Exploration of Mid-Air Haptics Experience Design

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– Damien Ablart

Summary

Ultrasonic Mid-air Haptics (UMH) is a novel technology that uses the mechanical properties of sound waves to create a pressure point in mid-air. This pressure point, called focal point, can slightly bend the skin and be felt in mid-air without any attachment to the body. This thesis focuses on both studying how to integrate this technology with other senses (i.e. vision and audition) and exploring the range of tactile sensations it can provide.

The first two projects presented in this document present the integration of ultrasonic mid-air haptics with audio-visual content. The first project describes the process of creating a unique haptic experience that was part of a six-weeks multisensory exhibition in a museum. The second project moved from the museum to a controlled environment and explored the creation of haptic experiences based on physiologic measurements for six short films. Both studies showed the positive value of adding ultrasonic mid-air haptics to traditional media through higher reported arousal and participants' high enthusiasm for multisensory content.

In the two latter projects of this thesis, it was explored how we could extend the range of possible tactile sensations provided by UMHs. We introduced a new technique called Spatio-Temporal Modulation (STM). It enabled the creation of brand-new tactile experiences, including more salient shapes and wider range of textures. We also provided some guidelines on how to control some of the tactile properties of the sensation, including strength, roughness, or regularity.

The findings of those four projects contribute to the growing body of knowledge of UMHs. A summary of the key contributions is provided at the end of the thesis as well as several leads for future works.

Author's Declaration

I 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. However, the thesis incorporates to the extent indicated below, material already submitted as part of the following scientific publications, written in collaboration with other researchers:

Mid-Air Haptic Experiences Integrated in a Multisensory Art Exhibition

Chi Thanh Vi, Damien Ablart, Elia Gatti, Carlos Velasco, and Marianna Obrist. Published in the International Journal of Human-Computer Studies (IJHCS), 108, pp.1–14 (2017). [1]

Integrating Mid-Air Haptics into Movie Experiences

Damien Ablart, Carlos Velasco, and Marianna Obrist. Published in the Proceedings of the 2017 ACM International Conference on Interactive Experiences for TV and Online Video (TVX), pp77–84 (2017). [2]

Using Spatiotemporal Modulation to Draw Tactile Patterns in Mid-Air

William Frier, Damien Ablart, Jamie Chilles, Benjamin Long, Marcello Giordano, Marianna Obrist, and Sriram Subramanian. Published in the Proceedings of the 2018 IEEE International Conference on Human Haptic Sensing and Touch Enabled Computer Applications (EuroHaptics), pp.270–281 (2018). [3]

Using Ultrasonic Mid-Air Haptic Patterns in Multi-Modal User Experience

Damien Ablart, William Frier, Hannah Limerick, Orestis Georgiou, and Marianna Obrist. Published in the Proceedings of the 2019 IEEE International Symposium on Haptic, Audio and Visual Environments and Games (HAVE) (2019). [4]

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[1] Ultrahaptics was recently rebranded as Ultraleap, but to keep the consistency with previous works included in this work, we will refer to it still as Ultrahaptics.

I would like to thank my parents, my brother and Lilla for being the best family I could have wished for! To Chiharu, for all the happiness she brings me every day.

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Chapter 1

Introduction

"Touch comes before sight, before speech. It is the first language and the last, and it always tells the truth." – **Margaret Atwood**

The sense of touch is complex and widely studied in different research fields such as psychology, neuroscience, sociology, or communication. This chapter aims to give a short introduction to the sense of touch and to position the contributions of this PhD thesis. First, we highlight the relevance of studying touch in HCI, the underlying motivations and challenges, as well as present the main research questions this PhD is addressing. Then, we present an overview on the key papers this thesis is based upon and how they help to answer our research questions and thus extend the current state of the art.

1.1 Motivation and Relevance of Touch

Margaret Atwood wrote, the sense of touch is "the first language". From the day we are born, it serves as a communication channel between the infant and their mother [5]. It also plays a crucial role in the way we explore the world and assess object properties [6]. The peculiar connection of the haptic sensory system with the emotional brain [7] also makes it a potent emotional vector.

All of these interactions are made possible thanks to the great variety of receptors touch is based on throughout the body. They are separated in two families: kinaesthetic and cutaneous [8]. The kinaesthetic receptors read inputs from muscles, tendons and joints and contribute to the perception of limb movements, while the cutaneous receptors are located in the skin and give information about textures, temperatures, or vibrations. Both the kinaesthetic and cutaneous receptors send information to the brain, where they are integrated with the other senses to give the most accurate information possible on the state of the body and its surrounding [9].

Modern psychology has studied extensively the sense of touch over the last decades. One of the topics of interest is to understand how it works and how accurate it is. In their tutorial, Lenderman and Klatzky [8] highlight some of the studied areas such as the spatial and temporal resolving capacity of the skin or the perception of object and textures (e.g. thermal quality, weight, orientation). Moreover, the way touch influences our lives has been studied. Some examples include its role when assessing the value of an item [6], the way romantic partners touch each others to communicate emotions [10], or how strangers can communicate emotions through touch [11].

The HCI community also has a growing interest for the sense of touch, as it seems a promising interface to interact with computers. To achieve this, new haptic devices are built and then studied. For instance, vibration actuators are embedded in a sport jacket [12] or in a chair [13], vortexes of air are directed towards user's palm [14], or an electric arc can tickle the user's fingertip when approaching a touch screen [15]. In this work we focused on a recently introduced technology – Ultrasonic Mid-air Haptics (UMH) – that uses cutting edge technologies to provide tactile sensations in mid-air. This technology is presented in more details in the next section.

1.1.1 The Proliferation of Ultrasonic Mid-Air Haptics

Ultrasonic mid-air haptics technologies have gained momentum in the last few years. This new technology allows the creation of novel tactile sensations without any physical attachments. In other words, it can be described as a contactless haptic technology [16]. This technology takes advantage of the acoustic radiation force to create a pressure point in mid-air. This focal point can slightly deflect human skin but is barely perceivable without movement. One technique is to vary the amplitude of the signal over time to create a frequency, thus making static focal points perceivable. Since its introduction, the technology has been improved to display several points [17, 18] and some first perceptual studies have been made [19, 20].

The added value of touch when using other devices, such as holding controllers or wearing haptically augmented gloves, has been demonstrated within HCI and associated fields, however the added value of UMHs is still unknown. In this thesis, we are interested in unravelling the potential of ultrasonic mid-air haptics in the context of multisensory and multimedia content and its possibilities to create unique and varied haptic experiences. In the next section, we will present the challenges linked to the creation of such experiences.

1.1.2 Towards Ultrasonic Mid-Air Haptics Multisensory Experiences

The integration of the sense of touch into multisensory interaction is a complex task, however it is of interest for the HCI community because it promises the creation of more immersive and compelling experiences. We present here some of the challenges of multisensory experience design that are common to touch interfaces and provide a motivation for the research questions presented in the next section.

In contrast to audio-visual design, there are no common guidelines established for designing multisensory experiences and especially its integration with mid-air haptics sensations. The two common approaches to create tactile experiences are either through emotions [12, 21] or by mirroring some of the elements from the audio and visual channels to the tactile experience [22, 23].

The emotional approach requires understanding of how a specific device impacts a user's emotional state. This can be done through a careful investigation of the haptic device through a user's study [21]. In the context of UMHs, a first exploration has been made [20], showing a positive effect on the users' reported arousal and some promising results linking the valence to specific parts of the palm.

The second approach maps some of the characteristics of the audio and visual channels to a haptic device. This can be done through the location of the action on the screen [23], a temporal aspect [22], or recordings through sensors while the movies is filmed [24]. In the case of UMHs, a first work gave some insight on how to describe haptics points with different frequencies [19], but it is still unsure how we can create a wide range of tactile sensations.

Another challenge is to measure the experience of the users while consuming multisensory content. One common approach is to use questionnaires [25, 26], but those are only reported values and it might differ from what the user really experienced. While many user experience methods have been proposed [27], there is still a lack of measures to capture multisensory experiences, especially ones that help us understand the added value of each sensory stimuli, and the emotional effect. Another approach it to directly measure user's emotions through different physiological measurements (e.g. heart rate, skin conductance or breathing rate) [12]. Such measurements provide more objective measurements but can require a larger sample size and a bulky apparatus that might change the user experience. A combination of both user reported and physiological measurements are considered in this thesis in order to help establish an understanding of mid-air tactile experiences in the wider space of multisensory experience design.

Those initial challenges helped us to find the research questions for this PhD that are presented below.

1.1.3 Research Questions

From the specificities of ultrasonic mid-air haptics and the challenges of haptic integration with other senses, several research questions arose and are addressed in this thesis. Here below, each of the four research questions are presented alongside a short summary of their relevance.

1. **What are the challenges of designing an art multisensory experience involving mid-air haptics?**

   Creating a multisensory experience (e.g. film, concert, or video game) involves both artists and technicians. The artists, on one side, express their creativity and the technicians, on the other side, provide the tools and technologies to achieve it (e.g. a specific sound or light system). When designing experiences with senses that are not traditionally used (i.e. smell, taste, and touch), more challenges might arise that require multisensory experts.

   In this work, we are interested in (1) describing the process of working with artists in the specific context of a multisensory art exhibition and (2) reporting the experience of visitors through questionnaires and interviews.

2. **Can mid-air haptics support the viewing of traditional audio-visual content?**

   Enhancing traditional audio-visual content with touch in a single experience comes with many challenges such as: what process should be followed to create a compelling experience? What are the tools available to display several senses simultaneously?

   In this thesis, we are interested specifically in (1) the technical challenge of integrating a UMHs with existing media (i.e. audio and/or visual content) and (2) identifying new approaches to create haptic experiences that would add value and increase the pleasantness of existing audio-visual content.

3. **Can we broaden the range of mid-air ultrasonic tactile possibilities?**

   Ultrasonic mid-air haptics devices take advantage of the radial pressure to deflect the human skin. But in order to be perceived, this pressure is modulated over time to create a frequency at a specific point. This technique presents the disadvantage to display only points and not lines.

   More specifically, we are looking for new techniques that would create new tactile sensation (e.g. textures or new locations on the body) or improve the current ones (e.g. better way to display shapes or multiples points at the same time).

4. **Can the ultrasonic mid-air haptic parameters impact users' perceptual and emotional responses?**

Currently, when using ultrasonic mid-air haptics, the only parameters available are the intensity and the frequency. It is also possible to create more complex patterns by moving the focal point or displaying several of them.

More specifically, we are interested in finding (1) how those parameters could influence the tactile experience of the users and (2) if they could change the emotional response of participants.

In order to address the above four research questions, this PhD thesis is structured around four main projects that are introduced in the following section.

1.1.4 Projects Outline

This thesis contains four published works that can be classified into two categories: (1) the Exploration of the Mid-Air Haptic Design Space (including Chapter 3 and Chapter 4) and (2) the Exploration of Mid-Air Haptics Design Parameters (including Chapter 5 and Chapter 6). An overview of the different projects and their interconnections is available on Figure 1.1.

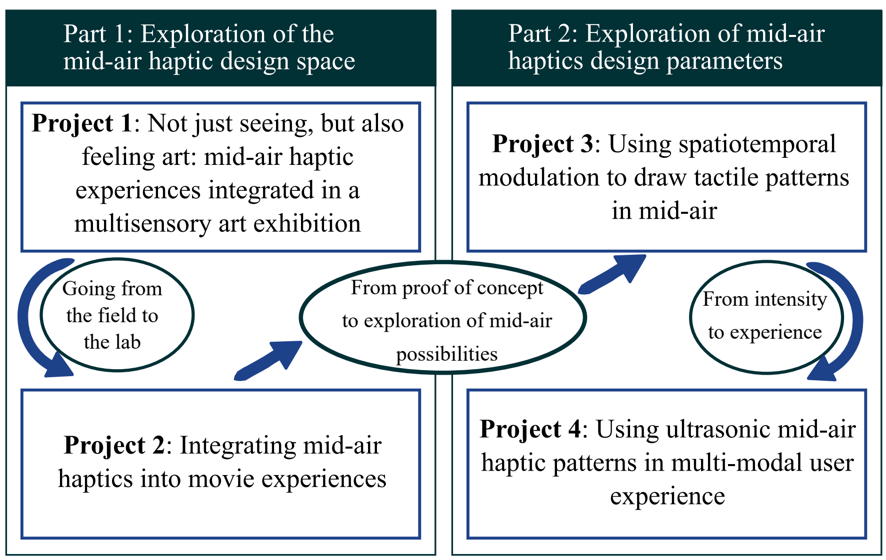

Figure 1.1: Breakdown of the projects presented in this thesis. The first part is composed of two papers (Chapter 3 and Chapter 4) and is describing the exploration of the mid-air haptic design space. The second part is also composed of two papers (Chapter 5 and Chapter 6) and summarises the exploration of the mid-air haptic design parameters.

Across all four projects that build up this thesis, we applied a combination of different quantitative and qualitative methods in order to help us answer the four research questions.

1.2 Exploration of the Mid-Air Haptic Design Space

This section presents how we explored the use of ultrasonic mid-air haptics in two exemplary contexts for multisensory and multimedia experience design (i.e. museum and short movies). Those projects aimed to answer the first two research questions (see Section 1.1.3) by providing a proof of concept of the added value of UMH feedback in conjunction with art pieces and audio-visual media. Also, we provide details on our processes for creating the haptic experience, giving new ideas on how to create haptic experiences.

1.2.1 Proof of Concept in a Museum

This first project was organised around the multisensory exhibition Tate Sensorium. This was an interdisciplinary collaboration on a six-week multisensory display exhibited at the Tate Britain art gallery in London, UK. This was a unique and first-time case study on how to design art experiences whilst considering all the senses (i.e. vision, sound, touch, smell, and taste), and integrating the novel mid-air haptic technology. The sense of touch was designed for one of the four paintings (i.e. Full Stop by John Latham (1961)) and was delivered through ultrasonic mid-air haptics. This was the first time that mid-air haptic technology was used in a public exhibition over a prolonged period of time and integrated with sound to enhance the experience of visual art.

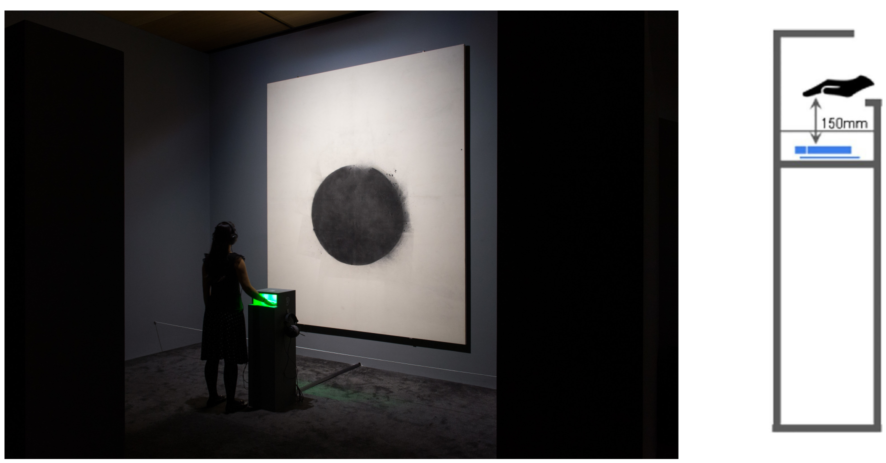

Figure 1.2: The Tate Sensorium project [1]. On the left, a participant trying the Full Stop haptic experience. On the right, the design of the plinth, allowing the users to feel the mid-air haptic feedback, 15 cm away from the device.

In order to design this haptic-audio-video experience, we ran a three steps process:

- Step 1: An initial exploration of the mid-air haptics sensations and possibilities with the sound designer.
- Step 2: The creation of a tool that would (1) contain only the haptic creations selected by the sound

designer during the workshop and (2) connect to his sound interface in order to give him full control over the haptic display (both the parameters and timings).

- Step 3: Iterative design and creation of the multisensory experience with the sound designer.

During the exhibition, we used the original creation and two other variations of the mid-air haptic experience (i.e. haptic patterns), which were alternated at dedicated times throughout the six-week exhibition. We collected questionnaire-based feedback from 2500 visitors and conducted 50 interviews to gain quantitative and qualitative insights on visitors' experiences and emotional reactions. The findings suggested multisensory designers and art curators can ensure a balance between surprising experiences versus the possibility of free exploration for visitors. More specifically about the painting that was haptically enhanced, participants expressed that experiencing art with the combination of mid-air haptic and sound was immersive and provided an up-lifting experience of "touching without touch". We are convinced that the insights gained from this large-scale and real-world field exploration of multisensory experience design exploiting a new and emerging technology provide a solid starting point for the HCI community, creative industries, and art curators to think beyond conventional art experiences. Specifically, our work demonstrates how novel mid-air technology can make art more emotionally engaging and stimulating, especially abstract art that is often open to interpretation.

As interesting as the results were, many questions were left unanswered, due to the lack of control of the different conditions (e.g. haptic patterns) and the lack of control over the procedure in a real-world environment. The next section presents the follow-up project that aimed to use mid-air haptics feedback in a controlled environment.

1.2.2 From the Field to a Controlled Environment

In this project, we decided to move from the field (i.e. museum) to the controlled environment of the laboratory. In order to have a comparison and because we couldn't have any actual museum artefacts in the lab, we decided to focus on multimedia content. More specifically we use the one-minute movie format because it provides a dataset of movies with the same length that included a complete narrative. This allowed us to test the added value of mid-air haptics feedback in a controlled environment.

In contrast to previous studies where the haptic experience is created to match a specific emotion [12], to mirror the screen [23], or to match the specific semantic space [13], we designed a single haptic pattern to enhance viewers' experiences. By pattern, we mean a mid-air haptic creation defined by an intensity, a frequency, and the movement of the focal point over time. We explored this pattern with respect to its temporal integration into movies (synchronised versus not synchronised with the peak moments in a movie). We focus on "one-minute films", which is a content format that conveys a complete narrative in one minute and allows a comparable set of movies of the same format and length. Then, we conducted a study following three main steps: (1) selection of movies, (2) creation and integration of haptic feedback (haptic pattern) into the movie narrative (synchronised vs not synchronised) and (3) evaluation of the users' viewing experiences (emotions) in two instances (separated by two weeks). For the evaluation, we compared the data of the following conditions: (a) synchronised haptic feedback versus no haptic feedback, (b) movie-specific design versus one cross-movies design, and (c) initial viewing versus repeated viewing after two weeks. We used a combination of measures (i.e. self-report questionnaires and skin conductance responses) to capture the effect of the haptic feedback on users viewing experiences.

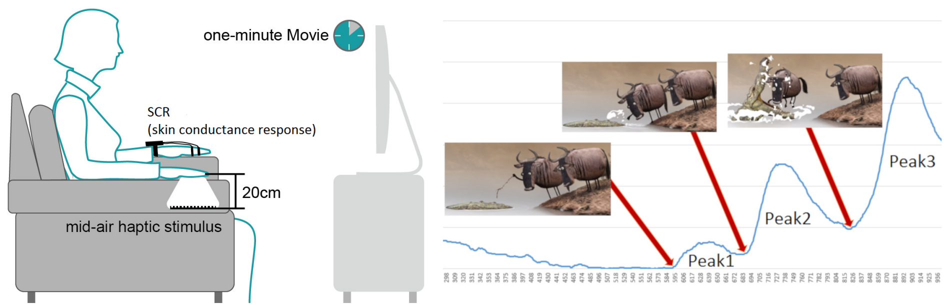

Figure 1.3: The setup used for the "one-minute" films experiment [2].

In this study, we demonstrated the integration of mid-air haptic feedback into audiovisual content in the form of a simple haptic pattern. This approach could be further extended towards a variety of pre-defined and custom-made or even automated patterns in the future. To do so, a systematic exploration of mid-air haptic feedback would have to be made, in order to characterise the different possible patterns that could be integrated.

1.3 Exploration of Mid-Air Haptics Design Parameters

We showed in the previous section that a mid-air haptics can be used for enhancing experience in a museum and for augmenting short movie experiences. But still, very little is known about the properties of mid-air haptics. The two next projects focused on the research questions 3 and 4 (see Section 1.1.3): how we can improve the haptic feedback and explore if there is any link between the ultrasonic parameters and the user experience.

1.3.1 Using Spatiotemporal Modulation to Draw Tactile Patterns in Mid-Air

Ultrasonic phased arrays focus acoustic pressure to points in space (referred to as focal points). At these focal points, the pressure can slightly deflect human skin and induce tactile sensation. Yet, in such systems, the ultrasonic transducers are driven at high frequencies (e.g. $40\,\mathrm{kHz}$ [16] or $70\,\mathrm{kHz}$ [28]), while mechanoreceptors within the skin are sensitive to frequencies ranging from $0.4\,\mathrm{Hz}$ to $500\,\mathrm{Hz}$ [29]. Therefore, the common approach, referred to as amplitude modulation, is to modulate the focal point to a lower frequency (referring to amplitude modulation frequency or F_{AM} for short). The perception of the focal point varies with the value of F_{AM} [19] and therefore F_{AM} is often fixed to $200\,\mathrm{Hz}$ which induces the strongest haptic response. Amplitude modulation can therefore be considered to be similar to and applied as one would use a mechanical vibrator for vibrotactile stimulation. Alternatively, one can create a cluster of focal points and apply amplitude modulation to each point, in order to render patterns or volumetric shapes [18] (see Figure 1.4 – left). Yet as the number of simultaneous focal points increases, the acoustic power produced by the device is divided between the points, making each individually weaker. When the number of simultaneous focal points becomes too large (e.g. in large patterns), the focal points are no longer perceived.

To get around this issue, an alternative approach exists that we refer to as spatiotemporal modulation. In spatiotemporal modulation the position of a single focal point is rapidly and repeatedly updated to describe a pattern by moving along a continuous trajectory, while the intensity remains at its maximum. Spatiotemporal modulation can still induce tactile sensation as mechanoreceptors are sensitive to motion [30]. Additionally, the temporal resolution of touch perception is only of few milliseconds (the exact value may range from $2\,\mathrm{ms}$ to $40\,\mathrm{ms}$ according to Loomis [31]). Therefore, if the focal point can complete the trajectory faster than the temporal resolution, the users will perceive the resulting stimulation as a single tactile pattern rather than a succession of tactile points or a moving sensation (see Figure 1.4 - right). The effect is similar to the persistence of vision, where a source of light can be seen as shape and not distinct points, when moved fast enough.

We ran two studies, the first one using vibrometry and the second one with users. In both of them, the optimal speed result is shown to be equivalent to the speed at which surface waves propagate from the skin deflection effected by the focal point. Overall, our investigations highlight the importance of the speed of stimulation movement in the design of tactile patterns.

1.3.2 Exploring the Effect of Mid-Air Haptic Parameters on User's Experience

In the previous work, we showed how the speed of a point is more important that the frequency when it comes to the intensity of the tactile feedback. In a following project, we studied how varying the draw frequency and the size of a simple shape could affect the users' perception of texture and emotional responses. Using a

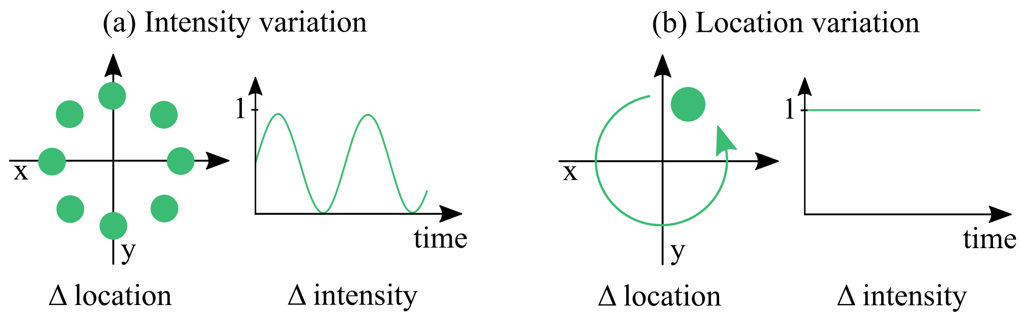

Figure 1.4: A comparison between the AM and STM techniques when displaying a circle. (a) is displaying 8 fixed points with a change of intensity over time where (b) has a constant intensity over time but a changing location. The points in (a) are dimmer to represent the weaker acoustic power [3].

wide range of STM parameter combinations in a first study, we determined the impact of those parameters on the tactile sensation. The first study used a wide range of STM parameters combination to explore how those parameters value could impact the tactile sensation.

Results showed that the intensity follows the results found in [3], the roughness and regularity have a similar trend with higher ratings around 25 Hz, the roundness is more perceivable when the shape is bigger, and the valence is not showing any clear trend.

