air haptics

The recent discovery, and commercialisation, of ultrasonic airborne haptics ignited a wide range of research activities on understanding human factors of mid-air touch, and on characterising properties of airborne tactile sensations. Most of the research focused on perception of sensations created using specific mid-air haptic parameters, and on elicited experiences, or emotions mediated through mid-air touch. Spacial and temporal discrimination studies were one of the early mainstream focus of researching perception of mid-air haptic sensations. Alexander et al. (2011) showed that users were able to discriminate the number of sensations between 0-4 focal points to an average accuracy of 87.3%, in context of a mobile TV device, augmented with mid-air haptics. Alongside the system description of the Ultrahaptics mid-air haptic display, Carter et al. (2013) also performed experiments on spacial resolution of perceived focal points. Results showed a minimum required separation distance of 5cm between two focal points of identical modulation frequency, and 3cm if the modulation frequency differed. Although these values are relatively high compared to vibro-tactile stimuli, results also showed improvements in discriminating focal points with training. Indeed, Wilson et al. (2014) further studied the localisation of static tactile points in mid-air and found an average of 8.5mm error in locating targets, where the localisation errors were typically 3mm larger in the longitudinal axis of the hand. Similarly, Yoshino et al. (2012) studied the visual-tactile threshold and showed the minimum perceived separation to be 10mm, using ultrasonic mid-air haptics integrated with visual displays.

In context of temporal resolution, Wilson et al. (2014) also studied the perception of apparent movement (Geldard and Sherrick, 1972) of mid-air haptic stimulation, by investigating correlations between number of points, point duration, point separation, and directionality. Results showed that higher number of points, and longer point duration improved the reported quality of movement, which generally scored higher in the transverse direction, than the longitudinal axis. Pittera et al. (2019a) also studied the illusion of movement using mid-air touch, stimulating both hands synchronously, such that the simulated movement is located in the intermediate space, unlike Wilson et al., where tactile movement was simulated on the body.

Beyond studies on characterising spacial and temporal properties of mid-air touch, perceived texture and intensity have been actively researched in recent years. For example, Frier et al. (2018a) showed that using spatiotemporal modulation of focused ultrasound, parameters of draw speed and pattern size affect perceived intensity of the haptic feedback. Frier et al. (2019) also showed that lower sampling rates, in conjunction with the draw speed of spatiotemporal modulation extend the intensity threshold of perceived mid-air tactile sensations. In context of perceived texture, Freeman et al. (2017) demonstrated mid-air haptic surfaces rendered as multiple levels of roughness, using different modulation waveforms of focused ultrasound. Beattie et al. (2019) also proposed an algorithm which uses a haptic mapping function to recreate textured graphics using ultrasonic mid-air haptics. More recently, perception of mid-air haptic sensations focused on directionality of sensations, and the identification of local shapes, patterns, and icons, which will be further discussed in chapter 9.

Moving away from fundamental studies of perception, more holistic studies focused on the overall user experience of mid-air haptics. For instance, Maggioni et al. (2017) measured the added value of haptics in short, audio-visual movie clips, and found that tactile stimulation creates more pleasant and creative experiences, with a higher overall liking of the media content . Obrist et al. (2015) investigated elicited affection through standardised pictures, showing a non-arbitrary mapping between mid-air haptic stimuli and mediated emotions, by manipulating spacial, directional, and haptic parameters. In another study, Obrist et al. (2013) established a vocabulary for ultrasonic mid-air tactile experiences, comparing focal points modulated at 16Hz and 250Hz. The findings showed that people distinguished between weak and strong, discrete and continuous, or tickling and ticklish sensations, but they also associated tactile sensations with experiences occurring in nature, such as flow of water, electric current, or wind.

3.4.3 Research on application areas of mid-air haptics

There is also a growing interest in researching application areas of ultrasonic mid-air haptic technology. Three popular research topics are: the use of mid-air haptic stimulation in entertainment (Ablart et al., 2017a; Hwang et al., 2017) and art (Vi et al., 2017), immersive virtual and augmented reality (Pittera et al., 2019b; Georgiou et al., 2018), and automotive user interfaces (Harrington et al., 2018; Shakeri et al., 2018).

Vi et al. (2017); Ablart et al. (2017b) studied the affective responses elicited when mid-air haptics is integrated with abstract art. A six weeks long multisensory installation in the Tate Britain art gallery highlighted the emotional and artistic benefits, in terms of creative interpretation and immersive experiences. Ablart et al. (2017a) showed the positive effect of mid-air haptics integrated with multimedia content on emotional valence and arousal. Synchronous audio-visual and haptic stimuli were rated as a favourable movie watching experience, even after multiple viewing sessions with two weeks time separation. In virtual reality, Pittera et al. (2019b) showed that limitations of hand tracking technologies and in precise tactile stimulation can be overcome by incongruent visual-tactile stimulation, increasing ownership and immersive VR experiences. Georgiou et al. (2018) implemented the first VR game environment with contactless haptic feedback, which was soon followed by more complex and more immersive VR experiences through mid-air touch (Martínez et al., 2018).

The application of mid-air haptics has been suggested in cars, to provide feedback on gesture controls. Shakeri et al. (2018) showed that using haptic feedback, compared to visual and auditory stimuli, reduced “eyes off the road time”, whilst not introducing any perceived mental demand during the secondary task of gesturing. Harrington et al. (2018) showed similar advantages of mid-air haptic feedback in an experiment, where slider and button controls were contrasted in a touch screen and gesture interface. Slider gesture controls with haptic feedback resulted in shorter interaction times, than their touch screen equivalent. This thesis aims to expand the application areas mentioned here, by exploring how science communicators could benefit from this technology.

3.4.4 To use, or not to use mid-air haptic technology in context of science communication?

In the previous sections, I have reviewed various types of haptic technology and their potential use-cases, including ultrasonic mid-air haptic technology. Here, I summarise specific properties of contactless haptic sensations and interaction, compared to other modalities of haptic interaction, to motivate the use of mid-air haptics in science communication scenarios.

Ultrasonic mid-air haptic technology and force feedback controllers have a high spatial and temporal resolution, with a fast update rate, which enables these devices to render active and dynamic haptic content (Carter et al., 2013). In contrast, static tangible artefacts have an even higher spatial resolution, but no or very low temporal resolution (Clements et al., 2017). Shape changing tangible user interfaces (TUI), such as pin arrays most often only have a relatively intermediate spatial and temporal resolution (Follmer et al., 2013). Simulating natural phenomena requires quickly changing tactile sensations, with a sufficiently high spatial detail, therefore force feedback and mid-air haptic devices appear to be a more suitable design choice.

Multipoint mid-air haptics, combined with its fast update rate, makes it possible to render 2D and 3D spatial patterns (Long et al., 2014), similarly to TUIs (2.5D) (Follmer et al., 2013), and 3D fabricated artefacts (Bonne et al., 2018). However, force feedback is typically a single point interface, which can be used to trace out the outline of 2D and 3D virtual tangible objects utilised by force feedback and movement (O'Modhrain et al., 2015). Just like with surface haptics, 3D printing, and force feedback, mid-air haptics can render different textures on 2D and 3D spatial patterns (Beattie et al., 2019). But the lack of mid-air haptic force feedback, due to the low ultrasonic pressure exerted on the hands, mid-air haptic sensations can simulate boundaries of objects, and let the user put their hands through to inspect the inside. This may be an interesting property when rendering scientific concepts, such as planetary or cell structure, where structural differences may be perceived between outer and inner layers. A similar effect may be achieve using force feedback controllers, though using kinaesthetic mechanisms instead of cutaneous sensations (Jones et al., 2006a).

TUI, force feedback, and mid-air haptic devices can all be programmed, and equipped with active sensing, such as capacitive touch sensing, or hand position and gesture tracking (Bornschein et al., 2018; Long et al., 2014). The combination of programmability and sensing, makes these devices to be interactive, and adapt the haptic rendering based on user interaction and a pre-defined set of rules. Interactivity is most likely a desired design feature, when the goal is to render natural phenomena, where the state of the system may change upon interacting with it. For example, a fundamental principle in quantum mechanics is that the act of observation interferes with the state of the system. Therefore, a non-interactive medium would not be suitable to render quantum phenomena for the haptic sense.

Pin arrays, static artefacts, and mid-air haptic sensations are predominantly perceived through the cutaneous channels (Hayward et al., 2004; Hoshi et al., 2010). In contrast, force feedback devices mainly stimulate and communicate through kinaesthetic sensations arising in muscles and joints. This implies that force feedback systems will be more appropriate to use in some scenarios, such as communicating physical forces, for example magnetic attraction and repulsion or spring oscillations (Jones et al., 2003; Jones M. et al., 2006). However, in other circumstances, such as communicating Brownian motion of atoms and particles may be more effectively communicated with moving mid-air tactile points on the skin.

Static artefacts, as well as mid-air haptic sensations afford the augmentation of tactile information with spatially congruent visual stimuli too (Furió et al., 2017; Pittera et al., 2019b).

This enables the creation of more natural and realistic simulations of natural phenomena for the eyes and hands. In contrast, spatially congruent visual-haptic scenes are not possible, or technologically and perceptually more challenging to achieve with TUI and force feedback devices (Jones M. et al., 2006).

Table 3.1 shows an overview of properties of haptic sensations, potentially relevant to communicating natural phenomena, and the ability of different haptic technologies to render these properties. In chapter 5 I further discuss the opportunities and challenges of mid-air haptics through the lens of these properties, based on the experience of science communicators.

Table 3.1: Overview of properties relevant to communicating natural phenomena through the haptic sense. Four classes of haptic technologies are compared across nine properties.

Property	Static artefacts	Surface haptics	Force feedback	Mid-air haptics
Spatial resolution	Higher	Intermediate	High	High
Temporal resolution	No	Low	High	High
Multipoint	Yes	Yes	No	Yes
Spatial patterns	Yes	Yes	Yes	Yes
3-dimensional	Yes	No	Yes	Yes
Programable & Interactive	No	Yes	Yes	Yes
Cutaneous	Yes	Yes	No	Yes
Kinaesthetic	No	No	Yes	No
Congruent visual-haptic	Yes	No	No	Yes

3.5 Summary

In this chapter, we have briefly examined the fundamentals of touch, including its basic anatomical structure, physiological function, and neural correlates. We looked at the psychological factors of the tactile sense, and its effects on cognition, perception, affection, and behaviour. We acquainted ourselves with the HCI perspective of haptic technology, the types of haptic devices, and the utility of haptic tools in science communication. Last but not least, we reviewed the research literature on mid-air haptic technology, taking into account its applications and capabilities as a user interface. In the final chapter of this introductory part of the thesis, I discuss my research approach to the projects that form the main body of this dissertation.

Chapter 4

Research approach

"What are you doing with all these rainbow array of colours on your table? (Waldeyer) – I'm just fooling (Ehrlich) – Very well. Go on with your fooling. (Waldeyer)" – Wilhelm von Waldeyer to Paul Ehrlich in the anatomy laboratory at the University of Strasbourg (Flexner, 1939).

In this chapter, I discuss an overview of the research approach and methods used to carry out the work of this PhD. As stated in the introduction, this doctoral thesis discusses the opportunities and challenges arising from the relationship between human tactile experiences, contactless haptic technology, and society's engagement with science. In the broadest sense, the overall research question addresses – *"How can engagement between science and society be supported by mid-air haptic technology?"* Therefore I needed methods to map individual perception and human experience, the interaction between technology and the human, as well as the dynamics of engagement at different scales and types of social groups, all centred around the same theme.

4.1 Overview

The research discussed in this thesis follows a highly interdisciplinary approach. The contribution may be positioned somewhere on the intersection of science communication, HCI, and haptics, of which each field is interdisciplinary by itself. Hence, I borrowed some methodology known to the social science of science communication, such as conducting focus groups, as well as some of the more practical evaluation methods of live public engagement events. Some of my research approach is based on measurements seen in HCI and haptics, such as psychophysical pilot studies, or eliciting experiences through interviews. On multiple occasions, I also needed to incorporate design approaches, such as relying on a heuristic framework or creating a new experience based on an existing design.

Where possible, I aimed to apply both qualitative and quantitative methods of data collection and analysis. Typically, quantitative approaches helped in acquiring a clearer insight when a subset of all tested conditions was favoured. For example, quantitative measures helped specify target affective responses favoured by science communicators in a questionnaire, or specify clearly which of the three methods of rendering tactile shapes is the most recognisable. However, qualitative methods were also necessary to either make a first exploratory study on an uncharted area of study, or to refine and better understand the results of quantitative results. On occasions, the mixed method approach was used to triangulate the findings, whilst sometimes qualitative analysis revealed participant strategies and experiences in addition to quantitative performance metrics. This thesis reports on nine empirical studies and two practical field works, summarised in Table 4.1. The studies involved: questionnaire based surveys, focus groups, structured interviews, as well as in-lab pilot and user studies. The qualitative data acquired during these studies was analysed using either an open coding scheme, thematic, or content analysis, depending on what we were looking for and how much detail we required. The quantitative data was analysed by descriptive statistics, as well as the appropriate significance testing where it was necessary. The field work we have conducted in the London Science Museum relied mostly on evaluation methods cited in literature, and the research team's observation during the pilot event, which was put to use in a second main event.

Table 4.1: Summary of research methods in the associated chapters.

Ch.	Study(s)	Method(s)	Participants	Participant type
5	Workshops 1, 2, 3	Focus groups	11	Science communicators
6	Study 1	Online questionnaire, interviews	61, 8	Science communicators
6	Study 2 (pilot)	In-lab user study, interviews	5	General public
7	2018 event (pilot)	Field work evaluation, questionnaire	46	Attentive public
7	2019 event	Field work evaluation, questionnaire	222	Attentive public
8	Work packages 1, 2	In-lab user study	6, 8	Sensory impaired
9	Pilot studies 1, 2	In-lab user study	9, 9	Research staff
9	Experiment 1, 2	In-lab user study	34, 25	General public

4.2 Methods of data collection and analysis

In this section, I review the methods used for data collection and analysis, and justify their choice in more detail at the relevant chapters that follow.

4.2.1 Interviews and focus groups

The data collection described in chapter 5 was based on design heuristics implemented in mid-air haptic probes, and used focus groups to elicit participant feedback. Unlike surveys, focus groups are used to gather deeper, rather than broad insight,to a topic (Lazar et al., 2017b). Focus groups typically involve an interview between a researcher and multiple participants at the same time. In this case, I conducted a semi structured interview with three groups of science communication experts. As an early exploratory study of this doctoral thesis, it was important to gain a deeper qualitative understanding of the opportunities and challenges of mid-air haptic technology in the hands of science communicators. We had to leave an open platform, for participants to highlight or disregard any of the three hypotheses tested, using the haptic probes, and also to introduce new themes, which we did not initiate.

The sessions were recorded, resulting in six hours audio material. The data was transcribed into a low fidelity script, and relevant information was extracted, following an open coding approach (Braun and Clarke, 2006). In this case, low fidelity refers to a transcript which is not a word by word, nor a non-verbal rich transcript of the recording, but rather a digest of relevant dialogues. The transcripts were coded by three of the co-authors independently, then synthesised, resulting in three themes. Open coding is a technique utilised by thematic analysis. Thematic analysis is a flexible, widely used method for identifying, analysing and reporting patterns (themes) within data. It minimally organises and describes the data set in detail (Braun and Clarke, 2006).

Similarly, in the studies described in chapter 6 and 9, I used qualitative research methods. The data was partly collected in form of short, fully-structured interviews with individual participants. The interviews were recorded and transcribed with high fidelity. Here, high fidelity means a word-by-word transcript of the interviews, enriched with non-verbal expressions. For example; in chapter 9 Content analysis was used to extract and abstract descriptors of the haptic stimuli, as well as the strategies of shape recognition. Content analysis is an in-depth analysis, which searches for theoretical interpretations of generating new knowledge (Lazar et al., 2017c). This data analysis technique is a systematic, quantitative approach to analysing the content or meaning of communicative messages (Allen, 2017). The objectivity, generality and systematic nature of this method allowed me to answer qualitative questions, supporting the results of quantitative results of the associated user studies. In chapter 6, I also conducted qualitative interviews, to verify and refine the preliminary results obtained from quantitative data.

4.2.2 Surveys and evaluation of field work

Besides interviews and focus groups, in the practical work discussed in chapter 7, I also used survey tools and other evaluation methods of public feedback in a field work setting. Surveys are a widely chosen research method, due to their ease of use. However, surveys can also easily lead to no, or faulty, conclusions if these are not created and validated before data collection (Lazar et al., 2017d). For this reason, the questionnaires used in the project discussed in chapter 6 were either carefully developed by us, through a series of methodological steps, or these have been standardised in previous research. For example, our DARTS questionnaire was developed using a Find-Fix-Verify inspired three step method, while the Need-for-Touch and Attitude-

Towards-Science questionnaires were taken from literature. Although data has been analysed from surveys and other means of public feedback, these were not always serving research purpose directly. Instead, the information was used to evaluate practical work, as well as to inform potential research concerned with evaluation objectives and processes in context of multisensory public engagement.

For the researchers who take part, and the organisers, evaluating the events' success, value, and effectiveness is hugely important. However, the use of traditional evaluation methods such as paper surveys and formal structured interviews poses problems in informal, dynamic contexts (Grand and Sardo, 2017). As suggested by Grand and Sardo, in a vibrant public engagement event, there is little time to use traditional research methods of data collection. However, to gather ecologically valid data, it seems necessary for researchers to eventually collect data at the field, directly from the public attending science communication events. Hence, methods that work in the field are needed; not only for evaluation, but for research purposes too.

As a first step, I used methods published in literature. For example, during the Dark Matter Experience (see chapter 7), a feedback wall and Postit notes were used to capture visitors' feedback. Feedback from both sources were coded, and grouped, in line with qualitative data analysis. However, neither of these occasions addressed a specific research question. It is of interest to design methods, which simultaneously serve as tools of evaluating public engagement outcomes, as well as creating valid data sets for researchers. This research objective is further discussed in section 10.2.3.

4.2.3 In-lab user studies

The study of tactile shape recognition (see Ch. 9), or the comparison of physical touch and mid-air touch probes (see Ch. 6), required in-lab user studies. This included both performance measures, such as accuracy of shape recognition or response time, but it also took into account self-reported data. Accuracy metrics are easily quantifiable in confusion matrices, for instance, while self-reported confidence levels are more subjective. For this reason, I learnt to distinguish one type of quantitative data from another, i.e. measured and reported. Working with human participants is a valuable research method, which offers deep insights if the appropriate experimental design is implemented, and the analysis is interpreted correctly (Lazar et al., 2017e).

The high validity and rich source of data originating from user studies also come with a great responsibility. As part of convening user studies, I have been completing research ethics reviews, and considered the validity of the sample size, diversity and balance, to promote generalisable results, free of biases. Complying with research ethics is especially relevant when participants with special needs or disabilities are invited to take part in a user study, such as the work packages discussed in chapter 8. Throughout this thesis, I did not face any particularly challenging ethical issues, but there have been a few considerations to be aware of and take in account during project planning. For example, working with disabled participants, I had to consider and provide suitable travel arrangements to the study site. I also had to design an accessible and convenient methods of data collection, such that participants feel empowered to take part and not be disappointed by potentially being incapable to accomplish the experimental tasks. Working on the field, also raised ethical concerns. The activities should accommodate visitors of all demographic groups, and disabilities, avoiding the sense of exclusion due to a non-empathetic designs of the activity, or different forms of post-activity evaluation.

Finding participants for generalisable results has been particularly challenging in the user study discussed in chapter 6. A highly educated user group, with positive attitude towards science would most likely bias their affective response to any scientific content, regardless the modality of presentation. However, the frequently recruited participants of university students and staff, are mainly people with characteristics mentioned above. On occasions, pilot studies with just a few participants were necessary to design the appropriate experimental conditions, practicality of the technical setup, and guide the research findings.

I believe the interdisciplinary approach and mixed method of data collection and analysis effectively guided my research throughout the PhD. Both of the empirical studies, and practical field work, contributed to discussing how mid-air haptic technology may support society in different settings, at different scales, or different audience needs. The following chapters will discuss the details of the studies undertaken during my research.

Part II

Opportunities and Challenges for Ultrasonic Mid-air Haptic Technology in the Science Communication Landscape

Chapter 5

I can feel it moving: Science Communicators Talking About the Potential of Mid-Air Haptics

5.1 Abstract

5.1.1 Contribution to thesis

The first project in the portfolio served as a qualitative exploration, mapping opportunities and challenges posed by mid-air haptic technology in public engagement. To gain deeper insights to science communication beyond the literature, and to inform future research questions, we dedicated this project to working with the specific user group of science communicators. The research question therefore asked: “Which features of mid-air haptics are identified as advantageous by *science communicators*, in context of public engagement and traditionally used tools of communication?” Data collection was based on multiple, interactive focus groups. Our aim was to identify commonly occurring themes, which may guide future research questions. The work involved collaboration with Dr Oliver Schneider, at the University of Waterloo. My contribution was to run the focus groups, collect data, and summarise findings in a publishable manuscript. I had support from co-authors in preparing the haptic stimuli and analysing the transcripts. A supplementary video was also created to help readers in visualising the haptic probes used in this project. This work has been published in the Human-Media Interaction section of Frontiers in Computer Science.

5.1.2 Project overview

We explored the potential of haptics for improving science communication, and recognised that mid-air haptic interaction supports public engagement with science in three relevant themes. While science instruction often focuses on the cognitive domain of acquiring new knowledge, in science communication the primary goal is to produce personal responses, such as awareness, enjoyment, or interest in science. Science communicators seek novel ways of communicating with the public, often using new technologies to produce personal responses. Thus, we explored how mid-air haptics technology could play a role in communicating scientific concepts. We prototyped six mid-air haptic probes for three thematic areas: particle physics, quantum mechanics, cell biology; and conducted three qualitative focus group sessions with domain expert science communicators. Participants highlighted values of the dynamic features of mid-air haptics, its ability to produce shared experiences, and its flexibility in communicating scientific concepts through metaphors and stories. We discuss how mid-air haptics can complement existing approaches of science communication, for example multimedia experiences or live exhibits, by helping to create enjoyment or interest, generalised to any fields of science.

Figure 5.1: Ultrasonic mid-air haptic technology *(left)* enables the creation of tactile sensations without attachments to the hand. We developed six mid-air haptic probes *(right)* of science concepts from particle physics, quantum mechanics, and cell biology; and then ran workshops with science communicators from each of those three scientific fields *(middle)*.

5.2 Introduction

Without appropriate science communication, science and technological advances may be feared and opposed by the public. In 2008, protests broke out against the launch of the Large Hadron Collider (LHC) at the European Organisation for Nuclear Research (CERN) (Courvoisier et al., 2013) in fear of destruction of the Earth. Another example of societal fear and the impact of science communication on public health is the “Chernobyl syndrome” and its debated effects on induced abortions (Auvinen et al., 2001). A further conflict between religion and science on the matter of creation, caused the ban of teaching evolution until 1968 in the USA, with the Scopes (monkey) trial exemplifying the impact of science communication on education (Holloway, 2016).

5.2.1 Technology enhanced science communication

New multimodal technologies, developed within the Human-Computer Interaction (HCI) community, may facilitate the dialogue between science communicators and the public, by supporting positive personal responses to science. While science instruction often focuses on the cognitive domain of acquiring new knowledge (Bloom et al., 1956), in science communication the primary goal is to produce *“one or more of the following personal responses to science: **A**wareness, **E**njoyment, **I**nterest, **O**pinion forming, and **U**nderstanding"* (Burns et al., 2003), also known as the AEIOU model. Science communication is not an offshoot of general communication or media theory (Burns et al., 2003), nor is is just dissemination of scientific results for the peer community or teaching scientific skills and concepts to children. Even so, science communication is thought to be a broader spectrum, ranging from the more informal style of public engagement to the more formal science education (Burns et al., 2003).

However, producing personal responses is a challenge when communicating phenomena that are imperceptible to humans, such as atomic structure, or the electromagnetic nature of sunlight. Multimodal interfaces are often used to convey these complex, and often invisible, scientific concepts (Furió et al., 2017). The sense of touch could add to these, helping people perceive and interact in ways other senses can not (Lederman and Klatzky, 2009). Touch feedback has been shown to influence our behaviour (Gueguen, 2004), and emotions (Obrist et al., 2015).

Physical models are often used to enable people to touch static representations of otherwise untouchable things, such as galaxies. For example, Clements et al. (2017) published the "Cosmic Sculpture" which transforms the map of the cosmic microwave background radiation into a scaled 3D model. The "Tactile Universe" (Bonne et al., 2018) creates 3D models of galaxies, used to engage visually impaired children in astronomy. Both of these projects were developed for public engagement, with the aim to engage interested publics of science festivals in conversations, or to engage underserved audiences, such as visually impaired students. Physical models, using commercially available 3D printers, have the advantage of high resolution (0.2-0.025 mm), allowing a detailed exploration of fine features. However, they are limited in presenting dynamic concepts or internal structure of variable density.

More recently, Augmented Reality (AR) has been used to address the limitations of static tactile probes. For example, "HOBIT" (Furió et al., 2017) was built and evaluated in the context of light interferometry. Here, physical (3D printed) equivalents of the optical apparatus have been augmented with digital content, e.g. equations or animations of wave properties. The studies on HOBIT highlight benefits of augmented reality, such as affordability, lower time consumption, or safety compared to live demos; while the augmented information can also enhance learner performance (Furió et al., 2017). The multisensory nature of augmented reality has benefits compared to stand alone 3D printed probes, but it does not provide dynamic physical effects.

While haptic technology, to the best of our knowledge, has not been used to support science communication, haptics has been used in science instruction (see (Zacharia, 2015) for a review). Researchers have proposed using force feedback "Phantom" devices, which use a stylus to provide force feedback across six degrees of freedom (Jones et al., 2006a). Jones et al. (2003); Jones M. et al. (2006) demonstrated the positive impact of the Phantom on students' understanding of viruses at the nanoscale, as well as how scientific apparatus, e.g. Atomic Force Microscopes function. On the other hand, the "Novint Falcon" force feedback system showed little evidence of positive impact on learners' understanding, when learning about concepts of sinking and floating (Chen et al., 2014). Force feedback seems to be better suited than static tactile probes for representing elastic, or magnetic forces, as well as conveying structural properties, such as density or stiffness. However, just like with 3D probes, communication of dynamic processes remains a limitation.

In addition, users interact through a probe, and do not gain direct tactile experiences. Haptics has also shown promise in instruction for younger children. There is evidence that tactile feedback on a table can improve reading outcomes (Yannier et al., 2015), and that 3D physical mixed-reality interfaces can improve interest and learning (Yannier et al., 2016). Researchers have also developed a set of lower cost "DIY" force-feedback devices, for extending science instruction from university education to high school. Force-feedback "paddle" devices were initially developed as low-cost options to teach dynamics and controls (Richard et al., 1997; Rose et al., 2014). The Hapkit (Richard et al., 1997) has since evolved into a lower-cost, 3D-printable, composable platform for instruction in other domains (Orta Martinez et al., 2016). When a sandbox-style software was added, the Hapkit was shown to render haptics adequately for education with an impact on student problem-solving strategies and curiosity (Minaker et al., 2016), and scaffolds support sense-making with high-school students learning mathematical concepts (Davis et al., 2017). The Haply (Gallacher et al., 2016) is another DIY platform, primarily a 2-DoF one, used for VR and haptic prototyping, and adapted for education and hobbyists.

5.2.2 Opportunity for mid-air haptic technology in science communication

In this paper, we explored the potential of haptics for improving informal science communication, challenging the suitability of ultrasonic mid-air haptic technology. Mid-air haptics describes the technological solution of generating tactile sensations on a user's skin, in mid-air, without any attachment on the user's body. One way to achieve this is through the application of focused ultrasound, as first described by Iwamoto et al. (2008), and commercialised by Ultraleap Limited in 2013 (formerly known as Ultrahaptics). A phased array of ultrasonic transducers is used to focus acoustic radiation pressure onto the user's palms and fingertips (see Figure 5.1 [left]). Modulating the focus points, so that it matches the resonant frequency of the cutaneous mechanoreceptors found in humans (~5 Hz to 400 Hz) (Mahns et al., 2006), causes a localised tactile sensation to be perceived by the user.

Spatial and temporal discrimination studies were one of the early mainstream focus of researching perception of mid-air haptic sensations. Alexander et al. (2011) showed that users were able to discriminate the number of sensations between 0-4 focal points to an average accuracy of 87.3%, in context of a mobile TV device, augmented with mid-air haptics. Alongside the system description of the Ultraleap mid-air haptic display, Carter et al. (2013) also performed experiments on spatial resolution of perceived focal points. Results showed a minimum required separation distance of 5cm between two focal points of identical modulation frequency, and 3cm if the modulation frequency differed. Although these values are relatively high compared to vibro-tactile stimuli, results also showed improvements in discriminating focal points with training. Indeed, Wilson et al. (2014) further studied the localisation of static tactile points in mid-air and found an average of 8.5mm error in locating targets, where the localisation errors were typically 3mm larger in the longitudinal axis of the hand. Although spatial resolution is not as detailed, as for digitally fabricated probes, a less than 1cm resolution of tactile features in mid-air is a promising property of the technology, in context of science communication.

With regard to temporal resolution, Wilson et al. (2014) also studied the perception of apparent movement (Geldard and Sherrick, 1972) of mid-air haptic stimulation, by investigating correlations between number of points, point duration, point separation, and directionality. Results showed that higher number of points, and longer point duration improved the reported quality of movement, which generally scored higher in the transverse direction, than the longitudinal axis. Pittera et al. (2019a) also studied the illusion of movement using mid-air touch, stimulating both hands synchronously, so that the simulated movement is located in the intermediate space, unlike Wilson et al. (2014), where tactile movement was simulated on the body.

With the use of multipoint and spatiotemporal modulation techniques, it is possible to create more advanced tactile sensations such as lines, circles, animations, and even 3D geometric shapes (Carter et al., 2013; Long et al., 2014). Hence, ultrasonic mid-air haptic technology is explored in more and more application areas, such as art (Vi et al., 2017), multimedia (Ablart et al., 2017a), or virtual reality (Pittera et al., 2019b; Georgiou et al., 2018). For example, Ablart et al. (2017a) showed the positive effect of mid-air haptics augmented movie experiences on user experience and engagement, in context of human-media interaction. However, we are unaware of any empirical research on the potentials of mid-air haptics in science communication, neither in scientific public engagement, nor in science education.

For this reason, we created six prototypes, demonstrating science concepts using ultrasonic mid-air haptic sensations (see Figure 5.1), an emerging type of haptic technology (Carter et al., 2013). We took these prototypes to 11 science communicators for feedback during three qualitative focus group sessions, themed around particle physics, quantum physics, and cell biology. The science communicators could experience mid-air haptic sensations of selected scientific phenomena from their respective field (two per field). The discussion during the workshops were transcribed and analysed following an open coding approach. In contrast to six hypothesised advantages of the technology, we identified three main themes which were valuable, as expressed by the focus group participants. Science communicators highlighted the value of tangible and dynamic sensations combined. Moreover, participants implied that the ability to easily share the tactile experience between users was important to science communicators, alongside the potential to flexibly create a story around the sensation, by the communicator. In other words, a single sensation can be described as an atomic nucleus, a brain cell, or as a distant star, which helps science communicators to intertwine the technology with the use of metaphors and other tools of storytelling. Overall, our qualitative analysis suggests that mid-air haptics may have the greatest impact on the hedonic dimensions of the *AEIOU* framework – enjoyment and interest.

In summary, the key contributions of this paper are: (1) a characterisation of mid-air haptic technology as a novel tool for science communication; (2) a design-driven exploration of the properties of mid-air haptic sensations and interaction techniques, explored in three scientific disciplines with six mid-air haptic experience prototypes; and (3) a discussion on opportunities and challenges for mid-air haptic technology within the *AEIOU* framework of science communication.

5.3 Materials and Methods

To guide the design process for mid-air haptic probes (see Figure 5.2) we considered different features of other tangible modalities and discussed them in relation to mid-air haptic properties. Notably, haptic probes were designed to be strictly unimodal i.e. no auditory or visual stimulation was associated with the haptic sensations. These probes were designed with the heuristics of mid-air haptic interaction with scientific concepts in mind, and served the purpose of letting science communicators express what their expectations would be from this technology.

5.3.1 Hypotheses: Relevant design Properties of Mid-Air Haptics

As with augmented reality, interactive-3D graphics, physical models, and force feedback controllers, emerging haptic technologies should be able to accommodate a combination of design features, relevant in science communication. Our hypothesis is that mid-air haptics could serve as a new technological solution within this design space, with six specific properties of haptic interaction being valuable to different extent: In this section, we start introducing the haptic probes by specifying our hypotheses, then describing these with their associated rationales.

H.1 (3D): Ultrasonic mid-air haptic interfaces can display volumetric sensations in *3D* space (Long et al., 2014) and the movement of focal points remains stable during user interaction, unlike levitated tangible pixels.

H.2 (stability): Location and apparent movement of focal points are programmable and undisturbed (Wilson et al., 2014).

H.3 (dynamicity): The force exerted by the touch of the user is not restricting any *moving* components of the haptic system.

H.4-H.5 (interactivity and structure): Integrated hand tracking also allows *interactive* and *structural* haptic sensations.

H.6 (augmentation): Covering the haptic display with an acoustically transparent projection screen (Carter et al., 2013), it is also possible to *augment* the tactile sensations with visualisations.

We further hypothesise that dynamic, interactive, and structural design features of mid-air haptics are the most characteristic of this technology, since three-dimensional and augmented tangible probes have already been addressed. Below, we further rationalise this hypothesis, in a heuristic presentation of the set of six features. This approach motivated the choice of concepts and implementation of mid-air haptic probes, as described in the following sections. Therefore, the design of our haptic probes directly address hypotheses H.3, H.4, H.5, and we eliminate hypotheses H.1, H.2, and H.6 from our analysis.

Feature 1: 3-Dimensionality

Visualisations, augmented or physical representations are primarily depicted as 3D objects, the natural appearance for many phenomena. Interactive, 3D graphics, such as found on the PHET simulations website (Physics Education Technology, 2018), are a good example of this feature. In contrast, tangible UIs can only display pseudo 3D shapes, such as the “inFORM” shape-changing display (Follmer et al., 2013).

Design Rationale: Although mid-air haptics is capable of producing volumetric sensations, and it is a relevant feature, we decided to develop only 2D haptic probes for our exploratory study. We expected 3D sensations would create additional confusion when participants interact with the device. Therefore, we did not specifically address hypothesis H.1.

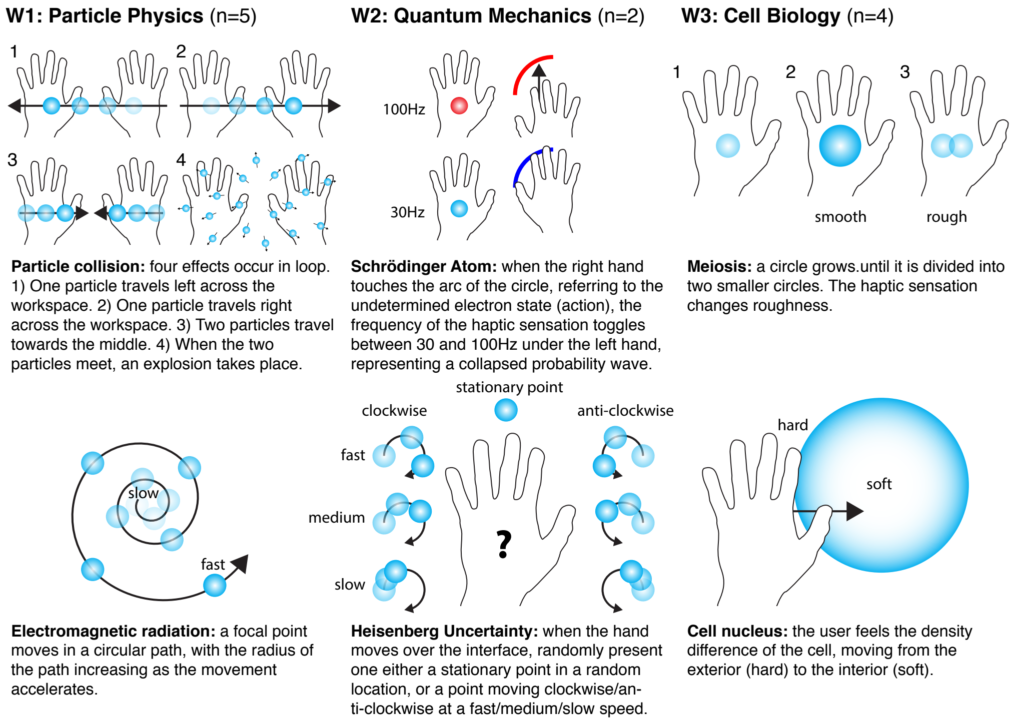

Figure 5.2: Design of the six mid-air haptic probes used in the three workshops: In W1, we presented two designs representing concepts in particle physics: particle collision and electromagnetic radiation. In W2, we presented two designs representing concepts in quantum mechanics: the Schrödinger Atom and Heisenberg Uncertainty. In W3, we presented two designs representing concepts in Cell Biology: Meiosis and a Cell Nucleus.