The second study used the most salient tactile patterns of the first study, which were used in conjunction with audio and visual stimuli that were taken from a standardised database [32]. The aim was to confirm the result from the first study and explore a multi-modal context.

We found that the tactile patterns' perceptions were consistent within both studies, confirming that it's possible to create different roughness/softness, regularities, or shape recognition. Moreover, the haptic feedback could successfully impact the audio-visual content, reinforcing the potential of ultrasonic mid-air haptic for media content.

1.4 Thesis Structure

This thesis is organised in 7 chapters: (1) Introduction, (2) Related Work, (3-6) four projects, (7) Conclusion and Future Work (see Figure 1.5). I summarise below of the contributions I have made to each of the projects included in this thesis (Chapter 3, 4, 5, and 6). My master degree being about programming and Human-Computer Interactions, my contributions are usually more focused on the design, development, data collection, and writing. On the other side, when it came to statistics, I was usually supported by more experimented members of the SCHI Lab team. A numbered summary is given in the Table 1.1.

Projects	Design	Data Collection	Analysis	Writing	Publication venue
Chapter 3	90%	50%	50%	40%	IJHCS 2017
Chapter 4	90%	100%	50%	60%	TVX 2017
Chapter 5	50%	50%	50%	40%	EuroHaptics 2018
Chapter 6	75%	100%	90%	75%	HAVE 2019

Table 1.1: My Contributions to each of the published papers (alias Projects) included in this thesis.

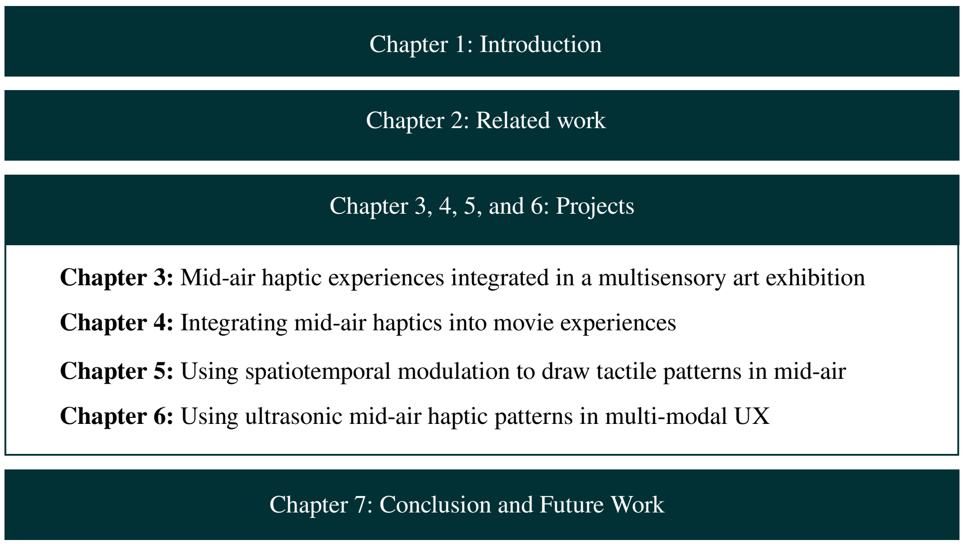

Figure 1.5: Overview of the Chapters' structure of the thesis.

Chapter 3: Mid-Air Haptic Experiences Integrated in a Multisensory Art Exhibition: This project was a collaboration with several artists and curators from the Tate Britain art gallery. I was in charge of the integration of the mid-air haptics technology into the overall multisensory art exhibition. I designed the tactile experience together with the sound designer and input from the other project members. I programmed the software needed for the exhibition and installed them in the gallery. I coordinated the data collection using questionnaires and interviews, iteratively designed the materials, analysed the data and contributed to the writing of the journal article.

Chapter 4: Integrating Mid-Air Haptics into Movie Experiences: I was the lead author of this paper and I designed the three experiments, implemented them, including the creating of the mid-air haptic pattern and all of the programming. I collected the data of the different experiment, analysed the results of both questionnaires and physiological data (skin conductance response). I lead the writing of the paper and presented our work at the ACM TVX 2017 conference in Hilversum, The Netherlands.

Chapter 5: Using Spatiotemporal Modulation to Draw Tactile Patterns in Mid-Air: This project was a shared project with William Frier. We split the work in half, he was in charge of the vibrometry study and I handled the user study. More specifically, I designed the user study, programmed the haptic patterns and integrated the different questionnaires in a single software. I ran the user study and analysed the data and reported it on the paper that was published at the Eurohaptics 2018 conference.

Chapter 6: Using Ultrasonic Mid-Air Haptic Patterns in Multi-Modal User Experience: I was the lead author of this paper that aimed to extend the work around the STM technique, especially from a user experience perspective. I designed the different studies, implemented the on-screen questionnaires as well as the haptic feedback. I ran the studies, gathered the data, and analysed them. I lead the writing of the paper and presented this work at the HAVE 2019 conference in Kuala Lumpur, Malaysia.

Chapter 2

Literature Background

"We are like dwarfs on the shoulders of giants [...]"

– **Bernard de Chartres**

The sense of touch is a complex aggregation of different stimuli (e.g. temperature, vibrotactile) involving various kind of receptors located on the surface (e.g. skin) and inside the body (e.g. muscles, bones). In order to be studied in the context of HCI, many haptic interfaces were developed, and efforts are made to understand how to make the best use of them.

This chapter provides an overview on why the sense of touch is crucial to humans and how researchers aim to understand it. Some of the devices used in HCI will be presented with their related software and standard. Finally, we will describe some of the approaches taken by the designer to integrate haptic feedback with media.

2.1 Basics of Haptic Perception

Haptic perception is a complex mechanism that involves several kinds of receptors in the skin and inside the body. This information is then processed and interpreted by the brain. There are two families of sensors, the first category encompasses all the receptors that are located in the skin and provides the "cutaneous" inputs. The second category includes all the receptors that are located inside the body (i.e. bones, muscles and joints) and that provides "kinaesthetic" inputs. In this Chapter, we will focus only on the first category as it is the one involved when using UMHs.

The cutaneous receptors are classified in two categories: (1) the mechanoreceptors and (2) the thermoreceptors.

2.1.1 The Cutaneous Mechanoreceptors

The cutaneous mechanoreceptors are divided in four categories: (1) slowly adapting type 1 (SA1) afferents that end in Merkel cells, (2) rapidly adapting (RA) afferents that end in Meissner corpuscles, (3) Pacinian (PC) afferents that end in PC corpuscles, and (4) slowly adapting type 2 (SA2) afferent that are thought to terminate in Ruffini corpuscles [33]. A representation of the glabrous skin and those four receptors can be seen on the Figure 2.1.

There is a sharp division of functions among the four cutaneous afferent (e.g. points vs edges, static vs dynamic etc.) and some are only present in specific locations of the body (e.g. PC are only distributed throughout the palm and fingers). This variation of receptors on the skin has impact on how we can interact with touch, for instance ultrasonic haptics are not perceivable on every part of the human body.

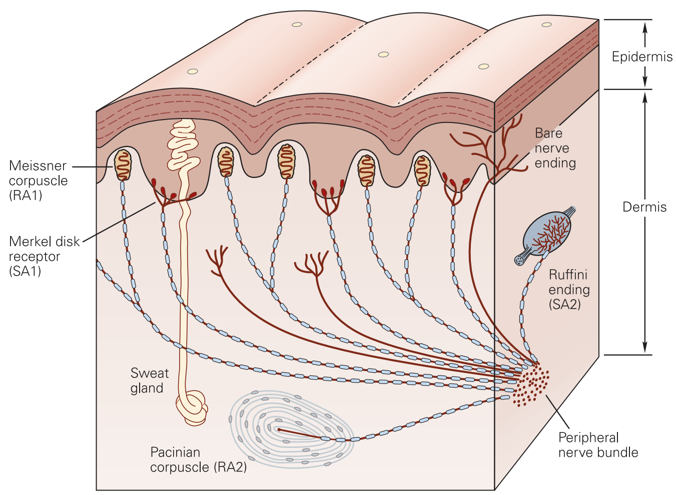

Figure 2.1: A representation of the glabrous skin including the four touch receptors [34].

2.1.2 Thermoreceptors

Thermorecepors are divided in two categories: cold thermoreceptors and warm thermoroceptors. There are independently distributed, and densities varies on the different part of the body [35]. Moreover, cold spots outnumber warm spots making the body more sensitive to cold than to warmth.

The neutral zone for temperature lies between 30 °C and 36 °C, making the body less sensitive to temperature changes in this area. Despite being very sensitive to changes, the spatial acuity is poor for localising thermal stimulation on the body and at differentiating spatially two thermal stimuli. Moreover, the change of temperature sums the intensity over space (i.e. the area stimulated matters for the perception). Therefore, it is very important to choose a relevant size of area for the stimulation.

	Type 1		Type 2	
	SA1	RA1	SA2	RA2
Receptor	Merkel cell	Meissner corpuscle	Ruffini ending	Pacinian corpuscle
Location	Tip of epidermal sweat ridges	Dermal papillae (close to skin surface)	Dermis	Dermis (deep tissue)
Axon diameter (µm)	7–11	6–12	6–12	6–12
Conduction velocity (ms)	40–65	35–70	35–70	35–70
Best stimulus	Edges, points	Lateral motion	Skin stretch	Vibration
Response to sustained indentation	Sustained with slow adaptation	None	Sustained with slow adaptation	None
Frequency range (Hz)	0–100	1–300		5–1,000
Best frequency (Hz)	5	50		200
Threshold for rapid indentation or vibration (best) (µm)	8	2	40	0.01

Table 2.1: Cutaneous Mechanoreceptor Systems [34].

2.2 Haptic Interfaces

Studying the sense of touch can be done through the exploration of physical objects [6] or interpersonal touch [11]. But when used in the context of HCI, there is a need for new kind of haptic interfaces, that can be controlled by a computer.

The field of building haptic devices is young and evolving fast, with new devices being release every year, and the existing ones being improved continually. Each device presents its own pros and cons, and is usually created for a specific use (e.g. enhancing movies [12], or communicating emotions at distance between two persons [36]).

Over the years, both the number of technologies available and their use have flourished. This section aims to give an overview of the available technologies and presents some of their implementations. The five categories presented in this section are: (1) vibrations, (2) force-feedback, (3) thermal, (4) electrical stimulation, (5) air pressure and (6) mid-air ultrasonic.

2.2.1 Vibrations Based Devices

One of the common components of haptic devices is vibrations through linear resonance vibration actuators or eccentric rotating-mass actuators [12, 23, 37, 36]. Those actuators have several advantages: they are cheap, widely available, small, have a low power consumption and they can produce a relatively strong feedback that can be felt on any part of the human body. On the downside, their intensity is hard to control, and their resonant frequency is fixed.

In many devices, those actuators are embedded in clothes or wearables. For instance, Lemmens et al. [12] created a tactile jacket by embedding 64 vibration actuators in a sport jacket (see Figure2.2). The actuators can be activated independently, allowing a wide range of patterns. This was facilitated through an interface that allowed to control the activated actuators over time. Some example of the patterns tested are vibration around the stomach to convey love (i.e. having butterflies in your stomach) or vibration in the lower back for fear (i.e. shiver down your spine). A user study involving fourteen participants showed that the actuation of the jacket had the intended effect of improving the immersion of 7 movie clips. Another example is the creation of tactile gloves by integrating a grid of tactile actuators [23]. The approach taken in this project was to mirror the screen onto the grid of actuators. For instance, if the action is going from the left side of the screen to the right side, the users would feel a wave going from their left hand to their right hand. A user study involving 80 visitors showed promising result for immersion and enhancing the experience. The gloves can be seen on the Figure 2.3. Lee et al. [38] created an armband containing a 7×10 grid of actuators. In this specific use-case, the grid of actuators was representing a football field and the vibrations were following the location of the ball.

Figure 2.2: A tactile jacket to enhance films. It embeds 64 actuators, allowing complex patterns to be display to users while they watch movies [12].

Figure 2.3: Vibrotactile Haptic gloves. It embeds a grid of actuators to mirror the content of a movies [23].

In [13], a grid of 3×4 actuators were placed in a chair's back to enhance gaming experience. A specific algorithm was developed to create smooth movements on the grid. This setup allowed to create immersive haptic feedback for driving games. The haptic chair can be seen on the Figure 2.4.

Another implementation of a haptic chair was presented by Nanayakkara et al. [39], this time to provide a musical experience for the deaf. This setup included both visual and haptic feedback, both directly translated from a musical track. The chair embeds a contact speaker that could transmit the vibration of the music to the chair, while the screen was displaying visual cues to translate the instruments or pitch. A sketch and the implementation of the chair can be seen on the Figure 2.5.

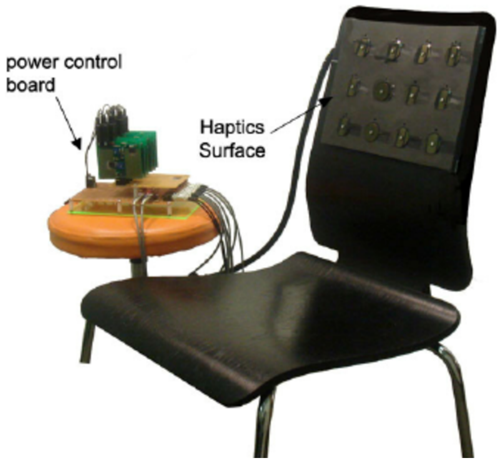

Figure 2.4: A haptic chair to enhance video games. It contains a grid of 3×4 vibrotactile in its back to provide haptic feedback during racing games [13].

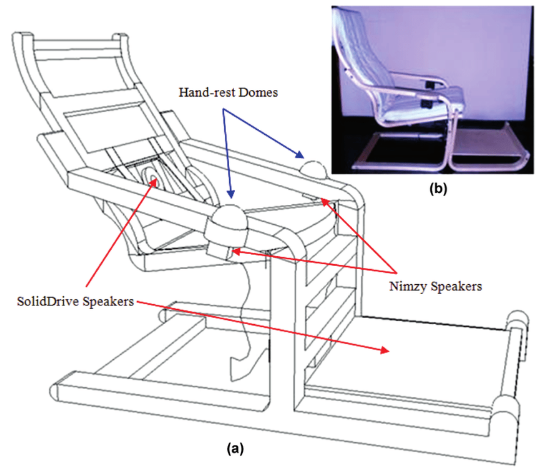

Figure 2.5: A haptic chair for music experiences. It embeds a contact speaker to provide the deaf with a haptic experience [39].

2.2.2 Force-Feedback

Force-feedback device are made of operable parts that will oppose resistance to the user as it moves. The resistance intensity and direction can sometime be controlled to give different sensations to the users.

Joystick sometime implement a force feedback mechanism. Okamura et al. [40] used a low-cost, single-axis force feedback joystick to teach undergraduate students about dynamic systems. This practical approach let the students feel by themselves and experience the concept. In their evaluation, they found improved the students understanding while making the learning more “fun”.

Some more advanced force feedback devices proposed articulated robotic arms. For instance, the Phantom device [41] is a robotic arm with 6 degree of freedom that can be used as output (move the arm) and input (read the movement on the arm). One example work done by Gatti et al. [42] was to use the Phantom device as an input with different force feedback settings to change user’s emotional state.

The Air Jet interface presented by Suzuki and Kobayashi [43] is composed of 100 air-jet nozzles presented on a 10×10 square, see figure on left. Air was not directly projected on user’s skin but on a handled device that users could move around to explore 3D shapes. A visual explanation of the setup can be found on the Figure 2.6.

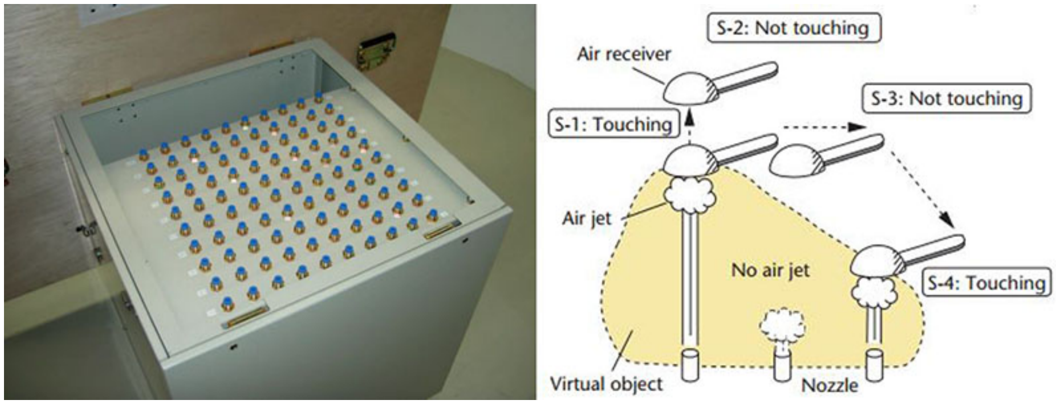

Figure 2.6: The air-jet device from [43]. On the left the air-jet device with the 10x10 array of air-jet nozzles and on the right the setup used, participants do not feel directly the air but through a handled device.

2.2.3 Thermal Based Devices

Most of the devices used to deliver thermal feedback used a Peltier device (see Figure 2.7). Here is a description of the Peltier device from [44]: "Peltier devices, also known as thermoelectric modules, have been the most widely used thermal stimulators in thermal displays [45], [46], [47]. These devices operate based on the Peltier effect, which refers to the creation of a temperature difference at the junctions of two dissimilar conductors in contact when a DC current passes through the circuit. Commercially available Peltier devices are typically made from two ceramic substrates with an array of N and P-doped semiconductors in between. These semiconductors are connected in parallel thermally and in series electrically. Depending on the direction of the current, one side of the substrate cools while the other heats, and a temperature difference is generated between the substrates. The difference in temperature and the rate of temperature change can be controlled by varying the direction and magnitude of the current passing through the device".

Thermal feedback entered the field of HCI recently and has been studied in various context those past few years. Wilson et al. [48] showed that cold stimuli are easier to perceived and warm stimuli tend to be more uncomfortable (see figure 2.8). In a follow up work [49], they showed that there is a strong uniformity in the interpretation of thermal feedback by users: warm feedback is related to presence of life, emotional positivity while cold feedback represents the absence of people and emotional negativity.

In more recent work, Wilson et al. [21] mapped emotions to the circumflex of emotions taking into account the rate of change (ROC) and extend of change (EOC). They showed that the valence is mainly directed by the EOC, with high EOC being negative valence and small EOC positive valence. The ROC has an effect on arousal; indeed, a high ROC is rated higher than small ROC. Moreover, the emotions do not cover all the circumflex, leaving some space for future works: maybe a combination of both vibrotactile and thermal feedback could extend the spectrum of emotions conceived by the sense of touch.

By observing the results of [21] and [49], we can observe how the emotional state is strongly influenced by the thermal variation more than the temperature itself (e.g. an object at 25 °C will elicit a very different emotional response than an object at 20 °C that will gradually reach 25 °C).

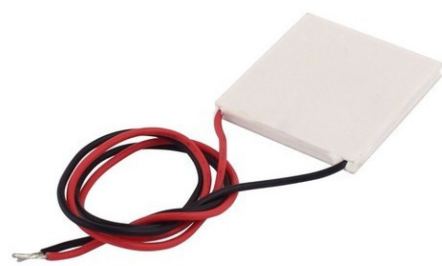

Figure 2.7: A Peltier element. It allows to deliver cold on one side and warm on the other depending on the current direction.

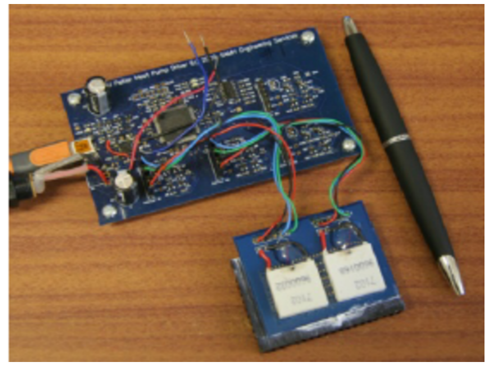

Figure 2.8: A simple thermal feedback setup. The two Peltier elements give thermal feedback on the participants' wrist [48].

Peltier devices have been embedded in wearables to provide users with thermal feedback [37]. The addition of temperature to wearable is bringing several challenges: a high power consumption, the need for a heat sink, and security concerns.

2.2.4 Electrical Stimulation

Electrical stimulation is a young field but has some applications. For instance, TeslaTouch [50] is based on the electrovibration principle, which does not require any moving parts and provides a wide range of tactile sensations. It was embedded in a tactile surface, giving feedback to the user on the fingers' tip (see Figure 2.9).

Spelmezan et al. [15] created Sparkle, a high voltage resonant transformer to create tactile electric arcs. Such system allows near-field interaction and can be considered as a tactile, thermal, and mid-air interaction. In this study, Spelmezan showed that Sparkle can create different tactile sensation depending on the strength of the signal. Users described this sensation with words such as rough/smooth, warm or tingle. The device in action can be seen on the Figure 2.10.

2.2.5 Mid-Air Haptics Through Air Displacement

AIREAL [14] is a haptic technology that delivers effective and expressive tactile sensations in free air. It used the principle of vortex generation, that can travel at a maximum distance of 125 cm in about 139 ms. With

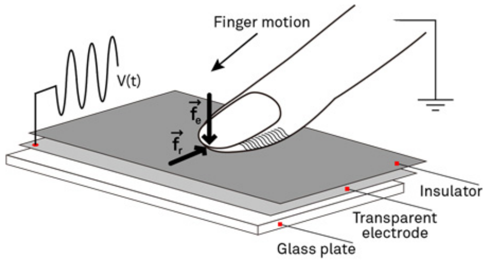

Figure 2.9: The TeslaTouch device. When users interact with the touch screen, some area provide a tactile feedback [50].

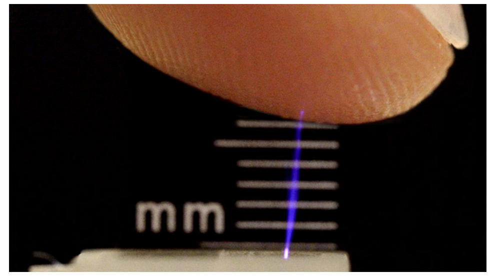

Figure 2.10: The Sparkle device in action. It is capable of delivering a haptic feedback through an electric arc at up to 8 mm of distance [15].

the addition of a tracking device, such as the Kinect device, it could track users' hand while playing a video game and send tactile sensations in real time. The device can be seen on the Figure 2.11.

Another approach to air displacement is to use air jets or fans. Martin et al. [51] created an air jet system box where the strength and location of the feedback could be controlled and aimed at the forearm of participants. Such device allows sending tactile feedback to the participants without any attachment and could successfully convey different arousal levels. A drawing of the setup can be seen on the Figure 2.12.

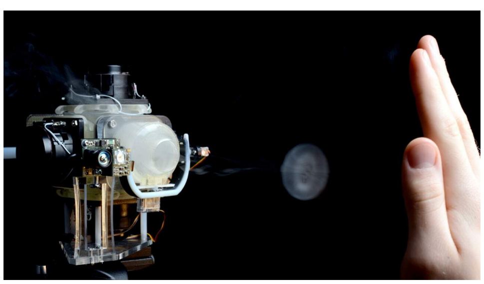

Figure 2.11: The AirReal device. It is capable of sending vortexes of air at up to 125 cm [14].

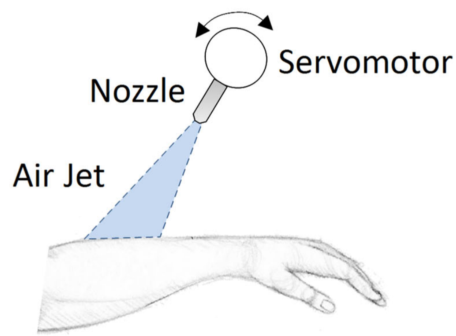

Figure 2.12: The air jets setup. It provides haptic feedback on the user forearm through air displacement. Different location and intensities are available [51].

2.2.6 Ultrasonic Mid-Air Haptics

Iwamoto et al [16] introduced the first implementation of UMHs by using a set of synchronised ultrasonic transducers (see Figure 2.13 left). They took advantage of the acoustic radiation force [52] to create a focal point that can slightly bend the human skin, inducing a tactile sensation.

The size of the focal point is defined by the frequency of the ultrasonic transducers. For instance, at a frequency of 40 kHz, the size of the focal point is approximately 8.5 mm in diameter [28]. The focal point can be displayed in different locations if the ultrasonic transducers can be independently controlled as in [17] (see

Figure 2.13 centre and right). With such device, the maximum display distance is approximately 50cm. Also, it is possible to change the amplitude (i.e. the strength) of the feedback by changing the decibel output of the ultrasonic speakers.