Feature 2: Stability

Another design feature is to create tactile representations, which do not collapse as a result of tactile exploration. Whilst a 3D printed galaxy (Bonne et al., 2018) remains *stable* during tactile interaction, acoustic levitation of floating tangible bits are fragile to touch (Seah et al., 2014). These can only act as visual displays, despite the use of tangible pixels.

Design Rationale: Mid-air haptic sensations are stable by nature, and tactile interaction does not influence the properties of the haptic feedback. Hence, stability is a constant variable in our haptic probe designs and we did not evaluate its explicit value in science communication, leaving hypothesis H.2 unaddressed.

Feature 3: Augmentation

With the development of technologies like augmented reality, visually and physically augmented science representations are explored in conjunction with tangible or tactile information. For example, in the case of "HOBIT" (Furió et al., 2017), visual depictions of light rays are augmented with animations of the underlying wave phenomena, text, and equations. In another project, tangible probes equipped with RFI tags are also able to layer information, for example, associate vibrations to a map displaying pollution in countries of the world (Stusak and Aslan, 2014).

Design Rationale: We were interested in exploring the potential of unimodal mid-air haptics, hence we decided not to augment the haptic probes with other sensory information, leaving hypothesis H.6 untested.

Feature 4: Dynamicity

Most implementations of communicating scientific phenomena require representation of movement. Such *dynamic* systems can be easily visualised through animations. However, during tactile interaction it is a key requirement to maintain an undisturbed movement, even after the user touched the probe. Dynamic physical bar charts (Taher et al., 2015) may support movement during interaction, given that the actuators exert greater forces than the user. Although, tactile probes, such as an elastic spring (often used at schools to illustrate transverse wave propagation) will be disturbed when people touch these.

Design Rationale: We focused on designing dynamic haptic probes, used during the particle physics workshop (W1). We implemented electromagnetic radiation with the representation of a swirling haptic particle (see Figure 5.2 [W1]). The radius of the orbit grew over time from 1 to 4 cm, in 8 s, while the angular velocity of the haptic particle increased (from $2\pi\,\mathrm{rad\,s^{-1}}$ to $4\pi\,\mathrm{rad\,s^{-1}}$). The acceleration of the haptic particle (associated with electric charge) was noticeable, and the radial expansion (associated with radiation) correlated to the acceleration. The focal point was created using amplitude modulation (AM) of ultrasound (Carter et al., 2013), at 200 Hz.

The particle collision (see Figure 5.2 [W1]) involved two ultrasound emitters, one for each hand. A haptic impulse was displayed from one board to the other with a delay of 200 ms to create an illusion of movement (Pittera et al., 2019a). The representation involved a movement from left to right and back with a delay of 1s (representing respectively the clockwise and anticlockwise particle streams). After three cycles, we simulated particle collision with a 'sparkly' sensation under both palms. The moving points were displayed using AM at 200 Hz, and the sparkling feeling was created using spatiotemporal modulation (STM) of ultrasound at 30 Hz. Both of these probes were addressing hypothesis H.3 on dynamic haptic sensations, and its value in science communication.

Feature 5: Interactivity

Interaction is key to communicate causal relations between input and output. Movement of the pointer on a graphical representation can change colours, or induce dynamic animations. We see many examples of this on PHET simulations (Physics Education Technology, 2018). Shape changing displays can produce variable stiffness, based on user input (Follmer et al., 2013), and thus enable interactive experiences. However, physical representations, such as the "Cosmic Sculpture" (Clements et al., 2017), do not change upon interaction.

Design Rationale: We focused on interactivity of haptic probes in the quantum mechanics workshop (see Figure 5.2 [W2]). For this, the hand tracking capability of mid-air haptics was crucial. Using algorithms described by Long et al. (2014), runtime modifications of the ultrasound stimulus are computed based on hand location to simulate the intended surface between the hand and the virtual object. This is true for both 2D and 3D objects. While a user is unable to enclose a 3D shape in a traditional sense, a 3D object, such as a sphere or pyramid can be explored from all sides using the palm and fingertips.

To convey the concept of Heisenberg uncertainty, we used two states: (1) a fixed point representing the position of the particle; or (2) an orbiting point representing the momentum of the particle. When a user moved their hand over the interface, they were randomly assigned to one of the two conditions. To signify the momentum condition, the direction (clockwise vs. anti-clockwise) and speed (ranging from slow to fast) of the orbiting point was randomised.

We chose this design in order to emphasise the importance of changing direction and speed, every time the participant interacts with the probe, avoiding semi-conclusive statements (e.g. it's moving). The changing properties of movement were highlighting the relevant quantities in identifying velocity and momentum. We used AM at 200 Hz and full intensity. The circle sizes ranged from 1π cm to 4π cm and the speed ranged $-10\,\mathrm{rad\,s^{-1}}$ to $10\,\mathrm{rad\,s^{-1}}$ at a frequency of 200 Hz. For triggering the random display of either cases, we used the Leap Motion sensor to track the users' hand. The haptic probe for representing an atom (see Figure 5.2 [W2]) was similarly interactive. When the participant touched the arc, representing the electron cloud, the frequency of the haptic feedback changed from 100 Hz to 30 Hz. These probes were designed to aid the focus group evaluation of hypothesis H.4 on interactivity.

Feature 6: Structure

Encoding structural information, such as density, is often desirable. Natural phenomena frequently impose boundary conditions, which highlight structural differences in objects. For example, the crust of a planet is distinguished from its core; or the cell membrane from its nucleus. Digital fabrication techniques allow representation of structural information, through distinct internal and external material properties (Torres et al., 2015). However, 3D printed probes allow only surface exploration or deformation. Users are unable to push their fingers through a solid spherical membrane, to find fluid state materials in the interior, without damaging the representation. Force feedback controllers on the other hand have the potential to provide structural information (Minogue et al., 2016).

Design Rationale: We focused on conveying structural information in the cell biology workshop (W3). In our example, we associated chromosome number with the frequency (perceived texture) of the haptic feedback. The cell was depicted as a circle displayed above the transducer at 20 Hz frequency. Over 2 s, the shape increased in radius from 2.5 cm to 5 cm, eventually splitting into two independent smaller shapes (see Figure 5.2 [W3]). During the process, we also increased the frequency of the haptic feedback from 20 Hz to 80 Hz, simulating the change in chromosome number (through change in perceived texture) and therefore implying meiosis and not mitosis.

The second concept of cell biology highlighted the structure of a cell in a simplified form. Concentrating on two aspects, cell membrane and cell nucleus. We represented the cell as a disc, where the users' hand was tracked with the Leap Motion. On the edges of the disc, the haptic feedback of 80 Hz frequency would create a more solid sensation (hard), than the interior of the disc (see Figure 5.2 [W3]). Reducing the frequency of the haptic feedback to 10 Hz in the middle of the shape, a distinct nucleus (soft) could be felt. These probes depicted structural information, addressing the claims of hypothesis H.5 on the value of representing structure through the haptic sense.

As highlighted through these rationales, in this heuristic approach of designing haptic probes for science communication, we believe that dynamic, interactive, and structural design features are the most characteristic of this technology. In the following section, we describe how these haptic probes were used to collect qualitative data, during three focus groups of science communicators, at the research workshops organised.

5.3.2 Materials: Mid-Air Haptic Probes for Three Fields of science

Considering the rationale presented in the previous section, we designed and implemented six unimodal mid-air haptic probes (i.e. demonstrations of using mid-air haptics for conveying specific scientific concepts). These haptic probes were used to facilitate a dialogue between science communicators, who are also domain experts in three different fields of science: *particle physics*, *quantum mechanics*, and *cell biology*. For every discipline, we organised a workshop, where two concepts were represented (see an overview in Figure 5.2). A video of the demonstrations can be viewed on this link: `https://youtu.be/QOnOWobSoBI`

We used a haptic device manufactured by Ultraleap Limited, which generates the tactile sensations using ultrasound (Carter et al., 2013) (see Figure 5.1 [left]). The integrated hand tracking system enables the design of interactive and structural haptic probes, while the high refresh rate of the device enables dynamic haptics. Haptic probes were created during a rapid prototyping design process, with multiple iterations, involving two co-authors. Their combined expertise is in theoretical physics and HCI (mid-air haptics experience design). The sensations were rendered with both amplitude modulation (AM) (Carter et al., 2013) and spatiotemporal modulation (STM) (Frier et al., 2018a), as outlined in the previous section (see design rationales). These methods of rendering allowed us to display spatial and moving patterns in a two-dimensional plain, from a perceptual point of view, with the use of a single focal point.

We chose three scientific fields based on two criteria. First, we wanted concepts discussed by disciplines that are invisible to the unaided human eye; second, disciplines that are likely to have a societal impact. We decided on particle and nuclear physics, which can cause fear in the public, as cited in the introduction (Swiss Info, 2008; Auvinen et al., 2001), quantum technology, which is believed to be living its second revolution and playing an essential role in future technologies (High-Level Steering Committee, 2017), and cell biology, which is the basis of talking about cancer research.

5.3.3 Participants: Science Communicators

Four overlapping groups are identified in the research field and practice of science communication. These are: (1) scientists in academia, industry, or government; (2) mediators, such as journalists, science communicators or teachers; (3) policy or decision makers in government or research councils; and (4) the lay public (Burns et al., 2003). We deliberately chose to run this exploratory, qualitative study with science communicators who are also active researchers, forming an overlap between scientists and mediators. Participant groups, such as teachers, the lay public, or policy makers are valuable in evaluating the user experience of the technology, or its benefits in learning, but are not aware of the objectives of science communication. We recruited eleven participants of this description to carry out three consecutive workshops (Ws). W1 had five participants, W2 had two, and W3 had four. W1 took place at the end of an outreach event at a school; W2 and W3 were held at our research laboratory. Participants were novices to mid-air haptic technology.

5.3.4 Procedure: Collecting Data in Three Workshops

Each of the three workshops lasted for two hours and consisted of four main phases described below. Ethics approval was obtained and consent forms were collected.

Phase 1 (15 mins)

After welcoming participants, we asked each of them to experience three to four sample mid-air haptic sensations. These were displayed using the "Ultrahaptics Sensation Editor" and the device described above. Sample sensations included a static focal point, an orbiting focal point, a circle growing and shrinking in size, and a vertical sheet.

Phase 2 (45 mins)

Following the familiarisation phase, we showed two haptic probes to participants. They were instructed to feel the tactile feedback, describe the sensation and make associations to a scientific concept. Participants were encouraged to have dialogues amongst themselves and with the researchers. While researcher 1 controlled the device, researcher 2 instructed, guided, and observed the participants. If participants could not describe what they felt, hints and guiding questions were given by the researchers.

Phase 3 (30 mins)

Once the haptic probes were explored, we asked participants to describe their ideas on new implementations, based on their interaction with mid-air haptics, and its characteristic properties that may differ from technologies they had experiences with, such as 3D printing, physical toys, or virtual reality.

Phase 4 (30 mins)

We concluded with a guided discussion. The participants were asked thematic questions in a semi-structured group interview. They were prompted to respond to three key questions facilitated by a moderator to ensure that each participant was able to express their opinion: *Q1:* How well did the demos resemble the scientific concept conveyed, and how difficult was it to interpret the haptic sensations? *Q2:* What are the benefits of mid-air haptics (if any), and consider its properties; what does it offer in contrast to other technological solutions they use in science communication? *Q3:* What new ideas of demos do participants have, based on the features of the technology, and what are their challenges in communicating science?

The same researchers, who designed the prototypes, were leading the workshops. Whilst one researcher controlled the apparatus, the other researcher facilitated the discussion and exploration of the mid-air haptic probes, following the procedure described above. All four phases of the workshops were audio recorded, resulting in six hours of audio material. We transcribed the data and extracted relevant feedback following an open coding approach (Braun and Clarke, 2006). The transcripts were coded by three of the co-authors independently, then synthesised, resulting in three themes.

5.4 Results

Qualitative analysis of the transcripts revealed three significant themes. The first of these themes suggests the validity of hypothesis H.3 on the value of dynamic haptics in science communication. However, we did not find any qualitative evidence for verifying hypotheses H.4 and H.5 on the value of interactivity and structural information. Instead, the value of sharing experiences, and creating stories with the haptic sensations was suggested. Results are discussed below and exemplified through participant quotes.

5.4.1 Theme 1: *"I can feel it moving"*: Mid-Air Haptics Support Dynamic Tactile Experiences with Low Level-of-Detail

Across all three workshops (W1, W2, W3), the biggest 'wow' factor, and uniquely quoted feature of mid-air haptic sensations, was its dynamicity. One participant, P2 in W2, explained how this dynamic feature of mid-air haptics could really make a difference in communicating science:

> *P2:W2: "One of the things that we struggle to communicate [in quantum mechanics] is that you can have the probability oscillating backwards and forwards. I think this [mid-air haptics] has a really cool potential to show that because, sort of, whilst* ***you can't see it, you're feeling*** *the evolution of probability... you're feeling that probability before you've actually measured it."*

Participants were generally fascinated by the dynamicity of mid-air haptics and described this technology's ability to represent sensations that are moving and changing, e.g. *P1:W1: "acceleration and creating waves"*, *P2:W2: "opening and closing 'till you have an oscillation"*, *P3:W3: "it is going really fast and then it slows down"*. Participants volunteered various scenarios to apply the newly discovered dynamic features of mid-air haptics, such as for representing DNA models, hydrogen molecules, or the Higgs boson.

Participants in the particle physics workshop (W1) appreciated the temporal variations the dynamic representation mid-air haptics affords in comparison to 3D-printed objects: *P1:W1: "something that could demonstrate waves in a tactile way is very good"*; *P5:W1: "it's the dynamics of the haptics...* ***3D printing is too static****, and in physics almost everything is time variant"*. Variations over time were also discussed in the cell biology workshop, and described with the example of cell forming and firing: *P1:W3: "Try to imagine you're a cell and you get a noisy signal. [Mid-air haptics] is actually a really good sort of depiction of a noisy signal because it's, I guess, harder to distinguish compared to, for example, a sound."*

This quote highlights that the unique characteristic of mid-air haptics - being an invisible non-contact tactile sensation - can be an advantage in science communication. The ability to represent dynamic depictions comes with the trade-off of a lower *"level-of-detail"*. This design consideration was further discussed by participants in the quantum mechanics workshop (W2) when they compared mid-air haptic sensations to 3D printed models, praising its dynamic characteristics, but noting that mid-air haptics does not have the level of details that 3D printed objects have.

> *P1:W2: "We've got some 3D printed models, really nice proteins that we printed. I mean, the advantage of those is the* ***level of detail****...you know, you're turning them around in your hands and looking at them is as close to what these proteins look like in our bodies. But obviously they don't move. [With mid-air haptics] we can show that dynamics much better. That's the big advantage."*

While the low level of detail was a disadvantage for some concepts, it could be an advantage for others, as exemplified by the cell forming example above (P1:W3). Throughout the initial explorations (phase 1 and 2) in the workshops, various participants also suggested adding visual (W2, W3) and/or sound (W1, W3) features to strengthen the tactile sensation. However, in the following discussion (phase 3 and 4), participants increasingly decided against adding graphics and sound. Participants appreciated the fact that a user needs to focus and thus learn to listen to their hand (i.e., *P2:W1: "I was listening.. it's like tracing your hand to kind of get into the right kind of sensitivity"*). This new sensation created excitement, and was considered a unique feature to engage people and boost interest, two main aims of science communication.

> *P1:W2: "With outreach stuff, it's always great to have a tool that is* ***portraying something simple and fundamental****. For example, our microscope, when we've got a camera looking at some leaf cells, there's so much we can say about it, as little or as much as we want. Where's with VR, you put it on and they're watching this video, and like there's only so much really, you can say with it. I find it much more limiting."*

Because mid-air haptics is more abstract and suggestive than 3D models and images, it requires participants to be more focused and listen to their hand. Mid-air haptics has a lower level of detail and might require additional feedback to handle complex scenarios. However, we found this combination of dynamic and abstract characteristics encouraged discussion and supported flexible narratives of core concepts, leading to Themes 2 and 3.

5.4.2 Theme 2: *"Hazard a Guess"*: Shared Experiences Led to Divergent Interpretations and Discussion

In all three workshops, mid-air haptics acted as a catalyst for co-discovery. Participants instinctively took turns exploring each tactile sensation, starting by describing the sensation (during phase 1) and then guessing the scientific concept we tried to convey (in phase 2, facilitated by the researcher who led all three workshops). The ability to just move the hand above the ultrasound array, then quickly withdraw when someone else wanted to feel the sensation, was considered a useful feature to engage audiences at science fairs and public engagement events. *P1:W2: "People can just rotate around quickly and have a feel."*

Mid-air haptics supports easy turn-taking between participants, like 3D printed objects but unlike VR headsets. While VR headsets support dynamic phenomena and have a high level-of-detail, they lead to much more individual experiences. In two of the three workshops, participants compared mid-air haptics to VR technology, a recent addition to their science communication tools. One participant, P1 in W2, described his experience with VR as follows, indicating the benefit of mid-air haptics for having a shared experience:

> *P1:W2: "VR was cool but it feels limited, because it's one person at a time. This is still one person at a time, but they **can be shared quite easily**. With VR, someone's got the headset on and they have to kind of describe what they're looking at. If you've got a group, it doesn't work as well. "*

When participants felt the same haptic effect, they would often talk about it and interpret it differently. For example, in W3, P2 felt one sensation like it was *"growing"*, while P4 described it like a *"flower opening"*; in W2, P1 felt a *"wave from bottom left to top right"*, while P2 talked about *"dragging the ball around"*. These divergent interpretations were due to the low level-of-fidelity: *P2:W1: "That's kind of like random almost tickling sensation."* And yet, in the end, diverging interpretations resulted in a resolution. Guessing what the scientific representation was became a game, or riddle, directed by the facilitator. The following exchange between participants in W3 demonstrates the process of co-discovering meiosis (a type of cell division) shown in Figure 5.2.

> *P2:W3: "Does someone else want to have a go?"*
>
> *P3:W3: "You don't want to hazard a guess?"* **(laugh)**
>
> *P2:W3: "Well, is there something growing?"*
>
> Facilitator *Yes*
>
> *P4:W3: "What's growing?"*
>
> Facilitator *Can you notice something after it's growing maybe?*
>
> *P2:W3: "It's not like a flower opening or something"* **(pause)**
>
> *P3:W3: " **(jumps in and says)** Cell division or something."*

During these exchanges, the facilitator was able to manoeuvre the discussion using comments and questions. Participants were visibly excited about and engaged with the scientific concept illustrated by *quick exchanges* between participants, *laughter*, as well as thinking *pauses*. This flexible discussion, involving multiple participants guessing and interpreting the mid-air haptic effects, meant the facilitator could really guide the exploration and tell a *story*.

5.4.3 Theme 3: *"Take them on a Journey"*: Many Stories with One Mid-Air Haptic Sensation

Science communicators come to realise that they are able to tell multiple stories using these dynamic, abstract tactile sensations. A single mid-air haptic focal point could form a representation for an atomic nucleus, a brain cell, or a distant star. It is in the hands of the science communicators to tell and vary the story depending on the audience as the following quote exemplifies: *P1:W1: "You got so much control over the sensation, you can* ***really take them on a journey.****"*

The discussion across all workshops (Phase 3 and 4) highlighted the science-agnostic potentials of mid-air haptics. In other words, due to its dynamic features and lower level of detail than for example 3D models, this tool leaves more freedom to the facilitator, to guide the stories to be told about scientific phenomenon.

> *P3:W3: "Sciences shouldn't be thought as independent but using each other's toys. This technology is a very nice way to* ***unite sciences****".*

All participants, especially in W3, mentioned the potentials of different narratives for different contexts. Science fair demonstrations need to be fast, intuitive, and engaging (*P3:W3: "you're trying to get through a lot of people very quickly"*). For a school setting it can be more complex, as it can be slower paced and allows the teacher or science communicator to tell a story, to engage and draw in the students.

> *P4:W3: "You need to keep it simple [at fairs]."*
>
> *P3:W3: "Anything that we spent ages with, like the cell division, is a really cool idea, but it's probably going to be better for smaller groups in schools. There, you've got the time to process it and tell them to really think about what they're feeling."*
>
> *P2:W3: "Yes, tie it into a bigger lesson."*
>
> *P4:W3: "Yes. Tie it in with the concept, maybe some other props, and then have this tech, and turn it into a big session rather than a science fair stand."*

In both contexts, at science fairs and in schools, the unique tactile characteristics of mid-air haptics can engage users and create interest, two key objectives of science communication. Moreover, mid-air haptics has the potential to turn this interest into understanding, in smaller group settings, where a facilitator can go from simple to complex concepts. In such contexts, more details can be added, both with respect to the story the facilitator tells, and the experiences they provide. For example, mid-air sensations can be complemented with visual animations and sounds, and other props.

Finally, participants in the cell biology workshop commented that this novel, tactile experience could also engage less-interested groups, such as older children (e.g. *P3:W3: "We do activities where we look at viruses using balloon models, but it is mainly for young children and their parents. For the odd older child, [mid-air haptics] might be a nice* ***way of engaging them****"*). P2 in W3 also mentioned the opportunity to attract new audiences, such as technology savvy adults, who otherwise would just walk by. *P2:W3: "They might not normally be interested in biology, but they've come to look at the tech. But then,* ***you're telling them more about the science.****"* Again, participants emphasised the relevance of being able to frame a story for different audiences, even if it starts with the tool that conveys the concept. Through new tools, such as mid-air technology, Science Communicators can achieve their objectives. They could notably create interest and engage in, and maybe even increase awareness of, their understanding of specific contexts.

5.5 Discussion

We explored the possible use of mid-air haptic technology in science communication, for the first time. Our findings highlight the opportunity of taking advantage of dynamic haptics and shareable experiences that mid-air haptics affords. This novel tool also allows for flexible approaches of storytelling, taking into account the interaction setting, such as who is involved, and where science communication takes place. Here, we discuss the possible implications, opportunities and limitations, and future research directions.

5.5.1 Talking About Science Through Mid-Air Haptics

In our workshops, participants described mid-air haptic sensations with words such as *P1:W3: "pulsing"* and *P3:W3: "rain"* and emphasised the sensation of movement and change. While those descriptions are in line with prior work on how people talk about tactile experiences (Obrist et al., 2013), in our exploration, people were able to connect those descriptors to a specific scientific concept. The fact that people deconstructed the sensation, is part of what led to engaging discussions. Our findings highlight that the dialogue, around the haptic probes, naturally resulted in a co-discovery process. This shared exploration of a scientific phenomena, contributed to the enjoyment of mid-air haptics technology, for public engagement.

5.5.2 Mid-air Haptics Produces Enjoyment and Interest

From the findings of Themes 2 and 3, we believe mid-air haptics may contribute the most to enjoyment and interest, the two hedonic dimensions of the five objectives of science communication, described in the AEIOU framework (e.g. *P1:W2: "it is really fun to play with"*). Mid-air haptics might engage new, wider audiences, who otherwise would not be interested in science. Participants said that the technology could engage older children and parents, as well as tech savvy people. The ability to create shared experiences and motivate co-discovery promote an environment for interpretation, which may contribute to greater enjoyment and engagement of the public. Previously it has been shown that augmenting abstract art (Vi et al., 2017) and multimedia content (Ablart et al., 2017a), with mid-air haptic sensations can indeed increase levels of enjoyment, which are measurable through physiological markers. Novelty may be a contributing factor to enjoyment, but public engagement with a specific science topic is typically a "one-off" context, and not a regular user interface. Therefore, even if novelty of interacting with mid-air haptic technology wears off, the novelty of interacting with new scientific concepts portrayed on a mid-air haptic display may persist. However, the terms "enjoyment" and "interest" are notably used as umbrella terms in science communication, with many granular dimensions, characteristic of each of these experiences. Thus in a research study to follow, we are examining target and perceived affective descriptors, elicited by this technology, in contrast to other communication modalities.

5.5.3 Story-like and Metaphor-Based Haptic Design Tools for Science Communication

One of the branches of science communication research, argues about the role of metaphors, rhetorical tools, humour, and storytelling when engaging with the public. Metaphor is a vital tool of science communicators. As Kendall-Taylor and Haydon (2016) put it *"An Explanatory Metaphor helps people organize information into a clearer picture in their minds making them more productive and thoughtful consumers of scientific information"*. Another contemporary approach to humanising science is through storytelling (Joubert et al., 2019). Through stories, students can relate more to either the concept, or the scientist. Even though recall might not be improved, humorous stories provide a hook, grab attention, and create excitement and enjoyment amongst the audience (Frisch and Saunders, 2010). Using narratives allows for "emotification", "personification", and "fictionification", which in turn contributes to mental processes at multiple levels, such as motivation or transfer to long term memory (Dahlstrom, 2014). With the aid of sensory technologies, communicators may be able to expand explanatory metaphors with sensory metaphors and augment their narrative. To this end, a major challenge is the complexity of content creation with mid-air haptics. Currently, the complexity of development means that science communicators are likely to outsource development to hapticians. One possible way to overcome this challenge is to create toolkits and user interfaces, which make the content creation effortless. Toolkits are very important in order to reduce the complexity of a specific application area, addressed by an emerging technology, opening it up for new content creators (Ledo et al., 2018). Research and development of mid-air touch specific toolkits may fol, in the context of science communication, should take a "metaphor-based" approach (Seifi et al., 2015), so that science communicators can easily design new probes, ideally in real-time.

5.5.4 Generalisability of the technology

Our work has explored three different fields of science, which are example demonstrations of the potential generalisation of mid-air haptics, for science communication. This included particle physics, quantum mechanics, and cell biology; however, the field of interest could easily be expanded to astronomy or environmental sciences, as well as many more. The analysis of qualitative data indicates further transferability of the technology, and mid-air haptic sensations, to other disciplines. Theme 1, described in section 5.4.1, highlights the dynamic features of mid-air haptics and its generalisability to other scientific concepts: *P1:W1: "something that could demonstrate waves in a tactile way is very good"*, where we note that waves are a universal phenomena describing acoustics, optics, ocean waves, and much more. The trade-off of a "lower level of detail" allows mid-air haptic sensations to be applied and explored in different disciplines, especially through different science stories described in Theme 3. The haptic probe illustrating a cell structure could be used to tell the story of galaxy formations, with galaxy nucleus playing the role of a cell nucleus, and the cell membrane playing the role of stars towards the edge of the galaxy. Hence, a story of "scales" from microscopic to cosmic may be recited with the aid of mid-air haptics.

Two recently published case studies illustrate the generalisability of the technology in science communication through metaphorical experiences. Trotta et al. (2020) exhibited a multisensory installation of dark matter, where the interested public was able to perceive cosmological particles in an inflatable planetarium. The exhibit was hosted on multiple occasions, where visitors' sense of touch was stimulated using mid-air haptics, integrated with other sensory stimuli and a two minute long narrative. O'Conaill et al. (2020) integrated mid-air haptics with cinema experiences on the topic of oceanography, renewable energy, and environmental science. In this case study, the aim was to create more immersive experiences for sensory impaired audiences, by associating haptic sensations with either visual or auditory content from the short documentary. This work also outlines research questions, such as whether haptics should be associated with visual information or auditory stimuli when engaging sensory impaired audiences. Both the dark matter and oceanography projects, where the corresponding author of this work has also contributed, show a potential to generalise the technology in science communication, beyond the currently presented haptic probes.

With regards to informal versus formal learning environments, mid-air haptic sensations have opportunities both in the classroom and in museums. In informal learning environments, a platform for co-discovery may be an attractive communication tool, where families and small groups can collectively interpret the exhibit. To set the narrative where facilitation is missing, multisensory integration may provide the missing context. However, this may prove counterproductive, since the *low level detail* of unimodal haptic sensation creates the utility of ambiguous representations. Ambiguity could be an advantage when facilitating engagement in more formal environments, such as a school lesson. As we saw in Theme 2, a small group of students may start guessing the intended interpretation, if that is guided by a teacher or other facilitator. In formal learning environments, there is typically more time to also combine various teaching probes, such as 3D printed models for higher details, and mid-air haptic technology for more immersive learning experiences. Mid-air haptics offers a tool to create dynamic and complementary experiences, in addition to static digital fabrication (Bonne et al., 2018) and the isolating side-effect of VR (Furió et al., 2017).

5.6 Conclusion

We synthesised three commonly recurring themes based on the focus groups, consisting of science communicators discussing opportunities, and challenges, of mid-air haptics in public engagement. These themes give a broad response to the direction in which further research should explore the value of mid-air haptics in science communication. We have not carried out a direct comparison of mid-air haptics, 3D printed probes, or VR tools, therefore we can not state with certainty how these communication tools would perform in competing conditions. We also must acknowledge that participants may have been biased to give positive insights, due to a lack of alternative haptic probes using other types of novel technology, serving as a control condition. However, we worked with expert participants, who were familiar with using VR and tangible probes during their science communication activities. Thus participants were able to evaluate mid-air haptics in context of their experiences of these alternative technologies, despite the lack of direct comparison. Regardless, further research validating these assumptions by comparison studies would be necessary to draw any explicit conclusions.

Counter to expectations set out in the hypotheses, analysis of the qualitative results suggested three opportunistic themes. Firstly, the ability to create dynamic tactile sensations was highlighted as an outstandingly relevant property of mid-air haptic sensations, in contrast to five other hypothesised significant properties. Secondly, it was implied that the shared experiences which the technology affords, by allowing multiple users to engage almost simultaneously, is a relevant opportunity at fast paced public engagement events. This theme signifies a contrast to more isolating experiences, such as VR (Furió et al., 2017), or in the words of a participant: *P1:W2: "VR was cool but it feels limited, because it's one person at a time. This is still one person at a time, but they* ***can be shared quite easily****. With VR, someone's got the headset on and they have to kind of describe what they're looking at. If you've got a group, it doesn't work as well."*. Thirdly, the characteristic sensation of mid-air touch, in contrast to physical touch, may pose an opportunity in storytelling and adapting the same probes to the expectations of various audiences.

We found one of the greatest challenges, noted by science communicators, to be the level of concentration and potentially long exploration time required, to make sense of the haptic sensation. This challenge initiated conversations on whether mid-air haptics is better suited for informal learning environments, or in a formal setting. In either case, the emphasis shifted towards the hedonic, or affective domains of the learning process, that is, the enjoyment and interest dimensions within the $AEIOU$ framework of science communication. Therefore, in the next chapter, we designed a study to follow up on this notion.

Chapter 6

Beyond Learning Outcomes: How do we Feel about Touching Subatomic Particles?

6.1 Abstract

6.1.1 Contribution to thesis

This work is directly related to the initial qualitative exploration presented in chapter 5. We narrowed down the research interest to only two of the five dimensions of *AEIOU* personal responses, and focused on communicating a single scientific topic. We studied the effect of touch on affective responses and hedonic experiences of different audiences, when they were presented with concepts of particle physics. However, as a prerequisite to the key objective of this project, we also worked with a participant group of science communicators. Thus, the research question asked: "How can we characterise the added experiential value of mid-air haptics for *disengaged publics*, compared to physical touch and audio-visual modalities of public engagement?" The aim was to identify what target affective responses of science communication were, using a rigorous method, and how well these may be matched by different tactile modalities when experienced by disengaged audiences. Furthermore, we wanted to produce a descriptive characterisation of mid-air haptic technology, in terms of science communication targets. This project was a continuation of the collaboration with Dr Oliver Schneider, at the University of Waterloo. My contributions were extending from experimental design, questionnaire and haptic probe development, co-ordinating the studies, quantitative and qualitative data analysis, as well as authoring the report.

6.1.2 Project overview

Practitioners of science communication often need to address different objectives of public engagement with science and the needs of different audiences. Different tools and methods are available for this purpose, but it is not clear how effective a particular tool is in fulfilling the desired objectives, especially if the objective goes beyond learning outcomes. In this project, we address this challenge by carrying out two studies, focusing on the hedonic experiences of science communication activities. First, we surveyed 62 science communicators and interviewed 8 experts, to synthesise a list of 18 target affective responses. The methods of inquiry were predominantly questionnaire based, with structured interviews verifying the preliminary results. The second study measured perceived affective responses of 5 participants, whilst taking part in a reading activity, a physical touch, or mid-air touch based activity. A ratio of the measurements in the two studies gave a match score for each activity, suggesting its effectiveness in achieving the target objectives. The list of descriptors most significant to perceived affective responses were used to characterise mid-air haptic technology in terms of target objectives.

6.2 Introduction

Research and practice in the field of science communication transitioned to a dialogue model, from the earlier deficit model (Burns et al., 2003). The deficit to dialogue model transformation brought a shift from public understanding, to public engagement. Engagement goes beyond the need to make the public understand, and it promotes a two-way interaction, rather than a one-way channel of communication. It requires the public to form opinions, change attitudes, behaviours, and in general to develop personal responses to science, in the form of emotional and cognitive processes. In this context, we define an affective response as: a reaction forming part of personal responses, which encompasses a set of experiences and emotions, influencing how an individual will engage with science in the future.

In the past, for purposes of science communication, actual live scientific demonstrations were held to communicate with the public. For example, the Royal Institution (UK) started hosting popular public lectures at Christmas in 1825, where new scientific discoveries were demonstrated to people (James, 2007). Later, other popular forms of science communication evolved through science journalism (Dunwoody, 2014), radio and television broadcasting (Mellor et al., 2011), online interactions (Puschmann, 2014), and recently even citizen science (Silvertown, 2009). Most recently, with advancements in technology, visual animations, auditory presentations, tangible probes, or virtual reality are used to engage with the public (Casado et al., 2017; Bonne et al., 2018; Stepanova et al., 2019). However, it is unclear how different types of media, technology or activities help to elicit specific affective responses, such as creating a sense of wonder, or surprise. Thus, it is a valuable opportunity to investigate and quantify how different technologies relevant to Human-Computer Interaction (HCI) may contribute to aims of science communication.

In our research, we focus on evaluating the role of touch in public engagement with science. It has been shown that tactile interaction has an impact on human affection (Beetz et al., 2012) (see literature review in section 6.3.2). The value of emotional engagement is also acknowledged in the education and science communication literature (Burns et al., 2003) (see review in section 6.3.1). However, to date, most of the research concerning the sense of touch in engaging with science focused on evaluating learning outcomes, and not the effects on affective responses (Jones M. et al., 2006) (see examples in section 6.3.3). Thus, we were particularly interested in comparing the communication modalities of reading and touching, as well as the effect of technology vs. no technology involved on users' affective responses. Specifically, we compared conditions of no touch, physical touch, and mid-air touch stimuli. In the respective conditions, e-print material, hands on plush toys, and a novel mid-air haptic technology were selected as methods of delivery.

Mid-air haptic interfaces are a recently commercialised technology, which uses focalised and modulated ultrasound to stimulate receptors in the skin, thereby giving rise to distinct tactile sensations (Carter et al., 2013). The technology has been implemented in public art installations (Vi et al., 2017), as well as science museum events (Trotta et al., 2020), but with little knowledge on what experiential and emotional responses it elicits. Hence, we build on afore-mentioned work and extend the knowledge on what role touch may play, in experiencing activities at public engagement with science settings. As the main research question of this work, we defined: *How can we characterise the added experiential value of mid-air haptics for disengaged publics, compared to physical touch and audio-visual modalities of public engagement?* To operationalise the data collection, this question was broken down to the following subquestions:

RQ1: What affective responses do science communicators aim to illicit during public engagement?

RQ2: How well can no touch, physical touch, and mid-air touch activities of learning about particle physics match the affective responses targeted by science communicators?

RQ3: How can we characterise mid-air haptic technology in terms of descriptors of affective responses?

Addressing the research questions, we carried out two studies. To find out the effectiveness of different communication modalities in matching Target Affective Responses (TAR) and Perceived Affective Responses (PAR), we ran study 1. In this study, we applied a method inspired by the Find-Fix-Verify approach seen in HCI research (Bernstein et al., 2010) to obtain a weighted list of Descriptors of Affective Responses Targeted in Science Communication (DARTS). Science communicators were asked to rate the significance of potential affective responses as desirable targets via an online survey, before interviewing experts on the preliminary results and verifying the target items. The items of DARTS served as a collection of both target and non-target affective responses, which we used in study 2 to determine the ratio of perceived and target affective responses in each condition. In study 2, a pilot user study with 5 participants was carried out, where we asked participants to assess their perceived affective responses in three variations on an activity about the Standard Model of Particle Physics. The variations corresponded to the three different modalities of delivery. The scaled down (pilot) study was an artefact of the COVID19 pandemic, which limited the scope of the planned (full scale) experiment. In a scaled up future study, we wish to explored the possibility of looking for correlations between the reported experiences and personal attitude towards science, as well as the participants' need for touch.