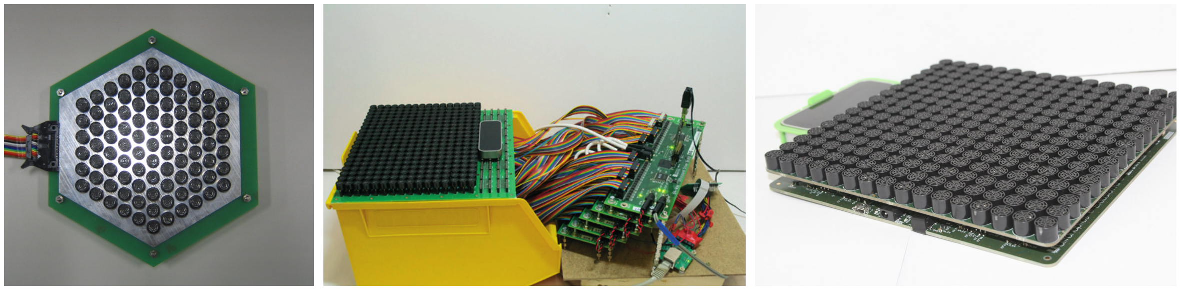

Figure 2.13: The evolution of the UMH devices. Left: the initial device introduced by Iwamoto et al. [16]. Centre: the first version of the Ultrahaptics device by Carter et al. [17]. Right: the first evaluation kit from the Ultrahaptics company that was used in the four papers presented in this thesis.

When simply displayed, a focal point can barely be felt by human receptors. It is therefore mandatory to apply some further technique before using it. The existing technique are based on the variation of some parameters over time, either the amplitude of the point or its location. The next subsection will describe the three techniques used in the literature: The Amplitude Modulation (AM) technique, the Lateral Modulation (LM) technique and Spatio-Temporal Modulation (STM) technique. A summary of each technique is also provided on the Figure 2.14.

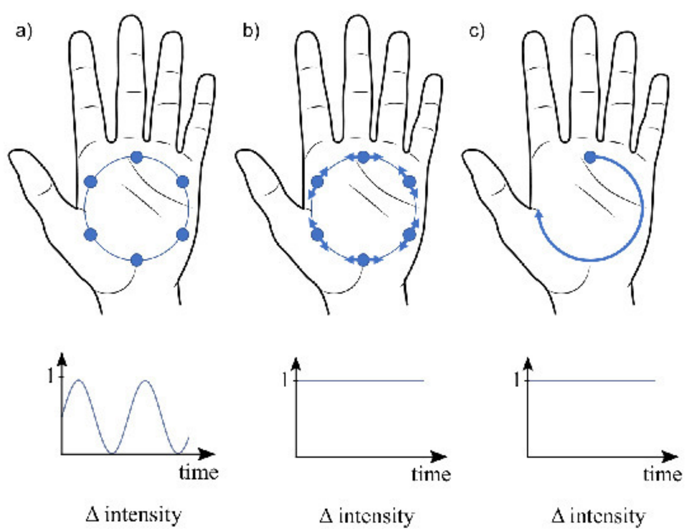

Figure 2.14: The 3 ultrasonic mid-air haptics techniques [53]. (a) Amplitude Modulation, (b) Lateral Modulation, (c) Spatio-Temporal Modulation. Each modulation technique varies the position and intensity of one or more mid-air tactile points differently over time [53].

The Amplitude Modulation technique

The Amplitude Modulation is the first technique introduced [16] and the most widely used so far (see Figure 2.14 (a)). This technique alternates the amplitude (i.e. the intensity) of the focal point over time between full intensity and minimal intensity. This change in intensity is usually instantaneous [17] or following a cosine curve [1]. This frequency is typically kept within 16 Hz to 256 Hz, which is a range of frequencies that can be felt by human skin [19].

With the AM modulation, two parameters are to be taken into account: (1) the amplitude at which the point is displayed, and (2) its frequency. While the first parameter changes the strength of the sensation, the later change the tactile properties of the tactile feedback. An exploratory work through explicitation interviews [19] revealed that a 16 Hz point was often described as “Pulsing” or “Soft Material” where the 250 Hz point was depicted as “Constant” and “Flowing”.

The implementation of the AM by Carter et al. [17] can display several points, with the intensity being kept at good level for up to 5 points. To do so, the points are alternated in a synchronised manner. The table 2.2 describe the intensity loss when using this technique.

Number of focal points	Absolute SPL (dB)
1	72.6
2	71.7
3	68.2
4	67.4
5	66.6

Table 2.2: The strength of focal points when different of points are produced simultaneously [17].

Long et al. [18] presented a method that further optimised the AM to enable the display a high number point (more than 10) in order to display shapes (i.e. circles). To achieve this, the points are divided in two groups and each group is displayed alternatively at the same frequency as the focal points to minimise the loss of intensity.

The Lateral Modulation

Lateral Modulation (LM) is a more recent modulation technique where a tactile point oscillates back and forth along a short line that is parallel to the skin, while the focus acoustic pressure is fixed to 1 [54] (see Figure 2.14 (b)). The authors of LM claim that this modulation technique generates a lateral force on the skin, which are usually perceived as being stronger than normal forces, and therefore is very different to AM.

The Spatio-Temporal Modulation Technique

The second technique, the Spatio-Temporal Modulation, is taking advantage of the location of the point instead of the amplitude to create the frequency. Introduced by Frier et al. [3], this technique only allows to draw curves (i.e. circle or line) (see Figure 2.14 (c)).

The three parameters that can be modified when using the STM technique are:

- the frequency: how many times the point will move alongside the curve each second.
- the length of the curve: how much distance the point will travel to describe the curve once
- the sampling rate: the frequency at which the point's location is updated on the curve.

Those parameters have different effect on the tactile experience. In the original work on STM [3], the authors found that the intensity of the feedback was correlated with the speed. Indeed, to get an optimal strength of feedback, it is recommended to use a speed of $5\,\mathrm{m\,s^{-1}}$. Also, in some further work by Frier et al. [53], some advices are given on how to optimise the tactile feedback strength by adjusting the sampling rate.

2.3 Designing for Haptic Experiences

The field of haptic experiences is young and there is no clear design process yet on how to integrate the sense of touch with traditional audio-visual media. This section presents the main approaches either through manual process or specifically designed tools.

2.3.1 Haptic-Audio-Visual Experiences

Various approaches have been explored to design haptic feedback for movies. Danieau et al. [24], for instance, recorded haptic feedback experienced during specific activities (e.g. horse riding) alongside video and sound. Users experienced the movies with 3 different haptic conditions (recorded, randomly generated, and no haptic feedback) and rated them using a Quality of Experience (QoE) questionnaire. Users rated the captured haptic feedback as more immersive than random haptic feedback and the random feedback was also better than no feedback at all. While those findings are interesting, this approach is mainly focusing on the mirroring of an action (motion) on the screen and hence the stimulation of the visual sense, rather than the sense of touch.

Lemmens et al. [12], in contrast, created patterns for a haptic jacket based on typical touch behaviours from human emotional touch communication (e.g. highly energetic movements to indicate surprise or happiness) as well as based on common wisdoms and sayings (e.g. butterflies in your stomach). Those patterns were presented together with short movies. Users reactions were assessed through physiological measurements (respiration, heart rate, skin conductance level) and questionnaires (SAM [25] and Immersion Questionnaire). The results suggested a positive effect of haptic stimuli on peoples' immersion, but they used only one haptic condition per movies, making any comparison between the designed haptics and other approaches impossible.

Israr et al. [22] proposed an approach based on a systematic exploration of haptic feedback and its integration with the other senses, as well as the content and the context of use. The authors built a library that establishes a classification between haptic feedback parameters (i.e. intensity, duration, and stimulus onset asynchrony) and semantic space (e.g. rain, pulse). This library was built and evaluated by users and can be used with various kind of media [55]. Nevertheless, there is still a need to investigate the impact of using a specific pattern during a media experience as it is very likely that the main focus will be on the visual content [56] and can thus outshine the effect of the pattern used.

More creative-focused approaches have been presented. For instance, Kim and al. [57] designed an authoring tool where users can pause a movie and draw the haptic feedback on the screen, focusing of the visual elements they judge relevant. This interface is designed to work with the haptics gloves they designed.

Haptics in public spaces

The integration of touch in public spaces has often been studied in the context of museums. London [58] provided visitors "touch objects" (e.g. a wise owl supervising the Sculpture Galleries and carved examples of different woods types) to experience the displayed artefacts. Visitors were also able to press a button next to an object to hear related audio descriptions. Another example is Ciolfi and Bannon [59] who presented a sandbox used in an archaeology workshop to recreate an archaeological scene for the attending children to enjoy "playing the archaeologist". Harley et al. [60] designed three interactive prototypes of prayer-nuts in an effort to convey and contextualize the historical, sensory, and its embodied information. These 3D printed tangible prototypes offered visitors sensory interactions of smell, touch, and sound with visual and audio feedback, which was relevant to the historical, social, and cultural context of the artefact. Loscos et al. [61] created a virtual environment where visitors could see virtual 3D artworks (e.g. statues) and experienced an associated haptic feedback. A two-contact-point haptic device was linked to the right index finger of each visitor enabling them to touch and feel the contours and stiffness of the artworks through haptic feedback. However, the authors also pointed out that asking visitors to wear an exoskeleton, to enable the haptic feedback, is contradictory to the idea of free exploration in a museum. Thus, any devices designed for museum visitors should be as little invasive as possible.

2.3.2 Haptic-Audio-Visual Tools

In a more recent approach this limitation is overcome allowing more creative exploration. Schneider et al. [62] developed a multi-device toolkit to facilitate haptic experience design. The authors designed a single interface capable of supporting various kinds of devices for creating patterns by drawing on the screen. A cascade of algorithms allows to translate a generic 2D pattern into a device specific pattern. In contrast to the previous approach, this approach might challenge the designer with too many options in the design of tactile experiences, especially when confronted with a totally new device, such as mid-air technology.

For instance, the FeelEffect library introduced by Israr et al. [22] contains a collection of pre-defined haptic patterns (e.g. light versus heavy rain, cat purring, feather stroking, teddy bear poking) to enrich storytelling through tactile feedback. For each haptic pattern the SOA (stimulus onset asynchrony, i.e. the interval between two actuations, in ms), duration (in ms), and intensity (volts) are provided. This approach allows content creators to use semantic related patterns in the creative design process and enrich media content meaningfully. This toolbox provides a valuable starting point to expand the design space for touch but is limiting the creativity and free expressiveness through touch.

Some efforts have been made to presents the user with more than a single modality when creating the haptic feedback. For instance, Zhang et al. [63] created an interface that incorporate three different views: 1) physical, 2) sensory & emotional, and 3) metaphor & usage view (see the interface on the Figure 2.15). For each haptic feedback in the library, the interface shows its properties on each view. The physical view display information on the duration, rhythm and structure (e.g. long note or short note). The sensory and emotional view place each haptic feedback on an emotional space composed of Valence and Arousal as axis, as well as emotional tags and roughness. Finally, the Metaphor and Usage Example view link the haptic feedback to the semantic space (e.g. heartbeat, alarm sound).

2.3.3 Emotional Communication Through Touch

Simulating human contact is an effective way to deliver emotional feedback (i.e. providing human-like sensations). For example, Bianchi and colleagues [64] proposed a device able to deliver "caress like" sensations of different intensity by actuating a piece of cloth hung on users' wrist. In particular, the device was able to deliver emotional information concerning the valence of the emotion through the velocity of the "caress", while the arousal of the emotion was successfully communicated by the "strength of the caress". Gender differences were reported in the haptic communication of emotion in the field of social psychology [65]. In [66], a haptic sleeve was proposed to mimic human touch for interpersonal communication through vibration patterns and was able to replicate both protracted (e.g. pressing), and simple (e.g. poking) touches. This sleeve was used

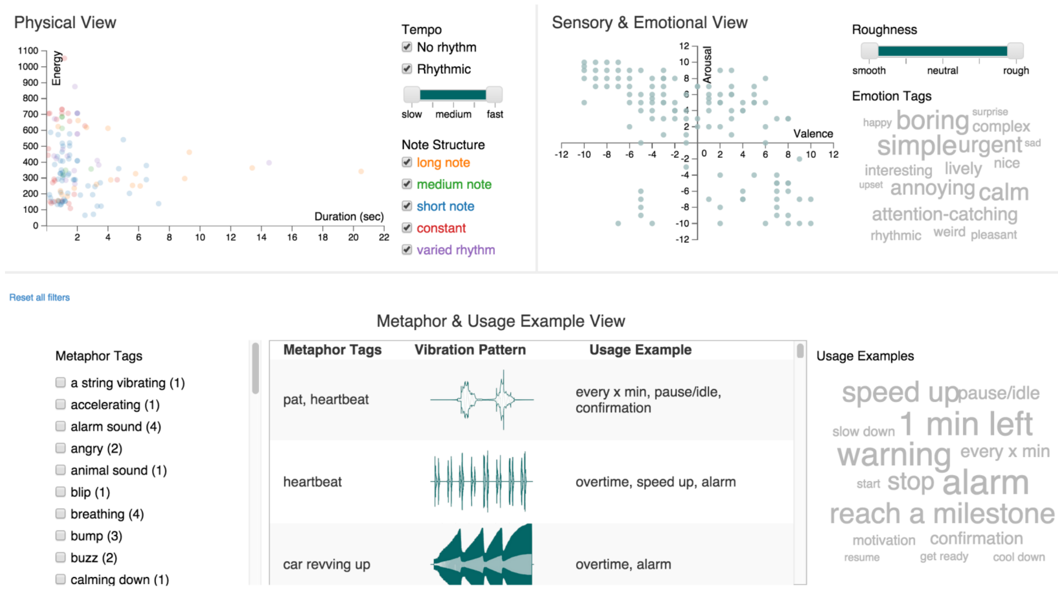

Figure 2.15: The VibViz interface. It features three separate views: 1) physical, 2) sensory & emotional, and 3) metaphor & usage view [63].

in a user study investigating the communication of emotions among a group of participants asked to create vibration patterns for 8 basic emotions [67]. Finding shows that participants could communicate emotions, and they provide insights into the gestures used to convey specific emotion – e.g. squeezing, grabbing, and pressing to convey fear.

The previous approaches mimic real human-to-human interactions (e.g. caress), but alternative methods using more "abstract" haptic feedback have been implemented in several devices, also with promising results [20, 68]. In these examples, users are asked to express their emotion through tactile feedback, which is subsequently played to a second pool of users who have the task of recognising the expressed emotion. In these instances, there seems to be no clear mapping between the haptic feedback and the human interactions. However, the haptic feedback is still effective in delivering emotional information. For example, in [69] participants used a force feedback joystick to express 7 different emotions. Joystick movements where played back later to a different group of participants, who could recognise the expressed emotions above chance level. Interestingly, this kind of emotional communication showed better results than communicating emotions through physical human handshakes.

Thermal feedback as also a powerful emotional driver [70]. Wilson et al. [48] explored the use of thermal feedback to convey emotional information and have shown temperature feedback to be relevant for HCI interactions in both static and mobile contexts. Salminen et al. [68] investigated the emotional response to warm and cold stimuli. Their results showed a significant effect of temperature on the degree of arousal reported by participants, but no effect was found in terms of pleasantness. These results are at odds with those of [49], where the subjective interpretation of warm feedback was reported to be related with positive content, and cold feedback was found to represent emotional negativity. This differences in the reported effect of thermal stimuli could be linked to the different experimental protocols. Indeed, in [68], the participants' emotional state was evaluated (e.g. "I felt aroused during stimulus presentation") whereas in [49] the participants' had to analyse a situation (e.g. "Choose which option best suited that temperature?").

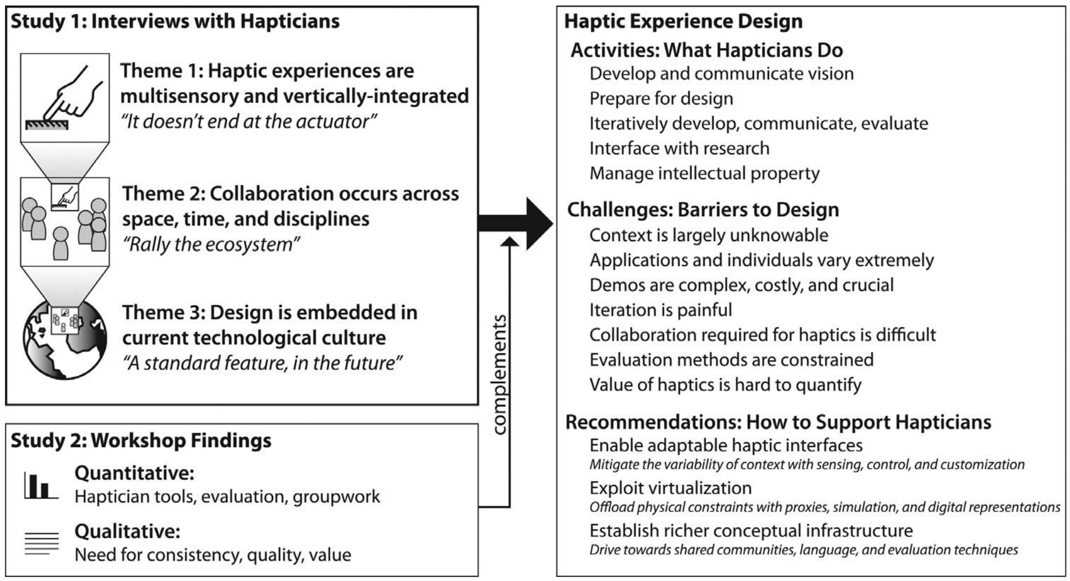

Figure 2.16: Overview of the process and contributions from [71].

2.3.4 The Challenges of Haptic Experience Design

Creating the haptic experience is not coming without any challenges. In their work, Schneider and colleagues [71] looked at what hapticians do and where they could be helped. They interviewed six hapticians and ran a workshop around three topics: (1) Haptic experiences are multisensory and vertically-integrated, (2) Collaboration occurs across space, time, and disciplines, and (3) Design is embedded in current technological culture (see 2.16). They extracted a list of activities that are common to haptician, their associated challenges and a list of recommendations. The list of challenges include the lack of context when designing, the interpersonal differences, the importance and complexity of making demos, the wide range of skills needed (e.g. hardware, software, design, psychology etc.), or the struggle to quantify the added value of haptic.

Another challenge of creating haptic experiences is the interpersonal differences between the users. In a review paper, Gallace et al. [72] present the effect of age, gender, and cultural differences on interpersonal touch. The cultural background especially plays an important role in the way people interact and respond to touch. Remland et al. [73] found for instance some cultural differences between different countries of Europe, the northern countries having less physical contact than the southern countries. Some differences can be linked to the cultural background, for instance in Italy, a hug and kiss on each cheek is considered a common form of greeting. This contrast with Japan, where greetings are usually done through a respectful bow without any tactile interaction [72].

2.3.5 Mid-Air Haptic Experiences

In this thesis, we focus on ultrasonic mid-air haptics and we propose here a list of experiences and challenges that are inherent to this technology.

Use-cases of Ultrasonic mid-air haptics

Ultrasonic mid-air haptics is a new technology and while the technical challenges are still many, it is important to find use cases and applications for this technology.

Van den Bogaert et al. [74] conducted a workshop with 15 participants to understand where people would expect mid-air haptics to enhance their home. The results were sorted and grouped under 5 categories:

- **Guidance**: guiding users, especially when their vision is impaired (coming home late at night).
- **Confirmation**: making sure users now the state of their interactions. For instance, when performing some input gesture, the mid-air feedback could signal the users they are in the right place to start a gesture.
- **Information**: provide the user with various information. Could be binary information (e.g. on/off) or continuous (e.g. percentage).
- **Warning**: Displaying a force field around dangerous locations.
- **Changing Status**: get a feedback when a status is changing (e.g. light is turning brighter).

Other use cases include virtual reality and augmented reality, as they both fit well well mid-air haptic interactions. Pittera et al. [75] showed in their paper that ultrasonic mid-air haptics can successfully be used to convey the rubber hand illusion. Such setup could be used to increase the immersion into VR experiences. Moreover, Monnai et al. [76] created a setup involving both ultrasonic mid-air haptics and floating images, showing potential for AR experiences.

Display information

UMH feedback, when used with a hand tracking device like the Leap Motion, allows new kind of interactions. One of the uses is to create 3D shapes [18] (see Figure 2.17). To achieve this, the location of the hand is computed and the crossing session with the desired object is computed. Then, the ultrasonic board display the section on the user's hand.

The first paper to display 3D shapes was using the AM setting and achieve above change shape discrimination [18]. Some more recent work by Martinez at al. [77] applied a mix of the STM and AM techniques to improve the recognition of the shapes. While their user study was too small to make a clear conclusion, they introduced several new techniques to display shapes.

Some preliminary work to use UMH feedback to display abstract patterns and textures has also been done. Freeman et al. [78] presented textured surfaces for ultrasound haptic displays. They used tessellation to render different geometric patterns with different parameters that can be tuned to create different haptic experiences.

Another use of UMHs is to warn users by sending them a touch feedback on the face, for instance if they approach a dangerous location. Mizutani et al. [79] used this technique to warn train passengers that were walking to close to the train line. They studied both the tactile stimulation thresholds and the auditory perception. Findings shows that the lateral modulation is promising for this use and successfully communicated the danger to users.

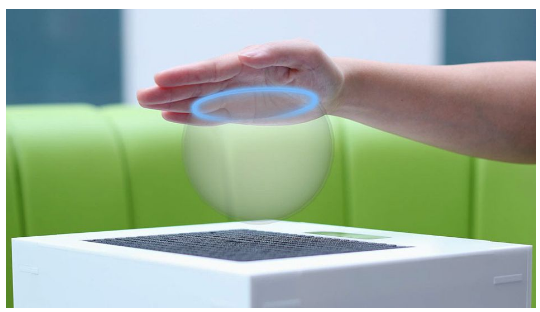

Figure 2.17: Representation of the display of a 3D shape using UMHs [18].

Integration in Multisensory Experiences

One of the first integration of UMH feedback in a multisensory context was done by Obirst et al. [20], were emotional pictures from a standard database [80] were used to create emotional haptic patterns. To achieve this, three user studies were run: (1) a first group of participants created haptic patterns for emotional pictures, (2) a second group of participants rated the emotional patterns to see which ones where the most effective in conveying specific emotions, and (3) a final group of participants rated the most relevant patterns on an emotional scale. Results show that haptic feedback can successfully convey arousal through intensity and movement speed. The results also seem to indicate that some parts of the hand might be linked to a positive or negative valence.

The first time UMHs were used in a public exhibition happened in the Tate Britain Gallery in London, for a specific event: The Tate Sensorium [1]. To create the haptic experience for this event, a group of HCI researchers worked with a sound designer during several months. The process included workshop, creation of specific software and pilot testing. This work allowed to get insight on how to create a real case multisensory experience in a large exhibition.

The Challenges of mid-air haptics

Designing with ultrasonic mid-air haptic experience brought the new challenge that users have difficulty to relate the sensation to any past experiences. Obrist et al. [19] started by exploring two frequencies using the Amplitude Modulation technique through explicitation interviews. After analysing the data, it came to light that participants used some specific terms to describe the two different frequencies. The high frequency point (250 Hz) was described as strong and constant where the low frequency point (16 Hz) was described as weak and "coming and going".

One of the connected problems with the novelty of UMH technology is the lack of understanding of how to quantify the added value of touch in multisensory experiences. Maggioni and colleagues [81] explored three different scales to assess short video clips enhanced either using UMHs or vibrotactile haptics. The scales used to assess the added value of touch were:

1. The Self Assessment Manikin (SAM) to measure the emotion [25]
2. The AtttrakDif questionnaire that measure pragmatic qualities, hedonic qualities and attractiveness of the experience [26]
3. Expectation questionnaire through two questions: (1) "I think the haptic feedback will be comfortable while watching a video" and (2) "I think the haptic feedback is able to convey emotions" rated on a 7 points Likert scale.

The results of this study are promising and provides designers with a first set of tools to assess their own haptic experiences.

The location of the hand is also an important parameter when using UMHs. Indeed, the size of a focal point being 8.5 mm, an offset of only few millimetres could change the tactile sensation. Freeman et al. [82] addressed this problem by adding LEDs around the haptic device (see Figure 2.18). The colour of the LED changes depending on the user's hand location, giving a direct visual feedback to the user on how well their hand is located for receiving an optimal haptic feedback. Such system could improve the quality of the haptic sensation, and at a low cost.