Our findings show that perceived affective responses overlapped with the target affective responses at ~6%, ~78%, ~39% in the no touch, physical touch, and mid-air touch conditions respectively. These results are based on 18 items of Target Affective Responses, which were systematically derived from quantitative and qualitative data provided by expert science communicators. The planned correlation studies were inconclusive, since the low sample number did not allow us to perform any meaningful analysis.

In summary, the contributions of this research are: 1) reporting a weighted list of descriptors of affective responses targeted in science communication; 2) identifying affective responses triggered by three different communication modalities i.e. e-print, hands-on tangible interaction, and mid-air haptic technology aided interaction; 3) characterising a novel haptic technology (mid-air haptics) based on what experiential and emotional responses it elicits when communicating abstract concepts of particle physics.

6.3 Related work

6.3.1 Affective Responses in Science Communication

Some researchers and practitioners consider science education and science communication as two independent domains. However, when we consider the role of emotions in education, and the shift from public understanding to public engagement, the boundaries are difficult to define (Burns et al., 2003). Where does communication end, and where does education start? In Bloom's original taxonomy of educational outcomes (Bloom et al., 1956), not only the cognitive domain of knowledge acquisition is detailed, but the affective domain too. Focus is placed on learners' attitudes, values, interests, and appreciations, where outcomes such as receiving, valuing, or characterising are included as significant targets, aside of cognitive outcomes such as remembering, evaluating, and creating (Anderson and Krathwohl, 2001). Burns et al. (2003) also reviewed target personal responses in science communication, and described the *AEIOU* framework. The vowels in the analogy stand for awareness, enjoyment, interest, opinion forming, and understanding, such as understanding the processes and values, or social impact of science. McCrory (2010) discusses practical insights to how teachers can increase interest in science lessons by fostering positive emotional reactions of students. Here, the education vs. entertainment debate highlights the trade-off between prioritised short term cognitive goals of understanding and acquiring skills, and the long term benefits of emotional engagement. Research on the role of storytelling for instance, showed positive effects on cognitive processes too, such as retention, and not only on emotional reactions and overall learning experience. Using narratives allows for "emotification", "personification", and "fictionification", which in turn contributes to mental processes at multiple levels, such as motivation, or transfer to long term memory (Dahlstrom, 2014). These related works suggest that there is value in studying the role of experiences and emotions in science communication, beyond evaluation of learning outcomes.

6.3.2 Affective Responses in Tactile Experiences

Several studies reported effects of touch on emotion, ranging between areas of human -animal (Beetz et al., 2012), -human (Hertenstein et al., 2006), -machine (Obrist et al., 2015) interactions. Beetz et al. (2012) published a review on the effects of human-animal interaction (HAI), comparing these to known attributes of the oxytocin hormone. A major overlap between positive effects of HAI, and positive effects of oxytocin was noted, such as effects on social interaction (greater empathy and trust), learning, or mental health (reduced stress, anxiety, depression). Since pleasurable tactile interaction is a major contributor in oxytocin release, the great extent of overlap suggested positive effects of touch on emotions. Yohanan and MacLean (2012) used a non-living haptic creature to analyse patterns of gestures used to communicate emotional expressions, as well as associating these with human intent. Five tentative categories were proposed, where intent and emotional state may overlap, including protective, comforting, restful, affectionate, and playful gestures.

Hertenstein et al. (2006) reported that touch can communicate at least eight distinct emotions in context of human-human interaction (HHI). Six of these – anger, fear, disgust (negative emotions) and gratitude, love, sympathy (positive emotions) – were accurately decoded by humans when their arms were touched by unacquainted partners (Hertenstein et al., 2006). These findings were extended by reports of accurately communicated happiness and sadness through touch, in a study including full body interaction (Hertenstein et al., 2009). In both cases, the mean accuracy rate of recognised emotion was between 50-70%, which is comparable to accuracy rates found in studying facial and vocal communication of emotions. What's more, the quality of touch, such as duration or intensity has been mapped to emotions (Hertenstein et al., 2009). For example, anger was associated with pushing and shaking, while love was linked to hugging and stroking.

Similar findings were reported by Huisman and Darriba Frederiks (2013) and Obrist et al. (2015), in context of technology mediated touch. Huisman and Frederiks created a tactile sleeve, which mediated recorded tactile gestures from a pressure sensor, through an output layer of motors, onto the forearm of users. Using the eight emotions deduced in the study by Hertenstein et al. (2009), authors replicated some of the findings, for example touch duration, intensity or surface area of engagement. More importantly, it was shown that some emotions were mediated and recognised more confidently and with less effort, than other emotions. For instance, disgust, gratitude and sympathy were less confidently discriminated than anger. The latter expression required significantly less recordings and was more easily expressed than gratitude. Obrist et al. (2015) used ultrasonic mid-air haptic technology to investigate mediated emotions, elicited through standardised pictures. The study used a Find-Fix-Verify method, adapted from work published by Bernstein et al. (2010). It was shown that a non-arbitrary mapping can be developed between haptic stimuli and mediated emotions, by manipulating spacial, directional, and haptic parameters of mid-air touch. Therefore, there is good evidence that touch is capable of influencing human experiences and emotions, even if this is a technology mediated interaction.

6.3.3 The Modality of Touch in Engaging with Science

The following examples of using touch in formal science education, from primary school to scientist training, illustrate the opportunity in intersecting haptics and learning environments. However, we believe the modality of touch may have opportunities of application in informal science education, or public engagement with science too. Haptic technology has been used for visualisation and training purposes, since as early as 1964. Project GROPE created a haptic display to render 6D force fields of interacting protein molecules for research chemists, making docking mechanisms easier to handle (Brooks et al., 1990). More recently, haptic enhanced learning mechanisms, such as the haptic bridge, have been proposed in a study using HapKit, where elementary school children explored two different representations of mathematical functions (Davis et al., 2017). Jones et al. (2003) compared full haptic and no haptic conditions of observing nanoscale viruses, using a Phantom nanoManipulator, which controls an atomic force microscope over the world wide web. Minogue et al. (2016) looked at using the Novint Falcon force feedback system to implement haptic enhanced science simulations of phase change and intermolecular forces. The same device has been used to explore added benefits of haptic simulations, in context of the Coriolis effect for physics undergraduate students (Hamza Lup and Page, 2012), and conceptualising buoyancy at elementary education (Chen et al., 2014). Most of these studies investigated effects of haptic aided instruction on overall learning experience and content retention, in contrast to traditional instruction techniques.

Another set of related work focuses on accessibility of science content for vision impaired learners, by incorporating the interaction modality of touch. Jones et al. (2006a) studied the use of a pen-like haptic device to teach cell morphology and function to vision impaired students. Jones M. et al. (2006) also contrasted a highly sophisticated Phantom haptic device, a gaming joystick, and a computer mouse, asking legally blind students to interact with instructional content on viruses. Nam et al. (2012a) explored the usability of haptic user interfaces in form of a Novint Falcon device, whilst teaching molecular properties to teenage vision impaired children. While access to information, cognitive workload and other learning outcome related metrics were the centre of the studies, reports also discuss hedonic benefits of haptics, such as increased engagement with science and more immersive experiences. However, there was little attention drawn in literature to the role of haptics in affective domains of science engagement, as reviewed in section 6.3.1, thus we wish to address this gap in knowledge in this paper. In particular, we wish to study more systematically the role of touch in the rise of technology aided public engagement with science exhibitions, such as the multisensory dark matter experience (Trotta et al., 2020), the Aquarium of the Pacific sensory movie theatre (O'Conaill et al., 2020), or the sensory VR experiences of "Tree" (Zec and Porter:, 2020) and "Overview Effect" (Stepanova et al., 2019).

6.4 Study 1: Identifying Target Affective Responses in Science Communication

In study 1, our aim was to identify target affective responses, thereby addressing the first research question: What affective responses do science communicators aim to illicit during public engagement? To obtain a list of Descriptors of Affective Responses Targeted in Science Communication (DARTS), we used a three step approach. This method was inspired by the "Find-Fix-Verify" approach described by Bernstein et al. (2010), and later adopted by Obrist et al. (2015). The items of DARTS are linguistic descriptors, describing the experiences of people upon engaging with science, as targeted or desired by science communicators. The Find-Fix-Verify approach splits complex crowd intelligence tasks into series of "generate" and "review" stages, producing more reliable results by assigning each stage to a different group of participants. Thus, this process prevents individual participants from contributing too much, too little, or introducing errors into the data collected.

During the first step (*Find*), three of the authors compiled a list of potential descriptors and distracters of affective responses. The list of items were collected, based on literature cited in section 6.3.1, and filtered to its final form by collective agreement of all authors. For the final list of items and their sources, please refer to appendix B. In the second step (*Fix*), we wanted to "fix" a list of descriptors, which are highly relevant as a target affective response. For this reason, we ran an online survey involving science communicators. In the survey, participants were asked to rate the importance of every item on our pre-compiled list, as well as make suggestions for missing descriptors. To *verify* survey results, in the third step, we also conducted interviews with a subset of participants, who scored high on being an expert in science communication. The collective results of the Find-Fix-Verify approach were used to define TAR – the list of target affective responses as a numeric quantity.

6.4.1 Find: Compiling items of DARTS by the research team

The first step of our approach relied on the research team's expertise and the literature to generate an initial, systematic list of DARTS items.

Participants

Three of the authors completed the task of collecting and filtering items for the proposed DARTS questionnaire. Among the authors, we had an HCI professor of multisensory experiences, an HCI associate professor in haptic experience design, and a science communication scholar, with communication science, computer science, and physics backgrounds respectively.

Materials and methods

The corresponding author compiled an initial list of 42 items (10 distractors included) into a spreadsheet, based on literature sources (McCrory, 2010; Burns et al., 2003; Shore, 1999; Hassenzahl et al., 2003). The spreadsheet was shared, asking all authors to comment on every item individually; for additionally suggested items; as well as the classification of items from two perspectives. The HCI perspective asked authors to categorise every item according to hedonic or pragmatic properties (Hassenzahl et al., 2003). Hedonic qualities refer to the psychological needs and emotional experiences of a user, while pragmatic qualities refer to practicality and functionality. The science communication perspective asked for a category as one of the $AEIOU$ dimensions (Burns et al., 2003). The aim of classifying items was to create a more specific and balanced list of descriptors, where every label had its operational definition. For example, "enjoyment", emphasises the need for appreciating science as entertainment or art; while "interest" means a behaviour that is evidenced by voluntary involvement with science or its communication (Burns et al., 2003).

Once all co-authors completed their individual task (3 days), the spreadsheets were shared, and summarised, re-ordered in a new data set. The summary was discussed verbally over 1.5 hours on a video conferencing tool, where justifications were shared, and minor "change of minds" were incorporated.

Out of the initial 42 items, 25 were in total agreement – including 4 pragmatic items, 1 hedonic (opinion) item, 13 hedonic (enjoyment), and 7 hedonic (interest) items. The 17 items which were not in total agreement were discarded, just like the 4 pragmatic and 1 hedonic item labelled as "opinion forming", leaving 20 items of total agreement. We have decided to discard the afore-mentioned 17/4/1 items, to focus only on descriptors which described a hedonic experience, as either enjoyment or interest, making the list more specific and relevant to our definition of "affective response". To account for the off-balance (13 vs. 7) between items labelled as either Enjoyment or Interest, we included 5 additional items from the AttrakDiff (Hassenzahl et al., 2003) user experience questionnaire. These additional items, such as "motivating" or "connective" were labelled as Descriptors of Interest, concluding the number of items with 13 descriptors of enjoyment and 12 descriptors of interest. For the final list of 25 items, please see appendix B.

6.4.2 Fix: An online survey completed by science communicators

In step 2, we involved science communicators in an online survey to rate the preliminary items of DARTS according to their relevance.

Participants

We recruited 62 science communicators to take part in the online questionnaire, including 43 females and 18 males, with one person preferring not to disclose their gender. 14 participants had at least 5 years of experience, 25 of them (mode) indicated their involvement with science communication to be longer than 10 years, with 13 people being involved for longer than 15 years. The majority of participants (17 people) indicated a monthly frequency of engaging with publics, or assisting with developing public engagement activities, while 16 people indicated quarterly, and 12 participants indicated daily involvement. We labelled participants as "experts", if they have been active science communicators for a minimum of ten years, with a minimum of monthly involvement on average, that is, they engaged in at least 120 events or activities. The age group of 25 participants were between 31-40 years, with 16 people aged between 18-30, and 15 people aged between 41-50 years. 33 participants indicated their primary location of public engagement as the UK, 19 as the USA, 5 in Chile, and Australia, Canada, and France contributing the minority. There was a large diversity in our sample with regards to the field of study. Physics, astronomy, and space science dominates roughly half of the sample, with life sciences contributing to a 25% of expertise, with the remaining subjects ranging from psychology to marine science. We grouped the job description of participants into six categories: event organiser; activity facilitator; programme / training manager / co-ordinator; content developer / activity designer/ invited speaker, presenter / helper or other.

Materials and methods

The preliminary DARTS questionnaire (DARTS1) was composed of five sections, as listed below.

1. We thanked the participant for taking this survey, briefly introduced its aim, and included a statement on details of ethical approval and informed consent.

2. We asked demographic details, such as level of expertise, professional role, and age group.

3. We presented the compiled list of 25 items, which included 21 descriptors of potential target affective responses, and 4 distractors, which are unlikely candidates. We asked participants to rate the relevance of each descriptor on a scale from 1 (not desirable at all) to 5 (very desirable).

4. We prompted participants to give a maximum of three adjectives, that describes a target affective response in their view, but was not on the list. They were also given the option to leave a comment, on an open ended question, asking how they design their activities and what matters the most to them.

5. We thanked participants again, and asked for their contact details and permission to be involved in a short, follow up interview.

The questionnaire was implemented in a Google Forms document (Hajas et al., 2020) and an invitation email to the pre-study was sent with the link to the questionnaire.

Procedure

We invited potential participants identified in our professional network, asking them to complete the online survey. We also asked them to forward the message to further science communication scholars or practitioners, following a "snow ball" recruitment method. The electronic mail included a short invitation paragraph and the link to the Google forms document itself. The questionnaire informed participants about the experimental procedure, and asked for their consent. The order of items on the questionnaire were not randomised, since the possibility of multiple synchronous responses and the snow ball recruitment method made randomisation impractical. Thus all participants filled out exactly the same form, but we do not anticipate this had an effect on the results. Responses were collected in a spreadsheet, which we were able to download, after terminating data collection. We collected data for the duration of one month, and deliberately asked participants to only refer their science communication peers, without sharing the survey on social media or mailing lists.

Results

Items rated higher than 3.75 of 5.00 (upper quartile) were labelled as provisional target affective responses. The quantitative measures of mean (m) score showed us that 13 of 25 items are target descriptors, such as "sense of wonder" ($m = 4.58 \pm 0.64$), "intellectual joy of understanding" ($m = 4.37 \pm 0.73$), or "surprising" ($m = 3.95 \pm 0.66$). From the answers to the open ended questions, and additionally suggested descriptors, we synthesised further 13 provisional target affective responses. These included descriptors, such as "thought provoking", "relatable", or "story-like". For complete details on suggested, provisional, and final target affective responses with mean scores and standard deviations, please refer to appendix B.

6.4.3 Verify: Qualitative interviews with expert science communicators

In the final step of this study, we aimed to verify the provisional target affective responses by interviewing expert participants with regards to the preliminary results.

Participants

We selected 8 of the expert respondents and asked them to take part in a follow up interview. Due to the small sample size, we aimed to select a balanced and diverse set of expertise in science communication. During one week, we interviewed 4 female and 4 male science communicators. From the UK, we had 3 participants, 4 from the USA, and 1 from South America. Interviewees were mostly communicating physics and astronomy or life science topics, but the channels of engagement covered science writing (news, blog, books), broadcasting (podcasts, radio, YouTube), as well as live events. The latter included Nerd Night, science centre and museum settings for various audiences (outreach for children, entertainment for adults, accessible events to disabled audiences). .

Materials and methods

We asked interviewees three questions directly related to the quantitative results obtained from the questionnaire. Firstly, we asked participants to assess the importance of descriptors, which scored on average 3.75 or higher, and find potential redundancies. Secondly, we asked experts to defend items which scored lower than the upper quartile but may be important regardless. Thirdly, we asked science communicators to argue pro and contra – why suggested descriptors by other questionnaire respondents may or may not be a relevant target. To aid the process, participants were given a document with the list of descriptors associated with the three questions. We also asked experts to elaborate on two open ended questions, where we aimed to find out the processes of their own public engagement activities, such as what are the key considerations during a Nerd Night, or Star Party. The second of these questions asked what role (if any) does touch play in their activities.

Procedure

The follow-up interviews were scheduled to take part after termination of data collection, analysis, and expert identification as part of the *Fix* step. Out of 23 identified experts, we invited 13 interview candidates, via email, to take part in a discussion. We only sent invitations to those people who were unknown to us, and eventually 8 of 13 participants were interviewed. Participation was voluntary and no reward was given. Two of the researchers attended the call, where one of them conducted the interview, whilst the other took notes and asked clarification questions, when it was necessary. The 30 minute long interview was conducted through video conferencing tools, recorded, and analysed after written consent was collected. Analysis of the responses given to the first three questions involved a challenged-defended-highlighted annotation system per question respectively, where consensus of 6 of 8 interviewees was needed to remove-restore-add descriptors to the final list of items on DARTS. The responses given to the open ended questions were analysed by two of the researchers, applying an open coding thematic analysis.

Results

Question 1: Generally, the list of provisional target affective responses is approved by experts as a good list, with the common theme and value being the “hedonic”, “affective”, “feeling” angle of hooking people in the learning (P4, P5, P7). Explicit remarks of participants highlighted this, e.g.: *P7: “Looking at these words, a lot of them are very connected [...] they are describing a common theme, and that is the feeling the person gets from the communication”.* Entertaining, enjoyable, pleasurable were identified as redundant by six of the experts, with entertaining being the most desirable, and pleasurable being redundant along with gratifying. Descriptors of connective (m = 3.9), engaging (m = 4.89), and intellectual joy of understanding (m = 4.37) were often highlighted as very desirable.

Question 2: In context of descriptors, which scored lower than 3.75, the two most prominent highlights and defences are directed at “playful” and “novelty”. Playful is strongly defended by P5 and P6 with arguments on why it is important, mostly for younger, but also multi-generation audiences: *P5: “Play is highly important, especially with younger audiences [...] play is how you get to the learning.”.* P7 sees playful as positive, but something that needs to be used in a more thoughtful manner, it has a risk of being distracting. Novelty and innovative were defended by P3, P4, P5, P6 but mostly used as synonyms. Novelty was important to engage even an uninterested audience in something well established as a topic, for example: *P6: “I was surprised to see that novel did not make the cut; because when we are planning things, we are trying to be novel. Even if we are doing something that we’ve seen before, a concept that’s well established, we would like to come at it in a novel way to engage kids and public by showing them perhaps something unexpected”.* The "surprise" element of novelty was interpreted more as a way of engaging the "interested" audience, who are frequent attendees. Amusing and sense of beauty were often discussed, but with some caution for the risk of it being distracting (P7) or that it is specific to a live event in a style of a comedy performance, whilst not desired at all in a science writing piece. A similar argument surrounded the sense of beauty: *P5: “Perhaps it brings in an element of "art" or "spirituality" into science, thus widening the hook for different audiences”.*

Question 3: Participants’ impressions on the frequently suggested target descriptors suggest that few of these suggestions are more universally desirable than others. For example; thought provoking, accessible, relatable and story-like are items strongly defended by seven of the eight experts. On the contrary; memorable and aspiring, are often interpreted as by-products of relatable or story-like, whilst fun is already covered by entertaining, in the original list of provisional target descriptors. Educational and informative are sometimes emphasised strongly, sometimes dismissed, partly due to subtle interpretations of the two words.

In response to open ended questions, one of the two most common themes across all interviews is that the audience should be feeling comfortable and welcome. This can be done through avoiding bad experiences, and providing accommodation for various needs. *P3: “In some ways the content matters less, because if someone is coming in and they had a terrible experience, it doesn’t matter how great your content was.”.* It can also be done through demonstrating that scientists are just humans, scientists are part of society, and everyone can learn to be a scientist. The second common theme was the importance of matching the style of activity with audience expectations. For example, Star Wars or Star Trek themed science communication media on the science of space and planets may engage fans, who might not have engaged otherwise with a plain topic of “planet formation”. Creating a social environment, adapting the use of language to the level of knowledge of the audience, or using playful, perhaps high-tech probes, may engage people who want to learn but are unable to attend university.

6.4.4 Summary

As a collective result of the Find-Fix-Verify method, we identified 18 target affective responses ($T = 18$). We demoted two items, “pleasurable” ($m = 4.05$ – lowest in comparison to “entertaining”, and “enjoyable”) and “gratifying” ($m = 3.81$) from the provisional target descriptors as identified by the questionnaire. Instead, we promoted “playful” ($m = 3.69$) and “sense of beauty” ($m = 3.73$), since these were border line and were mentioned positively by multiple experts during the interviews. In the matter of “novel” ($m = 3.56$) vs. “innovative” ($m = 3.60$) we promoted “innovative” as a target, based on the interviews.

In the next section, we present results of a study, where the refined DARTS questionnaire (DARTS2) was used to measure perceived affective responses in three different communication modalities. This enabled us to quantify the effectiveness of each modality in respect of the target affective responses, and to characterise each modality in terms of the target descriptors.

6.5 Study 2 (pilot): Measuring Perceived Affective Responses

In this pilot user study, we evaluated how participants’ perceived affective responses (PAR) matched the targets defined by science communicators. We compared three different conditions of a pseudo public engagement activity, with regards to the tactile modality. The activity was designed to introduce the Standard Model of particle physics, which is sometimes referred to as the periodic table of physics. The conditions were a baseline no touch (NT) condition, a frequently applied method of physical touch (PT), and a novel approach of mid-air touch (MT).

6.5.1 Participants

We recruited 5 participants (4 female) with mean age 27.0 ± 14.2. Since this study took place after the breakout of the global pandemic, we were unable to recruit a sufficiently large number of participants for a full scale user study. Instead, we recruited a small sample of colleagues and acquaintances from the general public, such that we could pilot the study materials and methods, and report preliminary findings. All participants were novice to mid-air haptic technology, and they had not taken part in higher education of physics.

6.5.2 Materials and methods

The activity and the stimuli

Activity We designed a pseudo public engagement with science activity about particle physics. The activity aimed to introduce the standard model of particle physics, including the basic properties of elementary particles, such as a photon or electron. We chose this topic for the following three reasons:

1. We were able to adapt the content in all three experimental conditions without excessive labour and product development;
2. It is a frequently communicated science concept in museums, public talks, and outreach activities (Particle Zoo, 2017);
3. We believe that the content strikes the right balance of novelty and complexity, in order to maintain participants' attention for the duration of the study.

Alternative choices, which we discarded, included activities on tactile galaxies (Bonne et al., 2018), and models of atoms (Harris, 2020). Since we were interested in evaluating the affective responses triggered in the three conditions, and not the learning outcomes, it was important to find content that was engaging enough, but not overwhelming with information. We refer to the activity as a "pseudo activity" because it was designed to mimic a public engagement activity, such as a stand at a science festival, but hosted as a controlled laboratory experiment. The activity was recreated as an e-print, as a hands on exploration, and as a set of mid-air haptic sensations to interact with. The three activity types were hosted on separate tables, referred to as "stations".

No touch condition The no touch condition involved textual information, written as a short multipage web document, loaded on a tablet computer. The e-print consisted of 10 separate pages, with roughly 30 seconds worth of reading content on each page. The document introduced what the standard model of particle physics is, the two particle families (fermions and bosons), and the sub groups of quarks, leptons, and gage bosons. This e-print was used as a script, when the researcher talked to participants during the physical touch and mid-air touch conditions.

Physical touch condition The hands on modality (physical touch) used 17 probes of the 22 pieces, regular weight, Standard Model set from the Particle Zoo project (Particle Zoo, 2020), which creates plush toy renderings of elementary particles. These physical probes are design to have different tactile properties, such as shape, weight, texture and facial expression, to illustrate natural properties of particles. For instance, the proton (a positively charged particle), has a happy facial expression, and is slightly heavier than an electron (a negatively charged particle), which has a sad facial expression. Similarly, an Up quark is shaped as an upright triangle, while the Down quark is pointing downwards with respect to its facial expression, to illustrate their electric charge. The PT probes we used included the six quarks, six leptons, and five bosons. Importantly, the label "Physical Touch (PT)" is a short hand notation to distinguish this condition from the "No Touch (NT)" and "Mid-air Touch (MT)" conditions. However, a key underlying difference, and potential confounding variable, between the PT and MT condition is the fact that the representations of the PT condition are *static, tangible manipulables*, not active haptic representations. For a summary of the physical properties of these toys, please see appendix C.

Mid-air touch condition For creating equivalent mid-air haptic sensations (mid-air touch), we used an Ultraleap Stratos Explore haptic device by Ultraleap Limited. The device uses focalised and modulated ultrasound to stimulate receptors in the skin, thereby giving rise to distinct tactile sensations (Carter et al., 2013). We mapped the physical touch parameters of: Shape, relative location, face & glance, and weight, to mid-air touch parameters of: Trajectory of movement, rate of movement, modulation frequency, and focal point radius respectively. For details on parameter mapping see Tables C.2 and C.3 in appendix C. We considered an additional step of validating the parameter mapping we have devised, based on the "Find-Fix-Verify" approach, similarly to how (Obrist et al., 2015) validated emotions associated with mid-air haptic sensations. However, ultimately we did not validate the mid-air touch representations, due to time constraints of the research project.

6.5.3 Variables

The independent variable was the modality (m) of the activity. Three conditions were investigated, which we labelled as no touch (NT), physical touch (PT), and mid-air touch (MT).

The dependent variable was the quantity defined by the authors as "match score" (M). By definition, the match score is a computed value, calculated as the ratio of $T = 18$ obtained in study 1 and the number of significant perceived affective response P obtained in study 2. Hence, the match score per modality is $M_m = \frac{P_m}{T} \in [0,1]$. The higher the match score, the more targets were fulfilled by the specific modality

We also measured participants' attitude towards science, and their need for touch through standardised questionnaires. In the original experimental design, we were going to use these metrics to cluster participants into different audience groups, and run correlation tests between these groups and match scores per modality. We allowed participants to converse and ask questions of the researcher, whilst reading the e-print in the NT condition, just like they would have done in the PT and MT conditions, to decrease its passive interaction nature.

Questionnaires to collect quantitative data

We used three questionnaires to collect quantitative data. Most importantly, we used an adapted version of DARTS1 – the questionnaire seen in study 1. DARTS-2 included the 18 target affective responses synthesised in study 1, and asked participants to rate the descriptors on a scale from 1 to 5, based on how well it described their experience of the activity in a specific condition.

Secondly, we used a simplified general attitude towards science questionnaire, created by Schäfer et al. (2018). This survey has been used in context of audience segmentation of the Swiss population, assessing attitude towards science and correlations to media consumption. It addresses many criticisms of earlier attitude tests towards science in multiple ways. For example, it accounts for both cognitive, affective, and behavioural dimensions of attitude by asking relevant questions in each of these three categories. The scientific literacy part of the questionnaire also moves away from a typical true or false format, towards a format of “I do not know”, “probably”, and “definitely” set of answers. We excluded parts on participants’ beliefs, subjective norms, information norms, and media consumption, since our main contribution is not a thorough audience segmentation. Instead, we focused on the general attitude test questions, which involved 10 items on scientific literacy, devised by the National Science Foundation (National Science Foundation, 2018), plus 1 item on interest in science, as part of the cognitive dimension. The affective and behavioural dimensions included two items each, as in the original questionnaire.

Thirdly, we also measured participants’ haptic orientation, or preference to touching products, using the standardised Need for Touch (NFT) questionnaire (Peck and Childers, 2003). the NFT is a psychological trait defined as *“a preference for the extraction and utilisation of information obtained through the haptic system”*. Half of the 12 items assess the autotelic need, while another half of the items assess the instrumental need for touch of people, on a 7-point Likert scale. Autotelic NFT items measure how much pleasure and enjoyment people gain from direct contact with an object. Instrumental NFT refers to the information obtained from the physical attributes of an object, such as its shape, weight or texture, as well as the confidence derived from touching the object (Manzano et al., 2018).

Interviews to collect qualitative data

To collect further data, we interviewed participants, asking the following questions:

- Which of the three type of activities (no touch, physical touch, mid-air touch) did you like the most, and why?
- Could you try to identify, and describe the emotions you felt whilst participating in your preferred type of activity? Why do you think you felt this way?
- What did the other two type of activities lack, why did you like them less?

Collecting qualitative data is important in this particular case, since identifying affective responses and justifying these can be a difficult task.

6.5.4 Procedure

Upon arrival of participants to the experimental space, we informed them about the procedure of the study and asked for their consent in writing. This was followed by the participants filling out the general Attitude Towards Science, and Need for Touch questionnaires on a tablet computer. After they completed the forms in the first 10 minutes, we escorted the participants to one of three stations, each of which hosted one of the three activity types. We spent roughly 10 minutes on every station, with a short break in between switching stations.

Due to the nature of evaluating affective responses, we decided a “within group” study design is more appropriate than a “between group” study. However, to control the content and only change the modality, participants heard the same narrative three times, which closely followed a pre-written script. For this reason, it was essential to counter-balance the conditions, avoiding negative effects of repeated content, such as lower levels of engagement. After every station, the participant was asked to fill out the DARTS-2 questionnaire, indicating the affective responses they experienced in the relevant condition.

Once all three activities were completed, we sat down with the participant and conducted the interview, which took roughly 10 minutes. The interviews were audio recorded, so that we could transcribe and analyse these. The entire session took on average 60 minutes.

6.5.5 Results

The following results are only preliminary, and should be considered with caution, due to the low number of participants taking part in the data collection process. The match scores are $M_{MT} = 38.9\%$, $M_{PT} = 77.8\%$, and $M_{NT} = 5.56\%$ in respect of the three tested conditions. Clearly, physical touch is the most effective in matching the target affective responses, with 14 of 18 descriptors rated higher than 3.75 (upper quartile) of a 5-point scale. Mid-air touch matched only 7 of 18 descriptors within the upper quartile threshold, whilst the no touch condition only matched 1 of 18 targets.

We also see differences in the ways each modality was characterised in terms of the descriptors. The data derived from the small sample size suggests that mid-air haptic representation of elementary particles are predominantly "innovative", "entertaining", and help create a "sense of imagination" (mean 4.8 ± 0.45). In contrast, handling plush representations can be best described as "intellectually accessible", "playful", "innovative" (mean 4.8 ± 0.45); and characterised as helping to create a "sense of curiosity", when reading about the same topic (mean 4.0 ± 1.4). Most interestingly, while "sense of imagination" is a target affective response matched by mid-air touch, as one of the most highly rated perceived affective responses, "sense of imagination" scored one of the lowest for the physical touch (mean 3.6 ± 1.2) and no touch (mean 2.6 ± 2.1) conditions.

Even though the physical touch match score is twice as high as the match score for mid-air touch, in follow up interviews, four out of five participants stated that mid-air touch was their favourite activity. Extracting and synthesising the relevant responses to why this might be, we can contribute this preference to the novelty effect. Participants found mid-air tactile interaction with particles more fascinating than the plush toys: *P3: "I liked this new, contactless way of connecting to the particles."* Another common theme that was highlighted by three out of five participants is the preference for multisensory interaction. For example, the participant who had a preference for physical touch said: *P1: "Because it's multisensory, you can see it, feel it, at the same time, it's more playful."* This was similarly backed up by another participant: *P3: "Without first trying the plush, I wouldn't have made sense out of the next one (mid-air touch). Reading was missing the visualisations. I could see the plush even if I didn't want to touch them."* The greatest criticism of mid-air touch was also the lack of alternative information: *P1: "It's not immediately clear, somebody has to tell you what you feel."* However, this may have contributed to some of the target affective responses being rated highly, such as creating a "sense of imagination" or rating the activity as "story-like", referring to the facilitation by the researcher. Besides novelty, the narration of mid-air touch stimuli might have made this modality the preferred condition for four of the five participants, as suggested by one of them: *P2: "I wouldn't have thought about explaining particle physics that way (mid-air touch), but somehow it worked. Especially* *explaining the spin with the speed and the other properties."*

The significance of testing across modality per descriptor is not meaningful in such a low sample size, being only five participants. Similarly, it was not meaningful to cluster participants into different groups based on their responses to the NFT and ATS questionnaires. Hence, we were unable to carry out analysis on correlations between preferred modality and audience type. Thus, these preliminary results do not allow drawing of general conclusions; however, we see that the method is able to characterise the diferent touch modalities in terms of the DARTS-2 questionnaire items.

6.6 Discussion

Novelty is often a confounding variable, when studying human-computer interaction and user experience, regardless of the technology and topic of study (Rutten and Geerts, 2020). We see this reflected in the preliminary results, where despite higher match scores for physical touch, mid-air touch was preferred by the majority of participants in a follow up interview. In this study, we also need to take into consideration the novelty of the scientific content (Standard Model of Particle Physics), when evaluating participants engagement with the activity and their overall experience. None of the participants were familiar with the particle physics concepts, and this might have skewed the subjective rating of their own experience during the activity.

Therefore one might ask whether the nature of scientific concepts being communicated, will impact how effectively one or another touch modality can represent it. In the previous chapter, we started by characterising different science concepts, for example particle collisions and electromagnetic radiation as "dynamic", or cell structure and cell division as "structural" concepts. Would all types of natural phenomena create the same affective responses when communicated through either mid-air or physical touch; or would some concepts create different affective responses when using specific touch modalities? Our choice of particle physics and the standard model as a topic of science communication is arbitrary, but fits in with a growing body of literature on the use of haptic technology for science education and science communication. For example, researchers studied individual concepts of "floating and sinking", "phase change", "viruses and cells", "Coriolis effect or galaxies", as reviewed in section 3.3.3.. Research groups are forced to choose a particular topic; however, we see this communal effort to be converging towards a new research opportunity. If the literature grows large enough, there will be opportunities to conduct a meta-analysis and inform the roadmap of research, in applying haptics to science communication.

A strength of this project is coming through the approach taken in Study 1, where we established a weighted list of Descriptors of Target Affective Responses in Science Communication (DARTS). Then, for the first time, we have introduced a new questionnaire on the intersection of user experience and science communication, to evaluate hedonic characteristics of different interaction modalities. The DARTS-2 tool is established based on empirical data, and although its validation is limited due to the restrictions on user testing in year 2020, future research opportunities are opened up using our questionnaire. For example, other researchers may wish to take the DARTS-2 questionnaire to evaluate the effectiveness of communicating science content through traditional journalism, virtual and augmented reality, or serious games.

Considering the limitations of our second study, we identified two factors. Firstly, in mid-air touch, visualisations are not present as a default, whilst in physical touch they are. In physical touch, we are unable to separate visual experience from tactile experience, unless the participant is blindfolded or the equipment is hidden behind a screen. Both of these options would create further confounding effects, such as creating a sense of uncertainty in people due to the unnatural state of sight deprivation. Mid-air haptic stimuli could be augmented with a video stream (not collocated) or using virtual reality, augmented reality techniques, but in this case we could not claim that the results are solely an effect of the haptic technology.

Secondly, in mid-air touch the properties of sensations, such as direction of motion, speed, shape were not always apparent without pointing these out. Material and geometric properties of physical touch, and their affordances in terms of haptic exploratory procedures, are more salient than for mid-air haptic stimuli. This is a noteworthy design consideration in ecologically valid environments of public engagement with science.

6.7 Conclusion and Future Work

Our research reports a weighted list of desired affective outcomes in science communication, assessed by science communication practitioners. Using these descriptors, we have evaluated how personal responses to activities involving different modalities of touch match with the desired outcomes of science communication. Our preliminary results show that the no touch condition has a match score of 5.56%, physical touch has a match score of 77.8%, whilst mid-air touch has a match score of 38.9%. Mid-air touch could also be characterised in terms of descriptors, such as “entertaining”, “innovative”, and creating a “sense of imagination”, both of which are desired target affective responses in science communication.

Even though the match scores are higher for mid-air touch, the qualitative data suggests that with sufficient narration, mid-air touch might be the preferred interaction modality in context of learning about particle physics. A limitation of this study is the lack of visualisation for the mid-air touch, and no touch conditions. Therefore, in the following two chapters, I discuss how mid-air haptic technology may be integrated into existing types of multisensory science communication, such as live events and multimedia shows.