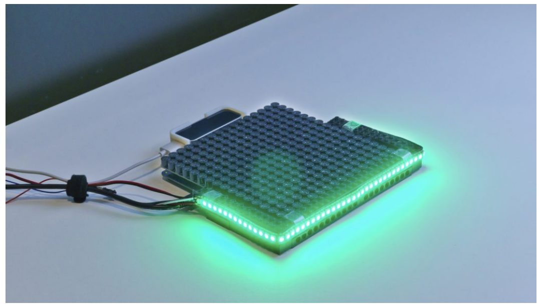

Figure 2.18: HaptiGlow setup. It is composed of the UMH board and surrounding LEDs to guide users' hands. [82].

Part I

Exploration of the Mid-air Haptic Design Space

Chapter 3

Mid-Air Haptic Experiences Integrated in a Multisensory Art Exhibition

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The use of the senses of vision and audition as interactive means has dominated the field of Human-Computer Interaction (HCI) for decades, even though nature has provided us with many more senses for perceiving and interacting with the world around us. That said, it has become attractive for HCI researchers and designers to harness touch, taste, and smell in interactive tasks and experience design. In this paper, we present research and design insights gained throughout an interdisciplinary collaboration on a six-week multisensory display – Tate Sensorium – exhibited at the Tate Britain art gallery in London, UK. This is a unique and first time case study on how to design art experiences whilst considering all the senses (i.e. vision, sound, touch, smell, and taste), in particular touch, which we exploited by capitalising on a novel haptic technology, namely, mid-air haptics. We first describe the overall set up of Tate Sensorium and then move on to describing in detail the design process of the mid-air haptic feedback and its integration with sound for the Full Stop painting by John Latham (1961). This was the first time that mid-air haptic technology was used in a museum context over a prolonged period of time and integrated with sound to enhance the experience of visual art. As part of an interdisciplinary team of curators, sensory designers, sound artists, we selected a total of three variations of the mid-air haptic experience (i.e. haptic patterns), which were alternated at dedicated times throughout the six-week exhibition. We collected questionnaire-based feedback from 2500 visitors and conducted 50 interviews to gain quantitative and qualitative insights on visitors' experiences and emotional reactions. Whilst the questionnaire results are generally very positive with only a small variation of the visitors' arousal ratings across the three tactile experiences designed for the Full Stop painting, the interview data shed light on the differences in the visitors' subjective experiences. Our findings suggest multisensory designers and art curators can ensure a balance between surprising experiences versus the possibility of free exploration for visitors. In addition, participants expressed that experiencing art with the combination of mid-air haptic and sound was immersive and provided an up-lifting experience of touching without touch. We are convinced that the insights gained from this large-scale and real-world field exploration of multisensory experience design exploiting a new and emerging technology provide a solid starting point for the HCI community, creative industries, and art curators to think beyond conventional art experiences. Specifically, our work demonstrates how novel mid-air technology can make art more emotionally engaging and stimulating, especially abstract art that is often open to interpretation.

3.1 Introduction

Humans are equipped with multiple senses to perceive and interact with their environment. However, in HCI, vision and hearing have been the dominant senses, and our sense of touch, taste, and smell have often been described as secondary, as the lower senses [83]. HCI researchers and practitioners are however increasingly fascinated by the opportunities that touch, smell, and taste can offer to enrich HCI. Recent examples of such experiences include the novel olfactory display by [84], taste-based gaming [85], olfactory in-car interaction [86], digital flavour experiences [87], and the added value of haptic feedback for audio-visual content [81]. In particular, there has been a growing interest in uncovering the specificities of haptic experience design [71] and the unique features of haptic stimulation that would allow the creation of emotionally engaging and meaningful experiences [42, 88].

With the advent of novel touchless technologies that enable the creation of tactile stimuli without physical contact (e.g. [17, 89, 90, 18, 14], a novel design space for tactile experiences has been opening up [19]. Most notably, it has been demonstrated that mid-air haptic stimulation can be used to convey emotions to the user [20]. This research has motivated further investigations of the design possibilities for creating novel mid-air haptics experiences [2]. Here we extend the use of mid-air haptics stimulation in the context of a museum, moving beyond a controlled laboratory environment to investigate the effect of multisensory stimulation on users' experience of art.

Museums and art galleries have always been in the forefront of integrating and stimulating multiple human senses, not only to explore new ways of representing arts, but also to increase the wider public interest in the artifacts being displayed. Harvey et al. [91] showed that the use of touch specimens, sounds, and smells to complement the object along with interactive components (e.g. role playing induction device) and dynamic displays can have a strong influence on visitors' experiences, especially creating a strong sense of flow – being fully immersed and focused in a task [92]. Another intriguing work that relates to multisensory museum experiences is the Jorvik Viking Centre [93], where multisensory stimuli were used to enrich the experience of a tour concerning the Viking past of the city of York. This experience allowed visitors to touch historical objects (Viking Age artefacts), taste the unsalted, dried cod of the Viking diet, smell the aroma of the corresponding displayed objects, see the animals and inhabitants of the Viking city, and listen to the Viking sagas. More focused on the sense of touch, Loscos et al. [61] presented how visitors could see and feel virtual 3D artworks (e.g. statues) using a haptic device that was connected to the user's right index finger to provide haptic feedback. This use of technology enabled users to touch and feel the contours and stiffness of the artwork.

Despite the increasing interest in the different senses as interaction modalities in HCI and related disciplines and professions (e.g. art curators, sensory designers), there is only a limited understanding of how to systematically design multisensory art experiences that are emotionally stimulating. Moreover, there also seems to be a lack of understanding on how to integrate different sensory stimuli in a meaningful way to enrich user experiences with technology [94], including art pieces. Carbon [95] replicated the work of Smith and Smith [96] and pointed out the mismatches in the amount of time and space people spent in viewing artworks in a laboratory versus a museum context. Specifically, museum visitors had longer viewing time than was mostly realized in lab contexts, as well as longer viewing time when attending in groups of people. Additionally, this work uncovered a positive correlation between size of artwork and the viewing distance. These findings emphasize the fact that there is a need to carry out museum related investigations in the actual environment of a museum. Only through an in-situ approach, the intended users who have an intuitive interest and knowledge about art environments, are reached and can provide valuable feedback on the multisensory design and integration efforts.

Building on these prior works, in this paper, we present research and design efforts carried out as part of a six-week multisensory art display – Tate Sensorium – in an actual museum environment (i.e. Tate Britain art gallery). For the first time, mid-air haptic technology was used in a museum context to enhance the experience of a painting (i.e. the Full Stop by John Latham) through its integration with sound. The multisensory integration of touch and sound aimed to aid the communication of emotions and meaning hidden in the painting: a large circular black spot in the approximate centre of an unprimed canvas (see 3.2b).

In collaboration with a creative team of art curators and sensory designers, the specific experience for the Full Stop painting was created. A total of three variations of the experience were created, keeping the sound the same but changing the mid-air haptic pattern to investigate the effect of the sense of touch on the visitors' art experience (see illustrated in Figure 3.5 and described in section 3.3.3). We hypothesized that museum visitors would enjoy more experience involving the pattern specifically designed for Tate Sensorium (Tate pattern, the most sophisticated and purposeful designed experience), followed by the experience involving the Circle pattern (congruent with the visual appearance of the painting) and finally the Line pattern (incongruent with the visual appearance of the painting). Visitors' experiences were assessed through a short questionnaire at the end of the Tate Sensorium experience and through interviews to deepen our understanding on the subjective differences of sensory enhanced art experiences. In the following sections, we first provide a review of related work on multisensory research and design in museums, followed by a general overview on the multisensory art display – Tate Sensorium in the Tate Britain art gallery. We include the description of the exhibited art pieces and sensory design space. We then focus on the work around the Full Stop painting and the design and development of the mid-air haptic patterns as part of the specific touch-sound integration. We provide a detailed description of the data collection process and the insights from the analysis of 2500 questionnaires and 50 interviews. We conclude with a discussion of our findings with respect to the lessons learnt, limitations and future opportunities for designing multisensory experiences outside the boundary of a laboratory environment.

3.2 Related Work

Museums are public places that contain a collection of artifacts that hold values in artistic, historical, and cultural contexts [97]. Importantly, museums offer "a multi-layered journey that is proprioceptive, sensory, intellectual, aesthetic and social" [98]. Given the experiential aspect of museums, they (and exhibitors) have always been looking for new ways to diversify and enrich the experiences that they deliver to the visitors. Therefore, there have been examples and efforts of enhancing art objects through sensory stimuli to engage visitors and convey meaning.

3.2.1 Multisensory Interaction in the Museum

Museums are a forerunner in harnessing new ways of interacting with public users. Therefore, they are recognized within the field of HCI as relevant places for designing interactive systems to reach out to the public. An example is Transcending Boundaries [99], an exhibition that explored the transcend between physical and conceptual boundaries (e.g. elements from one work can fluidly interact with and influence elements of the other works exhibited in the same space) via visual, auditory, and tactile interactions. In addition, there are various cases in which the integration of multiple senses has been explored in museums. For example, Lai [100] explored the "Universal Scent Blackbox", an artwork composed of boxes emitting five smells: grass, baby powder, whiskey tobacco, dark chocolate, and leather. Visitors to the installation could trigger an odour emission in another area for other visitors and vice-versa. This olfactory interaction attracted much interest from the visitors and became an inspirational probe for exploring olfactory interfaces for communication. Based on those prior explorations, it has been suggested that multisensory design in a museum may enhance the richness, and even the memorability, of the visitor's experience [101, 102], due to the emphasis on the multisensory nature of our everyday life experiences. Work by Teramoto et al. [103] has shown that auditory and visual modalities mutually influence each other during motion processing of external events so that the brain obtains the best estimates of such events. Within HCI, we can additionally observe various efforts of integrating interactive technologies (e.g. touch screens, multi-touch tabletop, see [104, 105, 106, 107]) into a museum context to make artworks more accessible and enjoyable. In particular, Correia et al. [104] used a multi-touch tabletop for multimedia interaction in museums, allowing visitors to access artworks' details and to assign tags to artworks.

Among the implementations of multisensory integration in museums, the integration of touch, together with vision and hearing, are the most frequent senses to be stimulated. For example, the Victoria and Albert Museum in London [58] provided visitors "touch objects" (e.g. a wise owl supervising the Sculpture Galleries and carved examples of different woods types) to experience the displayed artifacts. Visitors were also able to press a button next to an object to hear related audio descriptions. Another example is Ciolfi and Bannon [59] who presented a sandbox used in an archaeology workshop to recreate an archaeological scene for the attending children to enjoy "playing the archaeologist". Harley et al. [60] designed three interactive prototypes of prayer-nuts in an effort to convey and contextualize the historical, sensory, and its embodied information. These 3D printed tangible prototypes offered visitors sensory interactions of smell, touch, and sound with visual and audio feedback, which was relevant to the historical, social, and cultural context of the artifact. Loscos et al. [61] created a virtual environment where visitors could see virtual 3D artworks (e.g. statues) and experienced an associated haptic feedback. A two-contact-point haptic device was linked to the right index finger of each visitor enabling them to touch and feel the contours and stiffness of the artworks through haptic feedback. However, the authors also pointed out that asking visitors to wear an exoskeleton, to enable the haptic feedback, is contradictory to the idea of free exploration in a museum. Thus, any devices designed for museum visitors should be as little invasive as possible.

From the artistic side, new technologies have been used as innovative means for creating art pieces. For example, Yoshida et al. [108] created an interface for drawing using a stylus that provided different haptic feedbacks depending on the colours used to paint (e.g. participants experienced dark colours as heavy in weight and light colours as light in weight). In this work, the attachment of vibrotactile feedbacks to different colours created a novel experience for the creators of those digital/ media artworks. However, the authors did not investigate further the visitor's user experience once presented with these artworks. Another work explored the creation process of art integrating vision and touch [109]. The authors ran one-on-one guided design sessions where visual artists created tactile design prototypes augmenting an existing work in their portfolio as a visual context. They analysed the creation following two rationales: (1) the tactile construct (a set of attributes that define its physical characteristics) and (2) the tactile intent (the variety of meaning assigned to a tactile feature). This analysis provides insights on how to design creativity tools for artists, but does not further investigate the museum visitors' experience.

The above examples show the interest and growing attention from various stakeholders in exploiting the human senses in the experience of artwork. In particular, the proliferation of haptic technologies creates a new space for experimentations for both researchers and artists alike. All prior work around the sense of touch is however so far limited to actual physical contact between visitors and the artifacts. Consequently, it does not yet exploit the use of novel contactless technology. This consequently raises the question of what user experiences around art can be created through the use and integration of mid-air haptic feedback in a museum context, in particular given recent evidence suggesting that mid-air haptic feedback can convey emotions [20].

3.2.2 Haptics as an Aid in Communicating Emotions

Recent developments of novel haptic technology, such as focused ultrasound [17, 90], air vortex [14], and PinPad [110], aim to create new forms of tactile experiences. These works highlight the design opportunity of creating tactile sensations in mid-air, without requiring the user to physically touch an object, a surface or wear an attachment such as a glove or exoskeleton. Such experiences are of great interest when it comes to augmenting the experience of artworks, which are often fragile and would decay through multiple exposure to human touch. Yet, these new haptic technologies are intriguing to engage people with art emotionally, and to inspire artistic explorations and create memorable experiences.

Here we focus on communicating and mediating emotions through touch as a research area that allows the design of new emotion-related interactions [20, 111]. This is demonstrated in a recent work of Park et al. [112] on the integration of touch during phone conversations in order to enhance emotional expressiveness in long-distance relationships. Moreover, there is a growing number of wearable systems that allow different types of social touch and an increasing number of studies demonstrating the rich expressiveness of tactile sensations derived from novel haptic systems [10, 66, 113, 114, 115, 116]. Previous work has showed that participants used weak touches for positive emotions, and hard, fast, and continuous touches for negative emotions [112]. Others identified different types of touch for each emotion (e.g. stroking for love, squeezing for fear), but also reported participants' difficulty in differentiating the intensity of the expressions when applied through a wearable system on the forearm [66]. Altogether, these results promote the potential for communicating affective information through touch.

Most recently, this potential has been established for mid-air haptic technology using a haptic device that uses focused ultrasound to create one or multiple focal points on the human hand. A focal point is created using a fixed pressure (physical intensity) in mid-air using 40 kHz ultrasound waves and by applying the correct phase delays to an array of ultrasound transducers [17]. This focal point of pressure can then be felt when modulating the ultrasound waves within the frequency range of the mechanoreceptors of the human hand (i.e. Meissner corpuscle and Pacinian corpuscle [19]. Using this mid-air haptic device, Obrist et al. [20] created haptic emotional descriptions and identified a specific set of parameters (combining spatial, directional, and haptic characteristics) with respect to the two-dimensional emotion framework of valence and arousal. Based on this, the authors concluded that it is possible to communicate emotions through mid-air tactile stimulation in a non-arbitrary manner from one user to another. This work was a major inspiration for the team of practitioners, curators, and researchers working on the Tate Sensorium.

3.3 Tate Sensorium

Tate Sensorium was a six-weeks multisensory exhibition in Tate Britain, an internationally recognized art gallery in London, UK. In this section, we provide a general overview and background on the project, the overall ambition, and the specific aims for the multisensory augmentation of artwork through the use of mid-air haptic technology.

Tate Sensorium was the winning project of the 2015 Tate Britain IK Prize award that is specifically designed by Tate to support innovative installations using cutting-edge technologies that enable the public to discover, explore, and enjoy art in new ways. The ambition of Tate Sensorium was to enable museum visitors to experience art through all senses (vision, sound, touch, smell, and taste). This was achieved through the joint efforts of a cross-disciplinary team of collaborators from the art gallery, creative industries, sensory designers, and researchers (see details in the Acknowledgments at the end of this chapter). Flying Object (2015), a creative studio based in London, led the project and coordinated the activities across the various stakeholders.

Below we will first describe the setup of Tate Sensorium in the Tate Britain gallery (for an overview). We then provide the details on the artwork selection process and the design of the sensory stimuli for the finally selected art pieces (i.e. four paintings, see Figure 3.2), their integration and deployment in the museum, so that visitors were able to experience the different art pieces in a novel way. We will describe in even more detail the design of the haptic feedback using mid-air haptic technology and the scientific approach to collect user feedback (both led by the research team at the University of Sussex).

3.3.1 Overview on the Setup in the Museum

A large dedicated room inside the Tate Britain art gallery was used for Tate Sensorium. Figure 3.1 shows the layout of the room divided into four areas specifying the final set up for the four selected paintings including details on the painting locations, lighting, senses used, etc. Each painting had a dedicated space and was hung on a wall in each section of the room (marked 2, 3a, 3b, 4).

Visitors first entered the room and were welcomed just inside the entrance (in front of the point marked 1 in Figure 3.1). At that point, visitors put on headphones and listened to a welcome message, which briefly introduced the event and gave some general instructions. Visitors entered in a group of four at a time and viewed one painting at a time during the tour. After viewing the first painting, the group of four people split when reaching the second painting, so that two people continued with the second painting and the other two went to the third painting. These groups swapped afterwards, before moving forward all together to the fourth painting. The split was necessary due to the setup of the mid-air haptic technology for the second painting, which could only be used by two people at a time.

3.3.2 Artwork Selection and Sensory Design

The selection of the artworks was a collaborative process between gallery professionals and external experts from different fields (at Flying Object, University of Sussex, and other independent sensory experts). At first, not only paintings but also sculptures were part of the pool of potential artworks. The list of potential artworks was compiled by Flying Object and included suggestions from the team at Tate Britain as well. This resulted in an initial pool of potential artworks consisting of 60 paintings. The selection criteria for the paintings focused on non-representational (or abstract) paintings, as it was agreed that they would leave more room for viewer interpretation. In other words, without any clear visual identity of objects within the painting, the non-visual stimuli would potentially have a stronger impact on how the artwork would be perceived. Additionally, the not-so-clear visual identity would give room for other sensory stimuli to guide the interpretation of the experience, given that sensory information can prime specific notions in users [117].

The availability of the artwork for the exhibition and the preparation phase (2 months) was also a key criterion considered in the selection process. The final decision as to what artworks to select was made by the creative project team led by Flying Object, with sign-off by Tate Britain's management, in June 2015. Tate Britain's staff provided advice on the selection of artworks, based on their availability and suitability for inclusion (in terms of conservation, safety, and other artistic considerations). Further guidance on developing content (selecting appropriate interpretive/contextual information relating to each work) for the display, eventually translated into "sensory form" (e.g. audio material), was provided by Tate.

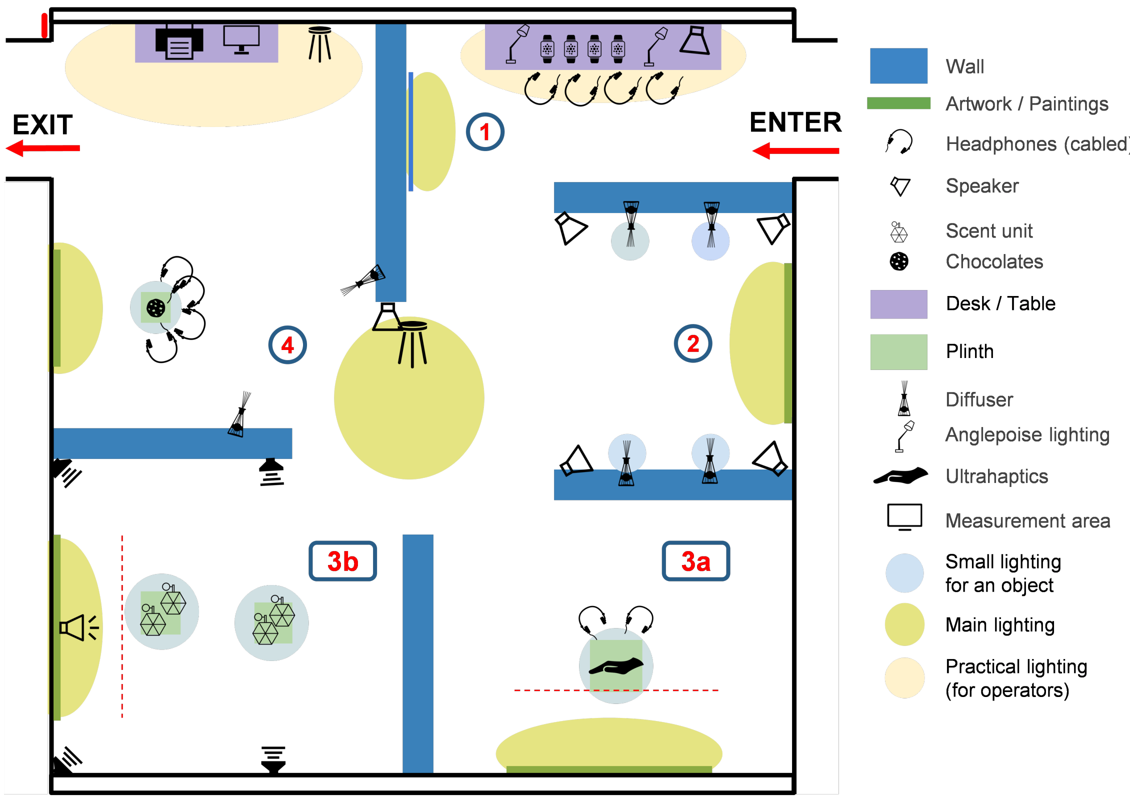

Figure 3.1: Room setup of the Tate Sensiorium. The room was split into different sub-spaces (design by Flying Object): Visitors enter on the right, where they receive the headphones and a wristband (1). Then they move to the room (2) to see the first painting Interior II alongside olfactory and sound stimuli. After that, they move to either (3a) to experience the Full Stop painting alongside mid-air haptic and sound or (3b) to see the painting In the Hold through olfactory and sound stimuli. After swapping, visitors move to the last station (4) to experience taste sensations for the Figure in a Landscape painting.

Four paintings were selected based on their potential for interpretation through different senses, as well as their availability at the museum for the duration of the display in August and September. The four selected paintings were:

- Interior II by Richard Hamilton
- Full Stop by John Latham
- In the Hold by David Bomberg
- Figure in a Landscape by Francis Bacon

Figure 3.2 shows the illustration shots of a participant experiencing the four selected paintings. High definition images of the paintings can be accessed via the Tate Britain website. The details of each painting are in the next section alongside the description of the sensory stimuli.

The suitability of the sensory stimuli was decided by considering the literature on multisensory perception

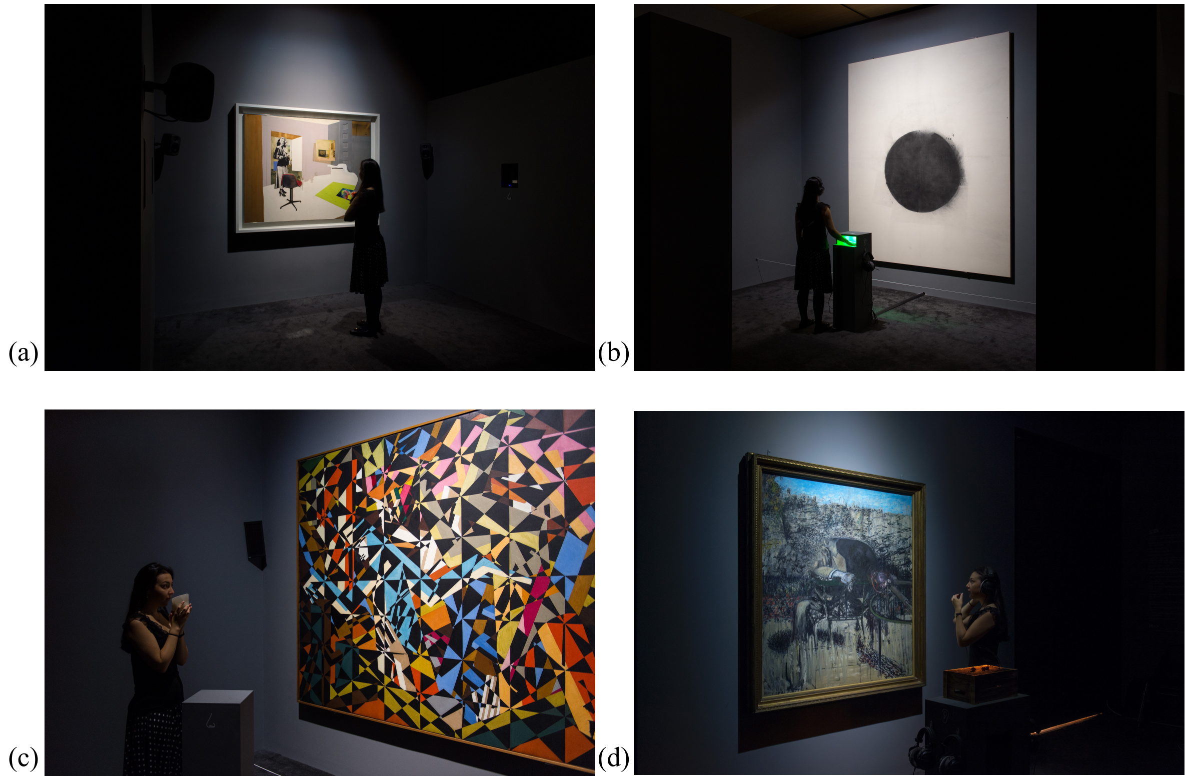

Figure 3.2: Tate Sensorium exhibition at Tate Britain in 2015. (a) Installation shot of Interior II (1964) by Richard Hamilton. Photo: Tate. Illustration shows a participant experiencing the first painting, combining vision, audition, and smell. (b) Installation shot of Full Stop (1961) by John Latham © John Latham Estate. Photo: Tate. Illustration of a participant experiencing the second painting combining vision, auditory, and haptic (with the haptic pattern projected on the user's right hand). (c) Installation shot of In the Hold (c. 1913-4) by David Bomberg. Photo: Tate. Illustration of a user experiencing the third painting combining vision, auditory, and smell (by holding a 3D printed scent object close to her nose). (d) Installation shot of Figure in a Landscape (1945) by Francis Bacon. Photo: Tate. Illustration of a user experiencing the fourth painting combining vision, audition, and taste (by eating a piece of chocolate with multiple ingredients, namely, charcoal, sea salt, cacao nibs and smoky Lapsang Souchong tea).

and experiences (by the university research team), suggestions from sensory professionals, and based on an iterative creative process. To do this, an on-site visit to the art gallery by the whole team was arranged. During the visit, the team experimented with the different senses in front of the artwork (e.g. using scented paper strips), as well as experiencing the mid-air haptic technology at the University with the project team.

The methodology for designing the sensory stimuli was as follows: (1) The team (of all people in the project) generated ideas for each of the four paintings selected, as well as a fifth reserved painting, prototyping them where possible (i.e. selecting actual scents or food ingredients, creating audio samples). (2) The team assigned a leading sense to each painting, along with a secondary sense (in the case of the painting Figure in a Landscape by Francis Bacon, a tertiary sense to accompany the taste). (3) The designers of each of those senses formed, with Flying Object, sub-teams to collaborate on the experience for each painting. (4) Through iterative discussions with experts and professionals between the teams, these sensory ideas were refined. Below, we present a detailed description of the “Full Stop”, which was selected for the present study, where we utilized mid-air haptics to design the experience of such a painting.

3.3.3 Sensory Design for the “Full Stop” Painting

Here we provide details on the specific design for the second painting (Full Stop by John Latham), which was augmented through the integration of sound with mid-air haptic stimuli using the mid-air haptic device described by Carter et al. [17] and developed by Ultrahaptics [1].

Background about the painting

The Full Stop painting by John Latham is an acrylic paint on canvas from 1961, with the size $3015 \times 2580 \times 40\,\mathrm{mm}$. It was presented in the room marked 3a in Figure 3.1 and can be described thus: “Full Stop is a monumental painting comprising a large circular black spot in the approximate centre of an unprimed canvas. The spot was created by repeated action with a spray gun, its curve delineated using weighted sheets of newspaper cut to the correct shape and, as a result, traces of rectangular forms are faintly visible outside the circumference. The circle’s edges are blurred, particularly on the left side where a sprinkling of tiny and slightly larger dots emerge from the dense black of the large spot. The semi-mechanical process of making the spot, in which many dots are applied to the canvas at the same time, suggests the mechanical process of printing rather than the more traditional painting processes normally associated with a canvas. The painting’s canvas is unstretched and is displayed pinned to the wall in the manner of a wall-hanging evoking signage and heraldry. The title, Full Stop, refers to text, and evokes the printed word. At the same time, the blurred edges of the spot and the slight halos around some of the larger dots at its circumference recall a solar eclipse, a black hole or the negative of photographs of light reflecting off planets in the dark galaxy”. (Quoted in Art after Physics, p.106.)

Sensory augmentation

Participants experienced this painting through the integration of sound and touch features. The sound was presented via headphones supplied by Polar Audio (manufactured by Beyer Dynamic) and which were worn by participants while in the room (see Figure 3.3). The sound was created by a sound expert accentuating the interplay between the positive and negative space in the artwork, especially emphasizing the painting’s duality of black and white. The audio was also designed to create a sense of scale, of roundness and reference to Latham’s use of spray paint, which was resembled in the mid-air haptic feedback.

[1] https://www.ultrahaptics.com/

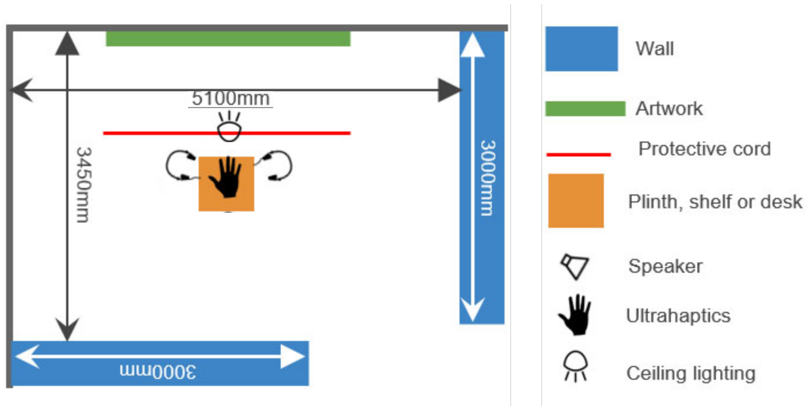

Figure 3.3: Detailed setup of the space for the painting. Full Stop (left), with the specifications of the setup on the right.

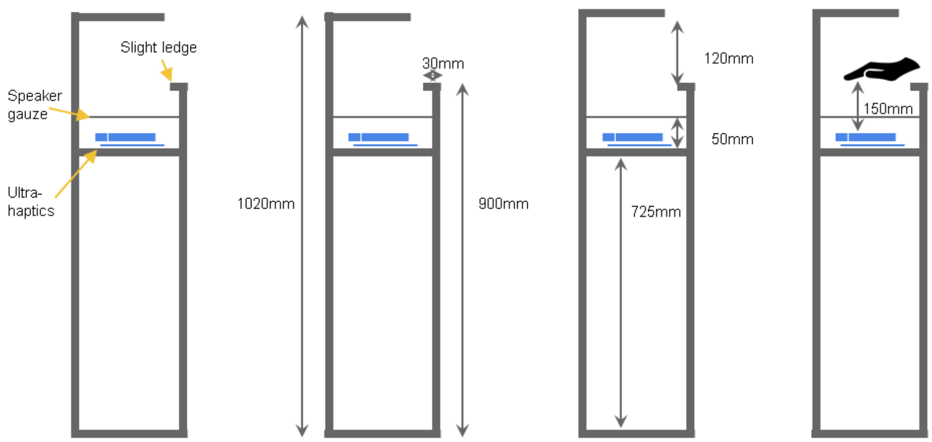

Figure 3.4: The plinth created for the haptic stimulus. Used for the Latham painting using mid-air haptic technology, the Ultrahaptics device (design by Flying Object).

Participants stood in front of a plinth box and put one hand, with the palm facing down, inside the top part of the plinth to have the haptic feedback delivered to their palm (see Figure 3.2(b)). The haptic device was placed inside the plinth, with the specifications shown in Figure 3.4. A speaker gauze was placed 50 mm above the device to prevent participants touching the device. The haptic feedback was presented through the gauze when participants put their hand on top of it [17]. The height of the plinth was calculated so that it fitted comfortably with adults, children, and disabled visitors in wheelchairs.

3.3.4 Mid-Air Haptic Pattern Design

Synchronization between the sound and the mid-air haptic sensation was handled by self-developed software that could read Musical Instrument Digital Interface (MIDI) inputs (using RtMidi 2.1). Thus, the mid-air haptic patterns could be synchronized automatically with the sounds created by the sound designer. In other words,

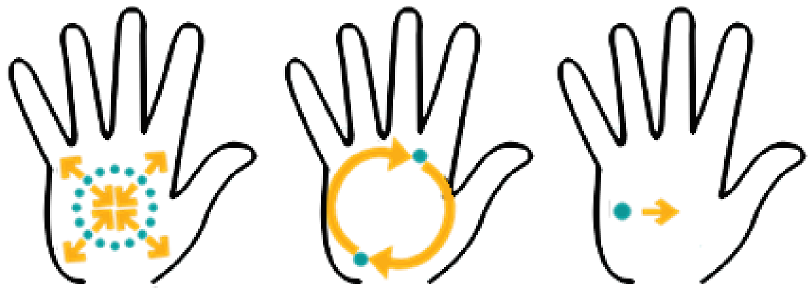

Figure 3.5: Haptic patterns for the Full Stop painting. Main Tate Sensorium pattern (left), and two alternating haptic patterns (middle 'simple circle' and right 'line'). In the Main Tate Sensorium pattern, there is a circle shape composed of 16 points of varying size (having an increase/decrease in diameter of the formed circle), synchronized with the rain pattern.

the sound designer could control the mid-air haptic patterns (frequency, intensity, and movement paths) to create a desired experience for the Full Stop painting. The final version of the sound file also synchronized with the desired mid-air haptic feedback sensation (as depicted in Figure 3.5, left). This sensation had the "Changeable circle sizes with rain drop sensations" feature to enhance the visitor's experience of the painting. Specifically, it was created by a round-shape haptic sensation synchronized with the sound. The circle shape was composed of 16 points of varying size (having an increase/decrease in diameter), and was integrated with the rain pattern created by using one point at random positions on the whole hand. Importantly, we further investigated the impact of the mid-air haptic stimulation on visitor's experiences. To do so, we created a set of seven alternative haptic experiences using three sources of inspiration: (1) the painting itself, trying to emphasize its visual properties (rounded), (2) contradicting the visual appearance of the painting (not rounded) and (3) emotional haptic stimuli based on the findings from Obrist et al. [20]. These seven patterns were:

- A circle with no size variation.
- A simple focal point in the middle of the palm.
- One point moving from left to right.
- Two points moving in a circle clockwise or counterclockwise.
- Two patterns designed based on the spatial and directional parameters identified by Obrist et al. [20] to represent positive and negative emotions (positive: one point moving from the edge of the fingers to the wrist in a predictable way; negative: one point moving around 6 locations on the palm creating an unpredictable path).

Eight participants volunteered to evaluate these seven patterns alongside the main haptic pattern. Participants experienced each haptic pattern in a counterbalanced order, and then rated both the valence and arousal of each pattern on a Likert scale (1 to 9). Participants were also encouraged to describe what they felt and how meaningful they perceived the sensory integration for the Full Stop painting (which was represented by an A3 poster on the wall).

The results showed that "Circle" (pattern #4) and "Line" (pattern #3) patterns were the most distinctive ones for the Full Stop painting in terms of valance and arousal, accordingly. In specific, the Circle pattern had the highest valence ratings (6.43 $\pm$2.15) among all the patterns (averaged 5.02 $\pm$0.65) and an arousal average rating of 4.14 ($\pm$2.48). The Line pattern had the highest arousal rating (5.86 $\pm$2.48) among all the patterns (averaged 5.11 $\pm$0.59) and a valence average rating of 5.71 ($\pm$2.48). Notably, the Line pattern has a contradicting shape with the painting (showing a circle shape). Therefore, it was expected to have lower ratings in valence and liking as well during the science days. The two patterns chosen are described below:

- The "Alternative Circle" pattern had a circle shape but was only composed of 2 points instead of 16, rotating on a fixed position and of constant size ($10\,\mathrm{cm}$ of diameter) on the palm.
- The "Alternative Line" pattern had a line shape and was composed of one point moving from left to right. When reaching the end of the line, the point started again from the left side and moved to the right to make the whole line ($10\,\mathrm{cm}$).

The three patterns (named Tate, Circle, and Line) were alternated during the Science days before closing the exhibition (see Figure 3.6). In contrast, on the other days of the exhibition, only the Tate pattern was shown.

3.4 Procedure and Method

In this section, we provide a detailed description of how the Tate Sensorium visitors experienced the multi-sensory installation and our method for capturing their experiences through questionnaires and interviews. Additionally, we explain the difference between Standard days and Science days (as depicted in Figure 3.6). Overall, the exhibition opened to the public for 1 month and 8 days.

As mentioned before, the purpose of Science days was to investigate the impact of different parameters of mid-air haptic stimulation on visitors' experience. The three patterns were alternated at different times on each Science day (on the other days of the exhibition, only the Tate pattern was shown). Additionally, on Science days, we collected visitors' perceptions through questionnaires on the relative importance of each sense (vision, auditory, smell, touch, and taste) when experiencing the paintings at Tate Sensorium. On the final day of the display, visitors were also asked to take part in a short audio-recorded interview lasting for 10 minutes (see below).

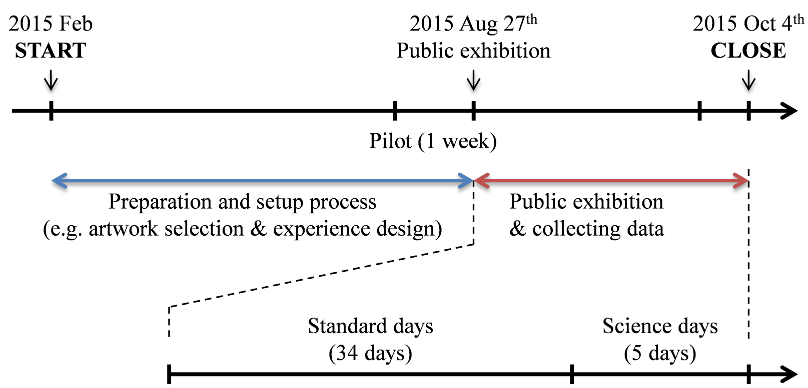

Figure 3.6: Overview of the Tate Sensorium project. The timeline includes a six–month preparation and design period, followed by a six–week (four weeks + two weeks extension) public exhibition and data collection period.

3.4.1 Step-By-Step Procedure

Participants entered Tate Sensorium in groups of four. This group size was to allow Tate Sensorium visitors a truly immersive multisensory experience, as well as to separate visitors to attend different paintings in a smooth traffic. Another purpose was to mimic a common group visit to a museum. Moreover, a group of four people was a manageable group per session (15 minutes) allowing each participant to enjoy the artwork with the multisensory experience. After entering the main door, participants were welcomed and then guided by a member of staff until the end of the tour. First, participants stopped at the point marked 1 in Figure 3.1. Here they were instructed to put on the headphones to hear a short introduction about Tate Sensorium (see Figure 3.7), as follows: "In each room we want you to focus on the painting and let your senses do the rest. Maybe the sensory stimuli will inspire thoughts, or memories. Maybe they'll suggest details in the paintings, or bring out shape or colour. Each of them has been made in response to the artworks, thinking about what they depict, and how and when they were made. We want you to find your own interpretation of each artwork, and we hope these stimuli will help."

Additional audio guidance for each painting was provided, giving some details about the painting itself (by whom it was painted), and the accompanying multisensory stimulation (e.g. walk around the room to explore the different smells). Participants also received a wristband to capture their skin conductance response, which was used to create a personalized printout at the end of the tour. This data is not included in this paper as it was not the focus of the study led by the University team. After the short introduction, participants removed their headphones and continued walking to the first painting (Interior II by Richard Hamilton, as marked 2 in Figure 3.1). Here, they stood in front of the painting and were instructed (through the speakers in the room) to experience it as naturally as possible, and to move around the room to explore the three different

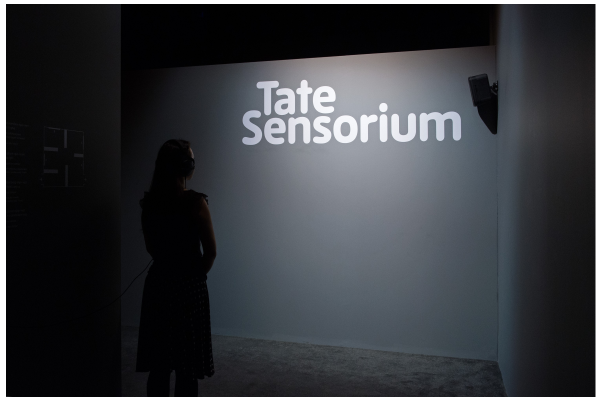

Figure 3.7: Tate Sensorium exhibition at Tate Britain in 2015. Tate illustration shot of a participant's first stop point, after entering the room, where they hear a short introduction about Tate Sensorium.

scents (see Figure 3.2a). Three minutes were given to all four participants to experience the painting. After that, participants were instructed by the staff to separate into two pairs of two participants to continue to the next painting. Pair #1 went to the room marked 3a in Figure 3.1 and view the Full Stop painting. Participants were asked to put on the headphones provided. Following the audio guidance, each participant was asked to put their hand into the empty space in the plinth to experience the mid-air haptic feedbacks (see Figure 3.3 for an example and Figure 3.4 for the plinth specifications). The mid-air haptic feedback was provided on the participant's palm and was synchronised with the sound provided through the headphones. After the sound-haptic stimulus finished (1 minute), the second participant took a turn in experiencing the mid-air haptic stimulus for the Full Stop painting. Participants were instructed to enjoy viewing the painting while experiencing the sound and touch integration. The total duration given for participants to be in this room was 3 minutes. Pair #2 went to the room marked 3b in Figure 3.1 and viewed the In the Hold painting. There were two plinths in this room. On top of each plinth are two 3D printed scent objects. Participants were encouraged to experience the painting and the scents by picking up the scented object and smelling it (see 3.2c). Participants were given 3 minutes to explore the painting in association with the sound and smell stimuli in this room. After, Pair #1 finished experiencing Room 3a, and Pair #2 went through room 3b, they switched roles. Pair #1 now moved on to room 3b and Pair #2 moved to room 3a, following the same procedure as described above for each of the two paintings. Once both pairs completed Room 3a and 3b, all four participants moved to the final room (marked 4 in Figure 3.1). Here, each participant put on the headphones again. They all stood in front of the Figure in a Landscape painting with a plinth in between. On top of the plinth was a box with 4 pieces of chocolate. Participants were encouraged to pick up a piece of chocolate and eat it (see 3.2d). Three minutes were given to participants to experience the painting and its associated taste and sound.

3.4.2 Methods Used: Questionnaire and Interview

Once participants had finished visiting all four rooms, they were requested to move to the exit point. Just before exiting, participants were encouraged to complete a short questionnaire about their experience of Tate Sensorium. The questionnaire consisted of three questions for each painting: (1) visual liking (of the painting itself); (2) multisensory experience liking (the sensory stimuli integrated into the painting); and (3) emotional reaction (arousal) (see Figure 3.8 for an illustration). These questions were used to quantify the added values of the designed sensory augmentation added to the experience of the paintings.

Participants answered using 5-point Likert scales (where 5 is the highest rating [118]. Participants were also asked to respond to some demographic questions (i.e. age, gender), and to report whether they would be interested in visiting such a multisensory experience again in the future (yes/no/maybe). This information was used in the analysis to explore differences between the experience ratings and users' personal backgrounds. Moreover, the curator of Tate Sensorium was interested in the age and gender distribution attracted by the multisensory display and if people would be interested in future events.

For the dedicated Science days, participants had an additional question on the importance of each individual sense (see Figure 3.9). Participants signed a consent form before answering the questionnaires. On the last day of the display, visitors of Tate Sensorium were also invited to take part in a short audio-recorded interview lasting about 10 minutes. The interviews aimed to explore: (i) the overall experience of the multisensory display, and (ii) gain specific insights on the experience created for the Full Stop painting, which integrated mid-air haptic feedback with sound. Here, we were particularly interested in understanding any qualitative differences in the perception of the three haptic patterns (the Tate Sensorium, Circle, and Line patterns as illustrated in Figure 3.5), which were alternated between groups of participants.

An interview guide was defined based on those two main areas of interest and included the following eight questions for each interview session: 1. How would you describe your Tate Sensorium experience? 2. What do you think particularly about your experience of the Full Stop painting? 3. How would you describe the haptic experience you received on your hand? 4. How meaningful was it for you? Why? 5. How did the haptic experience match your perception of the painting? 6. What qualities of the painting were supported through the haptic experience? 7. Would you have expected something else, if at all? 8. Anything else you would like to share or say about the experience of this art installation?

In each interview session, between two and four users participated at a time. Each participant was encouraged to express her/his opinion one after another, as well as to react to each other's responses to allow some discussion and reflection on the multisensory experiences. This could help to obtain further insight about the visitor experiences in their own words. Participants signed a consent form before taking part in the study,

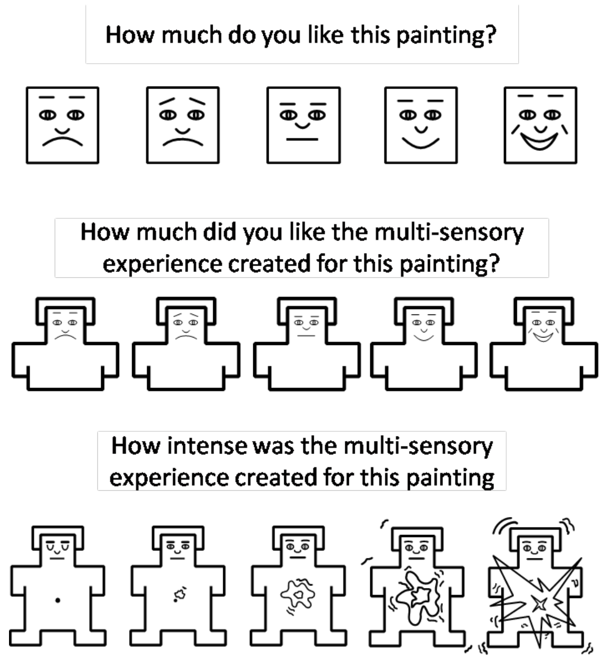

Figure 3.8: Questionnaire about Visual Liking / Multisensory Experience Liking / Arousal.

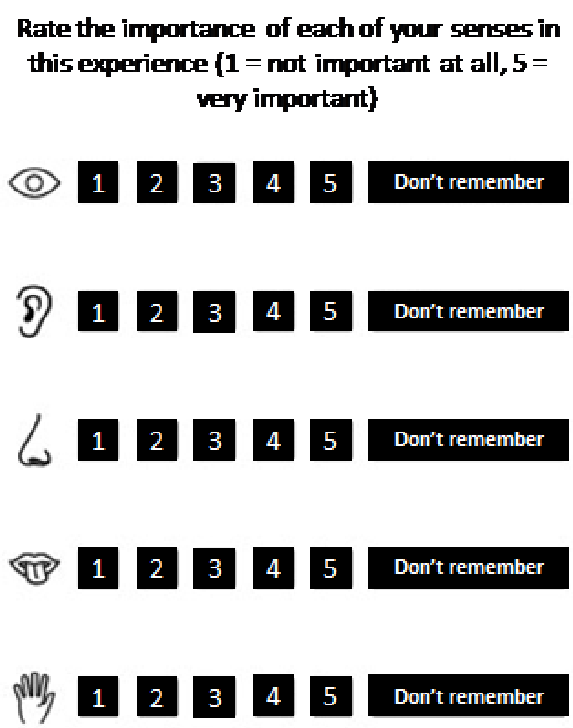

Figure 3.9: Questionnaire about the importance of each individual sense.

which was approved by the University of Sussex Science and Technology ethics committee.

3.5 Results

In total, we collected data from 2500 participants (1700 females, 800 males, mean age 36.00 SD 16.11). We analysed participants' visual liking, multisensory experience liking, and emotional reaction (arousal) ratings using a mixed effect design, ANOVA, where painting was considered a within-participants factor, and gender were considered between-participant factors. We used age to investigate how different age groups perceived the sensory augmentation of the paintings and to calculate correlations with the participant's ratings. We added 'haptic patterns' as between factor in the analysis in order to investigate any differences across the three haptic patterns used in relation to the participant's ratings.

Full interactions were considered in each ANOVA model we used. Overall, ANOVA's assumptions were tested on all the combinations of between and within factors. The Saphiro-Wilk test indicated the normal distribution of the data ($p > 0.05$ in all cases), Mauchly's test of sphericity was used to assess the sphericity of the data (again, $p > 0.05$ in all cases), and Levene's test the homogeneity of the data ($p > 0.05$ in all cases).