Part III

Integrating Mid-Air Haptic Sensations and Existing Sensory Channels of Public Engagement in Informal Learning Environments

Chapter 7

Taking the Attentive Public on a Multisensory Metaphorical Dark Matter Journey

7.1 Abstract

7.1.1 Contribution to thesis

This project was the first of two practical outcomes, designed to be deployed as field work. Unlike in part II, where the sense of touch was studied as a unimodal interaction channel, here we studied the role of mid-air haptic technology in context of a truly multisensory installation. The research question asked: "How can we integrate mid-air haptic sensations in multisensory, live public engagement activities, for the *attentive public*?" The aim was to design a public engagement with science activity, where all of the five primary senses of visitors are stimulated through state-of-the-art technology. Since we worked in the field, rather than in a laboratory setting, the methodology and contribution were different from those presented in previous chapters. Firstly, the exploration involved collecting feedback from visitors in a real-life scenario, and not from science communicators invited to focus groups, or participants of a controlled user study. Secondly, this work highlighted the practical aspects of public engagement and multisensory experience design, rather than in-depth investigation of personal responses. Observations on the process of evolving the activity was just as important as user feedback on the installation itself, as often highlighted in literature concerned with evaluation of science communication. These practical observations in the field addressed another research question: "How can we evaluate the effectiveness of multisensory public engagement activities in informal learning environments?" The target beneficiaries of this work are science communication practitioners, who might be interested in using technology enhanced sensory metaphors for purposes of engaging with the interested public. This project was done in collaboration with Imperial College London and the London Science Museum. My contributions were the creation of haptic stimuli, consulting on activity development, facilitation and feedback collection at the event, data analysis and reporting, as well as co-authoring the content of publication. This work has been published in the Journal of Science Communication – Practice insights section. A supplementary video was also created at the event, to illustrate the environment and narrative within the public engagement activity. The multisensory dark matter experience was on display in the London Science Museum on 31 October (2018) and on 29-30 June (2019).

7.1.2 Project overview

We present a novel approach to communicating abstract concepts in cosmology and astrophysics, in a more accessible and inclusive manner. We describe an exhibit, aiming at creating an immersive, multisensory metaphorical experience of an otherwise imperceptible physical phenomenon, as 'dark matter'. Human-Computer Interaction experts and physicists co-created a multisensory journey through dark matter by exploiting the latest advances in haptic and olfactory technology. We present the concept design of a pilot and a main exhibition at the London Science Museum, including the practical setup of the multisensory dark matter experience, the delivery of sensory stimulation and preliminary insights from users' feedback.

7.2 Introduction: Breaking Barriers to a Dialogic Encounter

Modern cosmology and astrophysics tell us that dark matter makes up 25% of the universe. Whilst dark matter is five times more abundant than normal matter, it is almost impossible to detect, and its fundamental nature remains unknown. Through the cross-disciplinary collaboration between physicists and human-computer interaction experts, we aim to create a multisensory, immersive experience that enables the public to feel dark matter with all their senses.

The dialogue model of public engagement demands a more participatory involvement of the public in all matters pertaining scientific research (Irwin, 2014). However, there are structural barriers to the implementation of a truly dialogical approach to public engagement. Much of our scientific knowledge is transmitted via intellectual means, based on abstract concepts and gained through reading and other mostly visual means. Often, acquiring understanding of a scientific subject requires high-level mathematical skills, thus creating an additional hurdle to engagement and interaction with the public at large.

This is especially true of astrophysics, whose objects of study are so far removed from the human scale that they are often hard to imagine. Yet, the public at large is fascinated by the cosmos, perhaps a lingering reflection of our ancestral connection with the universe. In our experience, interest in astronomy and astrophysics is often cited as one of the main drivers for many prospective physics students applying to Imperial College London, one of the top ten research universities in the world.

In order to overcome such obstacles to a dialogical encounter with the public, we posited that grounding facts and abstract ideas in bodily experience, might be a helpful way of creating meaning and widening participation. This may be especially true amongst non-expert and underserved audiences. Our aim is to design novel public engagement modalities, that bypass traditional knowledge barriers between experts and non-experts, thus creating a forum for a participatory encounter between the scientists and the public (Trotta, 2018).

A well-established body of work already exists in making science – and in particular astronomy–

more accessible by using touch and sound, mostly aimed at improving inclusivity for people with visual impairment. For a recent review, see (Arcand et al., 2017) and for a list of activities and resources, see (IAU Division C Commission C1 WG3, 2020). For example, the "Tactile Universe" project created 3D models of galaxies, used to engage visually impaired children in astronomy (Bonne et al., 2018). Similarly, the "Tactile Collider" is aimed at visually impaired children to engage with the field of particle physics, and demonstrate particle colliders through the use of 3D sound and large scale tactile models (Dattaro, 2018). Other work in this area include, for example, astronomical activities specifically intended for people with special needs (Ortiz-Gil et al., 2011), 3D tactile representations of Hubble space telescope images (Grice et al., 2015), of data from the X-ray Chandra Observatory (Arcand et al., 2019), of the Subaru telescope structure (Usuda-Sato et al., 2019), of the Eta Carinae nebula (Madura et al., 2015), and of cosmic microwave background radiation anisotropies (Clements et al., 2017), which was later used for the tactile stimulation part of the g-ASTRONOMY pilot (see below). Sound has perhaps received less attention to date, but some sonification prototypes have been explored (Casado et al., 2017; Lynch, 2017). Many of the educational projects funded by the International Astronomical Union's Office of Astronomy for Development have a multisensory component (Office of astronomy for development, 2020).

7.3 Background: Integrated Multisensory Experiences

Whilst this project represents the first joint activity of the authors, each of us have experimented with multisensory and innovative communication methods before. One of the authors (RT) explored some of the opportunities afforded by a multisensory approach with the project "g-ASTRONOMY". g-ASTRONOMY aimed to break the assumption that astronomy and astrophysics can only be understood in terms of visual representation. In collaboration with a molecular gastronomy chef, RT created novel, elegant and edible metaphors for some of the universe's most complex ideas. Evaluation demonstrated that this approach allows people to engage with some of the most important theories in astrophysics and astronomy in a new and accessible way. After acclaimed events (Institute of Physics, 2016) at Imperial Festival and Cheltenham Science Festival in 2016, g-ASTRONOMY was re-designed in collaboration with the Royal National Institute of Blind People, exclusively for people with sight loss. The workshop ran in 2017 and provided an immersive and interactive experience without the need for visual clues. Thanks to 3D printed models and edible substances, visitors simultaneously felt and tasted the evolution of our universe from the big bang to the formation of galaxies. People also experienced the multiverse theory through how different universes might taste, rather than how they look. Participants described the experience as "life-changing" (Trotta, 2016).

Another collaborator (EJCM) initiated "What Matter's" – an effort aimed at bringing together ten experimental and provocative design studios with ten innovative researchers from diverse disciplines. Backgrounds were ranging from historical preservation, through artificial spider silk, to nanotechnology and solar panels. The teams were given funding and six months to join forces and produce something. The guidelines were kept very broad on purpose. The results were combined into an exhibition that was premiered at the Dutch Design Week 2018. The outputs ranged from images of everyday objects using processes for the manufacture of graphene to a passive room-temperature control system based on the physics of nanotubes (Form Design Center, 2018). The project was a collaboration between Art and Science Initiative, Form Design Center and S-P-O-K.

In another, separate exploration, the team from the Sussex Computer Human Interaction (SCHI) Laboratory were involved in the creation of Tate Sensorium, a multisensory art display in London's Tate Britain (Ablart et al., 2017b). This exhibition went on to win the 2015 Tate Britain IK Prize award. The aim of this project was to design an art experience that involved all the traditional five human senses. To achieve this goal, a cross-disciplinary collaboration between industry, sensory designers, and researchers was formed. Flying Object, a creative studio in London, led the project. The SCHI team advised on the design of the multisensory experiences, including new tactile sensations through a novel mid-air haptic technology (Carter et al., 2013) and on the evaluation of the visitors' experiences (Obrist et al., 2013). Tate Sensorium was open to the public between August 25 and October 4, 2015. Within this timeframe, 4,000 visitors experienced the selected art pieces in a new and innovative way. The authors' collected feedback from 2,500 visitors through questionnaires and conducted 50 interviews to capture the subjective experiences of gallery visitors. Around 87% of visitors rated the experience as very interesting (at least 4 on a 5-point Likert scale), and around 85 percent expressed an interest in returning to the art gallery for such multisensory experiences (Vi et al., 2017).

Inspired by this approach, the SCHI Lab at the University of Sussex and a team of theoretical physicists and astrophysicists from Imperial College London joined forces to build a new platform for multisensory science communication. Astrophysics and cosmology offer the opportunity of exploring topics, that are normally difficult to communicate, to a non-expert audience. Multisensory representations allow for showcasing physical concepts, whilst bypassing the need for technical and mathematical details, by exploiting instead the full potential of the human sensory capabilities. Abstract concepts that, due to the constraints of traditional media, might be over-simplified in traditional public engagement approaches such as lectures, can find natural and powerful representations made possible by haptic technology, immersive audio, olfactory stimuli and even taste. This "embodiment of ideas" opens the door to a deeper emotional and intuitive response (Hamza-Lup and Stefan, 2010; Gibbs, 2013; Obrist et al., 2014), rather than a purely intellectual one. Multi-channel sensory stimulation, including olfactory effects, have been reported to improve engagement, enjoyment and knowledge acquisition (Olofsson et al., 2017; Brule and Bailly, 2018; Covaci et al., 2018).

A further potential benefit is the lowering of accessibility barriers, so as to reach audiences that might normally be overlooked by more traditional approaches, such as neurodiverse young adults or visually impaired people. It also has the potential to increase the "communication bandwidth", with the combination of the five senses being larger than their sum. This would benefit not only people with sensorial or learning differences, but the public at large, as educational research shows (Metatla et al., 2019) that a more inclusive approach is beneficial to everybody.

This project takes one step further than previous work in this area, with the aim of seamlessly integrating all five senses to produce an even stronger sense of embodiment in the participants. We wished to explore and evaluate the following working hypothesis. A metaphorical approach, rather than a data driven approach, to expressing cosmological ideas, leads to a higher perception of enjoyment and increased curiosity about the phenomenon. We do not necessarily wish to transmit a large amount of information to the public. Rather, we aim to stimulate engagement, curiosity and long-lasting impressions, hopefully leading participants to a positive attitude towards the underlying science, and to their further exploration of the topic via other channels.

7.4 A Multisensory Dark Matter Experience

To kick-start our collaboration and an exploration of the possibilities within, we embarked in the design and pilot implementation of a multisensory experience, showcasing the physics of dark matter. We chose dark matter as the subject of our pilot because it is an exciting concept at the frontiers of contemporary research, and intrinsically invisible in the conventional sense – thus symbolically tying in with the aims of our project. Dark matter is often discussed in the general media, so we wanted to propose a fresher, novel approach to an idea that the public at large might already have been exposed to, albeit in a more traditional manner.

Prompted by the concept of “a journey around the galaxy“, we set out to build a prototype experience that was engaging, exciting but also scientifically accurate and meaningful from a scientific point of view. Our target audience was a general public of young adults participating at science based social events, sometimes also referred to as the attentive public. We carried out two events: our pilot exhibit took place at the London’s Science Museum after-hours “Lates” event on October 31st, 2018 (henceforth, “the 2018 event”), open to an adult-only audience in the evening. A second exhibit, which built on incorporated insights and public feedback from the pilot, took place at the same venue but as part of the daytime Great Exhibition Road Festival on June 29-30th, 2019 (“the 2019 event”). This event mainly targeted families. Given the venues, both located in the central London “Albertopolis” area with a high concentration of iconic museums and cultural institutions, we could expect a public of science-savvy, typically well-educated adults and families of middle-to-high socio-economic background.

7.4.1 An Intimate Journey for Two

Early in our design process, we identified the need to shelter participants from the general hubbub of the exhibition space. This was necessary in order to maximise intimacy and focus with the multisensory aspects. We thus decided that the dark matter experience was going to take place inside an inflatable planetarium. This presented the added bonus of a black, fully enclosed and mysterious-looking structure that would hide the experience from participants waiting to enter, thus ensuring maximum surprise. The planetarium is designed for up to 10 participants, but we restricted the experience to two participants at the time. This was because of space restrictions, due to the equipment needed inside the planetarium, and also to create what we hoped would feel like an intimate, personal experience inside the enclosure.

We did not brief participants on what to expect inside while they were waiting in the queue, sometimes for up to 45 minutes(!). we only asked visitors to read and sign a health and safety waiver, describing relevant aspects of the experience in sufficiently general terms. The presented narrative, of the multisensory dark matter experience, was that the participants were to embark on a metaphorically and scientifically accurate (but physically impossible) journey through our galaxy. The journey proceeded with participants being transformed into dark matter detectors, by a mysterious pill (vaguely inspired by the 1999 science-fiction movie "The Matrix", taken at the beginning of the experience).

7.4.2 Coordinated Sensorial Stimuli

The journey was presented through timed visual, auditory, tactile, olfactory and gustatory stimuli within the planetarium. Upon reaching the head of the queue, each of the two participants received noise-cancelling headphones (Bose QC35) and were led into the planetarium. Then, they were directed to recline on large black bean-bags lying on the floor, where a fluorescent outline of a human body indicated the position they needed to assume. Next to each bean-bag, a small metal container with fluorescent borders and a black box, with a fluorescent outline of a hand, were placed. Figure 7.1 shows an overview on the elements of the setup.

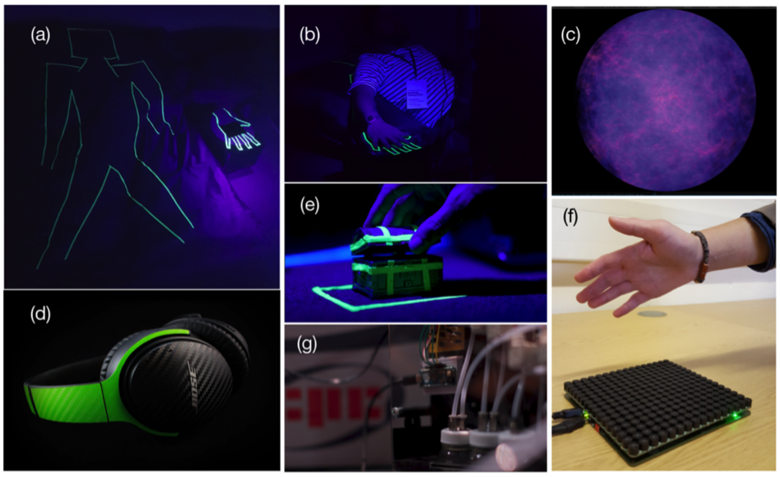

Figure 7.1: Multisensory elements to our dark matter experience: (a) Fluorescent body outline indicating where the participant needs to lie. (b) Haptics box with fluorescent hand outline. (c) Aquarius dark matter simulation projection. (d) Wireless noise-cancelling headphones. (e) Box containing popping candy pills. (f) Haptics board for mid-air skin stimulation. (g) Scent release device.

Once the participants were lying comfortably on the bean-bags, the auditory track started in the headphones. A deep, friendly voice described the narrative and instructed visitors to open the small metal container, where they would find an "experimental powder designed to increase the acuity of [their] senses beyond the physically possible". After being given the option to take the pill, they were instructed to place one of their hands on top of the black box, within the hand outline. Whilst participants settled in and received the introductory instructions through the headphones, a projection of the visual representation of scientific simulations of dark matter was presented in the planetarium. This was turned off to create darkness when other sensory stimulation kicked in, in order to re-direct the participants' attention.

The voice then accompanied the participants along their metaphorical journey through our galaxy, while coordinated auditory, tactile and olfactory stimuli represented the dark matter wind and dark matter density along the journey. The trip started on Earth, then took the travellers to the outskirts of our galaxy and back, to finish by falling into the supermassive black hole at its centre. The co-ordinated stimuli were based, at different levels of sophistication, on scientific results and data. Below we provide a short description of each stimulus.

Audio

A dark matter sound was artificially engineered for the experience, generating a storm-like, but unfamiliar, auditory sensation. It varied in intensity, pitch and texture to represent the concepts of dark matter wind during an earth-year and its density profile in our galaxy, adapted from mathematical models used in research. A voice-over described the practical aspects for the participants to get set-up, illustrating the concept behind the journey and giving instructions. It then guided the participant through the journey, describing physical concepts and phenomena in complete co-ordination with all other stimuli. The voice-over was recorded by BBC presenter and Science Communication lecturer, Gareth Mitchell, in studio quality to maximise the listening experience. The language used was free of jargon. The tone and content was authoritative but slightly tongue-in-cheek. For example, towards the end of the journey, the voice said: "You are now travelling at faster-than-light speed towards the central black hole of our galaxy, where the dark matter density is greatest. This is a journey that can only end when you fall into oblivion in the singularity of the central black hole. [Pause; dark matter stimuli increased in intensity; then, total silence and all sensory stimuli stopped] You have been annihilated, but have no fear: the atoms of your body will be recycled in the form of pure energy, in a few billions of years from today". The audio track is available online (Trotta et al., 2019).

Video

Participants were welcomed inside the dome by a dark matter simulation (European Southern Observatory, 2020) that set the tone for a suitably atmospheric experience. During the 2018 event, the video was switched off once the experience began to encourage focus on the other senses. During the 2019 event (which ran over two days), we switched the video off during Day 1, but kept it running during Day 2, in order to evaluate the relative weight of the visual stimulus over the others.

Touch

An ultrasonic mid-air haptic device was placed inside the black box with the hand outline. Mid-air haptics describes the technological solution, for generating tactile sensations on a user's skin, utilising acoustic radiation pressure, displayed in mid-air without any attachment on the user's body. We used a UHEV1 device manufactured by Ultraleap Limited. The device was able to produce the tactile sensations according to the change in dark matter wind during an earth-year, and its density profile in our galaxy. This was synchronised with the audio track.

Smell

Smell is strongly connected with emotions and memories. Enhancing the dark matter experience with the added value of smell impacts the emotions of the participants and thus boosting the memory retention of the experience itself. A black-pepper essential oil was selected because of its cross-modal properties, freshness, coldness and pungency. It was delivered using a scent-delivery device developed at the SCHI Lab (Dmitrenko et al., 2017). The scent was synchronised with the other stimuli twice along the journey, with different intensities reflecting local spikes of dark matter density.

Taste

The capsule offered to participants, made out of vegetable ingredients, contained unflavoured popping candy that dissolved into a sweet taste inside the mouth. Once consumed, it created a surprisingly strong crackling effect inside the mouth and skull, amplified by the subject wearing noise-cancelling headphones.

At the end of the journey, the voice invited participants to leave feedback upon exiting, and concluded with “May the dark matter be with you”. The whole experience lasted 3 minutes. The 2018 event was filmed and footage was edited into a short (less than 4 minutes) video, whose purpose was both to document the evening and to serve to facilitate further diffusion. The video is available on YouTube.

7.5 Feedback and Evaluation

After the experience finished, participants were asked to fill out a questionnaire outside the planetarium to gather feedback. For the 2018 event, a short self-report questionnaire aimed to evaluate the overall liking of the experience and feeling of immersion, but no demographic data was collected. The liking of each single sensory modality (i.e., audio track, scent, touch) was captured on a 9-point Likert scale. Visitors were also asked how likely they were to learn more about dark matter, how confident they would feel about explaining dark matter to a friend, and how much they would recommend the experience to others. At the end of the questionnaire, we asked the participants to use three words to describe the experience.

The 2018 installation was extremely popular, exceeding our expectations with people waiting up to 45 minutes to participate. There were an estimated 60-70 participants attending the planetarium during the 3 hours of the event, out of which 46 participants answered the self-report questionnaire. Visitors rated highly the overall liking, immersion, and liking of each single sensory modality and the likelihood of recommending this experience to a friend (mean average rates of 7.0, standard deviation of 1.2 scores). Their self-reported confidence of explaining the dark matter concept to a friend, was relatively low (mean average rates of 5.0 on a 9-point Likert scale, standard deviation of 2.0 scores). Figure 7.2 presents a word-cloud of the descriptors used by the participants, including, for instance, various references to “interesting”, “fun”, “cool”, and “educational”.

Figure 7.2: The word cloud created from participants' responses of the experience. The word cloud displays the words' frequency, symbolised through varying font size, such that more frequently occurring words are shown in proportionally larger font.

For the 2019 event, we iterated the questionnaire used, and introduced new evaluation methods suggested in literature (Grand and Sardo, 2017), as well as following internal evaluation of the pilot. From the health and safety form (which all participants had to fill out before taking the experience) we had 108 visitors on Day1 and 114 on Day2, for a total of 222 visitors. Nominally, this translates to 18.5 visitors/hr with an average turnaround time per pair of visitors of 6.5 minutes. This, however, includes latency times due to technical difficulties. Improving on the 2018 event, for this second run, we collected demographics data for 159 visitors (return rate 72%). Our survey results show that *"Curiosity on Multi-sensory aspects"* was the second highest reason for participating in the event (44 people), almost as important as *"Desire to learn"* (48 people), when we asked *"What mainly attracted you to the Dark Matter event?"*. Prior knowledge about dark matter was fairly low (mean= 3.4, SD= 1.9, mode= 2, on a likert scale 0-9), but awareness was high (85% were aware of the concept). Whilst the prior interest in science was unsurprisingly high (mean= 7.3, SD= 1.8, mode= 9); given the type of event, the level of education and professional background of our public was fairly wide. We had a good gender balance and a relatively varied mix of ethnicity. The most represented age group was 10-14 year olds, with a distribution of people across all ages (0 to 85). We had 12/144 visitors who self-identified as having a disability.

We evaluated the public's experience using two mechanisms. A multi-dimensional feedback matrix of sensory channel vs. personal response, and the opportunity for the public to leave comments on Post-its on a feedback wall right after the experience. A third evaluation method, a planned social media campaign, didn't work due to lack of focus on getting it off the ground during the event. We categorised the Post-it replies and grouped them according to themes and sentiment. Visitors left a total of 67 Post-its on the wall (a return rate of 30%). 61/67 were positive. A summary is shown in Table 7.1 and a photo of the actual wall in Figure 7.3.

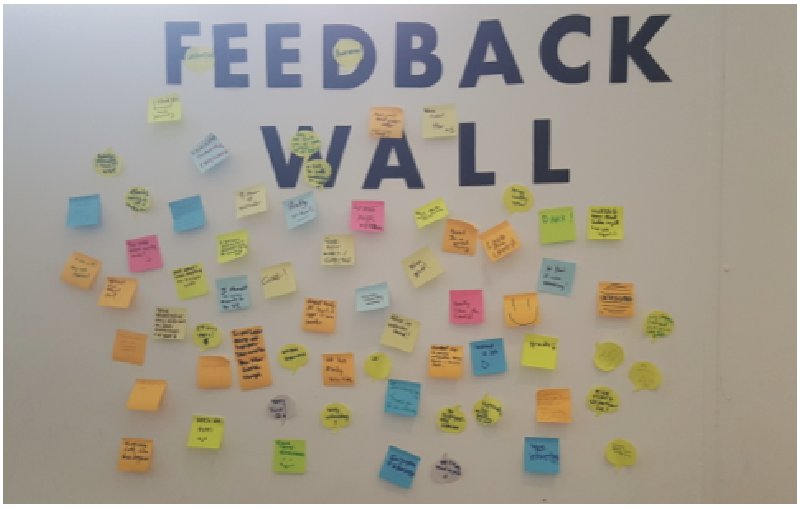

Figure 7.3: Feedback wall: We left sticky paper and pens near the exit of the planetarium, and encouraged visitors to give us brief feedback on a clearly labelled wall surface.

Table 7.1: Summary of notes left on the feedback wall.

Comments	Count
Positive comments	61
Fun/Cool/Enjoyable	19
Candy/Taste	8
Unexpected/Surprising/Unique	7
Interest/Interesting	6
Visuals-Good	2
Smell	2
Touch	1
Multisensory/sensorial/sensual	5
Informative	4
Wonder/Magic	2
Humour	4
Negative comments	4
Visuals-Insufficient	2
Non-informative	2

7.6 Discussion

Our motivation for developing a proof-of-concept experience was twofold. On one hand, to explore the cross-disciplinary opportunities afforded by pooling our respective expert knowledge. On the other hand, to identify shortcomings inherent in breaking new ground of multisensory science communication.

A significant source of improvements lies in the logistics of the experience itself. In the 2018 pilot, we were surprised and outpaced by the level of interest and sheer number of participants, with many leaving the queue, frustrated, after a long wait. Naturally, our main focus was on the experience that the participants would have, upon entering the planetarium.

However, during the event, we realised the one-on-one engagement potential of having a large number of people queuing with anticipation. Whilst we did engage queuing people in meaningful conversations (Figure 7.4), this was not something which we had a strategy for as a complement to the multisensory experience itself. Engaging with the crowd can be used to increase their awareness of the underlying science and technology, but also to instruct them and provide them with information that can streamline the logistics, once it is their turn to participate. In the 2019 event, we engaged the public before the experience, via a purpose-built 5 MCQ quiz on Dark Matter. The quiz was a significant improvement, effectively engaging the public. Once the correct answers were revealed with a UV pen, it also generated a great deal of discussions.

Whilst the actual experience inside the planetarium was designed to last 3 minutes (thus allowing for a theoretical throughput of 40 people per hour), we found that considerable time was spent in changing over participants, thus reducing the number of people we could accommodate and dramatically increasing queuing time. One positive sociological aspect of the long queue that formed outside the planetarium, was that visitors to the museum felt naturally drawn to what appeared to be an extremely popular attraction (the *"herd effect"*).

In our enthusiasm to deliver the 2018 pilot multisensory experience, we also overlooked putting a stronger emphasis on the novel nature of our collaboration. For some participants, the crucial fact that the experience was scientifically accurate and designed by actual dark matter researchers, in collaboration with human-computer interaction experts, did not come through. Similarly, the fact that cutting-edge haptic technology was being used and customised for this event, was not properly communicated. Emphasising such aspects might help draw more attention to the details and science behind the show, and give further direction to a perception-heavy experience.

From participants' qualitative feedback after the 2018 event, we concluded that we needed to understand the emotional load behind the different stimuli better and fine-tune their relative intensity. For example, some participants had a strong reaction to popping candy, which could be perceived as more distracting than enhancing. Others reported that the surprising effect of the candy set the tone for the whole experience that followed. For this reason, for the 2019 event we designed a mechanism to evaluate the role of sensory channels in personal responses evoked.

Figure 7.4: Dr José Eliel Camargo-Molina (centre) engaging the public at the event. The planetarium can be seen in the background.

For the multisensory matrix (see Figure 7.5 for setup and results) each participant was given 3 tokens to vote for the three strongest combinations of sensory channel and personal response they felt. The results showed that on Day 1, participants thought that Hearing and Touch were the predominant sensory modalities, with Taste topping the Enjoyment category. On Day 2, we changed the way the Dark matter visual stimulation was run, keeping it on for the entire stay inside the dome (differently from Day 1, when the visuals were switched off once the visitors settled down at the beginning of the recording). This change led to Vision becoming the most important sensory mode, topping even Hearing in the "understanding" category. These results suggest that taking away the visual modality (sensory deprivation) might enhance the perceived value of other senses. Taste remained the most popular contributing factor to Enjoyment in Day 2. In terms of Understanding, Smell and Taste both ranked much lower than any of the other senses, while Taste and Touch are comparatively more important for the Awareness dimension.

Day 1	Vision	Hearing	Touch	Taste	Smell	Total	
Awareness	9	6	12	11	8	46	18.40%
Enjoyment	10	10	14	17	7	58	23.20%
Interest	12	15	10	7	8	52	20.80%
Opinion	7	3	1	5	6	22	8.80%
Understanding	6	25	24	5	12	72	28.80%
Total	44	59	61	45	41	**250**	
	17.60%	23.60%	24.40%	18.00%	16.40%		

Day 2	Vision	Hearing	Touch	Taste	Smell	Total	
Awareness	17	14	16	11	10	68	18.18%
Enjoyment	24	15	17	31	11	98	26.20%
Interest	31	15	16	15	8	85	22.73%
Opinion	9	8	2	4	4	27	7.22%
Understanding	29	25	23	9	10	96	25.67%
Total	110	77	74	70	43	**374**	
	29.41%	20.59%	19.79%	18.72%	11.50%		

Figure 7.5: Multisensory matrix: We used a grid layout of voting boxes, where visitors were asked to drop three tokens. The tokens should symbolise the strongest coupling perceived by visitors on sensory channel and the elicited personal response.

7.7 Conclusion

With regards to the research question *"How can we integrate mid-air haptic sensations in multisensory, live public engagement activities, for the attentive public?"* – one aspect is clear: Metaphorical sensory experiences enable interested lay publics to engage with the scientific concepts. In this respect, metaphorical experiences are not less than data driven sensory experiences. We have seen that the sense of taste, delivered through sugar pills, contributed enjoyment to the experience, sometimes more than the sound track generated from real dark matter data.

We also observed that some participants were unaware of the cutting edge sensory technology they had experienced, since it was masked by the overall theme of science communication. This has left us with a missed opportunity to engage tech-savvy audiences. A potential solution to this, and the long waiting time, is an activity design where the main experience is preceded with smaller activities, which introduce haptic, olfactory, and gustatory technology at different sections of the queue. An obstacle to this ambition is the cost and technical complexity of some of the kit involved. Not every science communicator will have easy access to a portable planetarium, a mid-air haptic display, wireless noise-cancelling headphones and scent delivery device.

In response to – *"How can we evaluate the effectiveness of multisensory public engagement activities in informal learning environments?"* – we can say the following: Our pilot evaluation, with the use of the sensory matrix, highlighted that ergonomics is a key consideration when planning evaluation methods, which require complex decision making. The data shows a slight skewing effect towards the row of the matrix, which was closest to the participants on the table. Complaints and concerns with regards to not perceiving the tactile or olfactory stimuli, and the diverse dietary requirements of the taste stimuli, also open up new questions. How can we optimise scent and airflow intensity for scent delivery, so that it suits people with different olfactory sensitivity? How can we avoid the false impression of broken haptic technology, when a child and a grandparent, with reduced tactile acuity, participates together in a multisensory activity? It is, therefore, an interesting challenge to develop efficient and reliable evaluation methods for multisensory science communication, which comply with the already existing constraints on evaluation practices. In the next chapter, in a similar fashion of comparing metaphorical to data driven sensory experiences, we will study how can we integrate mid-air haptics in movie experiences, especially with accessibility and immersion in mind. Specifically, we will be comparing conditions where haptics is matched with visual information, vs. when haptics is matched with auditory stimuli.

Chapter 8

Improving Immersive Experiences for Visitors with Sensory Impairments to the Aquarium of the Pacific

8.1 Abstract

8.1.1 Contribution to thesis

In this chapter, the second practical work is discussed, as a case study. This multisensory public engagement experience was designed to be deployed in a commercial setting, but with two small user studies backing up the design decisions. An immersive documentary on oceans and renewable energy was curated, in collaboration with the Aquarium of the Pacific and Ultraleap Limited. This project is similar to the dark matter experience in the ways that the authors co-created a multisensory experience, which primarily aimed to communicate scientific and environmental concepts. Thus, the research question asked: "How can we integrate mid-air haptic sensations in multisensory, multimedia public engagement activities, for *sensory impaired audiences*?" The two key differences to the project described in chapter 7 are as follows: Firstly, the project was addressing a specific subset of the attentive publics, those who actively search for and participate in science content, but also have a sensory impairment. Hence, the multisensory integration served purposes of inclusive and accessible multimedia for disabled audiences. The mid-air haptic sensations, integrated with the audio-visual material, were developed with the inclusion of vision and hearing impaired participants. Secondly, unlike the Dark Matter Experience, this project was deployed in a fully commercial setting, where mid-air haptic technology was chosen to augment an environmental and science documentary. The target beneficiaries of this research were those who wish to design multisensory, commercially available, inclusive multimedia content, and base their own product design with the user studies, guidelines and discussions presented in this work. My contributions were primarily consultation based. I assisted with planning the experimental design, matching the haptic sensations to the audio-visual content, and consulting on accessible multimedia needs of visually impaired people. I also contributed to co-authoring the publication with thorough feedback on the draft, enhancing its academic writing style. However, I did not contribute to any actual content development or deployment, and I was not responsible for running or analysing the user studies. The case study was published at the ACM CHI '20 conference in collaboration with Ultraleap and the Aquarium of the Pacific. The multisensory cinema experience of the eight minutes long video, was on show in the Pacific Vision Movie Theatre, available from May 2019.

8.1.2 Project overview

This case study describes the development of a mid-air haptic solution, to enhance the immersive experience of visitors who are deaf, blind or wheelchair users, to the Aquarium of the Pacific's movie theatre. During the project we found that adding a sense of touch, using an innovative ultrasound technology, to an immersive experience can improve the sense of engagement users have with the content, and can help to improve understanding with the topics presented. We presented guidelines on the design of haptic sensations. By describing how this project took place, within the tight timelines of a commercial deployment, we hope to encourage more organisations to do similar work.

8.2 Introduction

The Aquarium of the Pacific (the Aquarium) is the fourth most attended aquarium in the USA with a mission to "instil a sense of wonder, respect, and stewardship for the Pacific Ocean, its inhabitants, and ecosystems". It's vision is to "create an aquarium dedicated to conserving and building Natural Capital (Nature and Nature's services) by building Social Capital (the interactions between and among peoples)" (Aquarium of the Pacific, 2019).

The Aquarium built *Pacific Visions*, a new building, enabling the public to experience "a state-of-the-art immersive theatre, interactive art installations, engaging multimedia displays, and live animal exhibits." Committed to going beyond the requirements of the Americans with Disabilities Act (ADA) and seeking a way to augment the movie experience for visitors who may have a sensory impairment, The Aquarium commissioned Ultraleap (UL) to provide a tactile experience to complement the movie. Wheelchair users were also included in the brief, as they would not be able to feel the effects of the rumble seats. The project took place over a four month period, with strict deadlines corresponding to *Pacific Visions* opening dates. To the best of our knowledge, this is a world first; augmenting a multisensory experience with mid-air haptics, for users with a sensory impairment, in a public deployment.

8.3 Related work

8.3.1 Immersive experiences

Ahn et al. (2016) showed the effectiveness of immersive VR experiences in communicating environmental themes and, subsequently, influenced real-life behaviour. For environmental organisations like The Aquarium, this suggests immersive experiences are a useful way to engage their visitors and promote their vision. Immersive movie experiences are an attractive alternative to VR for organisations that have to accommodate a large number of visitors. New technologies, such as Ultraleap's mid-air haptics, make it possible to consider tactile stimulation as an additional experience for users who may not be able to access all the sensory effects.

The design of complementary haptic experiences is, however, not a straightforward task. The principle of equipotentiality; "the idea that the same type of touch can be assigned very different meanings or consequences", mentioned by Hertenstein et al. (Hertenstein et al., 2009), is a concern. It raises the possibility that any design of the haptic modality, no matter how it correlates to the audio-visual content, won't necessarily be perceived in a similar manner by different users.

8.3.2 Mid-air haptics and audio-visual experiences

UL technology and the creation of mid-air haptics is described in (Frier et al., 2018b). Ultrasound is emitted from an array of ultrasonic transducers and focused on to a person's hand, (palm and/or fingers), to create tactile sensations. The hardware used in this project, a STRATOS Inspire, is shown in Figure 8.1 (the transducers are located behind the cover material and not visible in this picture).

Figure 8.1: STRATOS Inspire by Ultraleap

Previous studies have investigated the use of haptic feedback to enhance audiovisual experiences, both within an instrumented-hand setup or a free mid-air interaction setup. Ablart et al. (2017a) evaluated the sensory augmentation of audiovisual content using mid-air haptic feedback. The authors targeted short, i.e. one-minute long, movie experiences and reported on the effect of generic haptic patterns with respect to their temporal integration with the movie. No significant effect of the synchronisation of the haptic feedback with the content of the movie was found. In contrast, our studies found synchronising the haptic feedback with the audio-visual content (including audio description) seems to be a key aspect of creating compelling experiences. We explore possible reasons for this in the Discussion section.

Another interesting aspect is the influence of *prior knowledge* on users while experiencing a new type of multi-modal interaction. Mayer's cognitive theory of multimedia learning (Mayer,

2003) takes prior knowledge into account to explain how users learn from multimedia stimuli. Jones et al. (2006b) investigated how the introduction of haptic feedback can influence this model.

8.3.3 Haptics and accessibility

Haptic interfaces have been used in projects aiming to improve different interaction aspects for blind users. Nam et al. (2012b) developed a learning system, the *Molecular Property Module*, proposing different types of learning interfaces controlled via a Novint Falcon haptic device[0]. They suggest useful design guidelines and principles such as the importance of training for first time users or the dangers of over-stimulation and sensory overload that were applicable in this study.