When ANOVAs showed significance, Bonferroni-corrected pairwise comparisons were performed. Moreover, given the high number of participants, Cohen's d was used on each significant comparison as an index of the effect size. Note that the effect size was not computed at the ANOVA level, given the fact that the power analysis of multiple way mixed effect experimental designs can lead to negative values and difficult interpretation, and it is still an active field of research [119]. In addition to the questionnaire data, we collected qualitative data from 50 participants through conducting interviews on the last day of the multisensory display. All the interviews were transcribed and analysed by one researcher (who conducted the interviews) based on the main areas of interest defined above (see Section 3.6).

Based on repeated readings of the transcripts and discussions in the group, we clustered the findings into three main themes, which we present in the following sections after the quantitative results gained from the questionnaire.

3.5.1 Effect of the Different Mid-Air Haptic Patterns

With the aim of investigating the add-values of mid-air haptic in a museum context, we were particularly interested in evaluating the effect of mid-air haptic feedback on participants' experiences. For that purpose, three variations of haptic patterns were created for the Full Stop painting and alternated during the dedicated Science days (see Figure 3.5 for illustrations of the haptic patterns).

Table 3.2 summarizes the numbers of participants that experienced the different mid-air haptic patterns

Paintings	Sight	Sound	Touch	Scent	Taste
#1 Interior II	✓	✓		✓	
#2 Full Stop	✓	✓	✓		
#3 In the Hold	✓	✓		✓	
#4 Figure in a Landscape	✓	✓			✓

Table 3.1: Selected paintings and their associated sense designs.

(Tate, Circle, and Line). Please note that the alternation between patterns was constrained to the dedicated Science days, hence there is a different number of participants experiencing each pattern. The expectation was that participants would like the main pattern purposely designed for Tate most, followed by the Circle pattern, and the Line pattern being the least liked due to its incongruence with the visual appearance of the painting (rounded shape of the Full Stop on a large canvas).

	#1: Tate	#2: Circle	#3: Line
Number of participants	1889	133	152
Visual liking	3.99 ± 1.04	4.05 ± 1.03	3.97 ± 1.00
Multisensory experience liking	4.13 ± 0.97	4.14 ± 1.00	3.98 ± 0.99
Arousal	3.77 ± 1.04	3.90 ± 0.97	3.50 ± 1.13

Table 3.2: Overview on the results for the three mid-air haptic patterns created for the Full Stop painting Based on the number of participants and ratings on visual liking, multisensory experience liking and experienced arousal.

To test this hypothesis (that is: whether the different patterns influenced the ratings of the participants), three multiple way ANOVAs were used to analyse the visual liking, multisensory experience liking, and arousal ratings, having as independent variables the age of the participants, the viewing order of the paintings, and the different haptic patterns into the model.

The analysis showed that the different mid-air haptic patterns only had an effect on the reported arousal ($F = 4.129$, $p < 0.01$). No statistically significant interaction was observed ($p > 0.05$ in all cases). Figure 3.10 shows the averaged ratings for each pattern. Pairwise comparisons, using the Bonferroni correction, showed that pattern 1 and pattern 2 (Tate 3.77 ±1.04 and Circle 3.90 ±0.96) were found to be more arousing compared to pattern 3 (Line 3.50 ±1.13, Cohen's d to the closest value = 0.38). These results are in line with our expectation of the Line pattern being the least appropriate sensation in mid-air as it does not resemble the rounded characteristic of the painting.

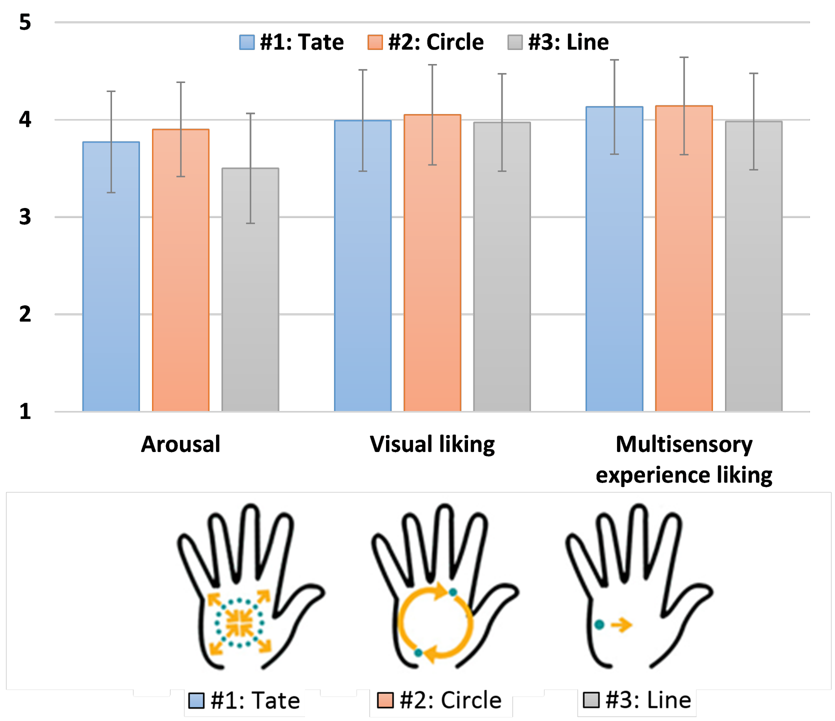

Figure 3.10: Ratings and representation of the three mid-air haptic patterns. (top) Ratings of arousal, visual liking, and multisensory experience liking for the different haptic patterns (with standard deviation, on a Likert scale of 1 to 5). (bottom) The schematic representation of the pattern on participant's hand: 1) Tate custom made; 2) Circle; and 3) Line.

3.5.2 Importance of Haptic Experience

Specific to the Science days (as described above and shown in Figure 3.6), participants were asked one additional question designed to assess the perceived importance of each sense in each of the multisensory experiences (e.g. Rate the importance of each of your senses in this experience). This was inspired by previous work assessing the relative importance, to people, of the five senses in a given experience [120].

Table 3.3 and Figure 3.11 show the average participants' ratings (with standard deviation) of the importance of the different senses for the Full Stop painting. All the senses were taken into account, even if they were not directly stimulated during the viewing of the Full Stop painting, to have a better understanding of their effect on the overall experience (some audio, visual, or touch stimuli might elicit other senses through memories for instance). A repeated measure ANOVA and post-hoc pairwise comparisons with Bonferroni correction were used to assess which senses were considered more important for the painting.

We found that ratings of touch as rated significantly more important ($p < 0.001$) compared to the ratings of scent and taste. This is as expected for this painting as it was designed with the mid-air haptic (the sense of touch).

Paintings	Sight	Sound	Touch	Scent	Taste
Mean	4.40	4.23	4.15	1.53	1.49
SD	0.91	1.03	1.15	0.96	0.95

Table 3.3: Summary of visitor ratings for each sense for the "Full Stop" painting experience.

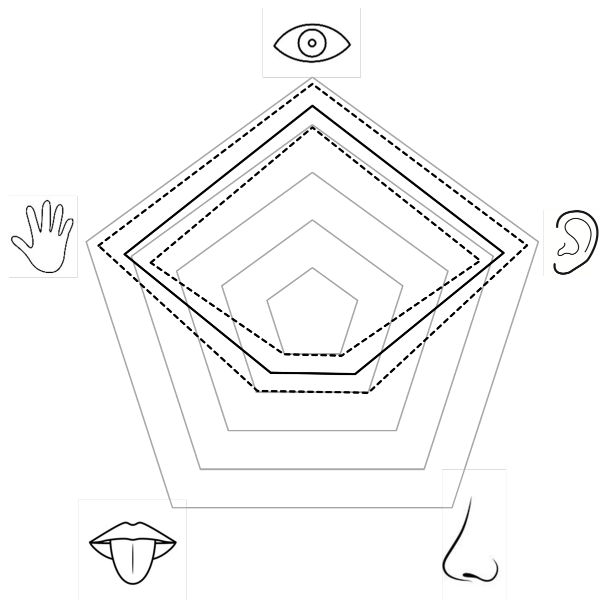

Figure 3.11: The reported importance of the senses for the "Full Stop" painting multisensory experience. Each sense is represented by a vertex of the pentagon, while each scale (from 1 - centre to 5 - vertex) are represented by the line and the points connecting the centre of the pentagon to the vertex. The solid black line represents the mean; the dotted lines represent standard deviation.

Multiple way ANOVAs were also conducted to assess any differences in gender, haptic patterns, on the relative importance of the different senses in their experience. No significant effect of any of these factors was found ($p > 0.05$ in all cases). That means that participants rated the added experiences of the associated sense similarly, regardless of their gender and haptic patterns.

3.6 Interview Findings

As mentioned before, the aim of the interviews was to gain more insights into participants' overall experience of the multisensory installation, and more specifically to obtain qualitative feedback on their experience for the Full Stop painting. Below we summarise the main findings, further illustrated through quotes from participants (n=50). We first present the qualitative findings of the overall experience of the multisensory exhibition (section 3.6.1 and 3.6.2), followed by the findings that focus on the experiences of the Full Stop painting, with the mid-air haptic feedback (section 3.6.3 and 3.6.4).

3.6.1 Overall Multi-Faceted Experiences: Immersive vs Distracting

Participants described their experience of Tate Sensorium as “stimulating”, “interesting”, “mind blowing”, “incredible, I really enjoyed it”, “something new, unusual”. While their feedback was overwhelmingly positive – which also fits the quantitative results – there were also some more critical voices. These critics were mainly based on different expectations, such as those expressed by some participants as “I’d say it wasn’t as strong as I thought it would be”, and “I expected something different, like something involving my whole body maybe, but I did like that I felt things very different in every painting.” Some participants literally expected a complete full body immersion in the painting through the stimulation of all senses. One participant was even ready to take off their shoes in expectation to be stimulated on the feet.

All participants strongly acknowledged that stimulating all the senses added another layer, dimension, and perspective to the experience of the paintings and thus opened new ways of thinking and interpreting art, in particular abstract art, which sometimes leaves people wondering how to interpret the work. One participant said: “It helped create like a story for each painting because some of these paintings are quite abstract, so then with the sounds or the smells you kind of begin to start creating an idea of what’s actually going on in the painting or what the story is.” The majority of participants stated that additional sensory stimuli did not change their initial liking of the artwork. However, some participants highlighted the potential of multisensory stimuli to turn their attention toward painting. “It made me feel really different. The Full Stop and the reason I liked it is I would never be very impressed with an image like that normally but the sound, it was really awesome.” The interviews brought to the fore the general feeling that sensory augmentation can awaken a museum visitor’s imagination, make the visit to the museum or art gallery more engaging, and has the ability to elicit strong reactions, establish a connection to, and build a narrative around the art.

The multisensory layers on top of the visual appearance of the paintings was described to allow stronger emotional reactions, such as empathy, being immersed, or even scared in front of the artwork. One participant described it as follows: “In a way that gave the painting a narrative having that chocolate, you could build up a story like maybe you’re walking on the field. [. . .] and you could almost pull the mood from the sunshine as well.” For the Full Stop painting, the sensory experience was described as very intense due to the integration of mid-air haptics and sound. While one participant stated that “I loved the sound of that one. It was kind of scary”, another participant focused on the sensation on the hand “It was strange, it freaked me out because I wanted to pull my hand out [from the plinth] but I didn’t want to because I wanted to carry on and see what it was like.”

In addition, participants highlighted the opportunity and danger of multisensory stimuli. For example, it could either ‘help focus’ on the particularities of an artwork or ‘distract’ from the artwork itself. Involving all the senses, when experiencing an artwork for the first time in such a setting could cause distraction, which was, however, not always described as negative distraction. Instead, it was sometimes a welcomed distraction, as the following statements represent: "I liked the painting and I was kind of disturbed by the strong sound" versus "It's a funny thing but here the visual part was distracting. I was closing my eyes and trying to listen to the sound and touching and imagining because I had the painting in front of me even if I close my eyes." For the Full Stop painting, one participant pointed to the positive emphasis of the haptic stimulus on the hand which made her notice the particularities of the artwork: "I could kind of see it because of the spray, I noticed it at the start, I think on the right hand corner it looks like it's petering out a bit and it made me see that because I was imagining small droplets and I saw that whereas I hadn't seen it... [without the feeling on the hand]".

3.6.2 Balance in Sensory Design: Curated vs. Explorative

The impact of the sensory stimuli on each individual's experience was not always straightforward and sometimes bipolar in the sense that multisensory augmentation of art can either open up opportunities for interpretation, but can also narrow down the visitor's perspective. On the one hand, participants described the multisensory experience as supportive in understanding art, creating a story, elevating the visual experience through touch, taste, and smell and sound. While on the other hand, the experience was described as too prescriptive, orchestrated, and shepherded. One participant stated: "I felt like it was leading you somewhere because it was already a choice, it was another choice from someone else, so I felt like I was being dragged into someone else's". Another participant made the following statement: "I think it was interesting to view the paintings in a different way but I think it was a little bit too conducted, especially the first one. You see this painting and you smell the smell and you know, it was too obvious in every one of them. The sound is matching perfectly the painting and the smell was matching perfectly the painting and the feeling of the hand was matching perfectly to little dots and the spray." There seemed to emerge, although only from a handful of participants, a feeling of not being in control, and maybe not being able to follow their own exploration of the senses alongside the art, but then again being excited about the novelty of the engagement. This leaves space for other ways of designing future multisensory experiences and creating an interactive setting in a museum serving the varying expectations of visitors: being guided or allowing for surprise.

3.6.3 New Mid-Air Sensation: Feeling Without Touching

Overall, the Full Stop painting emerged as the most liked painting, not just from the questionnaire data, but also from the interview responses.

The combination of mid-air haptic (a new technology not yet available for the end user market) with sound was perceived as immersive and really opened up a new way of experiencing art. Participants described the multisensory experiences as follows: "I'm speechless about that one. It made me goose bumpy"; "I loved it, I wanted to keep my hand in there. I loved feeling what the painting looks like and feeling the empty space and the negative space and then trying to relay that feeling onto the painting when I was looking at it."

Participants also stressed the uplifting experience of touching without touch, just feeling air and variations of air patterns on the hand: "I liked the touching thing, I found that particularly reactive"; "It was bizarre. It made me feel my body more, because I was actually touching something and it kind of like sent a pulse through me, which is cool", and the associated uncertainty introduced through the new mid-air haptic technology: "I suppose it was interesting with your hand in while watching the painting, and the not knowing, you can't see what's happening, so it was unknown what was coming. Whereas the smell, you knew there was a smell, it seemed less unpredictable." The familiarity with a sensory stimulation and consequently the predictability of the experience was an interesting topic that emerged in the interviews and opens up the question for future investigations of its long-term impact.

Moreover, participants expressed the potential of this technology for artists themselves, providing them with a new opportunity to paint, create art, and provide people with new experiences.

3.6.4 Integration of Touch and Sound: Three Experiences

As explained above we were able to vary the mid-air haptic feedback for the Full Stop painting on dedicated Science Days, including the day we conducted the interviews. Thus, we were able to collect qualitative feedback on the experience for each of the three haptic patterns: Tate, Circle, and Line. First, it is worth noting that the role of the sound in the combination of each of the three haptic patterns was described as very important. While the sound was dominant across all three haptic patterns, there was, however, a notable difference in the description of the experience between the three conditions. For the Line pattern, participants described the sound as very dominant, even more so than in the two other conditions. The Line pattern was perceived as less meaningful, as expected from our setup. The pattern was, moreover, described as distracting, random, and did not live up to the integration of a powerful painting and sound. Participants said: "The sound really brought some of the pictures alive, the Full Stop, if I'd have walked through the gallery and looked at that, I would have just gone past it, whereas because I was there with the sound, I found myself looking at different parts of the picture." Whereas others said: "No, it didn't add anything, it was a distraction for me in that particular". In contrast, participants who experienced the Tate pattern described the experience as much more balanced between touch and sound. One participant said: "I think the name Full Stop pretty much describes the painting, it is just a big black ball with white, but with like how the air is constant and then it stops, and then constant, stops, like it actually exemplifies the picture. It kind of makes sense." The Tate pattern was well integrated with the sound and emphasized the physicality of the painting, thus creating an affordance for touch. The Circle pattern was still meeting the expectations of roundedness inherent in the visual appearance of the painting, but in contrast to the Tate pattern it introduced movement in the form of a clockwise rotation on the palm, though synchronized with the sound. Participants neither particularly liked nor disliked the pattern or the sound, but interestingly shared a lot of stories evoked through the sensation. One participant said: "It's a very absorbing experience and really brought home that feel of the end of the world." Another participant become agitated when talking about the sensation: "I felt a bit like I don't know what's going to happen, is it going to grow bigger or smaller, is this going to explode." It almost seemed that due to the slight deviation from a perfect design, participants were looking for explanations and coming up with their own narratives and short stories about the meaning of the experience.

3.6.5 Summary

Overall, all participants reported that they were looking forward to seeing more of this kind of multisensory installation in a museum in the future. Among the five senses stimulated, sound, and taste signals were described as the most intensively experienced. Taste was either described as scary, invasive to put something in your body, or comforting. The latter was however not often mentioned, as the stimulus itself (chocolate soil) was not as pleasant as usual chocolate but mixed amongst others with charcoal, sea salt and cacao as reference to the darkness of the painting (Figure in a Landscape). With respect to the three different haptic patterns for the Full Stop painting, it became clear that participants wished for more time and another try to fully grasp the experience conveyed with the novel mid-air haptic device. One participant said: "If you ask me if I have the opportunity to go back to one of the rooms, I'd go to that one and try that thing again because it's addictive and just like feeling the whole body or something." That suggests the need for further explorations into users' experiences over time.

3.7 Discussion

Tate Sensorium, a multisensory art exhibition, was designed to enable museum visitors to experience art through all their traditional senses: vision, hearing, touch, smell and taste. Overall, Tate Sensorium attracted over 4000 visitors over a six-week period, out of which 2500 gave feedback via questionnaires and a sub-set of 50 participants took part in a short interview, sharing their experience of the multisensory display. Our work presents the design and implementation of Tate Sensorium, with a specific focus on the use and integration of mid-air haptic stimulation as part of the experience of a painting. Below we discuss our findings and lessons learnt from this unique case study in particular from the perspective of exploiting a novel haptic technology beyond a controlled laboratory environment. We highlight opportunities and limitations for multisensory experience design when creating emotional engaging and stimulating art experiences.

3.7.1 Mid-Air Haptic Design Space to Enhance Art

Our results showed that different haptic patterns could selectively influence the reported degree of arousal of users. The original Tate pattern and the Circle pattern elicited significantly more arousal compared to the Line pattern. The higher arousal of these two patterns might be, as hypothesised, due to the geometric similarity between the Full Stop painting and the haptic patterns. In contrast, the Line pattern was described as "distracting" due to the confliction between what was being seen and what was being experienced through touch. This finding is in line with what [42] previously reported for a lab setting, and extends their results for mid-air haptic stimulation [20].

In addition, while the differences of liking between the three haptic patterns remained non-significant based on the questionnaire, the qualitative data suggests that the participant's subjective experience changed depending on the used pattern. The sound integrated with the haptic pattern became more important when the haptic pattern was not considered as meaningful in relation to the visual appearance of the painting (in the case of the Line pattern). That might indicate a specific case of sensory dominance of sound over touch (e.g. [121]), but also that minimal changes in the stimuli can change the meaning of the conveyed experience. That was particularly interesting for the Circle pattern, which was rated in the middle of the liking scale (better than the Line pattern, but worse than the Tate pattern). Presented with the Circle pattern, participants seemed to be most stimulated in their imagination and expression of narratives. It is, however, an interesting question for further research to investigate what kind of paintings that mid-air haptics lends itself to (e.g. busier paintings with more details than the Full Stop).

Those insights into the subtle differences of haptic experiences and subjective perception of integrated sensory stimuli (i.e. sound and touch) can provide designers as well as curators and artists with a distinct opportunity to intentionally design for variation from the visual stimulus to create friction that leads to stronger engagement. This can be further facilitated through the development of new design creativity tools for artists by the HCI community [122]. In addition, visitors of Tate Sensorium were asked about their experience of the multisensory experience of the artwork (with the question "How much did you like the multi-sensory experience created for this painting"). Our results show that high liking was elicited in all three mid-air haptic patterns for the Full Stop painting, with no significant difference between them. This might be due to the novel experience when visitors first encountered with mid-air haptic, designed for the artwork. Future investigation specifically to regular visitors might reveal the differences in more details between different mid-air patterns.

3.7.2 Design Considerations for a Multisensory Art

By integrating mid-air haptic technology into a real-world environment, which has not been done before, the design team had to decide about the form of multisensory presentation that accounts for the experimental integration of this new technology in a museum context over an extensive period of time. From the visitor's feedback, we know that there was a high level of appreciation and liking for the multisensory experiences designed for the selected paintings. However, some visitors perceived Tate Sensorium as too pre-designed (choreographed) and somehow limiting the space for an individual journey (exploration). While this is an important point to keep in mind for future explorations, it is worth noting that it was a conscious decision by the project team to guide the museum visitor in a coherent and complete way through their experience of art enhanced through a new technology they have never experienced before (please note that this mid-air device was not available on the consumer market at that time). Alternative designs can be imagined, where the visitor is not even aware of the multisensory augmentation of an art piece and stays embedded in the natural flow of a museum visit. In conclusion, the insights gained from this research are clearly staged outside a controlled laboratory environment and still embedded in a semi-controlled set up in a dedicated area in the museum. That allowed us to collect relevant first hand experiences from the intended target users, just like suggested by recent work by Carbon [95], who highlighted the fact that there is a need to carry out museum related investigations in the actual environment of a museum.

Based on those design decisions, relevant follow up research and design questions emerge, such as whether the multisensory experience should become the piece of art in itself?; if multisensory stimuli should be a means to explore artworks according to the curator/artist's intention?; and if multisensory design should be simply used to facilitate individual exploration rather than be prescriptive? These are only some questions that come to mind that require further explorations and are ultimately a balance between the advanced state of a technology, and the ambition and requirements of the involved stakeholders. For Tate Sensorium, the purpose was clearly the augmentation of existing painting experiences via multisensory design. However, the interviews showed that there was an interest for exploration as well as for allowing artists themselves to create sensory experiences for their own artwork. This is in line with recent efforts [109], where visual artists created a tactile design prototype that augmented one of their existing works. A major challenge identified by the authors was the need to provide the artist with tools that allow them to express their imagination without reducing it due the technical limitations.

3.7.3 Opportunities for HCI Research and Design

Based on the involvement of curators, sensory designers, and creative businesses in this design and research project, it became clear to us that there is an immense need for tools and interfaces to facilitate the work and practices of sensory designers (e.g. sound designer). This consequently allow the meaningful exploitation of new technologies such as the mid-air haptic device used in this project. Such devices are often not easily accessible for designers or artists due to the requirements of specific programming skills (in our case C++). Although a collaboration across disciplines and areas, as demonstrated in this project, can overcome those technical challenges, it limits the creative exploration and exploitation of new technologies. Hence, it is great to see current developments around the latest version of the mid-air haptic device, that comes with a graphical user interface that allows designers and artists to freely explore different patterns and parameters. On top of this, there is still an enormous opportunity for the design of new interfaces and tools to support the engagement of artists and designers with technologies such as mid-air haptics. As stated by Resnick et al. [123] and emphasized by Shneiderman [122], there is a need for these tools to be designed with "low thresholds, high ceilings and wide walls". In other words, the designed tools should be easy for novices to begin using them, yet provide ambitious functionalities to scale up for the expert user and their needs, and hence support a wide range of design opportunities. In our research, we aim to push solutions using multilayer interface design, which provide users with different ways of interacting with the tool (e.g. the user interface of the tool is adaptive to the user's skills using it). Some examples of this are video games, search engines (e.g. Google, Yahoo), and video editing tools (e.g. Adobe Premier) with various workspaces to accommodate the user's expertise. As mentioned before, Azh et al. [109] analysed the creation of tactile feedback for visual arts and used the gained insights from this collaboration to guide the design of dedicated creativity tools for artists. Accordingly, tactile constructs and tactile intents define the "form" and "meaning" components of each tactile feature, respectively. Their findings indicate associations among the identified categories and between the two components, leading to design implications for expressive tactile interfaces. They also propose a user interface architecture, based on a design space for an expressive tactile augmentation design tool. This idea can be further extended and applied for other senses in the future.