Haptic interfaces have also been used, in attempts to improve the experience of hearing impaired users when interacting with multimedia content, notably music. When experiencing music, people can feel sound vibrations through different parts of their body. This is especially important for users with a hearing impairment. The Haptic Chair, Nanayakkara et al. (2009), amplifies the natural vibrations produced by music and conveys them to users through the haptic channel. Our setup is similar to the Haptic Chair, in the sense that users will have a passive experience, seated in a chair, and be able to perceive complementary information through the haptic channel, mainly via their resting hands.

8.4 Method

We approached the project by breaking it down into three Work Packages (WP), each centred around a user study: i) Exploration, ii) Implementation, iii) Final delivery. This case study focuses on the first two, as the final work package was primarily concerned with ensuring the physical integration worked, and that the experience maintained value as part of a larger multisensory show.

8.4.1 WP1: Exploration

Six participants, four male and two female, (ages unrecorded), were recruited by the Aquarium as representative of their target audience. Four participants were deaf, two participants were blind, (one of whom was autistic and a musical savant). None of them had previous experience with UL technology. We began by allowing participants to make themselves comfortable in the theatre chair and offered props to help them position their arm above the UL hardware, see Figure 8.2. This was to help with the ergonomic design of the final experience. Once comfortable, the participants were played six haptic sensations on to their hand. The objective was to familiarise participants with the concept of mid-air haptics and evaluate if specific haptic sensations would evoke specific emotions or ideas, especially within the context of the ocean or marine life. The mid-air sensations are represented in Figure 8.4. Participants were invited to comment on imagery and emotions that the sensations conveyed.

Participants were then shown two extracts from the work-in-progress movie with associated haptic content: Visual Match ($\mathscr{V}_{\mathscr{M}}$) and Audio Match ($\mathscr{A}_{\mathscr{M}}$). $\mathscr{V}_{\mathscr{M}}$ used haptics associated

Figure 8.2: A participant during the exploratory user study (WP1). The STRATOS Inspire is highlighed in green and the props in red.

with the visual imagery. For example, in a scene showing multiple fishes swimming around (Figure 8.3), a ripple haptic sensation (Figure 8.4 [f]) could be felt to try to convey the idea of multiplicity/randomness. During $\mathscr{A}_{\mathscr{M}}$, the pulse of the haptic sensation was matched to the music soundtrack, especially moments where there was strong bass. The clips were shown in a randomised order and the participants were not informed about the different haptic content approach of the clips. We wished to understand if users perceived value in either approach and, if so, whether a preference existed.

Figure 8.3: Illustration of a scene showing a multitude of fishes from the movie (example only).

Finally, participants were given an opportunity to explore the haptics, with either a visual or tactile explanation of how the sensations were formed. We were interested if the participants themselves, with a better understanding of how the haptics worked, might suggest other approaches to the project.

Table 8.1: Reactions to video clips in WP1.

Participant	Preference
P_1 (deaf)	neither
P_2 (deaf)	$\mathcal{V}_{\mathcal{M}}$
P_3 (deaf)	$\mathcal{V}_{\mathcal{M}}$
P_4 (deaf)	$\mathcal{V}_{\mathcal{M}}$
P_5 (blind)	$\mathcal{V}_{\mathcal{M}}$
P_6 (blind)	neither

Table 8.2: Mean values from scale measurements for the four key themes. t_0: Before viewings; t_1: After first viewing with haptics; t_2: after first viewing without haptics; t_3: After seeing the movie twice.

Order	Ocean	Food	Energy	Water
t_0	9.5	6.6	7.5	8.1
t_1	9.6	9.2	9.0	9.0
t_2	9.9	6.9	8.0	8.2
t_3	9.3	7.7	8.1	8.3

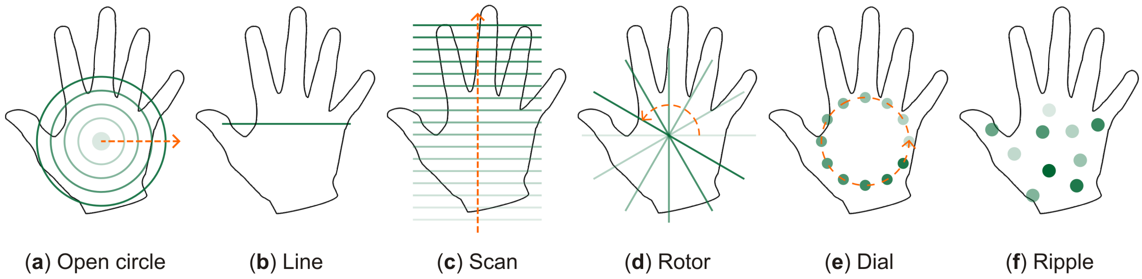

Figure 8.4: Illustration of the haptic sensations. The orange arrows and levels of transparency indicate movement. For example, the Open circle sensation (Figure 8.4 [a]) initially feels like a “point” in the middle of the palm. This point then expands and users feel a sensation like a circle growing radially on their hand and fingers.

8.4.2 WP2: Implementation

Eight participants, (four male and four female), ranging from 35 to 59 years old were recruited by a specialist agency, on behalf of Ultraleap. Five participants were visually impaired, two of whom were blind in both eyes, the other three had sight loss that benefited from wearing glasses. Three participants were hearing impaired, all of whom benefited from hearing aid use, and did not require sign language translation. Two of the participants were wheelchair users (one manually propelled, one motorised).

This study took place at UL headquarters in Bristol (UK). A 55 inch TV screen was used to show the movie and the sound was provided through speakers embedded in the roof of the study room, see Figure 8.5. Participants viewed the eight-minute movie twice, (with and without haptic feedback), in a randomised order. Due to time constraints the viewings took place one after the other. A pre-recorded audio description track was overlaid onto the video, for the participants who were visually impaired.

We wished to establish if the implementation chosen following WP1 added value to the movie experience for the target users. To determine preference, we simply asked participants to express their favourite, following the two viewings. Beyond preference, we were also interested in whether the haptics would improve the immersive nature of the experience and, if so, whether the improved immersion would result in a greater agreement with the themes presented. Four key themes were identified in the movie: the importance of the Earth’s oceans and three challenges facing humankind; producing enough clean energy, fresh water and food for a growing population. Prior to watching the movie and after each viewing, participants were asked to mark their response on an unmarked semantic differential scale, to statements reflecting these themes. For example, concerning food production the statement was "Technological solutions will allow humans to grow enough food for" with the scale ranging from "A small number of people" to "The population of Earth".

To assess immersiveness, participants were asked to respond to ten statements covering four measures, (temporal dissociation, focused immersion, heightened enjoyment and curiosity), associated with cognitive absorption (Agarwal and Karahanna, 2000). Again, responses were

Figure 8.5: Setup at Ultraleap headquarters.

marked on semantic differential scales. These, along with simple questions around movie length, were used to gauge the immersiveness of the experience.

Another goal of WP2 was to gain further insight into the design of the haptic sensations. We wished to understand if particular approaches would enable us to better assign a haptic sensation to a movie scene. Participants were shown eight short clips, each of a few seconds duration, from the movie along with their corresponding haptic sensation. For example, one clip showed an aerial view of wind turbines (blades rotating, see Figure8.6) with the audio description “Wind turbines turn across a green landscape”. The associated haptics were “rotor” illustrated Figure 8.4 [d]. For each of the 8 clips, participants were asked to rate, on a scale from 1 to 10, “*how well did the haptic sensation match the content of the video?*”. The perceived links, strong and poor, were explored in open questions. The entire study was recorded to allow for further analysis.

Figure 8.6: Illustration of a scene showing wind turbines from the movie (example only).

8.5 Findings

8.5.1 WP1: Exploration

When the haptic sensations were played without any associated imagery, participants responded positively or neutrally to most of them. Participants were curious to explore the sensations and three people expressed associations with richer imagery.

"Open circle" and "Scan" were the two most likely to convey ocean themes. Open circle: "like a wave surge, feeling motion,like being under water"(P4) – Scan: "that feels like a wave"(P3). "Ripple" with two negative responses was the least liked: "It is a bit edgy, like I am being interrogated for something I haven't done"(P6). Interestingly, the three participants who used the richest imagery in their descriptions were performers. For example, a music performer described, "Open circle" as "Sort of like I am in the middle of a beautiful nature scene - it makes me think of a garden...very pleasant..very nice"(P6). As hinted in (Mayer, 2003), individual skills or experiences may influence responses to the sensations. We were unable to conclude that a specific haptic sensation can be consistently associated with a specific theme or emotion in the absence of visual or auditory cues.

Five of the six participants perceived a value in adding haptics to video. P1 (deaf) felt the haptic sensations did not add value to either clip. P6 (blind) thought adding sensations could be helpful, but was unconvinced by either of the examples shown. He thought the $\mathscr{A}_{\mathscr{M}}$ implementation was too simplistic and not in-time with the music. Without audio description, he found it difficult to associate the sensations to the video during $\mathscr{V}_{\mathscr{M}}$. The four participants who enjoyed the haptics preferred $\mathscr{V}_{\mathscr{M}}$, the clip in which the sensations were associated with the visual imagery.

With such a small number of blind participants in the study, we sought additional advice from our co-author Daniel Hajas who is blind. He confirmed the requirement for an audio description. It was a useful reminder that the addition of haptics should not be seen as a replacement for other best-practice accessibility methods. Ideally, with a longer timeline, we would have liked to have conducted more research with people who are blind. Given the time constraints, we chose the method $\mathcal{V}_{\mathcal{M}}$ for WP2 but added audio description to link the haptics to the visuals.

(a) Improvised fingertips rest.

(b) Improvised wrist rest.

Figure 8.7: Illustration of hardware configurations.

The final aspect of the Exploration study concerned the ergonomics of the setup. To enjoy the haptic sensations for the duration of the video (≈8 min), users have to keep their hand in mid-air, around 15 to 20 centimeters above the surface of UL array. As illustrated in Figure 8.7a and Figure 8.7b, we prototyped a few methods to help participants hold their hands in place. Users preferred to have their hands unconstrained and it was decided that no support, other than having the option of a fingertip rest, was the best solution.

The idea of using a vertical setup arose, see Figure 8.8. The potential benefits could be: (i) taking less space and being more comfortable alongside users' legs ; (ii) less support required for the users' hand as the wrist is less mobile in a sideways orientation; (iii) the distance between the array and the hand is more likely to be maintained if the hand drops. To assess this idea, we ran an internal user test involving six UL employees. We were surprised to discover that four out of six participants preferred the horizontal layout. This orientation was our final recommendation to the Aquarium with a reference design for a fingertip rest.

Figure 8.8: Idea of placing the UL array vertically.

8.5.2 WP2: Implementation

Six out of the eight participants preferred the version of the movie with the haptic sensations. Following the second viewing, one person commented, "Not as much fun...Now it was like watching a normal film...not quite as interesting or as exciting as the first time" (P8). The *theme agreement* results are shown in Table 8.2 and there is some indication that haptics influenced theme agreement. The three themes with lower agreement, before watching the movie, all showed higher levels of agreement following the first showing with haptics. For example, participants increased their agreement with the theme of humankind's ability to produce enough food for the planet from 6.6 to 9.2 after first seeing the movie with haptics, compared to 6.9 after first seeing the movie without haptics. We also note that the average values tend to decrease at the end of the session, which may be a result of boredom, following two quick showings of the movie.

The *cognitive absorption* results are shown in Table 8.3. In each case the haptic experience scored higher, most noticeably in temporal dissociation. This is consistent with responses to questions on movie length. Six of the participants said they thought the movie with haptics appeared shorter, although they could objectively tell that the movie length was the same.

The ratings of the short haptic clips, along with our discussions with the users, allowed us to draw some conclusions about sensation design. The average rankings ranged from 5.5 for the worst combination to 7.4 for the best one. Sensations with a clear relationship to on-screen movements or audio description of movements were the most successful. For example, the association between the wind turbines and the “rotor” haptic sensation worked well (7.1). One participant mentioned: “when the windmills went you could feel it”.

Table 8.3: Mean values for the cognitive absorption measures.
$\overline{\textbf{H}}$ Without haptics. **H**: With haptics.

Measurement	$\overline{\textbf{H}}$	H
Temporal dissociation	5.8	7.0
Focused immersion	6.1	6.6
Enjoyment	7.5	8.4
Curiosity	8.5	9.0

8.6 Discussion

This study adds to a growing body of research, indicating that immersive experiences can play a role in engaging people, with environmental themes. Previous work has focused on VR experiences (Ahn et al., 2016) but this study begins to explore if immersive movie experiences, specifically enhanced for people with sensory impairments, can also be effective. While the nature of our study (small participant groups within which were complex differences) makes it difficult to generalise the findings more broadly, they suggest that this approach is worthy of further study. However, the authors are keen to stress the importance of also including conventional aids such as audio description and induction loop technology in any experience - mid-air haptics are an enhancement rather than replacement for such aids.

Concerning the design of haptic sensations within the context of a passive exploration, i.e. where users have their hands in a reasonably static position during the whole duration of the experience, we found that synchronising the haptic feedback and “motions” (as obvious as possible, both visually and in the audio description) seemed to be an efficient way to design compelling experiences. On the other hand, relating the haptics with on-screen positions seems to be inefficient, since it is hard to provide a meaningful reference to users.

The final hardware setup had the UL array, and the computer running the haptic program, both installed on a mobile unit, that could be rolled next to any designated chair within the theatre. An optional finger rest was placed at the back of the array. We found that it was important to provide support for the hands, but that users should be free to use it whenever they want, during the projection of the movie. We found that a general guideline would be to keep the experience as close to a typical movie experience as possible. The integration of the haptic program to the show control solution (Medialon), used by the Aquarium, proved to be straightforward in the end. The two programs were connected over the network and allowed for multiple setups to run simultaneously during a movie projection.

Beyond the study findings, we received a lot of guidance and feedback from participants. Two carers spoke about the value of reversing the normal dynamics of discussions, following family entertainment experiences. They explained that often parents, or siblings, spend time explaining parts of an experience that might have been missed by a family member who is deaf or blind. In this case, there was a role reversal with the user of the haptic array explaining their experience to the other family members. They felt this role reversal of being the person with the "additional experience" was particularly beneficial for younger children.

8.7 Conclusion

Overall, the project was received well, with both the inclusive design studies and final implementation reflecting well on The Aquarium. Initial feedback following installation has been positive, although no formal and controlled evaluation was planned on site. One young user, who is blind, was enthusiastic enough to send the Aquarium a review, see Quote 8.7.

> “Last Wednesday I got to experience the Aquarium of the Pacific’s new haptic machine in the Pacific Visions movie theater. “It was awesome!... I put my hand under the machine, and it would blow air into my hand so that I knew what was happening on the screen. It felt like someone was drawing into my hand, except it was air. By the end, I could tell what was wind and what was symbolizing the fish in the sea.” It felt like someone was going hand-over-hand with me, drawing the pictures right there. It was so fun to try this crazy new machine, and it was an eye-opening experience because I could visualize what was happening. It was an amazing experience, and I hope to try the haptic machine sometime again.”

Similar to Nanayakkara et al. (2009), users were enthusiastic about the potential for haptics to communicate more musical information such as pitch, loudness, instrument types etc. Therefore, we see a merit in matching haptic and auditory channels of information, supporting immersion in multimedia rather than a direct match between visual and haptic stimuli. The success of this exploratory study resulted in a new collaboration between the co-authors, working on integrating haptics with a movie on corals. This time, the initial proposition is to study a new type of haptic association, namely a character match (CM). The movie is narrated by four characters (CORA, Finn, Clyde and Zoe), with distinct voices and personalities. This may be amplified and identified through associated haptic sensations, which are distinct and recognisable, even if the voice is not heard while the character is on screen.

The fact that the Aquarium could schedule this project alongside a large renovation and expansion operation, implies it should be possible for other organisations to do similar work. This work was completed over a four month period and to schedule. We hope this project encourages others to do similar public engagement installations, exploring innovative solutions to make entertainment and educational experiences more inclusive. In the next chapter, we take ’inclusivity’ a step further, and explore the use of mid-air haptics as a tool for accessibility, in a formal learning environment, serving an expert audience.

Part IV

Mid-Air Haptic Technology Assisted Science Communication in Formal Learning Environments

Chapter 9

Mid-Air Haptic Rendering of 2D Geometric Shapes with a Dynamic Tactile Pointer Enhancing Science Accessibility for Vision Impaired Learners

9.1 Abstract

9.1.1 Contribution to thesis

Chapters of part II empirically studied the opportunities and challenges of mid-air haptics in science communication. We also discussed two practical works in informal learning environments, considering two different types of audiences. This final chapter of the research portfolio shifts emphasis towards the formal end of the science communication spectrum. Findings of the current chapter may be relevant for future research in the area of tactile methods of teaching geometry to visually impaired students, as illustrated in a motivating scenario in the introduction. The work discussed here originates from an observation made during the focus groups discussed in chapter 5. Namely, participants appeared to recognise more often and more confidently a sensation to be a circle, if it was displayed as a haptic focal point moving around a circular path, rather than displayed as a full outline. Therefore, the research question asked: “How can we apply mid-air haptic technology in formal learning environments, such that it is comparable to other technologies used for learning, by *vision impaired* learners and researchers?” However, prior to direct comparison of mid-air haptic sensations and tactile graphics, evaluated by visually impaired participants, we had to better understand the factors influencing shape recognition in mid-air. The aim was to verify the hypothesis, that a dynamically moving tactile pointer would be a more accurate, and confidence creating, method of rendering geometric tactile shapes, than more conventional methods. The experiments were concerned with psychophysical phenomena observed in controlled user studies, involving a sample of participants from the general public. The target beneficiaries of these results are researchers working in the field of mid-air haptic perception, and application design. The work was carried out in collaboration with Ultraleap Limited, although most of the research took place within the University of Sussex. My contributions were; project co-ordination, planning the experimental design, programming tools for experimenting, conducting user and pilot studies, and writing the publication. I received significant support from the second co-author in statistical analysis and consulting on the experimental design. This work has been published in IEEE Transactions on Haptics, and a supplementary video was created, which was used in the demonstration discussed later in this chapter.

9.1.2 Project overview

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 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. Our research supports the design of mid-air haptic user interfaces in application scenarios such as in-car interactions or assistive technology in education.

9.2 Introduction

In previous chapters we studied the opportunities, and challenges, of mid-air haptics in the broad spectrum of science communication. We found that rendering dynamic tactile sensations are a great opportunity for this technology, but also that it has the most potential in affective domains of learning. Integrating mid-air haptic sensations in a multisensory public engagement event, as well as in a cinema setting, we gained knowledge on what role the technology may play in informal learning environments. We have studied informal learning environments by involving two different audiences – the attentive public, and the sensory impaired public. However, studying how mid-air haptics may benefit sensory impaired audiences in formal learning environments, specifically the vision impaired community, is another valuable research opportunity. Although the participants of the user studies described in this chapter were sighted members of the general public, our findings mostly target vision impaired students (scenario 1) and vision impaired experts (scenario 2).

9.2.1 Scenario 1: Geometry Instruction for Visually Impaired Students

Imagine a visually impaired student learning elementary geometry. Traditionally tactile graphics are embossed on paper, to aid the instruction. In certain scenarios, such as in secluded areas, 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 9.1. If the tactile paper is acoustically transparent, mid-air haptic pointers may be used as an auxiliary tool, highlighting areas 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 (Bornschein et al., 2018). 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. However, before this study can be designed, we must understand the factors influencing tactile shape perception in mid-air.

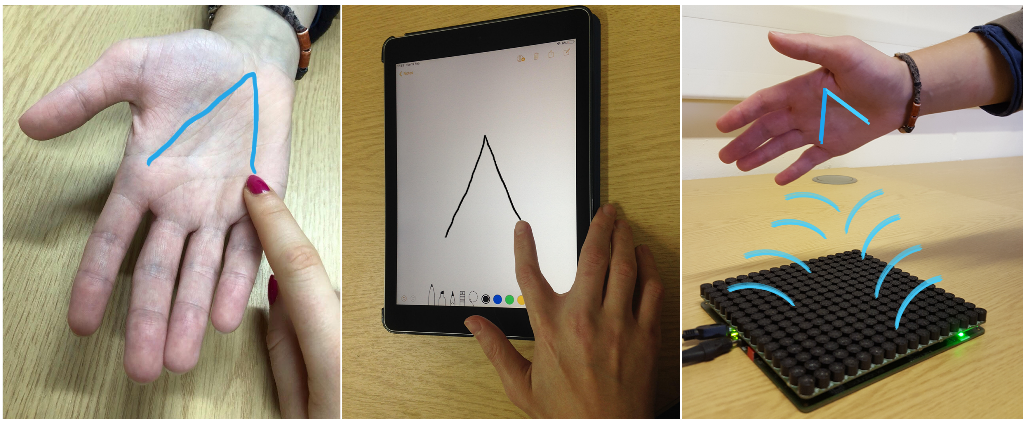

Figure 9.1: (left) A closeup photo of a finger, drawing a triangle into a palm; (middle) A person drawing a triangle on a tablet computer; and (right) A mid-air haptic kit stimulating a hand, in the pattern of a triangle.

9.2.2 Challenges of mid-air haptic shape perception

Mid-air haptics describes the technological solution of generating tactile sensations on a user's skin, in mid-air, without any attachment on the user's body. One way to achieve this is through the application of focused ultrasound, as first described by Iwamoto et al. (2008), and commercialised by Ultraleap in 2013. A phased array of ultrasonic transducers is used to focus acoustic radiation pressure onto the user's palms and fingertips. Modulating the focus points, such that it matches the resonant frequency of the cutaneous mechanoreceptors found in humans (~5 Hz to 400 Hz) (Mahns et al., 2006), causes a localised tactile sensation to be perceived by the user. With the use of multipoint and spatiotemporal modulation techniques, it is possible to create more advanced tactile sensations such as lines, circles, and even 3D geometric shapes (Carter et al., 2013; Long et al., 2014; Howard et al., 2019; Frier et al., 2018a; Matsubayashi et al., 2019).

As ultrasonic mid-air haptic technology is being explored in more and more application areas, such as in art (Vi et al., 2017), multimedia (Ablart et al., 2017a), virtual reality (Pittera et al., 2019b; Georgiou et al., 2018), and in-car user interfaces (Harrington et al., 2018; Shakeri

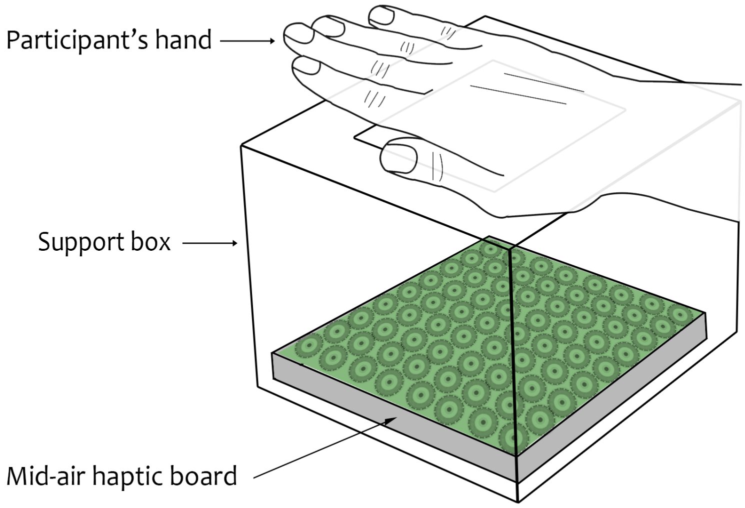

Figure 9.2: Experimental setup: An ultrasonic array is positioned inside an acrylic box. On top of the box there is an opening that allows participants' hand, specifically the palm, to be stimulated with mid-air touch.

et al., 2018), several challenges have emerged regarding tactile interaction in mid-air. One such challenge is shape identification. In contrast to physical touch, we cannot explore the interaction space and acquire tactile information with the same set of exploratory procedures as those discussed by Lederman and Klatzky (2009). For example, we cannot push or squeeze the surface of a tactile cube displayed in mid-air to determine its stiffness, lift it to judge its weight, nor follow along its contours with our fingers to determine whether it is a cube or not, in the same way we would do with a physical object. While progress in perceiving material properties in mid-air, such as texture is being made (Freeman et al., 2017), mid-air haptic technology faces some important challenges when geometric properties of haptic sensations are to be displayed and explored through mid-air touch. Namely, if the geometry of the displayed items remains ambiguous, e.g. if a circle were to easily be confused with a square, mid-air haptic technologies would be unsuitable for a wide range of applications that require accurate and reliable shape identification.

To address this important challenge, we have experimentally investigated new and existing approaches to displaying 2D geometric shapes in mid-air. Specifically, we distinguish between two ways of rendering 2D tactile shapes either as *static* or *dynamic*. In the former case, the stationary outline of a shape (e.g., a circle, square, or triangle) is displayed in mid-air, while in the latter case, a slowly moving pressure point traces the outline of the shape. In the following, we will measure the performance of these two haptic rendering approaches: 1) stationary shapes, and 2) dynamic tactile points, with regards to their ability to accurately convey 2D geometric information to the user.

To that end, and based on our own prior observations and experiences of people interacting with mid-air haptic technology, we have hypothesised that geometric shapes are recognised more accurately and more confidently when they are presented as dynamic stimuli. For instance, a circle is more likely to be recognised when a tactile pointer is moved around its circumference, than in its static counterpart (Rutten et al., 2019). In the context of physical touch, our distinction between static and dynamic stimuli is analogous to pressing a cookie cutter against the palm vs. drawing its shape on the palm with a finger or pointy object. Motivated by this analogy, we were specifically interested in studying mid-air touch to test our hypotheses derived from the primary research question: *How accurately and confidently can people identify 2D shapes in mid-air when displayed with a dynamic tactile pointer (DTP), instead of the outline of a stationary shape?*

Two experiments were conducted with $n_1 = 34$ and $n_2 = 25$ participants in which people were asked to identify the shapes they felt, and rate their confidence in their answer. A circle, square, and an equilateral triangle were displayed using the two rendering approaches (static and dynamic). Additionally, we explored both passive and active exploration, where participants were either prohibited or allowed to move their hand freely during the mid-air tactile interaction. Our analysis showed that participants were significantly more accurate and confident in identifying shapes, when presented with the dynamic modality. Furthermore, we also measured that a 300 ms and 467 ms pause of the DTP at the corners of the square and triangle respectively, improved people's ability to correctly recognise the displayed shapes by over 30%.

This project 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 rendering, 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 (Harrington et al., 2018). In both cases, a more accurate and confident identification of the communicated haptic shapes can significantly improve their effectiveness and thus improve adoption rates of mid-air haptic interfaces in the future.

9.3 Related work

We present a literature review on displaying haptic shapes, the implications of stationary shapes and dynamic tactile stimuli, as well as the role of active and passive touch in recognising geometric features.

9.3.1 Static and Dynamic Tactile Stimuli

In tactile graphics design, it is a frequent recommendation to use discontinuous tactile features, for example, to use open arrow heads instead of solid ones (Braille Authority of North America and Canadian Braille Authority, 2010). Such design guidelines support the notion that human tactile perception performs better at detecting a change in stimuli, rather than a continuous stimulus. This effect is researched through the comparison of oscillatory and static tactile stimulation. Oyarzabal et al. (2007) has shown that indented geometric patterns are more likely to be correctly discriminated when a low frequency vibration is applied to tactile pixels on a tangible shape display. In contrast, Pietrzak et al. (2006) studied participants' recognition performance of directional clues. They found that static patterns are better recognised than dynamic ones, when discriminating between eight tactile icons depicting various line gradients. This was associated with the fact that in the static icon condition, participants could explore the pattern in more detail, i.e. an advantage due to active exploration.

9.3.2 Active and Passive Touch

In 1962, Gibson not only defined active and passive touch (Gibson, 1962), but also performed an experiment on rotating stimuli. Gibson considered passive touch, and asked participants to identify shapes when these were pressed against the hand statically, and when these were rotated. Results showed a 72% accuracy in the rotation condition, as opposed to a 49% accuracy in the static condition. Further to the passive (rotation) and passive (static) stimuli, he also found active exploration of the shapes to be superior. He also reports on strategies named by subjects, such as counting corners or points when trying to identify geometric forms.

S. Schwartz et al. (1975) replicated Gibson's experiment, and found controversial results. Active and passive touch recognition of shapes did not differ significantly; however, in the passive (static) condition, an accuracy of only 38.5% was obtained, which was significantly lower than the accuracy obtained in the passive (sequential) condition (92.5%). In Heller's work, the influence of exploration time was discussed in context of form recognition (Heller, 1984). Heller's study showed that active exploration outperformed both the passive (static) and passive (sequential) stimuli, with 5 seconds of active exploration yielding a similar accuracy to 30 s of passive touch.

According to Holmes et al. (1998), kinaesthetic information plays a key role when we need to discriminate 2D shapes larger than the fingertip. Pasquero and Hayward (2003) also remind us how a tactile display should allow freedom of active exploration. Such integration of cutaneous and kinaesthetic perception has been studied in context of mid-air haptics too. Inoue et al. (2015) investigated Just-Noticeable-Difference (JND) values of position and angle perception, while allowing active, free-hand exploration for participants to inspect volumetric haptic objects in mid-air. HaptoMime (Monnai et al., 2014), and HaptoClone (Makino et al., 2016) further discuss active exploration specific applications of volumetric mid-air haptic sensations.

9.3.3 Haptic Shape Recognition

Form perception has been studied through multiple tactile interfaces, and multiple body parts. Kaczmarek et al. (1997) compared shape recognition via the fingertips on a 49 point electro-tactile array, with a raised dot pattern alternative. Participants discriminated four differently sized circles, squares and equilateral triangles to an accuracy of 78.5% in the electro-tactile array condition, and 97.2% in the raised dot condition. Bach-y Rita et al. (1998) replicated the study on the tongue, yielding similar results. Dynamic ways of rendering haptic shapes were also studied by Ion et al. (2015). Error rates of recognising 12 shapes was significantly lower using a skin drag interface than a vibro-tactile system. Participants also classified the stimuli created by the skin drag display, through the movement of a physical probe across the skin, as "clearer" and the vibrating stimuli as "blurry".

Theurel et al. (2012) studied the role of visual experience on the prototype effect in the haptic modality of shape recognition. Comparing squares, rectangles, and triangles in their canonical and non-canonical representations, the study with congenitally blind and blindfolded sighted adolescents showed that visual exposure to prototypical representations of shapes, allowed blindfolded participants to achieve faster recognition time. Hence, the prototype effect is not intrinsic to the haptic modality, since the congenitally blind participants were significantly slower, even though they performed ~ 20% more accurately in recognising shapes. Since our study involved sighted participants and invisible stimuli, we decided to display shapes in their prototypical orientation, eliminating potential confounding variables.

Shape recognition was also studied in mid-air haptics. Korres and Eid (2016) studied 2D patterns and measured identification accuracy to be 59.4% with mean recognition time being 13.9 s. Rutten et al. (2019) tested 2D sensations, where line-based patterns were better recognised than circular ones. It was also noted that a dial-like sensation was more accurately recognised than a static shape. Howard et al. (2019), studied the ability of people to discriminate line orientation using mid-air haptics. 83% of participants did not express a preference of line orientation in their subjective reports, and this finding was reflected in the indifferent identification scores too. Replicating, or contradicting, these findings on perception of horizontal, vertical or diagonal lines might be valuable in design processes, such as a decision on using a square shape vs. a triangle. Long et al. (2014) also showed that volumetric haptic shapes in mid-air can be perceived at 80% accuracy, but it did not evaluate users' performance on 2D geometry, a challenge that we address and expand on in the present work.

9.4 Experimental design

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

H.1 Shapes will be correctly recognised on significantly more occasions when rendered as dynamic stimuli than as static stimuli.

H.2 Shapes will be correctly recognised with significantly more confidence when rendered as dynamic stimuli than as static stimuli.

Evaluating our hypotheses, we performed 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 9.5 and 9.7. However, in experiment 2, we modified the dynamic stimuli to also evaluate a new hypothesis (H.3, see section 9.6) conceived after the analysis of experiment 1. Namely, in experiment 2, the dynamic stimuli 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 two pilot studies, as described in section 9.6.

In both of the experiments, we studied accuracy and confidence of shape recognition in an active touch, as well as a passive touch condition. We have done this to account for any effect that active and passive touch may have on shape recognition, as suggested by the literature. For this reason, we defined two secondary hypotheses, as follows:

SH.1 Shape recognition is significantly more accurate in the active static, than in the passive static condition.

SH.2 Shape recognition is significantly more accurate in the passive dynamic, than the active dynamic condition.

An overview of the experimental design is shown in Figure 9.3. Research ethics approval was obtained before recruiting participants.

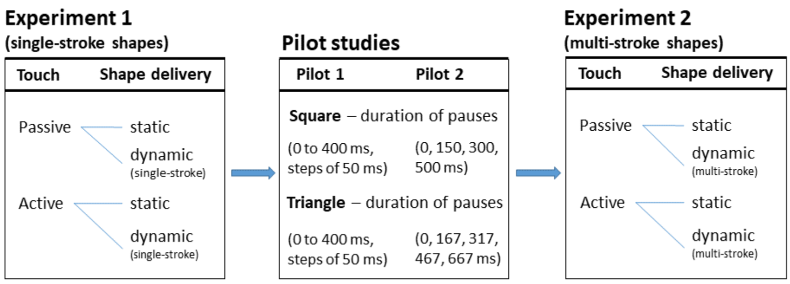

Figure 9.3: Summary of the two main experiments including two in-between pilot studies to determine the optimal parameters for experiment 2.

9.5 Experiment 1: Single-stroke shapes

In experiment 1, we tested hypotheses H.1 and H.2. Importantly, the tactile pointer was moved around the displayed shape giving no emphasis to any corners, as if drawn using a single continuous (brush) stroke.

9.5.1 Method

Participants

Participants were selected from the general public and aged 18 to 50 years. We set an upper age limit to account for the potential decline of tactile acuity with age (Rutten et al., 2019). 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 not having a 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.

Materials

Stimuli Originally, we considered eight shapes to test our hypothesis on. These were a circle, square, right-angle triangle, plus-cross, ellipse, rectangle, equilateral triangle and x-cross (see Figure 9.4). 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. (Theurel et al., 2012; Kaczmarek et al., 1997)). Using only three prototypical geometric patterns (Theurel et al., 2012), we wanted to eliminate any potential confounding variables due to similarities of shape geometry.

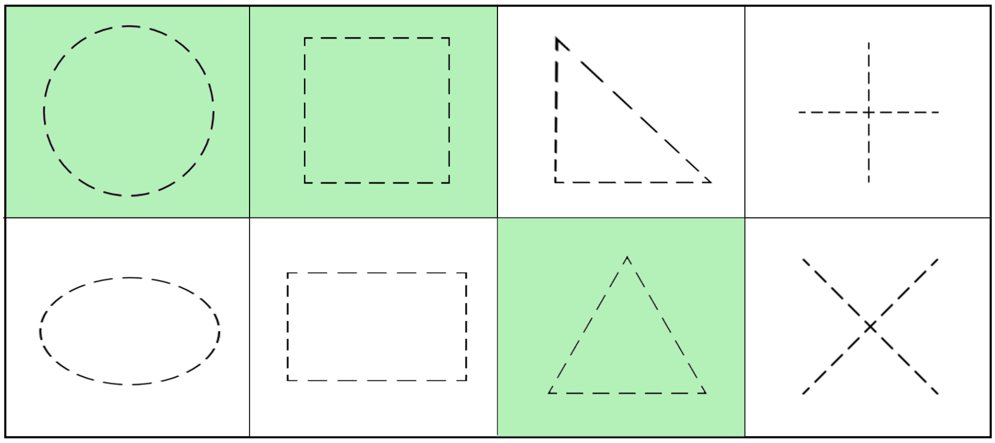

Figure 9.4: Overview on the original set of shapes considered in the study design phase. The final selection of three shapes used in our experiments are highlighted in green.

The method of rendering static and dynamic haptic shapes differ both perceptually and in the way that they are generated. The static stimuli employed spatio-temporal modulation (STM) (Kappus and Long, 2018), 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 (Chilles et al., 2019)) 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 stimuli employed amplitude modulation (AM) (Hoshi et al., 2010; Carter et al., 2013), where a single focus of oscillating amplitude intensity, between 0 and 1, is slowly moved around the shape perimeter. The oscillating frequency causes the human skin to vibrate at the same frequency (and its harmonics (Chilles et al., 2019)) 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 whether the method of rendering (static vs dynamic) had an effect on identification accuracy, we created a static and a dynamic version of the three chosen shapes, totalling six different stimuli. The parameters were kept constant across all six stimuli. 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) (Chandra, 2011). 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 (Frier et al., 2018a). 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 shapes using the dynamic stimulus type was chosen to be 0.5 Hz (2 s per complete shape), such that the movement feels natural, i.e., as if a finger drew on the palm. The pointer 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 9.2).

Device We used a mid-air haptic device manufactured by Ultraleap Ltd, which generates the tactile sensation using 256 ultrasound transducers. In order to fix participants hand at the same height and 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 9.2. 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, such as path geometry, transforms, or animations. 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. The dynamic and static stimuli were displayed in both active and passive conditions.

Prior to displaying the sequence of shapes, participants were given a chance to familiarise themselves with the experimental setup and the tactile sensations. 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. Following this, we displayed the six stimuli for 6 s respectively, but without disclosing the order of shapes. 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 for an indefinite duration and asked to announce what shape they felt. At the moment of announcement the stimulus was terminated. Participants were told that their options were limited to "circle", "square" or "triangle". In experiment 1, we also emphasised, that an "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". We also recorded the time between the start and termination of stimuli; however, we did not intend to use this data to test our hypotheses in this study.

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 group' experiment, where the active vs. passive conditions were counterbalanced and the stimuli were presented in a random order.

We strived to keep the experimental setup as controlled as possible, by keeping the room temperature comfortably warm ($\sim 21°$), 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: Which type of stimuli did you find easier to identify?*"; 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, and they received a £5 Amazon voucher for their time.

9.5.2 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.

Passive touch – accuracy metrics

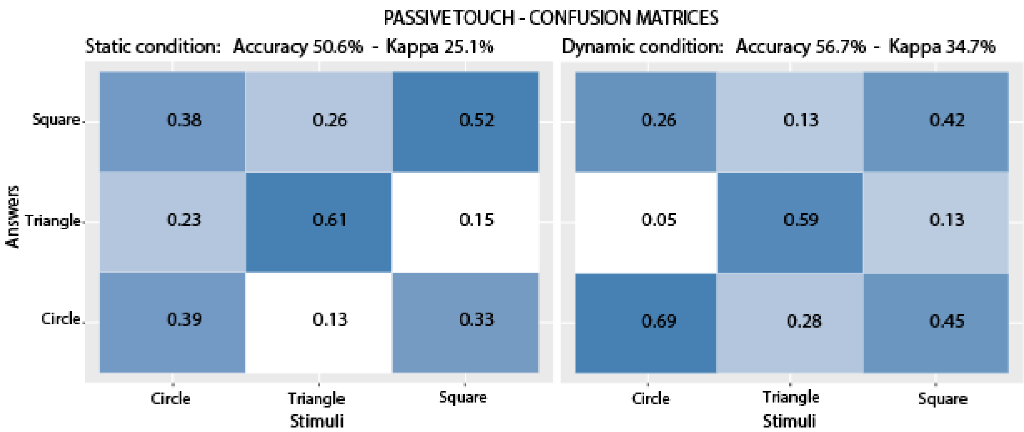

Figure 9.5: Confusion matrix for the passive static (left) and passive dynamic (right) stimuli, expressed as percentage.

A McNemar's test showed a statistically significant difference ($p < 0.001$) in accuracy across the static and dynamic stimuli. We also analysed data with respect to individual classes (i.e. circle, triangle and square). Figure 9.5 shows the confusion matrices for both static and dynamic

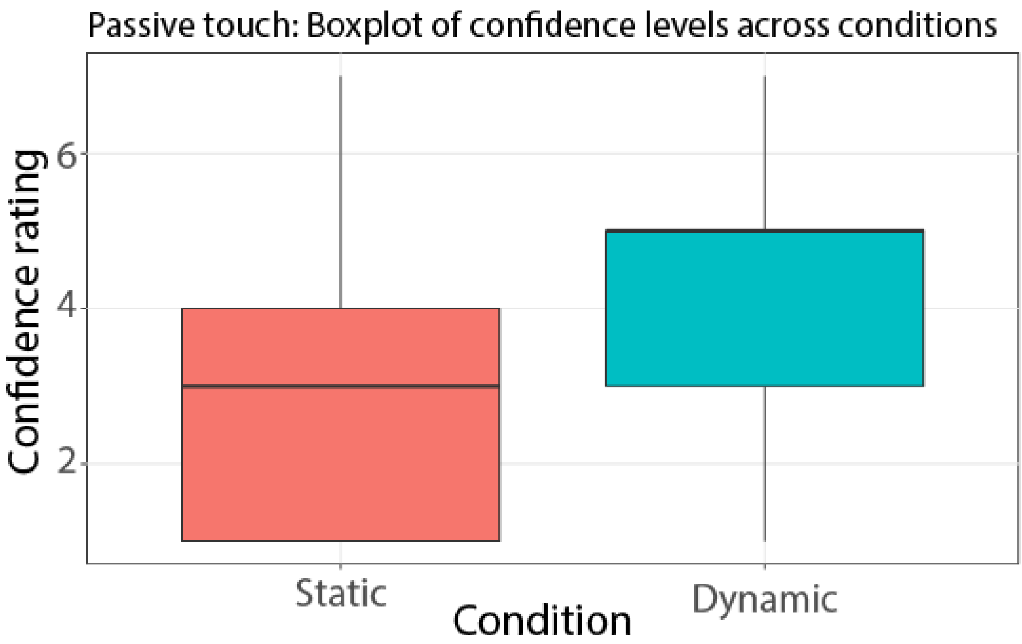

Figure 9.6: Box plot of confidence levels across the passive static (red), and passive dynamic (green) stimuli.

stimuli, but excludes the “I don’t know" answers. The overall accuracy for static stimuli was 50.6% and for dynamic stimuli it was 56.7%. This supports hypothesis H.1. 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% answered ’square’ when the stimulus was a circle, and 33% answered ’circle’ when the stimulus was a square, in the static stimulus type, 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 of the space, and because you couldn’t feel the edges.”*.

Passive touch – confidence levels

Figure 9.6 illustrates the box plot of confidence level for both static and dynamic stimuli. 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 stimuli. The test resulted statistically significant ($V = 4794$, $p < .001$). Participants are more confident in their choices when feeling shapes dynamically drawn (median = 5), than feeling static stimuli (median = 3). This supports hypothesis H.2. The recorded time measurements were 10.2 ± 8.6 seconds for static stimuli, and 11.2 ± 8.3 seconds for dynamic stimuli.

Active touch – accuracy metrics

McNemar’s test did not find significant differences between static and dynamic stimuli in the active condition ($p = 0.22$). This falsifies hypothesis H.1. We again analysed data with respect to individual shapes and created confusion matrices (see Figure 9.7). The overall accuracy for static stimuli was 57.3%, and for dynamic stimuli was 52.7%. Both types of stimuli brought participants to a high level of confusion in the active condition.

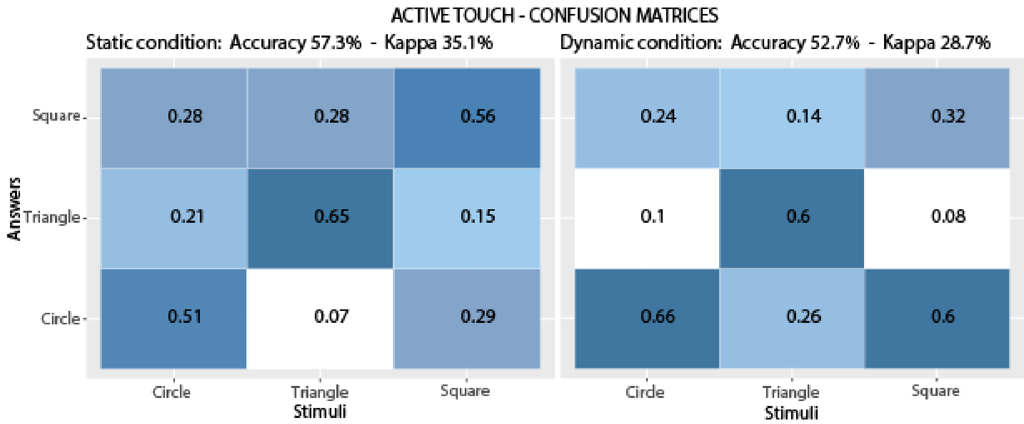

Figure 9.7: Confusion matrix for the active static (left) and active dynamic (right) stimuli, expressed as percentage.

Active touch – confidence levels

From the box plot shown in Figure 9.8, it appears that reported confidence levels are higher for dynamic stimuli. This is confirmed by a Wilcoxon signed-rank analysis ($V = 10591, p < .001$). The median scores are 3 and 4, for static and dynamic stimuli respectively, supporting hypothesis H.2. The recorded time measurements were 15.4 ± 10.7 seconds for static stimuli, and 14.8 ± 11.3 seconds for dynamic stimuli.

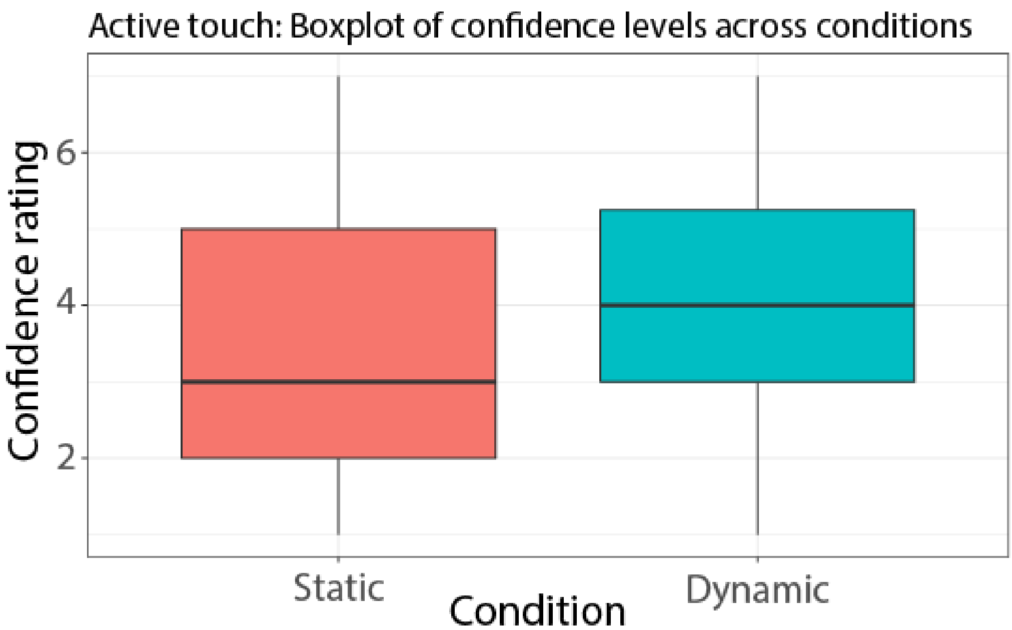

Figure 9.8: Box plot of confidence levels across the active static (red), and active dynamic (green) stimuli.

Qualitative results

In the passive condition, every participant said that identifying shapes as dynamic stimuli, was easier. Some only expressed a milder difference: *P15: "It's easier because it feels clearer, whereas the 'cookie cutter' case is more blurry."*. Others expressed a stronger disliking of static stimuli: *P7: "Oh, not again the muddy."*, or *P33: "It's very difficult to grasp when it's 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. For dynamic stimuli, two different strategies were mentioned. One, focusing on curvature characteristics: *P27: "The circle felt like a smooth curve, whereas with triangle and square you could feel the corners."*. Two, observing the dynamics of the moving point" *P26: "It slows down around the corners."*.

In the active condition, coherency of reports broke down and depended on the strategies people followed. Participants found dynamic stimuli 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 static stimuli to be slightly easier to recognise, if they adapted the strategy of tilting their hand, or focusing on points of stimulation on their palm.

9.5.3 Summary

Our results show that participants are significantly more accurate in recognising shapes, when these are displayed as dynamic stimuli (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, even though the effect size is small. For active touch, H.1 is false. Reported confidence levels are also significantly higher for dynamic stimuli, in both passive and active touch, making H.2 true for both conditions. The qualitative data revealed commonly used descriptors referring to the clarity of sensations, which we explore further in experiment 2. Although our time measurements are comparable to the mean recognition time (13.9 s) found by Korres and Eid (2016), this finding is only indicative and not conclusive. We did not control how long participants were allowed to think before giving an answer. The high standard deviations also suggest that for some participants identification and announcement might not have happened simultaneously.

9.6 Pilot Studies: Increasing Recognition

The results of experiment 1, backed up with qualitative reports, suggested that participants could not discriminate well between shapes, even if these were dynamically rendered. 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 For dynamic stimuli, 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.

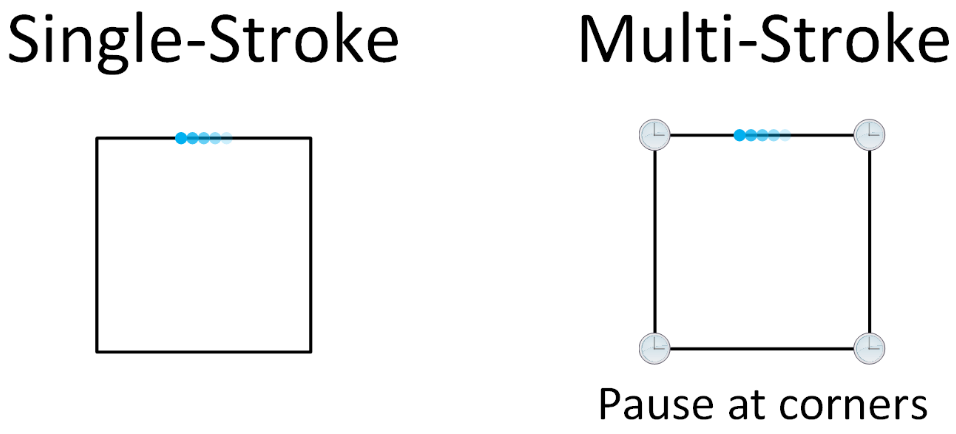

Figure 9.9: An illustration of rendering squares with DTP, either as a single-stroke (SSDTP) stimulus or as a multi-stroke (MSDTP) stimulus.

9.6.1 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 Zhang et al. (2012), 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 is expected that the number of edges, and vertices 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 (1995) through multiple scenarios, in search of 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.*" (Buxton, 1995). 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 and Richardson (1993) designed a unistroke alphabet to find equivalents of touch typing with the use of a stylus. As such, a touch input system enables the transition from novice to expert user, by means of increased input speed, whilst also enabling higher accuracy interpretation for the recognition system. Robust tools, such as the $1 Recognizer (Wobbrock et al., 2007) enabled non-experts to incorporate gesture recognition in their UI. However, it also opened up new research topics, such as how gesture articulation speeds affected 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 (2012) used ultrasonic mid-air haptics to transmit gesture input into unistroke, like haptic output, rendered on the palm. An accuracy of 44% recognition was demonstrated, but no rendering parameters were discussed or evaluated.

To test hypothesis H.3, we altered the dynamic stimuli to be composed of a collection of discrete haptic strokes. In experiment 2, the tactile pointer paused its movement when it reached a corner, whilst in experiment 1, the tactile pointer moved without interruption around the perimeter of the shapes (see Figure 9.9). Thus, we distinguished between two types of DTP rendering, the single-stroke (SSDTP) and the multi-stroke (MSDTP) mode. 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 recognition, we ran two pilot studies as described below. In the first pilot, we wanted to find out the answer to the question: "*Does recognition of the shape increase with the increase in duration of pauses at the corners?*". The second pilot was responsible for optimising the duration parameter, by determining the model for correlating duration and recognition, such as a linear or quadratic fitting model.

9.6.2 Pilot study 1

Method

Participants We recruited nine participants (f=4, m=5, mean age 29.6 ± 4.8 years). All of the qualifying criteria reported in experiment 1 were applicable in this pilot study.

Materials Participants were given two tasks, in the same setup as experiment 1. In task 1, we displayed four repetitions of nine different versions of squares, drawn over 2 s, with increasingly long pauses of 0 ms to 400 ms, in steps of 50 ms, at the corners. 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 presented in a randomised order. Participants were told what the shape was on the display, and they were given standardised instructions of the task in print, since it was crucial they reported how much the sensation resembled 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 counterbalanced. No compensation was paid.

Results

Figure 9.10 plots the mean scores of participants' ratings of recognition 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 a well defined 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 were statistically significantly different.

The results confirm that there is a direct relation between the time spent at the corners, as a kind of emphasis, and the participants' perceived sensation of a shape. However, from the graphs in Figure 9.10, it is not clear if the trend would descend for longer pauses, or continue increasing in a linear fashion. For a clearer representation of the best-fit-curve's trend, we omitted error bars on the scatter plots and zoomed in on the area of interest. To investigate the trend, we ran pilot study 2.

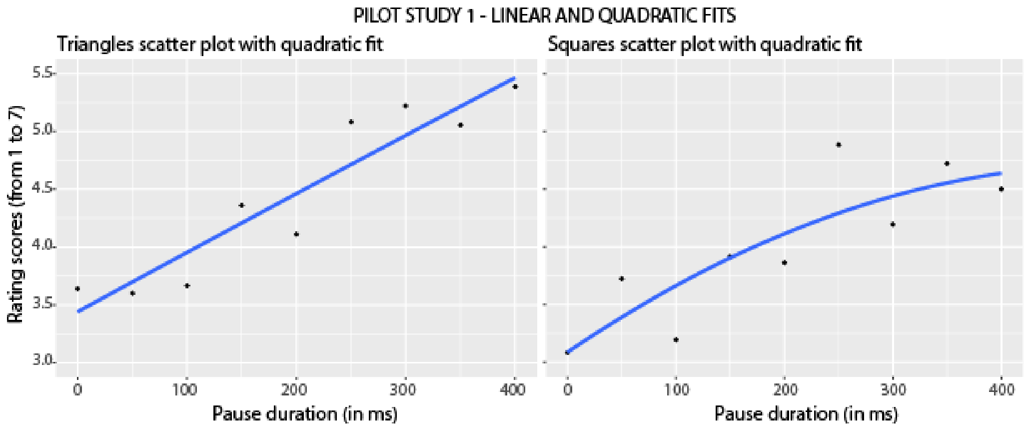

Figure 9.10: Scatter plot of recognition: The mean scores of participants' rating (1-7) is plotted against the nine pause durations tested (ms) for the triangle (left) and square (right) in pilot study 1. A best fit curve is shown in blue.

9.6.3 Pilot study 2

Methods

Participants 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, we chose to test values of 0, 150, 300, and 500 ms for squares. Another factor we accounted for, in pilot study 2, was 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 were drawn differed. However, since pilot study 1 showed that there were intervals of pause durations at corners, at which no significant differences were 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.

Results

For the triangle, we see from Figure 9.11 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 ($p < 0.05$) from other values tested using Wilcoxon tests. We see that too long a pause may decrease performance. In case of the square, participants may benefit from feeling the edges. A square rendered in 2 s, with a 500 ms pause at the corners, means that there is no time left to render edges. The tactile pointer is repositioned discontinuously from corner to corner.

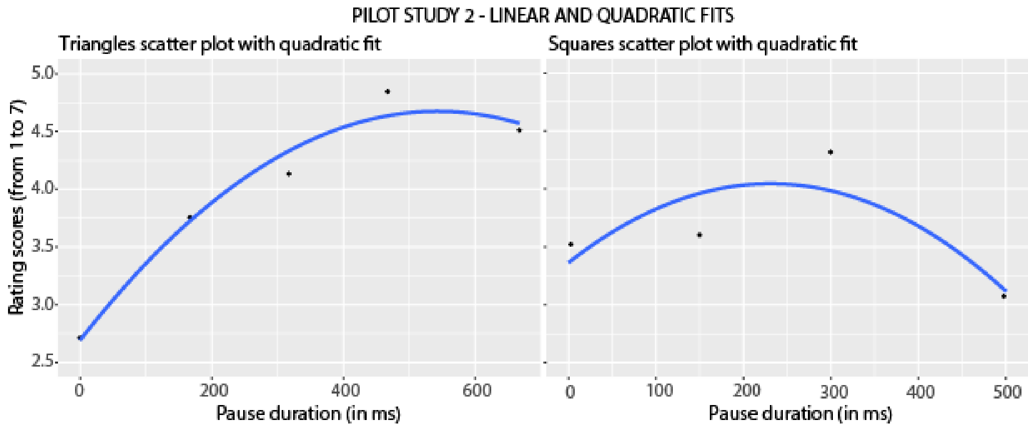

Figure 9.11: Scatter plot of recognition: The mean scores of participants' rating (1-7) is plotted against the five/four pause durations tested (ms) for the triangle (left) and square (right) respectively, in pilot study 2. A best fit curve is shown in blue.

9.6.4 Summary

Two pilot studies were conducted to investigate the effect of pauses at corners on shape recognition. The pauses interrupted the movement of the tactile pointer, rendering a haptic shape. It was shown that different pause durations can have a noticeable impact on recognition, 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.

9.7 Experiment 2 – Multi-stroke shapes

This experiment studied all three hypotheses H.1, H.2 and H.3. We measured participants' accuracy and confidence in mid-air haptic shape recognition, for static and dynamic stimuli in passive and active conditions. Importantly, we used the modified dynamic stimuli, where the tactile pointer took short pauses at the corners of the displayed shape, as if drawn using multiple (brush) strokes.

9.7.1 Method

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, on a scale from 1 to 7, was 2.08±1.20. No one declared a disorder compromising their tactile acuity. Participants of the pilot studies were excluded from taking part in this experiment.

Materials

The stimuli used in the static condition were identical to those used in experiment 1. In the dynamic method of rendering, 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 corners of the squares and triangles respectively. We expected that this method would help in distinguishing between circles and squares displayed as dynamic stimuli.

Procedure

The task and procedure for experiment 2 followed the same protocol as in experiment 1, except in 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?"*.

9.7.2 Results

Passive touch – accuracy metrics

Confusion matrices for the two types of stimuli are shown in Figure 9.12. The overall accuracy for static stimuli was 51.7%, and for dynamic stimuli was 83.0%. This is a statistically different result (McNemar's test, $p < 0.001$) and a significant improvement compared to the results in experiment 1, supporting hypothesis H.1. Values for the dynamic stimuli 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.

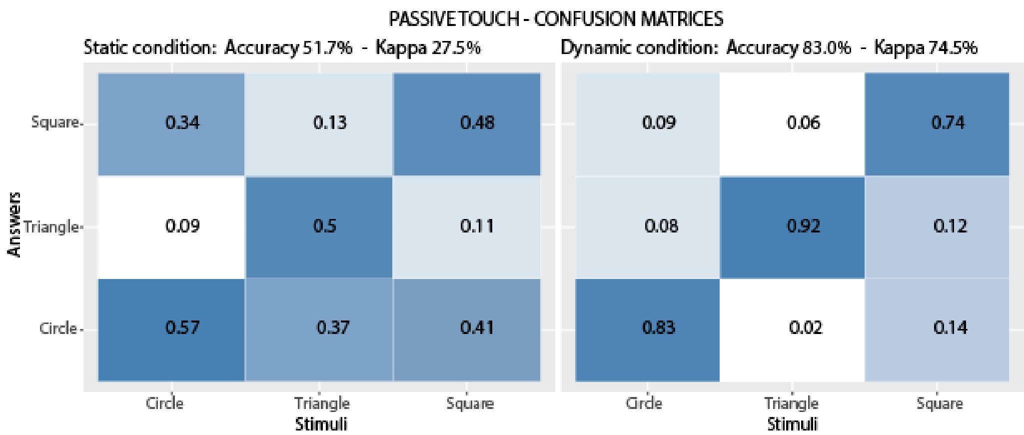

Figure 9.12: Confusion matrix for the passive static (left) and passive dynamic (right) stimuli, expressed as percentage.

Passive touch – confidence levels

A Wilcoxon signed-rank analysis confirmed a significant difference ($V = 912$, $p < .001$) between confidence levels in the two stimulus types. Once again, participants were more confident in dynamic stimuli (median = 5), than in static stimuli (median = 3), as shown on the box plot in Figure 9.13. This supports hypothesis H.2. The recorded time measurements were 7.8 ± 5.6 seconds for static stimuli, and 7.8 ± 5.3 seconds for dynamic stimuli.

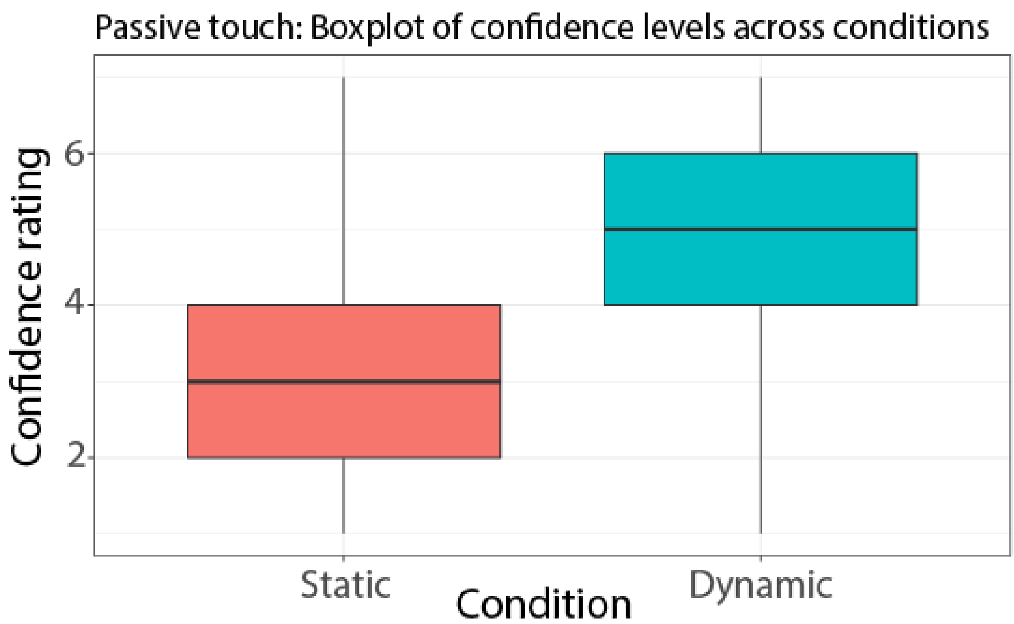

Figure 9.13: Box plot of confidence levels across the passive static (red), and passive dynamic (green) stimuli, in experiment 2.

Active touch – accuracy metrics

Figure 9.14 shows the confusion matrices for the active condition. The overall accuracy for static stimuli was 57.3%, and for dynamic stimuli was 84.7%. This is a statistically significant difference (McNemar's test, $p < 0.001$) and makes hypothesis H.1 true.

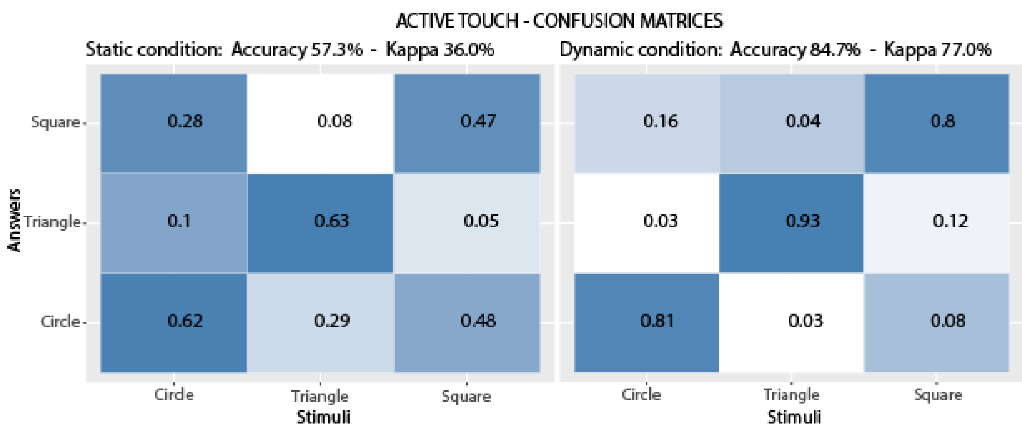

Figure 9.14: Confusion matrix for the active static (left) and active dynamic (right) stimuli, expressed as percentage.

Active touch – confidence levels

The reported confidence levels are again higher for dynamic stimuli (Wilcoxon signed-rank test: $V = 2574$, $p < 0.001$). The median score for the confidence level rating is 4 for static stimuli and 5 for the dynamic types (see Figure 9.15). This supports hypothesis H.2. The recorded time measurements were 9.3 ± 5.7 seconds for static stimuli, and 8.4 ± 5.5 seconds for dynamic stimuli.

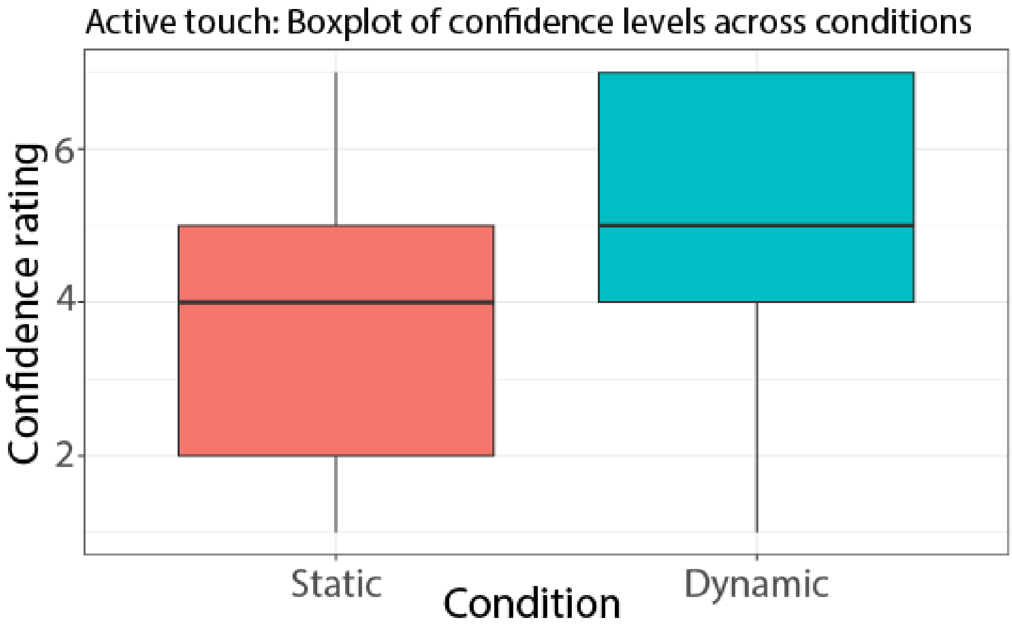

Figure 9.15: Box plot of confidence levels across the active static (red), and active dynamic (green) stimuli, in experiment 2.

Qualitative results

Our aim was to quantify 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 process, we further abstracted information relevant to the respective category.

In Q1, we looked for how many people found either of the stimulus types 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 most frequent adjectives and their occurrences in each theme, see Tables 9.1, 9.2, and 9.3.

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 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.

Table 9.1: Positive and negative descriptors of perceived quality of sensations

Theme	Perceived quality of sensation	
	Positive	**Negative**
Total count (static)	4	13
Total count (dynamic)	12	3
Frequent descriptors (static)	–	blow, wall of air (5) block (3)
Frequent descriptors (dynamic)	pencil/finger tip (3), smooth (1)	–

Table 9.2: Positive and negative descriptors of perceived quality of shapes

Theme	Perceived quality of shapes	
	Positive	**Negative**
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),	–

Table 9.3: Positive and negative descriptors of perceived ability to recognise shapes.

Theme	Perceived ability to recognise shapes	
	Positive	**Negative**
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)	–

9.7.3 Summary

Comparing the accuracy results obtained for dynamic stimuli in experiment 1 and experiment 2, using a χ^2 test of homogeneity, we see a statistically significant difference in both the passive ($\chi^2 = 87.23, df = 1, p < 0.001$) and active conditions ($\chi^2 = 61.23, df = 1, p < 0.001$). Thus, 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 in the passive touch for dynamic stimuli increased from 56.7% to 83.0%; while the accuracy also increased in the active touch, dynamic stimuli, from 52.7% to 84.7%. These results confirm hypothesis H.1. We see that for the dynamic stimuli in both passive and active touch, the median value of confidence is 5, which is significantly different from that for static stimuli, thus supporting H.2. The qualitative analysis also shows that people find static shapes more blurry or fuzzy, compared to dynamically drawn shapes, which have been named as clear, or having a higher definition. The answers given by participants to the interview questions show that recognising shapes presented as dynamic stimuli is easy, while it is hard for static stimuli.

9.8 Discussion

Our study reports on how accurately and confidently people can identify 2D shapes, using mid-air haptic stimulation. Here, we discuss how our work contributes to haptics and HCI research. We also outline possible application scenarios that can benefit from our findings.

9.8.1 Mid-Air Haptic Shape Recognition

We learnt three key lessons. Firstly, in experiment 1 we showed that people can recognise more accurately and confidently the tested shapes, when these were rendered with DTP, instead of a stationary outline. Our experimental design did not allow for a rigorous analysis of interactions between the active static, active dynamic, passive static, and passive dynamic conditions. However, we were able to make observations with regards to our secondary hypotheses (SH.1 and

SH.2) based on quantitative data. Remarkably, while passive touch dynamic stimuli performed 6.1% better on accuracy than static shapes, in active exploration the dynamic stimuli performed 4.6% less accurately. Although the results in active touch are not statistically different, this is in line with previous studies (Gibson, 1962). It is likely that a shape presented as a full outline is better understood when explored actively, than when passively felt. This is apparent from comparing the accuracy results of static stimuli in the passive (50.6%) and the active (57.3%) conditions. In contrast, if both the tactile pointer and the participant's hand is moving, this may conflict the creation of accurate mental representations.

Secondly, experiment 2 showed that breaking down a shape into individual chunks (i.e. using multiple strokes) can increase the accuracy of shape recognition by ~ 30%. Feeling a continuous loop led to higher levels of association with a circle, and feeling well distinguished corners enabled participants to make a clear link with either 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 cited in the literature. Gibson found a 72% accuracy of shape recognition, in a passive (rotation) touch condition. This is similar to our results of 83.0% accuracy of dynamic stimuli in the passive condition. He also reported participants' recognition strategy to be "counting corners and points" (Gibson, 1962), which we also found. Ion et al. (2015) 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 experiment 2. The qualitative reports of Ion et al. (2015) "clearer" skin drag stimulus vs. "blurry" vibro-tactile stimulus are also matching our qualitative findings.

In addition, the two pilot studies provided the optimal pause duration parameters for the specific size and draw speed of the tested shapes. These were experimentally deduced, however, we believe that this parameter can be defined precisely for a general geometry, as a function of other parameters, such as perimeter, number of sides, or rate of drawing. Reports of participants also clearly support the numerical findings: *P9: "Having definitive pauses at the vertices, 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, it did not consider any use case restrictions. In some control interfaces, such as automotive, time is of the essence and therefore a trade-off may exist between accuracy and sensation duration. Similarly, the 9%-14% confusion between squares and circles in Experiment 2 is significantly lower than that in Experiment 1, but it is still a relatively high level of uncertainty for using controls in contexts of automotive. Thus, optimising shape recognition time and performance in high cognitive demand scenarios remains an open question.

9.8.2 Further application Opportunities

In the introduction of this chapter, we have described a scenario (Scenario 1), where mid-air haptic technology could benefit vision impaired students in secluded regions. The work described in this chapter could also be applied for science accessibility, for instance; at academic conferences to provide an additional channel of non-visual, non-verbal information to expert audiences with vision impairments. Moreover, there are further application scenarios, which are outside the scope of this dissertation, but are relevant points of discussion.

Scenario 2: Closed Haptioning – A Demonstration of the Haptic Channel for Improving Accessibility of Audio-Visual Content beyond Closed Captions and Audio Description for Expert Audiences at Eurohaptics 2020

Closed captions and audio description became the de facto method of creating accessible audio-visual content for people with hearing and visual impairments respectively. However, in some cases it is not possible to adequately convey all relevant information through the existing channels of creative content and its assistive alternative. For example, in educational videos, a continuous narration of a scientific concept, illustrated via animated content, may not afford the use of audio description to detail the visual scene. Thus, in a demonstration at Eurohaptics 2020, we propose to use ultrasonic mid-air haptic technology for including "closed haptions" with a three minute long video. Our video illustrates the concept of Single-Stroke and Multi-Stroke Dynamic Tactile Pointers – a novel method of rendering tactile shapes in mid-air, discussed in the previous sections.

Eurohaptics is a prestigious academic conference on haptic science, technology, and application, with accessibility being the theme of the 2020 gathering. This demonstration was catered for in the form of a playful challenge. Attendees were asked to complete three difficulty levels in SQuiz – a shape quiz ($\sim$ 1 min per level), where each level is associated with a method of rendering. Each level included a straight line, circle, triangle, square, and rectangle, presented in a random order as illustrated in Figure 9.16. Upon revealing the number of correctly identified shapes in each level, we discussed how the stimuli were rendered, and the working hypothesis on why different methods were perceived more or less difficult.