3.7.4 Design Trade-Offs and Limitations

Although this project revealed several insights into immediate reactions and reflections on the multisensory experience (overall very positive), it is certainly a challenge to draw on generalizations about the individual effect of the senses on the overall experience of art and its possible impact on art preference. Conducting research in a typically noisy real-world context that has several stakeholders involved makes it difficult to generalize. Nonetheless, the different lessons learned here might facilitate large-scale studies involving multiple sensory signals in highly ecological contexts. Moreover, given the nature of Tate Sensorium, there is a limitation in terms of the amount of questions that we could include in the questionnaire, giving us only a snapshot of the users' experiences. In particular, we would have liked to expand on the questions related to the overall experience of the sound-touch integration for the Full Stop painting. This would help to understand better the influence of the augmentation of mid-air haptic on top of the visual appearance of the painting (akin to [124] who previously investigated the added value of sound). Based on the interviews, we know, however, that participants usually used the visual characteristics of a painting to explain their experience with the other sensory stimuli. Studying multisensory experiences outside a controlled laboratory environment comes with challenges and although our research took place in the field, it was controlled to a certain extent. Participants were guided through the different sections of the room but were still given freedom to experience the artwork (e.g. Full Stop) and the associated multisensory design (e.g. mid-air haptic feedback). Doing this ensures a valid background for comparing different conditions of mid-air haptic stimulation while providing participants the same experience as they normally have in a museum. Our results indicate that the use of technology should not limit visitor's freedom in exploring the space in the exhibition. This was reflected in their qualitative feedback and must be considered by designers in their follow-up installations. Yet, it is limiting a completely free exploration one can have in a museum environment. It is up to the researcher and stakeholder to find the right balance between design and research. Furthermore, we did not explore the aesthetics and culture in museum as it is beyond our core expertise in HCI. Instead, we focused on exploiting the potential of novel haptic technology to create emotionally engaging and stimulating experiences in particular through its integration with other senses, in our case with sound. Nevertheless, it would be an interesting research topic for future investigation, from the perspective of aesthetic science, to study multisensory art appreciation [125, 126]. Finally, the interviews revealed the need for more time to explore and experience this new type of experience. One of the two couples who visited Tate Sensorium twice said: "I think compared to yesterday I tried to relate the sensory more to the picture because yesterday I didn't know what to expect so I was trying to look at how that works. Today I think I understand more, especially with the Full Stop with the air and the echo sounds, it made more sense with the picture." This demonstrates huge potential for further exploration of experiences and engagement over time.

3.8 Conclusion and Future Work

Traditionally, museum attendees tend to experience art mostly through vision. Tate Sensorium allowed us to reflect on the process of enhancing art by considering all our major senses, particularly the sense of touch using novel mid-air haptics. The degree of success of this initiative depends on who one asks. From the point of view of the art gallery, the results of Tate Sensorium exceeded their initial expectations. The one-month exhibition was extended for two additional weeks given the massive interest from the public. From the creative team's point of view, it was also a success despite small technical problems with lightning and sound at the beginning. Overall, the whole installation ran smoothly and attracted media interest within the UK and worldwide such as the BBC (2015), the Wired (2015), and The Wall Street Journal (WSJ, 2015). From a research point of view, this project provided a unique opportunity to collect user data on multisensory art experiences and in particular on mid-air haptic experiences from a large user group. However, that opportunity also comes with practical constraints such as negotiating the integration of the data collection in the overall display design and timing, compromising the design of the haptic feedback and limited control over the artwork selection.

While the HCI research team contributed to the design and integration of the multisensory stimuli and materials, the final decision was mainly made by the creative team and curator of the art gallery. Balancing the different stakeholders' requirements and thoughts on the project could be challenging. However, at the same time, this environment encouraged the team to think beyond their traditional ways and methods of designing experiences and studying them. Museum visitors were not recruited for an experiment, but they came to enjoy art, new ways of experiencing paintings, and to engage their senses in a new exciting way. Therefore, the experience they received needed to be interesting and memorable. Despite compromises (finding the right balance between the various stakeholder requirements) and potential limitations, we believe that our work allows a glimpse of how to create, conduct, and evaluate multisensory experiences in a museum. With projects such as Tate Sensorium, we are convinced that our understanding of multisensory signals in relation to art, experiences, and design, based on novel interactive technologies, can be advanced. In particular, we hope that this case study will inspire other researchers and professionals in the creative industry, to explore new ways of engaging people and exploiting all human senses in the design of new multisensory interactive experiences in the museum.

Acknowledgements

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Chapter 4

Integrating Mid-Air Haptics into Movie Experiences

Damien Ablart, Carlos Velasco, and Marianna Obrist. Published in the Proceedings of the 2017 ACM International Conference on Interactive Experiences for TV and Online Video (TVX), pp77–84 (2017). [2]

"Seeing is believing, but feeling is the truth". This idiom from the seventieth century English clergyman Thomas Fuller gains new momentum in light of an increased proliferation of haptic technologies that allow people to have various kinds of 'touch' and 'touchless' interactions. Here, we report on the process of creating and integrating touchless feedback (i.e. mid-air haptic stimuli) into short movie experiences (i.e. one-minute movie format). Based on a systematic evaluation of user's experiences of those haptically enhanced movies, we show evidence for the positive effect of haptic feedback during the first viewing experience, but also for a repeated viewing after two weeks. This opens up a promising design space for content creators and researchers interested in sensory augmentation of audiovisual content. We discuss our findings and the use of mid-air haptics technologies with respect to its effect on users' emotions, changes in the viewing experience over time, and the effects of synchronisation.

4.1 Introduction

Audiovisual media has become omnipresent in people's everyday lives and has a significant impact on their feelings and emotions [127, 128]. Over the last few years, the sense of touch has gained attention as a means to enhance users' experiences, particularly to create more immersive media experiences. For example, Surround Haptics provides smooth tactile motions on the back through a system that is integrated in a seat [13], a tactile jacket that triggers vibrations to intensify emotions [12], AIREAL uses vortexes of air that delivers tactile sensations in free air [14], and Ultrahaptics that display ultrasonic waves to create tactile sensations in mid-air [17]. The first two examples require physical contact, while the latter two generate tactile sensations in the air, not requiring any physical contact between the user and the interface.

In this paper, we focus on mid-air haptic technology and its effect on media experiences, as it has not been studied before. More precisely we focus on mid-air haptic feedback and their potential role in movie experiences. There is a growing body of knowledge on the perception of mid-air haptic stimuli (localisation and discrimination) [129] and the creation of shapes in mid-air [18]. However, the effects of these kinds of stimulation on human emotions has only recently been studied.

In contrast to previous studies where the haptic experience is created to match a specific emotion [12], to mirror the screen [23], or to match the specific semantic space [13], we designed a single haptic pattern to enhance viewers' experiences. By pattern, we mean a mid-air haptic creation defined by an intensity, a movement, and a frequency over time. We explored this pattern with respect to its temporal integration into movies (synchronized versus not synchronized with the peak moments in a movie). We focus on "one-minute movies", which is a content format that conveys a complete narrative in one minute and allows a comparable set of movies of the same format and length. Then, we conducted a study following three main steps: (1) selection of movies, (2) creation and integration of haptic feedback (haptic pattern) into the movie narrative (synchronised vs not synchronized) and (3) evaluation of the users' viewing experiences (emotions) in two instances (two weeks separated). For the evaluation, we used three conditions: (a) with and without haptic feedback, (b) movie-specific design versus one cross-movies design, and (c) repeated viewing after two weeks. We used a combination of measures (i.e. self-report questionnaires and skin conductance responses) to capture the effect of the haptic feedback on users viewing experiences.

The present study contributes to the growing literature of haptic experience [62] and multisensory experience design [130]. First, we demonstrate the integration of mid-air haptic feedback into audiovisual content in form of a simple haptic pattern. This approach can be further extended towards a variety of pre-defined and custom-made or even automated patterns in the future. Second, we describe a methodological procedure to study the immediate and more long-term effect of haptic feedback. Finally, we discuss future directions for research, and possible developments in the broader context of media experiences.

4.2 Related Work

In this section, we discuss relevant previous work that has explored the potential of the senses to enhance movie experiences. We first present an overview of the media and the senses and we then focus on the use of mid-air haptics and the challenges of designing haptic feedback for one-minute movies.

The senses (i.e. smell, taste, and touch) are a relevant component of Human-Computer Interaction [130] and have been studied in the context of interactive media [131]. The MPEG-V ISO standard [132] and Mulsemedia [133] are good examples of the effort made to create standards for the multisensory integration into media.

The sense of smell has been studied with media, in a recent survey Murray [134] exposes various context of olfactory integration with media. On the other hand, the sense of taste has received little attention but recent works [135] show interesting new interaction mechanisms that could open new ways of integrating taste with media. The sense of touch is presented in the next section.

4.2.1 Haptically Enhanced Media Experiences

Touch is a powerful means to communicate emotions [10]. Indeed, researchers have aimed to reproduce its richness in haptic feedback system. Simple examples of such systems include vibrations of our mobile phones [136], video game controllers [137], and force feedback in steering wheels for racing games [138]. More specifically, Israr et al. [13] introduced the idea of Surround Haptics, a new tactile technology that uses a low-resolution grid of vibrating actuators to generate high-resolution, continuous, moving tactile strokes on the human skin. Different game events are mapped to different haptic feedback patterns. Those patterns are sent to the user through a chair embedded with vibratory actuators on the back. This is an interesting example of more immersive experiences that is based on a carefully designed video-tactile-audio gaming environment.

While the previous example of Surround Haptics requires actual physical contact with the user, new haptic technologies that promote the idea of touchless interaction for media experiences have emerged over the last years. Sodhi et al. [14], for example, developed AIREAL, a haptic technology that delivers tactile sensations in free air using vortex-based tactile actuation. An air vortex is a ring of air that can travel at high speeds over larger distances to create free air haptic experiences.

In the present research, we are particularly interested in mid-air haptic technology presented by Shinoda et al. [90], the only mid-air technology that allows the creation of real-time patterns with various frequencies and intensity. It is composed of a series of ultrasonic transducers that emit very high frequency sound waves. When all of the sound waves meet at the same location at the same time, they stimulate the human's skin creating haptic sensations in mid-air. No gloves or attachments to the user's body are required as the feeling is directly projected onto the user's hands (or body part).

Previous work using this mid-air haptic technology has provided insights into the perception and localisation of mid-air haptic stimuli [129], the creation of complex haptic patterns such as shapes [18], and most recently the mediation of emotions through mid-air haptics [20]. The challenge is still to understand how to create the right haptic experience for a given media or movies.

4.2.2 Designing Tactile Experiences for Movies

Various approaches have been explored to design haptic feedback for movies. Danieau et al. [24], for instance, recorded haptic feedback experienced during specific activities (e.g. horse riding) alongside video and sound. Users experienced the movies with 3 different haptic conditions (recorded, randomly generated, and no haptic feedback) and rated them using a Quality of Experience (QoE) questionnaire. Users rated the captured haptic feedback as more immersive than random haptic feedback and the random feedback was also better than no-feedback at all. While those findings are interesting, this approach is mainly focusing on the mirroring of an action (motion) on the screen and hence the stimulation of the visual sense, rather than the sense of touch.

Lemmens et al. [12], in contrast, created patterns for a haptic jacket based on typical touch behaviours from human emotional touch communication (e.g. highly energetic movements to indicate surprise or happiness) as well as based on common wisdoms and sayings (e.g. butterflies in your stomach). Those patterns were presented together with short movies. Users reactions were assessed through physiological measurements (respiration, heart rate, skin conductance level) and questionnaires (SAM [25] and Immersion Questionnaire). The results suggested a positive effect of haptic stimuli on peoples' immersion but they used only one haptic condition per movies, making any comparison between the designed haptics and other approaches impossible.

Israr et al. [22] proposed an approach based on a systematic exploration of haptic feedback and its integration with the other senses, as well as the content and the context of use. The authors built a library that establishes a classification between haptic feedback parameters (i.e. intensity, duration, and stimulus onset asynchrony) and semantic space (e.g. rain, pulse). This library was built and evaluated by users and can be used with various kind of media [55]. Nevertheless, there is still a need to investigate the impact of using a specific pattern during a media experience as it is very likely that the main focus will be on the visual content [56] and can thus outshine the effect of the pattern used.

More creative-focused approaches have been presented. For instance, Kim and al. [57] designed an authoring tool where users can pause a movie and draw the haptic feedback on the screen, focusing of the visual elements they judge relevant. This interface is designed to work with the haptics gloves they designed. Schneider et al. [62] extended this approach in a multi-device toolkit in order to facilitate haptic experience design. The authors designed a single interface capable of supporting various kinds of devices for creating patterns by drawing on the screen. In contrast to the toolbox approach, this toolkit might challenge designers with too many possibilities in the design of tactile experiences, especially when confronted with a new device, such as mid-air technology.

This paper expands on these previous works by designing tactile experiences using mid-air haptics technology.

4.3 Study

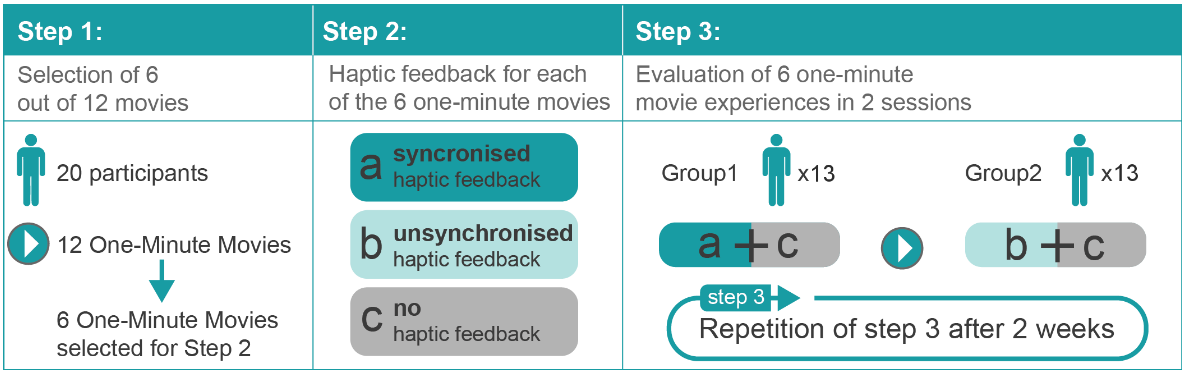

Figure 4.1: Overview on the study set up. It includes the three main steps: (1) selection 6 out of 12 movies, (2) creation of the haptic feedback (i.e. haptic patterns) for the 6 selected movies, (3) evaluation of the 6 movies with and without haptic feedback in two sessions.

In our research, we investigate the effect of mid-air haptic feedback on short movie experiences. We focus specifically on "one-minute movies", a content format that conveys a complete narrative in one minute and bridges traditional TV with online video consumption (e.g. YouTube). This particular format is featured in the annual "movie minute festival[1]" that challenges movie-makers, writers, animators, artists, designers, and creative producers to develop exciting new content.

Most importantly, this "one-minute movies" format provides us with a specific comparable timeframe for our study investigating the effect of mid-air haptic feedback on viewers' experiences. The study was divided into three main steps: (1) selecting a set of one-minute movies, (2) designing the haptic feedback, and (3) evaluating the viewer experience over time. See an overview on each step in Figure 4.1. In the following sections, we explain each of the three steps in detail.

4.3.1 Step 1: Selection of the One-Minute Movies

The one-minute movies for our study were selected from the international one-minute movie festival collection available on YouTube. Before the first step in the user study, we selected a total of 14 one-minute movies and invited four researchers in the field of HCI to watch and rate them using the SAM. Doing so we wanted to

[1] http://www.filminute.com

ensure a good spread of represented movies as well as a level of agreement with respect the perceived level of valence (positive/negative) and arousal (activation) for each movie.

Each of the four invited HCI researcher was asked to watch the 14 movies and rate them according to arousal and valence using the Self-Assessment Manikin (SAM) questionnaire [25]. We also asked them to rate their liking of the movie on a 7-point Likert scale (1 being 'didn't like it at all' to 7 'liked it a lot'). We compared the ratings for each movie and discussed them with the invited researchers with respect to the agreement on valence (if it was perceived positive, negative, or neutral) and arousal (if the movie had at least one moment of excitement, "peak moment"). The first criterion was to exclude any movies that might lead to contradicting emotional experiences and could hence be avoided for the user study. The second criterion was to inform the design of the haptic feedback along peak (arousing) moments. Based on those two criteria, two movies were excluded (one because of contradicting ratings on the valence, the other because it was perceived neutral with respect to arousal). The remaining 12 movies were used in the first step of the user study (see Figure 4.1).

Based on this initial pre-study step, we then recruited 22 users for our first step in the user study that lasted around 30 minutes and was rewarded with 6.5 USD. Each of the 22 users was invited to watch the 12 selected one-minute movies in a controlled lab environment. We used again the SAM questionnaire [25] to collect the arousal and valence ratings from users and asked them to rate their liking of each movie using the question "How much did you enjoy the movie?". We also recorded the users Skin Conductance Responses (SCR) for each movie using the Shimmer2 GSR device[2].

To analyse the SCR data (18 out of 20 valid, 2 excluded due to technical problems), we first prepared the data for the analysis by (1) using a windowing function (taking the mean of values in a widow of size 9 to smooth the data and remove imperfections, (2) standardizing the raw data for each user (values from 0 to 1), (3) reducing the frequency of data from 50 Hz to 20 Hz. We then plotted all the data for each user and performed a visual analysis for each movie. All movies showed potential for the second step of the study, meaning that they all had elicited 'peak moments' (captured in the SCR responses) based on which the haptic feedback could be designed. We also took the questionnaire ratings into account in order to balance between low and high valence/arousal movies in the final selection of movies for step two. In the end, we selected six out of the 12 movies for the next step (see Table 4.1).

4.3.2 Step 2: Creation of Haptic Feedback

Here we describe the creation and integration of the specific mid-air haptic feedback for the six selected movies. This second step was divided into two main parts: (1) the first part is concerned with the timing of the haptic feedback and (2) the second part discusses the design of the haptic feedback (i.e. haptic pattern).

[2]http://www.shimmersensing.com/

one-minute movies	*Valence*	*Arousal*
Black Hole	Neutral[0.60]	Neutral[0.58]
Chop Chop	Cheerful[0.71]	Neutral[0.53]
Grandpa	Neutral[0.47]	Neutral[0.54]
Loop	Sad[0.38]	High[0.63]
The Key	Neutral[0.63]	Low[0.41]
Wildebeest	Cheerful[0.73]	Neutral[0.59]

Table 4.1: List of the six selected movies for step two in our study. Balancing between low and high valence and arousal movies (scaled to 0 and 1, where 0 is referring to low ratings and 1 to high ratings.

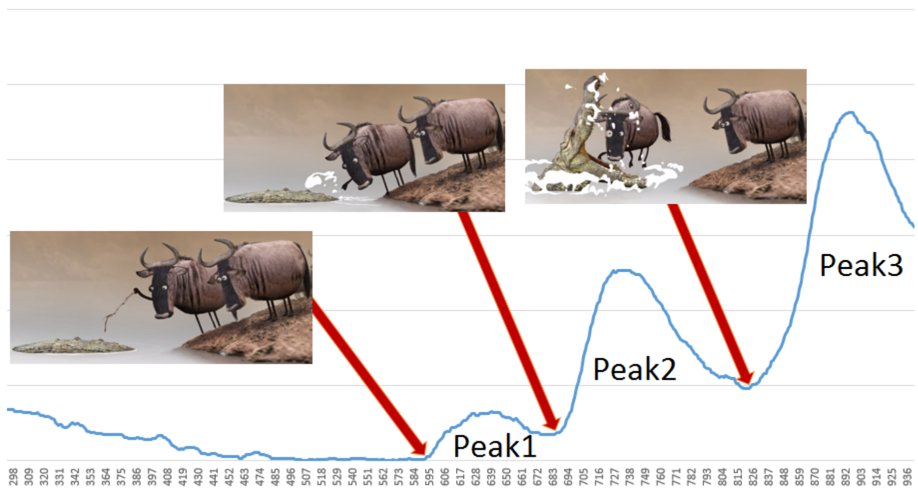

Figure 4.2: Example: "Wildebeest" movie. Timings and related events with the time on horizontal axis (1 unit = 20ms) and SCR in vertical axis (normalized from 0 to 1).

Temporal integration of the haptic feedback

In order to find the right timing for the haptic feedback (refers to the synchronisation of the haptic feedback with peak moments in a movie), a two-way manual approach was used. First, we used the SCR data (visual representation for each of the 6 selected movies, including amplitude and timing) to inform the key peak moments in the movie across users (see Figure 4.2). Second, we verified the 3 to 5 highest peaks revealed by the SCR data based on the narrative of the movie by comparing the timings taking into account the delay of the SCR measurements. For example, Figure 4.2 shows that the third peak in arousal is linked to the crocodile eating the gnu. This peak can be seen in user's SCR data at second 41, and fits the particular moment in the movie around second 39 (taking into account the 1 to 3 seconds' delay of the SCR recording). We created six synchronized haptic sequences, one for each of the short movies according to the recorded peak moments.

In addition, we create one more haptic sequence which was shared across all movies simulating an unsynchronized integration of haptic feedback. For that purpose, we defined one pattern of peak moments at second

12, 32, 42 and 48, which resemble the other creations in terms of number of peak moments and durations.

This haptic sequence is the same for all movies. Please note that there is a small possibility that the unsynchronised condition cross with the synchronisation condition, as it was nearly impossible to avoid all 6 conditions. However, we tried to keep the same sequence across all movies to show if haptics even asynchronous has an effect or not.

Design of the haptic pattern

As described in the previous section, each haptic sequence is based on a 60 seconds' timeframe and defines the timing for integrating the haptic feedback. More precisely it sets the timestamps for the design and integration of the synchronized and not synchronized (asynchronous) haptic pattern.

The mid-air haptic pattern itself consists of a single point displayed on the hand. This point changes location every 100ms, following a pseudo-random pattern on a five by five centimetres' square surface (similar to the feeling of rain drops on the hand, however in a dry form [19]). By using this distributed pattern, we avoid focusing on a particular part of the hand, which might be perceived either more positive or negative as previous work has shown (see [20]), and would distract the focus from the temporal integration of the haptic pattern.

The frequency of the displayed point was kept constant at 200Hz and the intensity varied between 30% and 100% depending on pre-defined peak moments in a movie in the synchronous condition or a random time in the asynchronous condition. This design is inspired by the idea of background sound (i.e. soundtrack) which is usually present throughout a movie and increases at important moments in the movie to emphasise the emotions and immersion. Using this approach removes the surprise effect a haptic stimulus might otherwise have if it just appears at peak moments.

4.3.3 Step 3: Viewer Experience Evaluation

The aim of this evaluation step was to understand the effect of mid-air haptics on users' viewing experience. The evaluation was repeated two weeks later to account for any novelty effects of the new mid-air haptic technology used in our stud [17].

Study design and methods

For this final step in our study, we recruited 32 users. Each user experienced the final 6 movies with and without haptic feedback. One half (i.e. 16 users) received the haptic feedback synchronised with the audio-visual content (movie specific design as described in the previous section) and the other half received the unsynchronised haptic pattern which was the same across all movies (based on pre-defined fixed timestamps across all movies). The order between with and without haptic feedback was counterbalanced across users and repeated after two weeks for each user in each of the two conditions (synchronised versus unsynchronised haptic feedback).

We used a combination of measures (i.e. SAM, Liking Scale, and SCR) to capture users feedback. Users were asked to confirm that they have no sensory impairments and to complete a short demographic questionnaire (age, gender) before starting the experiment. This study was approval by the local University Ethics committee.

Study set up and procedure

For the experiment, users seated comfortably in a chair and watch the movies on a 24” computer screen. Their right hand was positioned on a custom-made armrest that was built as a box integrating the mid-air haptic device. A hole on the top indicates where users would put their palm, so that they can perceive the haptic stimulus on their hand from below.

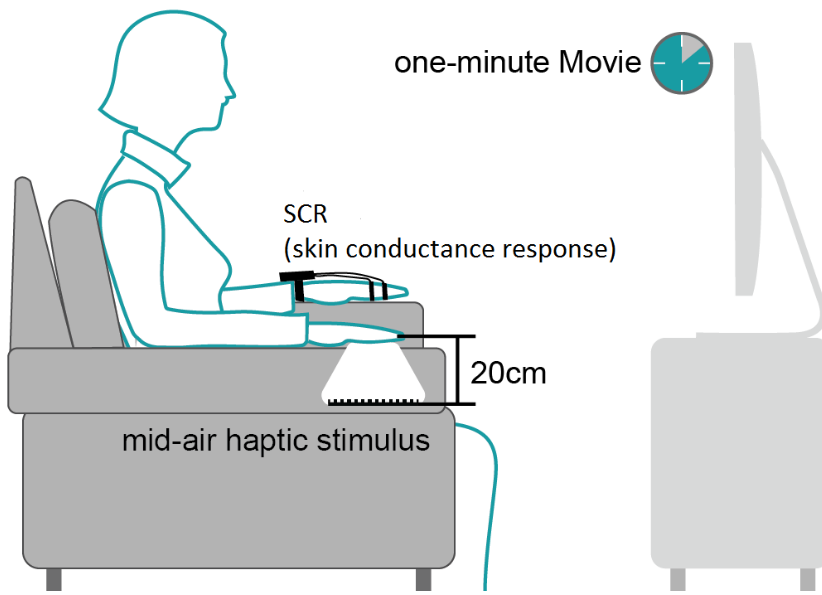

Figure 4.3: The study set up. It shows a user with on the left hand the Shimmer2 GSR device (recording the galvanic skin response) and the right hand above the mid-air haptic device.