For queue management, an illustrative video of the findings was on display. Beyond vocal narration and closed captions, the visualisations of haptic stimuli were synchronised with a corresponding haptic channel, displayed via the ultrasonic mid-air haptic array. The haptic stimuli matched the visual animations, both in content and time, thereby functioning as closed haptions. Similar efforts of closed haptioning were published by O'Conaill et al. (2020), in context of improving the accessibility and immersive experience of a short documentary on oceanography, as discussed in the previous chapter. Members of the conference community were encouraged to leave suggestions for future work on a "research feedback tree" (a cardboard desktop tree with branches, where wooden tags can be hung with short messages).

The target audience of this communication project was the expert haptics community from academia and industry worldwide. Our aim was to give a thought provoking demonstration of how mid-air haptic sensations could be seen as an alternative channel of accessibility, while also surprising experts with the findings of haptic science. This fits in suitably with the accessibility theme of the conference, as well as the targets of science communication, identified in chapter 6, matched with the expectations of the expert audience. Unfortunately, due to Coronavirus restrictions, we were unable to carry out the physical demonstration, despite the accepted demo paper.

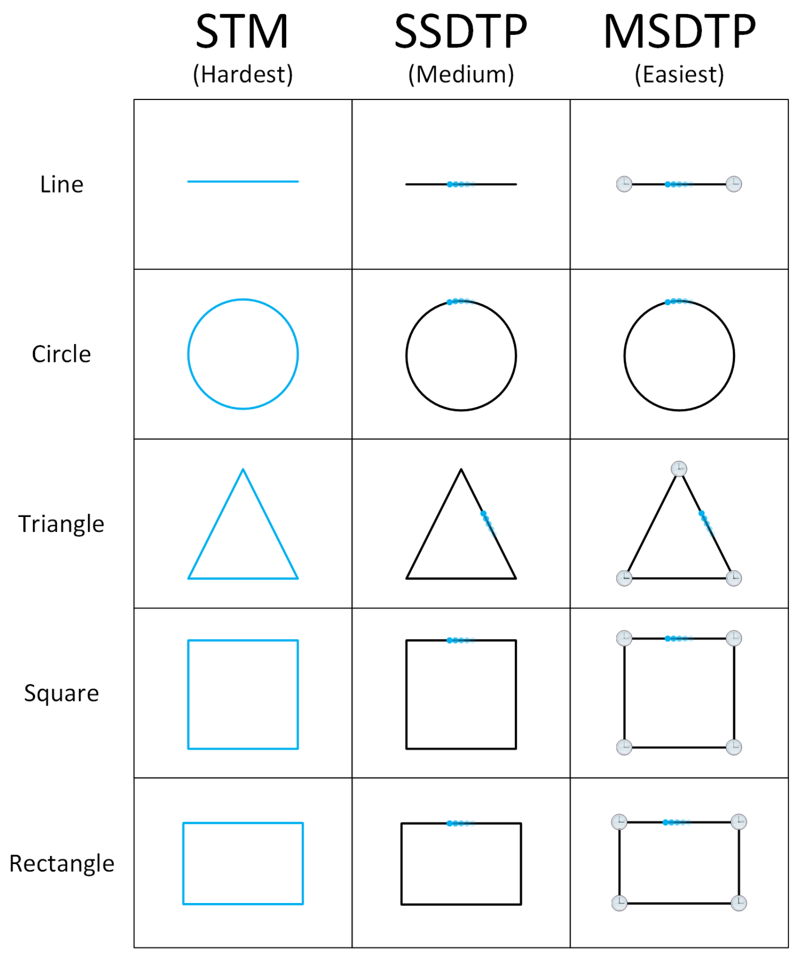

Figure 9.16: Illustration of the demo activity. Five shapes are rendered using three different techniques, associated with three difficulty levels of pattern identification. The shapes are presented in a random order in each level.

Scenario 3: Haptic Controls in Automotive Systems

Imagine a driver wishes to turn the volume of the radio down, and increase the temperature in the car. It is an important interaction design task of in-car interaction to provide interfaces that do not require the driver to take their eyes off the road (Harrington et al., 2018; Shakeri et al., 2017). One possibility is to use 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 is a circle, a rotating movement in either direction could adjust the radio volume. Swiping movement brings up a new icon, for instance a triangle. Here, rotating movement of the hand in either direction results in changing the temperature.

However, what makes a mid-air haptic 2D shape recognisable, requires a deeper understanding of the underlying cognitive and perceptual processes, when a pattern is rendered and perceived as a set of haptic strokes. It may be that the pauses at the vertices function as spotlights, directing the attention of the user to a specific location in the local geometry. This hypothesis implies that other mechanisms of influencing attention, for example a change in the haptic intensity at vertices but no change in movement, should be able to reproduce the results. If MSDTP rendered haptic shapes indeed rely on cognitive mechanisms related to attention, this may interfere with other tasks that require high levels of concentration. To evaluate the effectiveness and safety of such a system, we foresee an experiment replicating our findings in a car simulator, especially focusing on circumstances where users are subject to high cognitive demand, or potential risk.

9.8.3 Project limitations and research progression

Limitations of this study

One of the drawbacks of our method is the arbitrary choice of shape size. Recent work by Frier et al. (2019), 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 DTP 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 (Langford and J. Hall, 1973). 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 small number of shapes tested. We have shown that displaying dynamic shapes are better recognised if they are 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. To address these limitations, I have started a research placement at Ultraleap Limited, progressively researching related topics, such as the impact of haptic “brush style” or “brush movement” on shape recognition. The overall aim of this work in progress is to identify and optimise a range of significant parameters, as summarised in the following subsection.

Parameter Optimisation for Tactile Shape Recognition in Mid-Air

In my research internship, I wished to generalise the method of rendering any 2D shape with a DTP, and maximise the recognition rate of these shapes. The ultimate task has been to overcome the arbitrary parameter choices, and to define and optimise the relevant parameter space, such as rate, orientation, size, or type of stimulus used as a tactile pointer. The task was broken down into two threads of research. Firstly, investigating the DTP “brush style” – asking what is the best style for a “tip” of the tactile pointer? The brush style refers to the point like tactile sensation animated around a path, i.e. the haptic properties of the focal point, such as texture and size. Secondly, investigating the DTP “brush movement”, – asking what is the best method of moving the DTP? The brush movement refers to dynamic parameters of animating the focal point around the path, such as speed, pause duration, and sampling rate.

With regards to “brush style”, we identified three cases of interest to study: synchronous amplitude modulation, asynchronous amplitude modulation, and spatiotemporal modulation tip styles. Using a synchronous AM style, the tip would be an amplitude modulated focal point, moving around the path continuously, regardless of the phase of the modulation. In contrast, an asynchronous AM style would render the path, by moving the location of the amplitude modulated focal point, only when the sample is at zero intensity. Thirdly, a spatiotemporal tip style would render shapes by off-setting a small circle around the path, where the circle is rendered using spatiotemporal modulation. Based on physical measurements (Chilles et al., 2019; Frier et al., 2018a), we may assume that all of these tip styles would give rise to different perceptions of the quality of the DTP, influencing the overall quality of the tactile shape.

In terms of DTP "brush movement", we also identified three parameters of interest to study. Firstly, the velocity of the DTP, which includes both direction and speed of movement. The speed of movement is a function of rate at which a path is completed (currently fixed at 0.5 loops per second), and the path length, which depends on shape size and geometry. We can assume that a too slow or too fast movement around the path would influence the recognition of shapes. Secondly, the pause time after each stroke – currently optimised for only fixed shape (square and triangle), and fixed velocity. We can also assume that the pause time will depend on the speed of the movement. Thirdly, the angle between two consecutive strokes – currently tested for 60 degrees, 90 degrees, and a smooth curve. We hypothesise that there exists a maximum angle of inflection, where distinguishing a polygon from a circle becomes in-perceivable, regardless of speed of movement and pauses at corners.

Another question arising from the studies discussed in this chapter is how do we assess the quality of the 'brush style' and 'brush movement'? What's the best brush style, and what's the best way of moving the DTP? One possible approach is to Evaluate line segments only. A problem with this is knowing whether results would apply to recognising a multi-line geometry. Another approach is to follow the same evaluation as previously, and evaluate shape recognition rates. A problem with this approach is the interrelations between parameters e.g. velocity vs. pause duration. It is also arguable what the key assessment criteria is; for example whether accuracy of recognition, recognition time, confidence, strength of tactile sensation, or perceived clarity is a more significant measure. An additional challenge lies in the definition of shape recognition. How do we know if people only count corners, or actually recognise the shape in its entirety? A potential solution we proposed is the study of recognising shape orientation, and irregular shape geometry e.g. rectangle vs. square, or isosceles vs. equilateral triangle.

9.9 Conclusion

In this chapter, we wanted to answer "How can we apply mid-air haptic technology in formal learning environments, such that it is comparable to other technologies used for learning, by *vision impaired* learners and researchers?" In chapter 5 we found that rendering dynamic tactile sensations is an opportunity for mid-air haptics to be applied in informal science communication, by means of creating tactile representations of natural phenomena. However, this time we also found that a dynamic tactile pointer significantly enhances shape recognition, which may have implications for formal science communication too.

It is recommended that mid-air haptic devices render two-dimensional geometric shapes through the use of a dynamic tactile pointer, instead of displaying the full outline of the shape. It is also recommended to break down polygons into discrete sides, by interrupting the movement of the pointer at the vertices. The optimal pause duration for a 6 cm square, and equilateral triangle is 300 ms, and 467 ms respectively, when displayed at a rate of 2 s. According to these specifications, the accuracy of passive touch shape recognition is 83.0%, with active touch at 84.7%. These results are comparable to accuracies measured for mid-air haptics displaying 3D shapes, as well as studies using raised pin arrays and vibro-tactile displays. Yet, further studies of parameter optimisation are desirable, prior to direct comparison of tactile graphics and mid-air haptics, recruiting vulnerable participants in an experiment on geometry instruction.

These insights may play a crucial role in a plethora of application areas, such as mid-air haptics control design, in an automotive context. But more relevant to this thesis, the technology may be capable of some necessary requirements of assistive technologies for visually impaired distance learning children. Whether the comparable tactile shape recognition can be further improved, or whether it is sufficient, remains a question to be researched. Involving vision impaired participants, qualified teachers for visually impaired, and direct comparison of mid-air haptics with existing assistive technologies would be necessary. Although this thesis is unable to answer the afore-mentioned research question, some of the challenges of tactile graphics, and potential solutions offered by mid-air haptics, will be discussed in the next chapter.

However, as our planned demonstration at an academic conference on haptics and accessibility illustrates, mid-air haptics may also be useful in formal learning environments, other than in schools. Expert audience members, with sight loss, at a scientific conference may gain access to visual content of educational material, through the use of closed haptioning. Moreover, given the domestication of mid-air haptic displays, this haptic channel of accessibility would become available to the lay public, consuming scientific content from their living room. Thus, we foresee the future application of mid-air haptic technology in both formal and informal learning environments, educating and entertaining, abled and disabled audiences alike.

Part V

Implications for Research and Practice

Chapter 10

General discussion

Previous parts of this dissertation have charted different ways of engaging different audiences with learning about science through the use of mid-air haptic technology. In this chapter, I offer a general discussion of the practical and research implications of my studies, sectioned into three topics. Firstly, I present an overall discussion of the research findings in relation to the initial research questions. Secondly, I discuss three directions in which future research could progress, implied by the lessons learnt during this PhD programme. Thirdly, I highlight the limitations of the work presented in this thesis. I do not, however, enter into a verbose discussion of the project findings in the context of related literature. Project specific discussions, included in sections 5.5, 6.6, 7.6, 8.6, and 9.8, aim to provide detailed reflections on the projects' contribution, in light of prior research. Here I aim to emphasise the opportunities for future research directions, and give an overview of the overall thesis, before ending with a few concluding remarks on the PhD research experience.

10.1 Overview of research questions and corresponding findings

In this thesis, I presented some opportunities and challenges arising from the relationship between human tactile experiences, mid-air haptic technology, and society's engagement with science. Across five research and practical projects I studied *"how can engagement between science and society be supported by mid-air haptic technology?"* The projects involved different audience groups, such as science communicators, or audiences with sensory impairments. I also considered multiple forms of public engagement, such as live interaction in museums, as well as multimedia experiences; and applied various evaluation or research methods best suited to the type of engagement studied. I ran studies to understand how mid-air haptic technology could serve the needs of both informal and formal science communication. The scientific topics which I used as examples, ranged from more theoretical work, such as particle physics or dark matter research, but also included concepts of environmental science and elementary school geometry knowledge. More specifically, in the preceding chapters, I asked the following four key research questions and discussed the corresponding findings.

10.1.1 A qualitative study with science communicators and mid-air haptics

My initial research motivation has been to identify commonly occurring themes regarding the opportunities and challenges of using mid-air haptics in public engagement, which may guide future research questions. Thus, I dedicated a project (discussed in chapter 5) to working with science communicators exclusively, throughout three focus group workshops, yielding qualitative insights. This study set RQ1: Which features of mid-air haptics are identified as advantageous by *science communicators*, in context of public engagement and traditionally used tools of communication?

My main hypothesis, broken down to six more specific hypotheses, was that mid-air haptics could serve as a new technological solution within the design space of public engagement with science. This hypothesis highlighted the following six specific properties of haptic interaction being valuable to different extent:

H.1 (3D): Ultrasonic mid-air haptic interfaces can display volumetric sensations in *3D* space (Long et al., 2014) and the movement of focal points remains stable during user interaction, unlike levitated tangible pixels.

H.2 (stability): Location and apparent movement of focal points are programmable and undisturbed (Wilson et al., 2014).

H.3 (dynamicity): The force exerted by the touch of the user is not restricting any *moving* components of the haptic system.

H.4-H.5 (interactivity and structure): Integrated hand tracking also allows *interactive* and *structural* haptic sensations.

H.6 (augmentation): Covering the haptic display with an acoustically transparent projection screen (Carter et al., 2013), it is also possible to *augment* the tactile sensations with visualisations.

I further hypothesised that dynamic, interactive, and structural design features of mid-air haptics were the most characteristic of this technology, since three-dimensional and augmented tangible probes have already been addressed. Therefore, the design of my haptic probes directly addressed hypotheses H.3, H.4, H.5, and I eliminated hypotheses H.1, H.2, and H.6 from my analysis.

Counter to expectations set out in the hypotheses, analysis of the qualitative results suggested three opportunistic themes. Firstly, the ability to create dynamic tactile sensations was highlighted as an outstandingly relevant property of mid-air haptic sensations, in contrast to five other hypothesised significant properties. Secondly, it was implied that the shared experiences which the technology affords, by allowing multiple users to engage almost simultaneously, is a relevant opportunity at fast paced public engagement events. This theme signifies a contrast to more isolating experiences, such as VR (Furió et al., 2017), or in the words of a participant: *P1:W2: "VR was cool but it feels limited, because it's one person at a time. This is still one person at a time, but they **can be shared quite easily**. With VR, someone's got the headset on and they have to kind of describe what they're looking at. If you've got a group, it doesn't work as well."*. Thirdly, the characteristic sensation of mid-air touch, in contrast to physical touch may pose an opportunity in storytelling and adapting the same probes to the expectations of various audiences. I built on this notion in chapter 7, when developing a multisensory journey through the dark matter wind in our galaxy.

This project implies that augmenting, or rendering, imperceptible scientific phenomena through mid-air touch, can enhance enjoyment of and interest in science; just like it has been shown with regards to abstract art (Vi et al., 2017) and multimedia (Ablart et al., 2017a). With the aid of sensory technologies, science communicators may be able to expand explanatory metaphors with sensory metaphors and augment their narrative, which in turn may facilitate the learning process (Kendall-Taylor and Haydon, 2016). The case studies discussed in chapters 7 and 8 illustrate the generalisability of the technology in science communication through metaphorical experiences. In other words, the findings synthesised in chapter 5 are not only applicable for the specific scientific concepts explored, and specific haptic probes used, but in other fields of science too.

I found one of the greatest challenges noted by science communicators to be the level of concentration, and potentially long exploration time, required to make sense of the haptic sensation. This challenge initiated conversations on whether mid-air haptics is better suited for informal learning environments, or in a formal setting. In either case, the emphasis on potential advantages of mid-air haptic technology in communicating science shifted towards the hedonic, or affective, domains of the learning process. That is, the enjoyment and interest dimensions within the *AEIOU* framework of science communication were implied as valuable outcomes of interaction with the technology. In planning the next study, I followed up on this notion and opportunity, in the project presented in the subsequent chapter.

10.1.2 A mixed method and mixed modality study with science communicators and the general public

Building on findings of the first exploratory project, I continued by studying the effect of touch on affective responses and hedonic experiences of disengaged audiences, when they were presented with concepts of particle physics. I used a mixed method approach, where both quantitative data was collected through questionnaires, and qualitative data was extracted from participant interviews. I also worked with mixed modality stimuli, i.e. comparing conditions of e-prints, physical touch probes, and mid-air haptic sensations in contrast to only evaluating mid-air haptics. Similarly to the previous project, I worked with science communicators during the first half of the project, although this time, I recruited many more science communicators than before. In the second half of this project, I also involved members of the general public, so that I could directly compare various experimental conditions. The aim was to identify what target affective responses of science communication were, using a rigorous method , and how well these may be matched by different tactile modalities when experienced by disengaged audiences.

Hence I set RQ2: How can we characterise the added experiential value of mid-air haptics for *disengaged publics*, compared to physical touch and print modalities of public engagement? In the first of two studies, the methods of inquiry were predominantly questionnaire based, with structured interviews verifying the preliminary results.

As a result of a three step approach, I identified 18 target affective responses relevant to science communicators. These target items, mixed with other descriptors of human experiences and emotions, enabled us to measure the performance of mid-air touch, physical touch, and no touch stimuli with regards to engaging people in particle physics. Measuring participants' ratings of their perceived affective response, in individual modalities, it was possible to characterise mid-air haptic interaction with concepts of particle physics, in terms of science communication objectives. Due to unforeseen external factors, collecting data from a sufficiently large number of participants was not possible, therefore the correlation studies could not be analysed in any meaningful way. Yet, the data derived from the small sample size suggests that mid-air haptic representation of elementary particles are predominantly "innovative", "entertaining", and help create a "sense of imagination". In contrast, handling plush representations can be best described as "intellectually accessible", "playful", "innovative"; and characterised as helping to create a "sense of curiosity", when reading about the same topic. . Most interestingly, while "sense of imagination" is a target affective response matched by mid-air touch, as one of the most highly rated perceived affective responses, "sense of imagination" scored one of the lowest for the physical touch and no touch conditions. This implies that mid-air touch may indeed be an effective sensory communication modality in public engagement, augmenting storytelling or narration, both of which leverage a sense of imagination to achieve science communication objectives (Dahlstrom, 2014).

10.1.3 A practical evaluation and empirical study of multisensory public engagement activities with the general and sensory impaired publics

In two of the projects, I concentrated more on how mid-air haptic sensations could be integrated in a multisensory public engagement event, rather than how well the mid-air touch modality performs compared to other modalities. I contributed to designing a dark matter experience, to be exhibited in an ecologically valid learning environment, attracting a much larger pool of visitors than it would be possible with inviting participants to a laboratory study. As such, I asked RQ3.1: How can we integrate mid-air haptic sensations in multisensory, live public engagement activities, for the *attentive public*? Throughout two events, I was able to use methods of evaluation cited in literature, in context of a fast-paced field work. The aim was to design a public engagement with science activity, where all of the five primary senses of visitors are stimulated through state-of-the-art technology.

On the one hand, I was interested to find out whether mid-air haptics would stand out in any way from the experiential point of view, when presented alongside other sensory stimuli. On the other hand, I wished to see whether data-driven stimuli, such as the visual or audio track, would receive qualitatively more positive feedback than the metaphorical sensory stimuli, such as touch or taste. Touch received no outstanding mention in the evaluation of senses. However, I found that metaphorical sensory experiences enable interested lay publics to engage with the scientific concepts. In this respect, metaphorical experiences are not less than data-driven sensory experiences. I have seen that the sense of taste, delivered through sugar pills, contributed enjoyment to the experience, sometimes more than the sound track generated from real dark matter data. Some participants were unaware of the cutting edge sensory technology they have experienced, as this was masked by the overall theme of dark matter. Since haptic technology is not as widely known in the public as audio-visual user interfaces, multisensory science events could also create an opportunity to engage the audience with how an experience was curated for them. While many people will be interested in topics, such as astronomy, less people will volunteer to engage with subjects of HCI technologies which they have not heard of. Thereby, multisensory science communication might facilitate an event-in-event approach, where engineering or technology communication is embedded in more popular public engagement with science.

Similarly, a second multisensory public engagement experience was designed to be deployed in a commercial setting, but with two small user studies backing up the design decisions. An immersive documentary on oceans and renewable energy was curated in collaboration with the Aquarium of the Pacific and Ultraleap Limited. A key difference compared to the dark matter experience is that this project was addressing a specific subset of the attentive publics, those who actively search for and participate in science content, but also have a sensory impairment. Thus, the multisensory integration served purposes of inclusive and accessible multimedia for disabled audiences. The mid-air haptic sensations integrated with the audio-visual material were developed, with the inclusion of vision and hearing impaired participants. Hence, I also asked RQ3.2: How can we integrate mid-air haptic sensations in multisensory, multimedia public engagement activities, for *sensory impaired audiences*? Initial feedback following installation has been positive, although no formal and controlled evaluation was planned on site. Although, the blind and deaf participants expressed a preference for visual-haptic match versus an audio-haptic match, users were enthusiastic about the potential for haptics to communicate more musical information, such as pitch, loudness, or instrument types. This enthusiasm for mapping touch and sound has been noted by other researchers too, such as by Nanayakkara et al. (2009). The user study, on determining the preferred match of information modality in the multimedia content, also gave rise to discussions on what other content could haptic stimuli match. For example, the character-haptic match approach was proposed, where identifiable haptic sensations can be matched with personalities of various characters.

In both of the projects to be deployed in a ecologically valid learning environment, I aimed to emphasise opportunities and challenges of evaluating the integration of mid-air haptics into multisensory science communication. Thus, I asked RQ3.3: How can we evaluate the effectiveness of multisensory public engagement activities in informal learning environments? With regards to the dark matter experience, our evaluation, with the use of the sensory matrix, highlighted that ergonomics is a key consideration when planning evaluation methods, which require complex decision making. Complaints and concerns with regards to not perceiving the tactile or olfactory stimuli, and the diverse dietary requirements of the taste stimuli also open up new questions, in terms of evaluation methods. For example, how do we set intensity levels of a sensory stimulus, such that it is perceivable for elderly, without being too intense for younger participants?

With regards to the Aquarium of the Pacific project, my co-authors were able to carry out cognitive absorption measurements, evaluating the experience of participants. This is helpful in designing the multisensory content, but much less feasible during the evaluation of an on-site activity. It is also important to note, that during the user study, participants had access to the full mid-air haptic sensation and the audio content. However, the lack of cinema quality speakers, rumbling chairs, and the social setting, might have skewed the overall experience in favour of mid-air haptics. A notable and unexpected outcome is the observed role reversal in the dynamics of post activity conversation. Instead of carers filling in potentially missed information by sensory impaired users, the users themselves could share their own experiences with the sensory technology. The extent of such role reversal, if correctly quantified, leaves an opportunity for evaluating the effectiveness of multisensory experiences in science communication.

In both practical projects, I had to face the lack of consensus on how to evaluate public engagement activities, by academics and practitioners alike. This prompted further review of the evaluation literature, as will be briefly discussed in the following section.

10.1.4 A mixed method study of mid-air haptic shape recognition in formal science learning environments

The work discussed in chapter 9 originates from an observation made during the focus groups discussed in chapter 5. Namely, participants appeared to recognise more often and more confidently a sensation to be a circle, if it was displayed as a haptic focal point moving around a circular path, rather than displayed as a full outline. The aim was to verify the hypothesis; that a dynamic tactile pointer would be a more accurate and confidence creating method of rendering geometric tactile shapes than more conventional methods, such as rendering 2D patterns via spatiotemporal modulation. If such a claim was proven, it would offer stable grounds for involving participants with vision impairments in a user study, and researching how mid-air haptics may eliminate some limitations of tactile graphics. For example, whether mid-air haptic sensations could assist novice users of tactile graphics in interpreting complex graphical content. However, prior to direct comparison of mid-air haptic sensations and tactile graphics, evaluated by visually impaired participants, it was necessary to better understand the factors influencing shape recognition in mid-air.

Ultimately, I wanted to find out answers to RQ4: How can we apply mid-air haptic technology in formal learning environments, such that it is comparable to other technologies used for learning, by *vision impaired* learners and researchers? This referred to both students in schools, and researchers at academic conferences. In this project, I carried out two in-lab user studies and two pilot studies with members of the general public. Firstly, experiment 1 confirmed that dynamic tactile shapes are more accurately recognised than static tactile shapes. Secondly, pilot studies helped with finding optimal parameters of temporal segmentation of the haptic sensations. Thirdly, experiment 2 concluded that dynamic tactile shapes composed of multiple haptic strokes, rather than rendered as a single continuous haptic stroke, are more accurately recognised. Based on my findings, it is recommended that mid-air haptic devices render two-dimensional geometric shapes through the use of a dynamic tactile pointer, instead of displaying the full outline of the shape. I also recommended breaking down polygons into discrete sides, by interrupting the movement of the pointer at the vertices.

These results are comparable to accuracies measured for mid-air haptics displaying 3D shapes (Long et al., 2014), as well as studies using raised pin arrays (Kaczmarek et al., 1997), and vibro-tactile displays (Ion et al., 2015). Yet, further studies of parameter optimisation are desirable, prior to direct comparison of tactile graphics and mid-air haptics, recruiting vulnerable participants in an experiment on geometry instruction. Importantly, the technology may be capable of some necessary requirements of assistive technologies, for visually impaired distance learning children. As my (accepted but cancelled) demonstration at an academic conference on haptics and accessibility illustrates, mid-air haptics may also be useful in formal learning environments, other than in schools. Expert audience members, with sight loss, at a scientific conference may gain access to visual content of educational material, through the use of closed haptioning. Some of the challenges of tactile graphics and potential opportunities of mid-air haptics will be discussed in the next section, as avenues of future research.

10.2 Directions of research progression

One of the outcomes of this PhD, was the synthesis of new research avenues on the intersection of haptics and science communication, based on the initial charting of opportunities and challenges. On one hand, the study of shift in attitude, mediated through mid-air haptic technology, by means of mathematical modelling would be a significant contribution to the psychology or sociology of multisensory science communication. On the other hand, the systematic study of how mid-air haptic technology may complement, or overcome, some of the challenges of tactile graphics in geometry teaching for visually impaired students would be useful. Thirdly, I believe there is merit in developing methods of systematic evaluation of multisensory public engagement events, and verifying these methods in ecologically valid science learning environments.

10.2.1 Predictive models of shifting attitude towards science in informal learning environments

In chapter 2, I introduced the notion of multiple levels of interaction between science and society. I argued that high scientific literacy and fostering scientific culture is desirable because of the economic, utilitarian, cultural and democratic benefits that come with them. Public Awareness of Science (PAS) may be regarded as a prerequisite – in fact, a fundamental component of Public Understanding of Science (PUS) and scientific literacy. The study of scientific culture, scientific literacy, and even public understanding of science is a complex, sociological process, making it difficult to investigate in a laboratory setting. However, the simplest level – PAS – may afford inferential conclusions drawn from studying individual members of the public.

PAS can be defined as a set of positive attitudes toward science (and technology) that are evidenced by a series of skills and behavioural intentions. The public is often segmented, based on their attitude towards science, where measurements of the state of attitude are typically done via large scale national surveys. The attitude of public segments is one of the predictor variables of behavioural intentions, alongside other social factors, such as how much effort it is to acquire scientific content, or what is the peer or family attitude towards science. Throughout chapters 5 to 8, the vowel framework plays a key role in my analysis too. To enable interaction between science and the public, science communicators aim to use appropriate skills, media, tools and dialogues to produce personal responses to science, such as Awareness, Enjoyment, Interest, Opinion Forming, and Understanding.

Since both the vowel framework and attitude are built on shared constructs, such as affection or cognition, an interesting question arises. How does changing factors of the vowel framework impact the state of attitude?

In mathematical terms, attitude can be thought of as a 3-vector, having direction and magnitude. Attitude can be positive or negative, strong or weak, but it is also variable. It has three components: affective, cognitive, and behavioural (Schäfer et al., 2018). These components may be defined and altered by the experiences of an individual. In context of science communication, the experiences may be created by the modalities of science communication. The three streamline methods of traditional journalism, live interaction, and online interaction; including further distinctions between a live talk, or a short 'hands on' activity will hypothetically create different experiences. At an abstract level, the experience may be defined by an experience matrix, which facilitates the attitude shift by transforming personal responses into components of attitude.

This gives rise to two hypotheses. Firstly, that different methods of science communication will have unique experience matrices. Secondly, that the experience matrix will act as a transformation matrix on the vector of personal responses, in such a way that it can directly impact the initial state of attitude. If so, the shift in attitude could be quantified and mathematically modelled, using appropriate predictive methods of inferential statistics. Assuming that a single experience has a short term effect, acting as an *impulse on the state of attitude*, we can make a further hypothesis. Using the values of experience matrices as prior probabilities, it may be possible to define long term impact of the experience itself on attitude, acting as *momentum on the shift in attitude*.

Given there is a correlation between components of the V vowel framework on attitude, we could model a predicted shift in attitude as a result of repeated experiences:

$$A' = A_0 + \Delta A + \epsilon, \tag{10.1}$$

where A' is the predicted, new attitude, A_0 is the initial attitude measured, ΔA is the effect that changes attitude, and ϵ is a latent variable, which may affect attitude shift beyond the vowel analogy.

We expand this to a vector equation:

$$\vec{A}' = \vec{A}_0 + \mathbf{X}\vec{V} + \epsilon, \tag{10.2}$$

where $\mathbf{X}$ is an experience matrix, and V is a vector of the vowel analogy.

Expanding to dimensions, where a means "affection", b means "behaviour", and c means "cognition", we get:

$$\underbrace{A'}_{a',b',c'} = \underbrace{A}_{a,b,c} + \underbrace{X}_{3\times 5}\underbrace{V}_{5\times 1} + \underbrace{\epsilon}_{3\times 1}. \tag{10.3}$$

We see that ΔA is a 3-vector, as a result of transforming a 5×1 vector, using a 3×5 transformation matrix. We also see that elements $X_{i,j}$ are the weightings, where $i \in \{a, b, c\}$ and $j \in \{A, E, I, O, U\}$. Setting estimated, prior probabilities for the initial $X_{i,j}$ elements as weightings, a recursive model of updating probabilities may be able to optimise these values. Measuring A_0 and V, and simplifying with $\epsilon = 0$, A' could be predicted. Determining ϵ would account for factors influencing attitude, outside the vowel framework, such as shared vs. individual experiences.

It is important to acknowledge that the underlying dimensions of attitude and personal responses are difficult to use for generating quantitative measurements. Without measures of individual components, a mathematical analogy describing the processes of attitude shift can be established, but the analogy is limited in its use as a functional mathematical model. However, similar predictive modelling has been done in HCI in recent years. Aymerich-Franch et al. (2019) used Bayesian inference to predict embodiment of robot avatars, through the measurements of independent factors, such as sense of ownership, guilt or shame in a study on the ethics of communication.

10.2.2 Evaluating the utility of mid-air haptic technology augmented tactile graphics in formal learning environments

"Graphicacy" is a term used for describing literacy in reading and interpreting graphics, incorporating non-verbal displays, such as diagrams, charts, maps, or graphs. This skill is expected from all educated adults, including those who are impaired in their vision (Sheppard and Aldrich, 2001). To enable visually impaired learners in using graphics, the most widespread alternative to date is presented in form of tactile graphics produced on paper. Multiple methods of creating tactile graphics exist, two of the more popular ones being Swell Form and embossing techniques. In the former, chemically treated paper is subjected to high heat, resulting in the swelling of paper covered in graphite based ink. In the latter, mechanically intruding pins leave indentations on paper, in the style of dotted lines assembled from tactile points, similar to braille marks. Although other methods exist too, for example thermoform, they all have challenges that can be classed into two major categories: production technique, and information content.

The choice of production may depend on the purpose of the tactile graphics, considering factors include durability, number of distinct textures required, or the need of text labels (Sheppard and Aldrich, 2001). Challenges of information content arise from the differing perceptual abilities of the tactile and visual senses – visual graphics cannot be translated directly into tactile equivalents, due to the 500 times lower bandwidth of touch (O'Modhrain et al., 2015). Aldrich and Sheppard (2001) and Sheppard and Aldrich (2001) reported studies on students and teachers perspectives on using tactile graphics in schools. Somewhat unsurprisingly, it was found that more complex tactile graphics, with high level of details are less usable by blind children. When 40 students were asked, they preferred three prominent alternatives. These were verbal descriptions of the graphics, splitting a large tactile graphic into multiple smaller ones, or layering information by placing multiple tactile graphics on top of each other in increasing complexity. With regards to layering information, mid-air haptic technology may have an opportunity to play a role, as briefly discussed in chapters 5 and 9 in context of mid-air haptic augmentation. Simpler content of tactile graphics could be augmented with additional mid-air haptic sensations, such as added tactile points, simple shapes, or even simple haptic animations. Teachers also expressed an observation, where students seemed to struggle with relating the 2D tactile graphics with 3D concepts, such as conceptualising the shape and location of human organs (Sheppard and Aldrich, 2001). Mid-air haptic augmentation could, to some extent, offer solutions, where a 3D mid-air haptic sensation of a sphere is hovering over the 2D sketch of a spherical object. This would make mid-air haptics comparable to force feedback displays, in the analysis of O'Modhrain et al. (2015), where multiple haptic displays were discussed with regards to their suitability for displaying tactile graphics. Here, force feedback displays were the only haptic displays affording 3D tactile interaction, but without some of the benefits attributed to pin arrays, where the tangential and normal cutaneous forces are believed to contribute to the effectiveness of these displays. As such, mid-air haptics affords 3D tactile interaction with the added benefit of cutaneous stimulation.

Teachers also suggested that communicating mathematical shapes could benefit from being drawn stage by stage to enable a child to "understand" the building up of the picture, rather than (being) faced with the end product (Sheppard and Aldrich, 2001). This suggestion could be a well suited hypothesis and research direction, building on my work presented in chapter 9. What I claimed is that a stage by stage building of simple geometric shapes is more accurately recognised by sighted participants, with no experience in interpreting tactile graphics. Another unexpected finding of the research by Aldrich and Sheppard (2001) is that enthusiasm of working with tactile graphics and its perceived usefulness correlates with age. While younger children (age 6) still enjoy the process of creating tactile graphics and reading these, the older students (age 19) find it very frustrating, or useless overall (Aldrich and Sheppard, 2001). This effect was attributed to the fact that as students age, they are encountered with increasingly complex tactile graphics, which are difficult to use. Considering the remarks made by science communicators in chapter 5, whereby children of age 6 have very different needs than late teenagers, the introduction of mid-air haptic augmented tactile graphics could counteract this loss of enthusiasm. Just like how balloon models of viruses can enthuse younger children, while teenagers find tech savvy solutions more engaging; one could assume that this effect is transferable to the perception of using tactile graphics with teenagers.

In addition, during a conversation with Dr Grecia Garcia Garcia, a researcher studying tactile graphics, I learnt further challenges of tactile graphics design. On one account, participants appear to struggle to trace back points of interest on a curve to markings on the axes when reading tactile graphs. Although designs have been proposed to overcome this challenge, for instance by introducing a guiding grid, the question presents itself – would using mid-air haptic sensations as auxiliary tactile feedback help in this task? With the advent of mid-air haptic technology, it may be possible to stimulate hairy skin just as well as glabrous skin. This would make possible systems, where the fingers are tracing tactile graphics, while parts of the hand, other than the finger tips and palm are stimulated using haptic ultrasound. Hybrid systems of this design could assist novice users of tactile graphics in the training process. Just like tactile graphics alone is labour intensive (Sheppard and Aldrich, 2001), most likely mid-air haptic displays will also require time and specific skills, but it could resolve challenges, such as durability, replicability, or share-ability of tactile graphics. Therefore, future research investigating the role of mid-air haptics in tactile graphics design may ask a number of different questions. How does static tactile graphics shape recognition perform in contrast to dynamic mid-air haptic shape recognition in 2D geometries? How would older students perceive the usefulness of mid-air augmented tactile graphics? How would mid-air haptics aid tactile graphics users in specific tasks, such as tracing points to axes?

10.2.3 Evaluation of multisensory public engagement

Evaluation is a key component of public engagement with science, throughout the entire development and delivery procedure. Evaluation is not just about "how did we do at the end", but about evaluating the process of product development. During my studies, I attended a series of masterclasses on science communication, hosted by the Societal Engagement team at Imperial College London (Societal Engagement at Imperial College London, 2020). The masterclass focusing on "Planning and Evaluation", highlighted the stages of the evaluative process, which include the following:

Front-end evaluation: Evaluating the target audience, and their engagement habits. For example, what do audiences engage with, and where can they be found?

Formative evaluation: This stage involves pilot testing and iterations.

Summative evaluation: Here science communicators need to ask – how did the product of public engagement perform?

This three stage philosophy of evaluating public engagement with science is similar to the "formative" and "end-user evaluation" breakdown of user experience (UX) research. Summative evaluation can be done for both output and outcome, where output measures the number of people reached and their demographics, and outcome measures how well the aim of the public engagement was matched. In context of this thesis, at the dark matter experience, I conducted a formative evaluation in the form of the 2018 pilot event; however, only output was measured and no strategy was developed for measuring outcome. An interesting point of discussion, with regards to these stages of evaluation, is how we could apply the same framework in light of public engagement through the tools of multisensory HCI. However, consulting literature on evaluation methods within public engagement shows that, as of this date, there are no standardised indicators of evaluation, which could be adapted or built upon to fit requirements of multisensory activities (Neresini and Bucchi, 2011).

While teaching and research have standardised indicators to evaluate performance, public engagement is still thought of as a goodwill exercise. Generally speaking, this raises the question whether science communication can be integrated in the value system at the organisational level of research institutions, or whether it remains a sidekick activity. Publics do not interact with science as a macro establishment, but rather with individual scientists at the micro level. Research institutions may, therefore, play an important role as an intermediate stakeholder in managing evaluation methods of public engagement (Neresini and Bucchi, 2011). Organisations may motivate high quality and quantity science communication through rewarding achievers with promotions in their academic status. It is widely recognised that evaluation can be particularly useful for an organisation to systematically, and critically, reflect on its own activities rather than for plainly measuring the achieved results (Neresini and Bucchi, 2011). Yet, Neresini and Bucchi (2011) showed that across European research institutions, the majority of organisations do not have any form of science communication, let alone evaluation of their public engagement. Out of 129 physical and biomedical institutions approached by researchers, only 40 participated in a study looking into indicators of successful public engagement. Questionnaire data and public websites revealed correlations between the size of organisation and the existence of a PR office, amongst other indicators, and how strategically public engagement is embedded in an organisational structure. More importantly, only one out of twelve institutions studied in the second phase of the study actually turned out to be doing systematic evaluation of its public engagement efforts. Additionally, five institutions occasionally put into place evaluation of specific initiatives, mostly through self-administered questionnaires to participants immediately after the conclusion of each initiative. Nevertheless, 25 out of 48 staff members interviewed have recognised the importance of evaluation in this area (Neresini and Bucchi, 2011). A similar lack of standardised evaluation can be observed in public participation methods, such as referenda and civil forums, where public representatives are involved in policy or decision making (Rowe and Frewer, 2000).

Numerous organisations (National Co-ordinating Centre for Public Engagement, 2020; Royal Academy of Engineering, 2020; University of Manchester, 2020; Imperial College London, 2020) have created and have actively promoted various evaluation toolkits. Many of these practical resources focus on front-end (planning) or summative types of evaluating public engagement activities. The emphasis is mostly on evaluating the range and size of audiences reached, assessing learning outcomes and shifts in opinions, but little is evaluated in terms of "user experience". For instance, evaluative questionnaires published as part of public engagement toolkits do not question visitors experience in line with the dimensions of the $AEIOU$ framework. Neither do these tools specifically evaluate public engagement activities in terms of science communication objectives, such as those that we identified in chapter 6. Perhaps the use of questionnaires, such as the "DARTS-2" questionnaire, which we developed for the purposes of a user study on touch, is too specific to be used as a generic evaluation tool. Nevertheless, the approach I present with regards to identifying and separating hedonic and pragmatic objectives of science communication, and evaluating these in a targeted manner, could benefit existing evaluation toolkits. I see merit in introducing evaluation techniques of user experience seen in the field of HCI, such as those synthesised by Vermeeren et al. (2010), into the field of science communication. Developing new evaluation methods and researching the effectiveness of these, on the intersection of UX and public engagement, could benefit both communities of academics and practitioners of HCI and science communication. Suggestions by Grand and Sardo (2017) have the potential to introduce considerations of ecological validity of public engagement events into UX research. Similarly, the multitude of techniques discussed by Vermeeren et al. (2010) have the potential to expand the toolkit of public engagement teams with regards to evaluating their activities.

10.3 Limitations of this doctoral thesis

To chart opportunities and challenges of a new technology in a specific application area, it was necessary that I consider a broad angle of research projects. A drawback of this approach is that it encompasses limitations, which are the result of absent in-depth studies of some very specific research conditions.

I am aware of a shortcoming related to the qualitative work done with science communicators, presented in chapter 5. Although the research synthesised three likely opportunities of mid-air haptic interaction in public engagement, it did not provide any verification of these themes. For example, I did not explicitly verify whether mid-air haptic displays enable a superior shared experience for groups of users compared to VR environments, or tangible probes, as suggested by the analysis. Supporting the qualitative results with quantitative evidence collected by means of a user study would have required resources of additional skill and time, which I did not have in the collaboration. To test only one of three claims thoroughly, it would have been necessary to recreate the same scientific concept and narrative using 3D printing and VR multimedia creation, beside the mid-air haptic equivalent. There have been plans for short term, or even longitudinal studies in public spaces, to test the other two claims about dynamic tactile sensations and storytelling. Both of these attempts proved to be a disproportionately demanding task, when I considered various experimental protocols. Thus, the collaboration chose to pursue a related, but different research direction, instead of verifying the qualitative findings of this project.

With regards to the project discussed in chapter 6, I must highlight one major drawback. I followed a three step process to acquire a reliable set of target affective responses from science communicators. In the second study of the project, the main aim was to find out what the perceived affective responses of users were, when learning about particle physics through three distinct communication modalities. Even with a smaller number of participants, I could characterise the separate modalities, in terms of descriptors of experience used. However, an additional aim was to find out which modality had the highest match score between target and perceived affective responses, within the disengaged audience group. I was searching for signs of a correlation between perceived experiences of mid-air haptics and different audience groups. Hundreds of participants were necessary, since I needed to filter participants attitude towards science into groups of “disengaged”, “interested”, and “specialists”, similarly to national surveys of public attitude towards science. I was going to start data collection during face to face user studies, when the global pandemic broke out, which hindered this effort and left us the option of only running a small scale pilot study.

In the context of the dark matter experience, and the Aquarium of the Pacific project, I find it very valuable to intertwine practical observations with empirical research findings in the overall thesis on this topic. Yet, it is a limitation of the findings, that I have not compared the effects of two different conditions on a specific dependent variable, such as the hedonic qualities of the experience with and without integrated mid-air haptic sensations. Although such an experimental design was considered, it was not recommended by the event host and research collaborators with more experience in public engagement. Previous experience of Prof Trotta, as well as the staff in the London Science Museum, suggested that controlled studies at crowded public engagement venues are unlikely to provide reliable and useful data for analysis. What is more, attempts to run controlled experiments in public spaces may also subtract from visitors overall experience, which is unethical. Unlike in previous projects, the goal was to integrate mid-air haptics in a fully multisensory experience, and evaluate the overall outcome. Even if research approval is obtained, valid experimentation at science communication events are very challenging, and may even take away from visitors overall experience which is unethical. Thus, my co-authors and I decided to run a pilot and a longer, improved experience, and rely on observation and evaluation methods suggested by other experts in our own context.

On the contrary, it is a limitation that the cognitive absorption measurements of the Aquarium of the Pacific project were conducted in a lab setting. This may not fully apply when the multisensory multimedia content is showing in the movie theatre, but to perform controlled studies, it was necessary to recreate the experience in the lab. It is also unlikely that we can generalise the findings to the entire community of sensory impaired people, since 6-8 users in a sample is not sufficient for statistical testing of claims. However, it is important to acknowledge the difficulty of recruiting disabled research participants (Lazar et al., 2017a). It is also important to note, that both the dark matter experience, and the Aquarium of the Pacific experience were managed and published as case studies, with the aim to bring attention to multisensory science public engagement. With a sufficiently large set of case-studies, a future research project would be able to carry out a meta-analysis of the individual findings.

There is also a shortcoming of the studies presented in chapter 9. Due to travel restrictions in 2020, I was unable to demonstrate the concept of “closed haptioning” at Eurohaptics 2020, and organise a systematic evaluation of using mid-air haptics for accessibility in a formal learning environment. The project showed that higher pattern recognition can be achieved with the tested method of haptic rendering – a result intended to have applications in formal learning environments. However, I could not verify how effective mid-air haptic displays were in communicating the research findings, in contrast to a video demonstration. Gathering data from a specialist audience on rendering visual animations with a dynamic tactile pointer could have provided valuable opportunities for discussing new, but related, research directions. This does not subtract from the value of the presented research findings, but limits the extent of inferences on how effective the DTP rendering method would be in academic conferences, or schools, in terms of accessibility.

10.4 Summary of implications and contributions

Despite these limitations, the exploratory studies and new research directions presented in this thesis offer a valuable starting point for other researchers, in the intersection of haptics and science communication. I foresee future applications of mid-air haptic technology alongside other user interfaces, in both formal and informal learning environments, educating and entertaining, both abled and disabled audiences alike. One implication of this thesis is how effectively science communication can leverage the spectrum of haptic interaction, enabled by mid-air haptic technology. My findings imply that only one of six hypothesised properties of mid-air haptic sensations is significantly beneficial in representing natural phenomena, and this is the property of interaction with dynamic tactile sensations. While interactive or structural haptics appears to be less important, science communication may leverage the way multiple people can easily exchange the haptic sensations projected in mid-air, without handling physical objects. Another implication is how practitioners may create effective multisensory experiences in engaging with science, in ecologically valid environments. Mid-air haptic sensations are most effective when other sensory channels clearly set the context, such as a voice-over narrating a metaphorical journey through the galaxy, or the scenes are audio described for the visually impaired. The results of case-studies also imply that metaphorical sensory information is sufficient to be effective in meeting the objectives of science communication, and there is little need for the sensory experience to be data driven. A third key implication is that mid-air haptic technology may also be effective in conveying specifically intended scientific information, such as a geometric shape, or physical properties of an elementary particle.

Figure 10.1 shows an infographic, which summarises the findings of this thesis. Along the vertical axis, a segmentation shows concise sets of findings, associated with individual projects from chapter 5 to chapter 9. The horizontal axis is segmented into three broadly different audience types, based on their expectations and needs, i.e. science communicators, the lay public, and vision impaired audiences. The individual fields of text summarise how mid-air haptic technology may meet the needs of these user groups, based on the project findings. The infographic shows additional associations with further segmentation of the three broadly different audiences, illustrating narrower classifications, such as the disengaged lay public, or attentive vision impaired audiences. Furthermore, indications are shown with respect to whether the findings are relevant in informal or formal learning environments. The legend of Figure 10.1 denotes the meaning assigned to the colour and shape scheme applied to the fields of text.

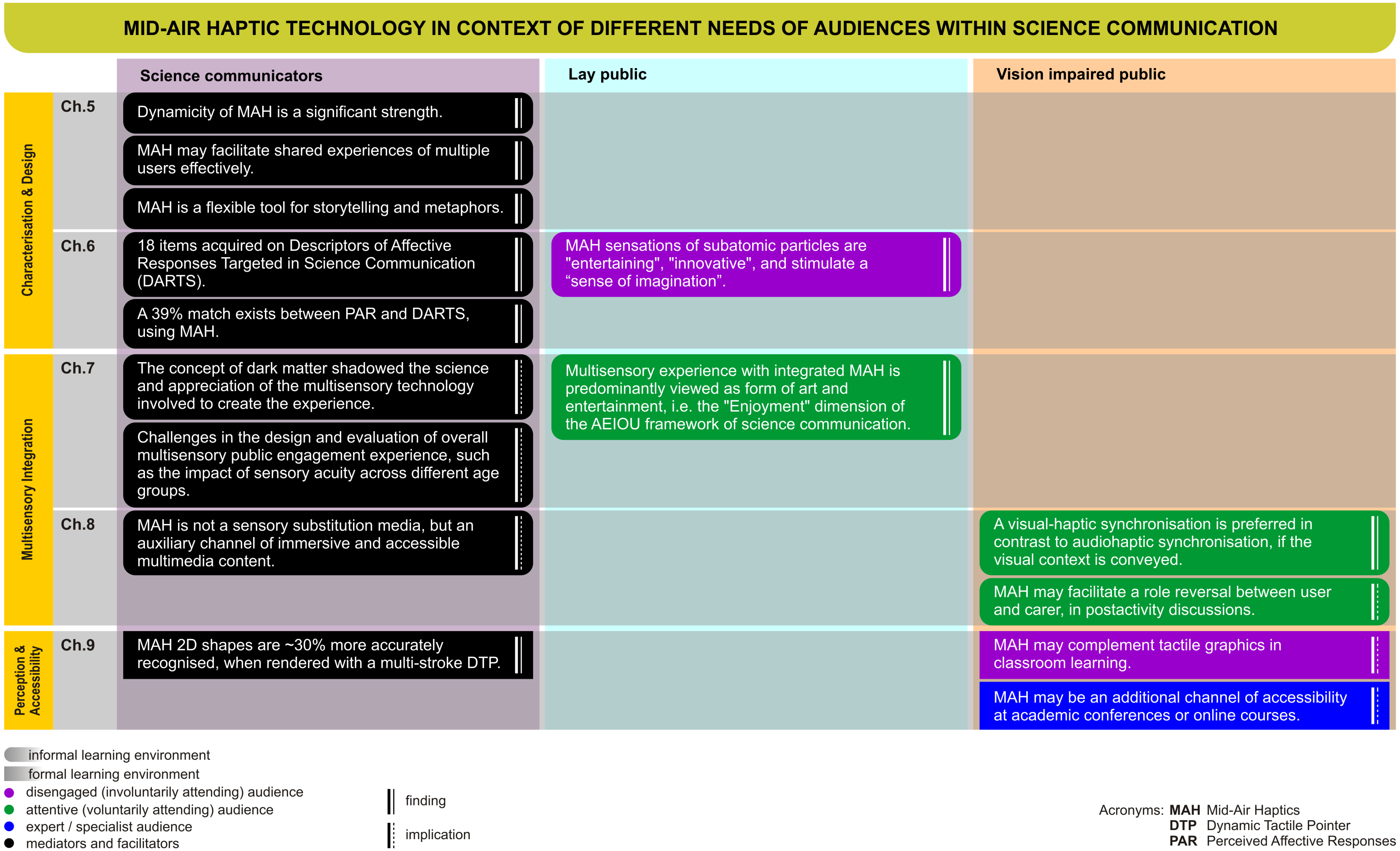

Figure 10.1: Infographic of project findings across the thesis.

In summary, this dissertation makes a two-fold contribution to the fields of haptics and science communication. Firstly, by characterising ultrasonic mid-air haptic technology in the context of public engagement with science objectives, and the needs of different audiences. Beyond the afore-mentioned themes of leveraging haptic interactions afforded by the technology, I also characterise mid-air haptics in terms of perceived affective responses. Secondly, by developing and verifying a more effective method of rendering mid-air haptic sensations, capable of conveying information relevant to scientific concepts. The DTP haptic rendering method has become an active research interest of Ultraleap Limited, and as part of the company's research team, I am carrying out further studies on this contribution. While optimisation of DTP sensations for rendering haptic icons remains an active research topic, this thesis also shows that DTP style sensations can be effectively used to convey information about elementary particles, such as charge, spin, or mass. In my concluding remarks, I will elaborate on the overall merit of carrying out my PhD studies and writing up this dissertation.

Chapter 11

Concluding remarks

"Our passion for learning ... is our tool for survival." – Carl Sagan in his popular book "Cosmos" (Sagan, 1985).

Section 10.1 of the previous chapter stands as a technical summary of the research questions, and corresponding findings, presented in this thesis. Therefore, in this short closing chapter, I am synthesising a few concluding remarks, mostly focusing on the overall PhD experience and its contribution to my science identity. Despite the limitations of this thesis, considering the circumstances and timeline of the PhD degree, my collaborators and I achieved a considerable amount of self-improvement and academic contribution. With regards to self-improvement, I spent considerable time on acquiring a wealth of knowledge on science communication, the biology and psychology of touch, haptic technology, and Human-Computer Interaction. This, in perspective of coming from a physics background rather than psychology, computer science, or social science, can by itself be considered a worthwhile investment. I studied topics at the intersection of three multidisciplinary fields of science, which is difficult to achieve in other levels of higher education. I also gained valuable skills of working with research participants and conducting qualitative research, as well as the basics of statistical methods of analysis. Furthermore, I learnt the process of writing and publishing academic papers, collaborating with other scientists, and used technical collaborative tools.

Although costing time and energy through multiple aborted research proposals, early stage projects also taught me that not every idea turns into an opportunity in science. Writing this thesis also helped me see how the start of a scientific path can evolve, opening up new research directions, and highlighting the value of previous findings retrospectively. As the past 9-12 months also evidently showed us, academic research may be hindered by external factors beyond our control, such as a global pandemic. As a result, a large percentage of the three year long PhD degree was spent on initial studying, disseminating research findings, more administrative and logistic tasks, re-designing projects, or simply compiling a coherent thesis.

However, I feel that the time that was spent on research in its scientific sense, made a small but valuable first exploration of the opportunities and challenges a novel haptic technology may have in public engagement with science. I studied how science communicators see ultrasonic mid-air haptic technology in context of science communication, and how well the interface can be characterised, in terms of science communication objectives. We were able to integrate mid-air haptics, on multiple occasions, into multisensory science communication experiences, at live shows or in cinemas, evaluated by multiple user groups in a practical setting. What is more, I made the first steps into exploring how mid-air haptic technology could serve the needs of visually impaired learners in formal environments, such as a school or an academic conference. There is a lot more research that could be done to follow up on our preliminary findings, as discussed in the previous chapter. What this thesis really aims to achieve is to introduce ideas of science communication, haptics, and Human-Computer Interaction to each other, and chart a new research landscape. The marriage of engineering, computer science, psychology, and visualisation, empowered society to gain access to higher levels of computer literacy through HCI. With the marriage of the disciplines discussed in this thesis, i.e. multisensory HCI focusing on science communication, it might mean that even people who are not highly trained will be able to appreciate and benefit from science, through an emerging field of *Human-Science Interaction*.

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Appendix A

From voltages to tactile patterns: A system description of ultrasonic mid-air haptic displays

This appendix is intended to help on-boarders to understand how ultrasound is used to create tactile sensations, using the example of a circle path. The objectives of this appendix are:

1. to introduce a distinct, and universally accepted terminology relevant to the Ultrahaptics system;
2. to distinguish between different types of *"emitters"*, *"modulations"*, and *"renderings"* in one place;
3. to provide simple term, lay man analogies, assisting with understanding the tactile stimulation – from voltages to recognising tactile patterns in mid-air.

A.1 About the hardware

At the heart of ultrasonic mid-air haptics is the ability to create and direct sound waves.

A.1.1 Ultrasonic radiation and the phased array

Generating the acoustic field The device (UHEV1) consists of 16x16 ultrasonic transducers, operating at 40 kHz. What this means is that electric potential difference (voltage) makes the actuator, a piezo crystal, expand and contract 40000 cycles a second. The crystal is coupled to a cone, with a specific geometry and physical property. The vibration and slight deformation of the cone gives rise to pressure variation in the transducer-air interface, igniting ultrasonic pressure waves.

Phase delays, focal points and control points Pressure from a single transducer is not sufficient to apply the necessary force on the air-skin interface to deflect the skin, therefore the sum of pressures from multiple transducers is a requirement. Pressure is summed over in a defined position by applying phase delays in transducers, arranged in an array. This means, assuming transducers to be a point source, that wavefronts of semi-spherical pressure waves coming from multiple transducers will interfere at the same position at the same time. This point is referred to as a focal point (from the acoustic point of view) or a control point (from the phase delay algorithm point of view). Given the large number of transducers, the acoustic field becomes very complex, and multiple interferences are introduced. The unwanted interferences are secondary focus points. This unwanted regions of high pressure can be minimised with counter measures.

Depending on the cone specifications, transducers will have different directivity functions, which will influence phase delay calculations, besides other parameters, such as distance between transducer and control point, or speed of sound. It is important to understand, that the ultrasonic phased array is similar, but not quite the same as electromagnetic phased arrays, for example used for radar. Radio wavefronts can be steered multiple ways. Either by emitting electromagnetic waves in a single antenna and mechanically move the radar dish, or use a phased antenna array. In the case of a radar array, the phase delays in subsequent transverse waves can be used to steer the wavefront in a specific direction. With the longitudinal pressure waves of the ultrasonic transducer array, the phase delays enable high pressure, interference regions but do not steer the sound wave.

Sample rate – from transducer cycle to control point cycle The sample (or update) rate defines how fine control we have over the transducer cycle. If the sample rate is 40 kHz, we can control every transducer cycle within a second. If the sample rate is 16 kHz, we can only change the state of every 2.5th transducer cycle.

A.2 About focusing sound into perceivable tactile sensations

Creating an acoustic field of phase delayed ultrasonic waves is only useful if we are able to do it in such a way that at a well defined position, a high enough sound pressure is built up and it's also perceivable for human mechano-reception. For this, three control mechanisms are needed: emitters, modulations, and renderings. In simple terms, emitters tell sound waves coming from transducers how to behave and where to meet. Modulation tells the gathered sound waves (a focal point) how to become perceivable for humans. Rendering tells focal points how to move or distribute to form more complex tactile patterns.

A.2.1 Type of emitters

An emitter is an instruction to tell the transducers where to focus sound, and what kind of sound. There are two types of emitters known to us. An Amplitude Modulation Emitter (AME) and a Time Point Streaming Emitter (TPS).

Amplitude Modulation emitter (AME) The Amplitude Modulation Emitter (AME) passes two parameters to the transducers. The maximum intensity (proportional to the square of amplitude), and the intensity modulation frequency. This type of emitter can not be repositioned while it is firing. In order to reposition the focal point, the emitter must be stopped, repositioned, then restarted. The modulation frequency of intensity can be set to various wave forms, such as a binary step function, a square wave, or a sinusoidal.

Time Point Streaming (TPS) emitter The Time Point Streaming (TPS) emitter extends the functionality of the AME, by enabling the repositioning of focal points without stopping the emitter. This means, the emitter can dynamically update the instruction sent to transducers on five parameters, including the 3D spacial coordinates, modulation frequency and maximum intensity. As we will see shortly, this enables a modulation technique where intensity can be fixed and modulation frequency set to 0. This is because the ability to update position will take over the role of modulation. Important to note, while the TPS emitter enables spatiotemporal modulation (STM), it is not one and the same concept. A TPS emitter can also be used to amplitude modulate the focal point, see for example the Synchronous Amplitude Modulation (SAM), or even to emulate Asynchronous Amplitude Modulation (ASAM).

A.2.2 Type of modulation techniques

High enough force to deflect the skin is a necessary but not sufficient condition to create tactile sensations. The focal point must be modulated to the resonant frequency of the mechanoreceptors. Thus, modulation refers to a single perceivable focal point. We will distinguish between three types of modulation techniques, which create tactile sensation on the human hand. The four modulation types are essentially four different possible configurations of emitters and sampling rate. These will be referred to as:

1. ASAM – Asynchronous Amplitude Modulation;
2. STM – Spatiotemporal Modulation;
3. SAM – Synchronous Amplitude Modulation;

ASAM – Asynchronous Amplitude Modulation Asynchronous Amplitude Modulation (ASAM) is what an AME emitter allows, and is what people often refer to as Amplitude Modulation (AM) in academic papers. Intensity of the ultrasonic carrier is modulated to a frequency resonant with mechanoreceptors, at a single position per emission. As noted earlier, the human skin is unable to perceive a 40 kHz vibration, even if the pressure is sufficiently high to make significant deformation on the air-skin interface. The solution is to modulate the ultrasonic pressure wave, the carrier. Starting with the simplest case, we can modulate the amplitude of the transducer. What this means, is that for example at 16 KHz sample rate, and at 200 Hz modulation frequency, (assuming a binary amplitude modulation) every 80th sample (or 200th transducer cycle) has maximum intensity, while every other sample (or 2.5th transducer cycle) has 0 intensity. This means in 16000 samples, we get 200 "taps" of maximum pressure. If the modulation frequency were to be reduced to 100 Hz, we would have a tap at every 160th sample. The binary modulation is not optimal, so choosing a sinusoidal modulation of amplitude, we distribute the 0-1 intensity values over the number of samples between two taps, as a sine or cosine function. The spacial coordinates of the focal point [x, y, z] remain constant, while one cycle of modulation completes.

STM – Spatiotemporal Modulation Spatiotemporal Modulation (STM) is what a TPS emitter allows. A pure STM point has a fixed intensity parameter, and therefore the modulation frequency set to 0. The X, Y, Z, coordinates of the point like sensation are approximated by a small, but still 2D circular path around the X, Y, Z origin. Translating the control point around the circular path at a high angular velocity, referred to as draw frequency, the movement takes the role of modulation. What this means is that at a 100 Hz draw frequency STM sensation, the control point moving around the circular path will coincide with the point of interest on the hand 100 times a second. This is equivalent to modulating the amplitude at a fixed position to some extent, but not fully. The intensity modulation profile of an ASAM point is different from the intensity modulation profile of an STM point. Using an analogy, a STM control point approaching the point of interest on the circle path is like a train. However, there is draft pushed in front of the train, and pulled behind the train.

SAM – Synchronous Amplitude Modulation A mixed modulation, or Synchronous Amplitude Modulation (SAM) is what a TPS emitter also allows. Essentially, the SAM is a STM point, where not only the draw frequency is set, but also the modulation frequency. Thus, the focal point is both translated around the circular path at a high angular velocity, but also the intensity of the focal point is modulated between 0 and 1. SAM could be also referred to as Spatiotemporal Amplitude Modulation (STAM).

A.2.3 Type of rendering techniques

When discussing modulation, I refer to only-and-only creating a perceivable tactile focal point. In contrast, I use the term "rendering" to describe the process of rendering more complex patterns, such as 2D or 3D geometric shapes, or animated haptic sensations. For the purpose of this white paper, I'll use the example of a 2D circle to explain types of rendering that are available to users. So let's imagine, we want to create the sensation of a tactile circle in mid-air, and not just a point.

Using Asynchronous Amplitude Modulation (ASAM) We can render a 2D circle sensation using ASAM, though it is not optimal. First task is for us to decide how many spacial points will be used to approximate a circular path. That is, a how many sided polygon will represent the circle. If we choose a 20 sided polygon approximation it means the following. Out of the total of 16000 samples, (at 200 Hz modulation frequency of ASAM) we use up 80 samples to vary the intensity before switching to a new position and repeat the 80 samples of varied intensity at that position. Since we have 20 position coordinates, this uses 1600 samples. Meaning, every position will be allocated 10 taps, i.e. 10 maximum intensity samples. This seems right, because 10 taps times 20 positions gives us the 200 taps per second, i.e. the 200 Hz ASAM frequency. The question is, whether the 10 taps happen subsequently in the given position, before moving to the next position, or 1 tap is allowed for each position, which is repeated then 10 times. The answer seems to be related to the sampling. The 16 KHz sample rate, means we control every 2.5 transducer cycles. Imagine the circle path approximated with 80 points instead of 20. Now at 200 Hz ASAM frequency, 80 samples times 80 points, yields 6400 samples. This means we are allowed 2.5 taps per position. Again makes sense, because 80 points times 2.5 taps is 200 Hz ASAM frequency. Here is the problem. If we were to do tap-tap-tap per point, before moving on, position would have to be updated at half a tap. Practice seems to show that the device doesn't like that. The solution is that we do tap-point-tap-point, and repeat this on the full circle path 2.5 times. Our start position and end position will change from [x, y, z] to [-x, y, z] but from the point of view of creating focal points, this is preferable.

Using Spatiotemporal modulation (STM) Since we use a small circle to render a 1D point sensation using STM, it is very easy to imagine the way to render a 2D circle. The only parameter to change is the radius of the circle path. This gives the perceptual outcome of a solid outline circle sensation. In this case, spatiotemporal modulation is both a modulation technique to excite receptors around the path to be rendered, but also the rendering method itself. Just like TPS emitter vs. STM modulation, STM modulation vs. STM rendering might be confusing at first but should be thought of as distinct processes.

Using a Dynamic Tactile Pointer (DTP) The Dynamic Tactile Pointer (DTP) is another method to render complex patterns, not a modulation technique. This time, an already modulated point sensation (the tactile pointer) is offset as a function of time, to animate movement around a circle. Although perceptually only a moving point is registered, over time a cognitive integration of the path enables the rendering of a circle sensation. The modulation of tactile pointers can be either of the forth-mentioned modulation techniques.

A.3 Author notes

The numbers used in the explanations, such as 200 Hz for AM, or 20 point polygon approximations of circle paths are only used as examples, as typical values. These numbers were chosen to help illustrate the point, with easy to handle use numbers. If the sample rate is set to 25 kHz, or AM frequency is set to 143 Hz, the numbers change respectively. However, the terminology should endure.

Appendix B

DARTS: Descriptors of Affective Responses Targeted in Science Communication

This appendix reports details of the descriptor items studied in chapter 6.

Table B.1: List of evaluated descriptors. In the status column, "P" refers to provisional target items (i.e. mean > 3.75). "S" refers to suggested items by participants in the questionnaire, at least three times. The "!" and "-" status symbols indicate whether the descriptor was promoted or demoted to the final list of target affective responses after the expert interviews.

Descriptor	Mean	SD	Mode	Status	Source
Entertaining	4.5	0.62	5	P!	McCrory (2010)
Pleasurable	4.05	0.8	4	P-	Shore (1999)
Playful	3.69	0.8	4	!	McCrory (2010)
Enjoyable	4.68	0.54	5	P!	Burns et al. (2003)
Amusing	3.48	0.76	3	-	McCrory (2010)
Disgusting	1.48	0.67	1	-	McCrory (2010)
Unpleasant	1.19	0.47	1	-	* Hassenzahl et al. (2003)
Engaging	4.89	0.55	5	P!	Burns et al. (2003)
Gross	1.53	0.74	1	-	McCrory (2010)
Novel	3.56	0.8	4	-	Hassenzahl et al. (2003)
Gratifying	3.81	0.81	4	P-	McCrory (2010)
Surprising	3.95	0.66	4	P!	Shore (1999)
Intellectual joy of understanding	4.37	0.73	5	P!	McCrory (2010)

Descriptor	Mean	SD	Mode	Status	Source
Sense of wonder	4.58	0.64	5	P!	McCrory (2010)
Sense of imagination	4.23	0.73	4	P!	McCrory (2010)
Sense of beauty	3.73	0.91	4	!	McCrory (2010)
Sense of amazement	4.19	0.76	4	P!	McCrory (2010)
Dull	1.03	0.18	1	-	Hassenzahl et al. (2003)
Curiosity	4.55	0.53	5	P!	McCrory (2010)
Anticipation	3.6	0.82	3	-	McCrory (2010)
Connective	3.9	0.9	4	P!	Hassenzahl et al. (2003)
Innovative	3.6	0.82	3	!	Hassenzahl et al. (2003)
Undemanding	2.79	0.89	3	-	Hassenzahl et al. (2003)
Unpredictable	3.02	0.86	3	-	Hassenzahl et al. (2003)
Motivating	4.24	0.72	4	P!	Hassenzahl et al. (2003)
Thought provoking	–	–	–	S!	Study 1.2
Relatable	–	–	–	S!	Study 1.2
Accessible (intellectually)	–	–	–	S!	Study 1.2
Story-like	–	–	–	S!	Study 1.2
Interactive	–	–	–	S-	Study 1.2
Aspiring	–	–	–	S-	Study 1.2
Challenging	–	–	–	S-	Study 1.2
Sense of accomplishment	–	–	–	S-	Study 1.2
Inspiring	–	–	–	S-	Study 1.2
Educational	–	–	–	S-	Study 1.2
Fun	–	–	–	S-	Study 1.2
Memorable	–	–	–	S-	Study 1.2
Encouraging	–	–	–	S-	Study 1.2

Appendix C

Parameter mapping – natural, physical touch, and mid-air touch properties of elementary particles

This appendix contains detailed information about the parameters used in study 2 of chapter 6.

C.1 Natural properties of elementary particles

Table C.1 shows the natural properties of elementary particles. These values are results of observations, and the physical touch or mid-air touch representations should consider these values as a reference.obversations

Table C.1: Natural properties of elementary particles.

Particle	Family	Spin	Charge (e)	Mass (MeVc^{-}2)
u	quark (fermion)	0.5	+2/3	2.16
d	quark (fermion)	0.5	−1/3	4.67
c	quark (fermion)	0.5	+2/3	1,270
s	quark (fermion)	0.5	−1/3	93
t	quark (fermion)	0.5	+2/3	172,900
b	quark (fermion)	0.5	−1/3	4,180
e	lepton (fermion)	0.5	-1	0.51099895
μ	lepton (fermion)	0.5	-1	105.658375
τ	lepton (fermion)	0.5	-1	1776.86
ν_e	lepton (fermion)	0.5	0	$< 2 \times 10^{-6}$
ν_μ	lepton (fermion)	0.5	0	< 0.19

Particle	Family	Spin	Charge (e)	Mass (MeVc⁻2)
ν_τ	lepton (fermion)	0.5	0	< 18.2
g	vector (boson)	1	0	0
γ	vector (boson)	1	0	0
W^+	vector (boson)	1	+1	80,379
W^-	vector (boson)	1	-1	80,379
Z	vector (boson)	1	0	91,187.6
H	scalar (boson)	0	128	125,100

C.2 Physical touch properties – Particle Zoo plush probes

Table C.2 shows a summary of mapping natural properties of elementary particles to physical touch properties of metaphorical plush probes.

Table C.2: Parameter mapping for physical touch representation of elementary particles. Shape refers to the shape of the plush, relative location refers to the the layout on the table (Top/Bottom-Left/Right-Row-Col), face and glance refers to the facial expression or eyes of the plush, and weight is the weight of the plush.

Particle Name	Family ↓ Shape	Spin ↓ Relative location	Charge ↓ Face & glance	Mass ↓ Weight (g)
u	up-triangle	TL11	top & up	57
d	down-triangle	TL21	top & down	57
c	up-triangle	TL12	top & flower	283
s	down-triangle	TL22	top & 3	113
t	up-triangle	TL13	top & straight	397
b	down-triangle	TL23	top & straight	397
e	circle	TR11	middle & straight	57
μ	circle	TR12	middle & straight	113
τ	circle	TR13	middle & straight	198
ν_e	square	TR21	middle & left	57
ν_μ	square	TR22	middle & left	57

Particle Name	Family ↓ Shape	Spin ↓ Relative location	Charge) ↓ Face & glance	Mass ↓ Weight (g)
ν_τ	square	TR23	middle & left	57
g	6-star	B11	middle & cross	57
γ	right-fork	B12	middle & cross	57
W^+	5-star	B13	middle & up	400
W^-	5-star	B14	middle & down	400
Z	down-fork	B14	middle & midline	397
H	5-star	B15	middle & cross	397

C.3 Mid-air touch properties – sensations

Table C.3 shows a summary of mapping natural properties of elementary particles to mid-air haptic properties of metaphorical sensations.

Table C.3: Parameter mapping for mid-air touch representation of elementary particles. Trajectory refers to the geometry of the particle's movement, rate refers to the number of complete paths rendered in one second (negative values signify clockwise motion), STM modulation frequency is the haptic frequency of the focal point, and FP radius is the radius of the focal point.

Particle Name	Family ↓ Trajectory	Spin ↓ Rate (s^{-1})	Charge ↓ STM ModFreq (Hz)	Mass ↓ FP radius (mm)
u	triangle	-0.5	16	4
d	triangle	0.5	64	4
c	triangle	-0.5	16	16
s	triangle	0.5	64	8
t	triangle	-0.5	16	20
b	triangle	0.5	64	20
e	square	0.5	64	4
μ	square	0.5	64	8
τ	square	0.5	64	12
ν_e	square	0.5	128	4

Particle Name	Family ↓ Trajectory	Spin ↓ Rate (s^{-1})	Charge) ↓ STM ModFreq (Hz)	Mass ↓ FP radius (mm)
ν_μ	square	0.5	128	4
ν_τ	square	0.5	128	4
g	circle	-1	128	4
γ	circle	1	128	4
W^+	circle	-1	16	20
W^-	circle	1	64	20
Z	circle	1	128	20
H	circle	0.1	128	20