At the beginning, we allowed users to familiarise themselves with the haptic set up and calibrated the haptic stimulus for each user: a simple focal point was displayed in the middle of the hole where users put their hand. The setup ensured that users kept their hand still while watching the movies (Figure 4.3). On the left hand, which was resting on arm rest, users were wearing a SCR device. Users were told not to move the left hand during the experiment and to use the right hand to answer all questionnaires (displayed on the screen between each movie).

The study itself involved a succession of six movies. However, the first movie played to each user was a 3 minutes baseline video showing a series of landscapes without any animation or sounds. During that time, SCR data was collected and used as a baseline for the SCR analysis of each user. Then the six movies were played twice, with and without haptic feedback.

Before each movie, a five second black screen was displayed to give enough time to people to put their arm back above the haptic device (right armrest) and to introduce a pause between filling in the questionnaire and starting the next movie. In order to avoid any order effects, we randomised the order of the movies using a balanced latin square of size 12 (6 movies $\times$ 2 haptic conditions). After each movie, including the baseline, three main questions were asked about (1) Arousal: "How much of your emotion is activated" Self-Assessment Manikin, (2) Valence: "How did the movie made you feel?" Self-Assessment Manikin, (3) Liking: "How much did you enjoy the movie?" on the semantically Labelled Hedonic Scale (LHS) [139].

Software used

A combination of several software parts was used in the study: c++ for programming the mid-air haptic technology, the Shimmer software for the SCR recording, and c# for the presentation of the questionnaires and movies. All different parts - haptic feedback, movies, and SCR recording - needed to be synchronised in order to ensure the right integration and interpretation of the data. The synchronisation and timing between the software was assured by high precision internal media timers (precision $<1\,\mathrm{ms}$).

For the SCR recordings, we used the Shimmer 2 sensor attached to two fingers: the index and middle finger of left hand. The settings were set to $50\,\mathrm{Hz}$ for the frequency of measurement and $56\,\mathrm{k}\Omega$ to $128\,\mathrm{k}\Omega$ for the resistance measure.

Data analysis

The data was collapsed across all movies (the baseline movie was left out from the analysis) and a $2 \times 2 \times 2$ mixed design analysis of variance (ANOVA) with haptics (off and on) and session (first and second), and group (synchronous and asynchronous) was performed on each of the rating scales and the SCR.

The raw data of the SCR were first normalized to $20\,\mathrm{Hz}$, then an amplitude correction was applied which consisted of subtracting the lowest value recorded across movies and to all other values. Afterwards, the log of each value was calculated and the analyses were performed on these values [140].

4.4 Results

The results of our analysis of the questionnaires and physiological recordings are presented in this section alongside with the users' information.

4.4.1 Users

In total, there were 54 users involved in all the steps of the study. Due to technical problems with the SCR recording, we removed a total of 8 users from the analysis. The pre-study involved 20 participants (9 female, average age 25), the group 1 which refer to the synchronised haptic condition (synchronised with the peak moments) involved 13 participants (4 males, average age 24.5), and the group 2 which refer to the cross-movies haptic condition (unsynchronised with the peak moments) involved 13 participants (5 males, average age 26).

4.4.2 Questionnaires Ratings

A significant interaction ($p < .05$) between session and haptic stimulation was found for the valence ratings, and a significant main effect ($p < .05$) of haptic stimulation was found for the arousal ratings. Paired-samples t-tests performed on the interaction term failed to reveal a significant result ($p = .059$), nonetheless, the valence ratings appear to be higher in the first as compared to the second session, when the haptic stimulation was off (see Figure 4.4, 1A and 1B). Moreover, Bonferroni-corrected comparisons revealed that the users reported feeling significantly more aroused when the haptic system was on, than when it was off ($p = .014$). A visualization of all the mean ratings is presented in Figure 4.4.

4.4.3 Skin Conductance Responses

A summary of the results of the SCR is presented on Figure 4.5. Only a significant effect of session was found ($p < .001$). In particular, pairwise comparisons revealed that the users were more aroused in the first session than the second session. While no main effect of haptics was found, there was a small general tendency to obtain higher values when the haptic system was on ($M = 0.48$, $SD = 0.29$) than when it was off ($M = 0.43$, $SD = 0.027$).

4.5 Discussion

We studied the possibility of augmentation of one-minute movies with mid-air haptic feedback. Our findings provide insights into how users' arousal and emotional valence are influenced by mid-air haptic stimulation,

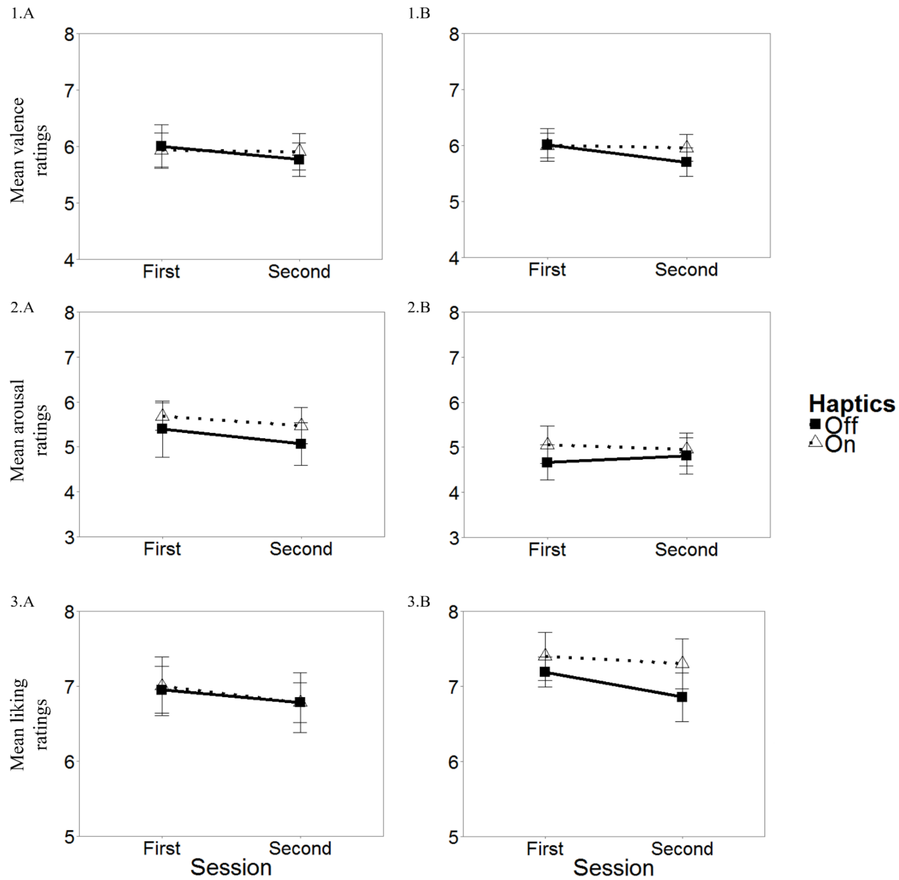

Figure 4.4: Summary of the questionnaire results. The numbers correspond to the different variables assessed, namely, valence (1), arousal (2), and liking (3), whilst the letters correspond to the (A) synchronous and (B) asynchronous groups. The error bars represent the standard error of the means.

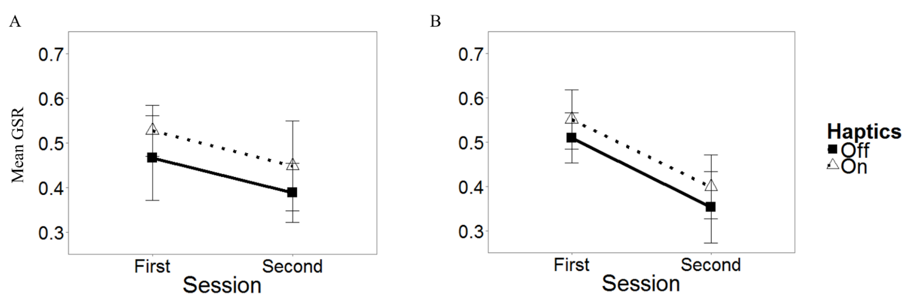

Figure 4.5: Summary of the SCR results. The letters correspond to the (A) synchronous and (B) asynchronous groups. The error bars represent the standard error of the means.

that is presented in a synchronous or asynchronous fashion alongside the movies. Below we discuss our findings and their relevance for designing haptically augmented movie experiences.

4.5.1 Effect of Mid-Air Haptics on First and Second Time Viewing Experiences

Our results show that the arousal ratings are high across all conditions. This result is in line with previous work demonstrating the arousing effect of haptic feedback while watching movies [24, 12]. While a positive effect was expected for the synchronous condition, the same effect is true for the asynchronous. In other words, even when the haptic pattern does not mimic a specific movie sequence, and is placed randomly alongside the movie, users are still more aroused than with no haptic stimulation. While this is promising in particular for the novel use of mid-air haptic feedback, it is worth noticing that based on the SCR data users' arousal is dropping during the second session in both groups. This can be explained due to the fact that users already knew the movies (familiarity), and were less excited to watch them. Moreover, the novelty effect of the device is also lowered, and yet the experience with haptics is more arousing than without.

In terms of the valence ratings, a borderline significant trend was found for the interaction between $Session \times Haptics$ (see Figure 4.4). Post hoc analysis failed however to reach statistical significance but we observed a trend in dropped valence ratings in the second session. This might be linked to the expectation of the haptic feedback causing frustration when it is absent. Indeed, most previous work showed that adding haptic feedback to movies and and other multimedia experiences is valuable and gives a boost to the persons' experience [12, 57]. However, its sustainability over time still needs to be verified.

4.5.2 Effect of Synchronized Versus Asynchronized Mid-Air Haptic Feedback

No interaction was found on the synchronisation condition (temporal integration of the haptic pattern). This could be explained by the use of a specific mid-air pattern integrated at different relevant peak moments in each movie instead of designing and using a variety of patterns (e.g. making us of different spatial distributions of focal points [20], shapes [18]). Thus, the synchronization of the haptic feedback might be less evident to users, as the pattern was generic and relevant for either synchronized and unsynchronized moments in a movie.

Most previous approaches focus on synchronised feedback [57, 12, 141] where patterns are specifically designed for a sequence. However, considering our findings, which will need further validation, it is promising that the difference between the aforesaid conditions is not significant as this gives rise to alternative design approaches, that could ultimately be simplified through providing producers and content creators with pre-defined patterns, tools to create their own patterns, or even automate the generation of haptic patterns based on the extraction of audio-visual content from a movie, as done in [142]. The synchronisation becomes less important as the emotion can be activated at different times during the sequence of a movie. Such future exploration opportunities around synchronization could become of value in relation to the MPEP-V ISO [132] standard concerned with the delivery of 'sensory information' as part of a general framework.

4.6 Conclusions

This paper provides insights into the effect of mid-air haptic feedback (a new haptic technology) on users viewing experience, specifically applied to one-minute movies. This specific content format (60 seconds narrative) allowed us to systematically investigate the design and evaluation of synchronized versus unsynchronized mid-air haptic stimuli and their effect on users perceived valence and arousal. Mid-air haptic feedback, by its ability to increase immersion, affect emotions, and contribute to the overall quality of experiences without requiring any attachment to the viewers' body, is an opportunity for interactive TV and online video. The findings are promising and open up a space for future explorations of other formats, full length movies enhanced through mid-air haptics.

Part II

Exploration of Mid-air Haptics Design Parameters

Chapter 5

Using Spatiotemporal Modulation to Draw Tactile Patterns in Mid-Air

William Frier, Damien Ablart, Jamie Chilles, Benjamin Long, Marcello Giordano, Marianna Obrist, and Sriram Subramanian. Published in the Proceedings of the 2018 IEEE International Conference on Human Haptic Sensing and Touch Enabled Computer Applications (EuroHaptics), pp.270–281 (2018). [3]

One way to create mid-air haptics is to use an ultrasonic phased-array, whose elements may be controlled to focus acoustic pressure to points in space (referred to as focal points). At these focal points the pressure can then deflect off the skin and induce a tactile sensation. Furthermore, by rapidly and repeatedly updating the position of a focal point over a given trajectory, ultrasound phased-array can draw two dimensional curves (referred to as patterns) on a users' palms. While producing these patterns, there are three major parameters at play: the rate at which the pattern is repeated, the pattern length, and the focal point speed. Due to the interdependence between these parameters, only the repetition rate (frequency) or the speed can be set for a tactile pattern of a given length. In the current study, we investigate which approach (frequency or speed) is most effective at maximising the tactile sensation. We first carried out a vibrometry study to show that optimising the speed can maximise the skin deflection caused by a focal point following circular patterns. A further user study was undertaken to show that optimising the speed consequently maximises the perceived intensity of the tactile pattern. In both studies, the optimal speed result is shown to be equivalent to the speed at which surface waves propagate from the skin deflection effected by the focal point. Overall, our investigations highlight the importance of the speed of stimulation movement in the design of tactile patterns.

5.1 Introduction

With the arrival of gesture tracking technologies (Kinect, Leap Motion), the interaction space is no longer constrained to tangible surfaces and can now move to mid-air. Yet, the lack of tangibility in these mid-air interactions pushed researchers to develop solutions to convey feedback in the form of haptics in mid-air. Some solutions make use of air vortices [14] and air-jets [143]. But the leading technology in such applications currently uses ultrasonic-phased arrays [17, 28, 16].

Ultrasonic phased-arrays focus acoustic pressure to points in space (referred to as focal points). At these focal points, the pressure can slightly deflect human skin and induce tactile sensation. Yet, in such systems, the ultrasonic transducers are driven at high-frequencies (e.g. $40\,\mathrm{kHz}$ [16] or $70\,\mathrm{kHz}$ [28]), while mechanoreceptors within the skin are sensitive to frequencies ranging from $0.4\,\mathrm{Hz}$ to $500\,\mathrm{Hz}$ [29]. Therefore, the common approach, referred to as amplitude modulation, is to modulate the focal point to a lower frequency (referring to amplitude modulation frequency or F_{AM} for short). The perception of the focal point varies with the value of F_{AM} [19] and therefore F_{AM} is often fixed to $200\,\mathrm{Hz}$ which induces the strongest haptic response. Amplitude modulation can therefore be considered to be similar to and applied as one would use a mechanical vibrator for vibrotactile stimulation. Alternatively, one can create a cluster of focal points and apply amplitude modulation to each point, in order to render patterns or volumetric shapes [18] (see Figure 5.1.a). Yet as the number of simultaneous focal points increases, the acoustic power produced by the device is divided between the points, making each individually weaker. When the number of simultaneous focal points becomes too large (e.g. in large patterns), the focal points are no longer perceived.

To get around this issue, an alternative approach exists that we refer to as spatiotemporal modulation. In spatiotemporal modulation the position of a single focal point is rapidly and repeatedly updated so as to describe a pattern by moving along a continuous trajectory, while the intensity remains at its maximum. Spatiotemporal modulation can still induce tactile sensation as mechanoreceptors are sensitive to motion [30]. Additionally, the temporal resolution of touch perception is only of few milliseconds (the exact value may range from $2\,\mathrm{ms}$ to $40\,\mathrm{ms}$ according to Loomis [31]). Therefore, if the focal point can complete the trajectory faster than the temporal resolution, the users will perceive the resulting stimulation as a single tactile pattern rather than a succession of tactile points or a moving sensation (see Figure 5.1.b). The effect is similar to the persistence of vision, where a source of light can be seen as shape and not distinct points, when moved fast enough.

As far as we know, spatiotemporal modulation has never been studied, and so it is unclear as how its parameters should be chosen to maximise the created sensation. One naïve approach would be to consider the rate at which patterns are drawn (we defined this rate as the spatial modulation frequency -F_{STM} for short-)

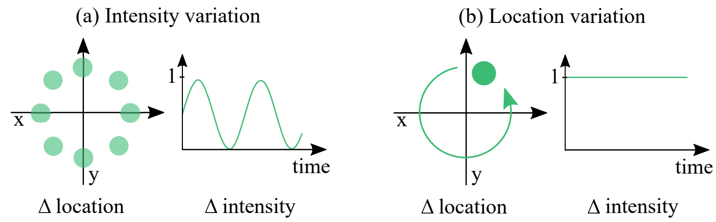

Figure 5.1: A comparison between intensity modulation and location modulation when displaying a circle (a) is displaying 8 fixed points with a change of intensity over time where (b) has a constant intensity over time but a changing location. The points in (a) are dimmer to represent the weaker acoustic power.

and assign that rate to be the same as the amplitude modulation frequency (i.e. having $F_{\text{STM}} = F_{\text{AM}}$). The argument behind that approach is that if the pattern is periodic, each point forming the pattern will be repeated at a given frequency as in the case of amplitude modulation. For instance, if one observes the acoustic field in one position of the pattern, one will note an alternation of high and low acoustic power, which correspond to the focal point coming and going from this position, with a rate equal to F_{STM}. The observation that the displacement at a stationary point in the pattern looks a lot like amplitude modulation, and therefore one could optimise F_{STM} the same way one optimises F_{AM}, leads to fixing F_{STM} to 200 Hz or thereabouts. However, the average acoustic power present at that position will be far weaker than having an amplitude modulated focal point at this position, especially for large patterns.

Another approach is to consider the speed of the focal point during the stimulation (referred to as FP_{speed}). If L is the length of a given spatiotemporally modulated pattern, then we can define $FP_{\text{speed}} = F_{\text{STM}} \times L$. A useful analogy to spatiotemporal modulation can be made involving trains, where the carriages (analogously to focal points) move along the rails (here the pattern) and produce vibrations on the soil (similarly to the skin). To further continue the analogy, it has been both numerically predicted and experimentally demonstrated that in high speed rail networks, ground vibrations can be amplified when the speed of the travelling trains approaches or exceeds the speed at which the surface waves propagate in the ground [144, 145]. In the light of recent studies, which show that tactile stimuli produce surface waves that propagate on the skin and affect our perception [146, 147, 148], the above train analogy becomes even more likely for the case of spatiotemporal modulation when surface waves are considered. Therefore, we hypothesise that if the focal point moves at a correct speed, constructive interference will result and the deformation it induces could amplify the propagating surface wave it produces and *vice versa*. We then predict that there is an optimal speed for which the deformation induced with a focal point is amplified to a maximum, and moreover the required speed is equal to the propagation speed of surface wave across the skin. We further hypothesise that the speed of the focal point will have more impact on the resulting perception than F_{STM}, due to the predicted surface wave effect.

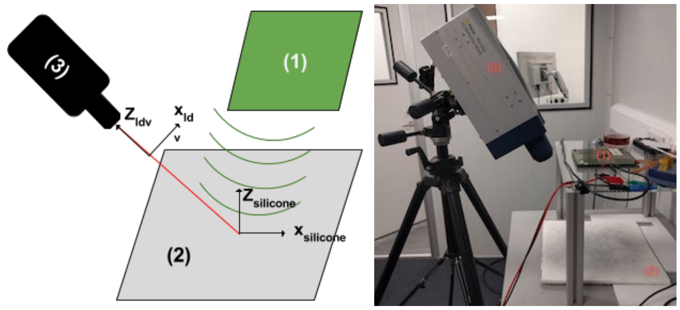

Figure 5.2: Experimental Set-up. (1) The ultrasound phased array, (2) the silicone slab and (3) the Laser Doppler Vibrometer

To test our hypotheses and investigate whether the surface wave phenomenon in our analogy also holds true for spatiotemporally modulated patterns, we ran a series of vibrometry measurements where we recorded spatiotemporally modulated circles of different radii that were drawn at different speeds. A complementary user study was also performed to assess whether there was any effect of the spatiotemporal modulation speed of circular patterns on the perceived intensity of tactile sensations.

5.2 Vibrometry

In this study, we wanted to test for the existence of an optimal speed to drive spatiotemporally modulated patterns, which would ideally induce maximal displacement on a surface. We believe that the optimal focal point speed should be equal to the surface wave propagation speed. Additionally, we hypothesise that speed related effects on displacement are greater than frequency related effects. To measure the displacement induced with spatiotemporally modulated patterns, as well as their interference with resulting surface waves, we ran a series of vibrometry measurements.

5.2.1 Measurement Set-Up

Our measurement set-up was composed of three main elements: An ultrasound-phased-array to produce spatiotemporally modulated patterns, a silicone slab on which the patterns were projected and a Laser Doppler Vibrometer to measure the displacement induced by the spatiotemporally modulated patterns (as shown on Figure 5.2).

The ultrasound phased-array we used was a Ultrahaptics Evaluation Kit from Ultrahaptics Ltd.[1] and was composed of 16×16 (i.e 256) ultrasound transducers. The ultrasound phased-array is producing focal points $8.6\,\mathrm{mm}$ in diameters at a given position and with a given acoustic power. The produced output can be updated

[1]https://www.ultrahaptics.com/products/evaluation-kit/

with a $16\,\mathrm{kHz}$ sampling rate.

The spatiotemporally modulated patterns were projected on a $35\,\mathrm{cm}\times35\,\mathrm{cm}$ wide and $1\,\mathrm{cm}$ thick slab, cured with commercially available silicone, Ecoflex 0010[2], which was used as a mechanical analogue for human skin. The use of silicone rather than human subjects, provided control over the measurement condition. Ecoflex 0010, was selected as an analogue for human skin due to it having a similar density ($1100\,\mathrm{kg\,m^{-3}}$ for human skin, where the silicone is $1030\,\mathrm{kg\,m^{-3}}$) and similar viscoelastic material properties in both surface effects and in bulk [149, 150]. We acknowledge that the mechanical behaviour of Ecoflex will not be the identical to real skin, due to human skin being a much more complex structure (e.g. multiple layers and anisotropy) [151], however, it is thought that the vibrometry of silicone will provide insight into the general behaviour of viscoelastic materials when excited by focused ultrasound.

Due to the small amplitude of the vibrations, we used a laser Doppler vibrometer (abbreviated to LDV) to measure them. The LDV is a common tool to carry out non-contact vibration measurement. Vibrometry data is obtained by firing a laser beam from the LDV towards the surface to be measured and capturing reflected incident photons using a photodetector diode also inside the LDV head. Differences between the original and reflected laser signal are analysed to find the vibration modes of the reflecting surface based on the Doppler effect. For this study, we used a PSV-500-Scanning-Vibrometer from Polytec[3].

The silicone was placed on an experimental bench, on top of which, the ultrasonic phased-array was maintained up-side down with a stand, parallel to the silicone and at a distance of $28.5\,\mathrm{cm}$. The LDV was placed at a $60°$ angle and pointed towards the silicone, which was $36.4\,\mathrm{cm}$ away from the LDV head. For each measurement scan, the LDV was measuring surfaces with a resolution of $1\,\mathrm{mm}$. Each measurement point lasted $256\,\mathrm{ms}$, was recorded with a sampling rate of $128\,\mathrm{kHz}$ and was repeated 6 times before being averaged. Each measurement was synchronised between the LDV and the Ultrasound phased-array using a trigger signal. Furthermore, a $50\,\mathrm{ms}$ null output was preceding and following each measurement. Two types of measurement were conducted: line measurements (see Section 5.2.2) and square measurements (see Section 5.2.3). The line measurements involved a $17.5\,\mathrm{cm}$ long section of the silicone and lasted 30 minutes, while the area measurements covered an area of $10\,\mathrm{cm}\times10\,\mathrm{cm}$ and lasted 105 minutes. Micro-reflective beads were spread on the surface of the silicone to improve laser reflection and hence measurement quality.

The raw data obtained from the LDV is composed of the velocity over time for each coordinate position on the measured surface. Firstly, due to the $60°$ between the LDV and the silicone, the measurements from the LDV were in a different coordinate space relative to the silicone (see Figure 5.2). Using a Python script with the `scipy` package, we pre-processed the data, transforming each point into the correct basis using projective

[2]Ecoflex 0010: https://www.smooth-on.com/products/ecoflex-00-10/
[3]https://bit.ly/2IxZcAa

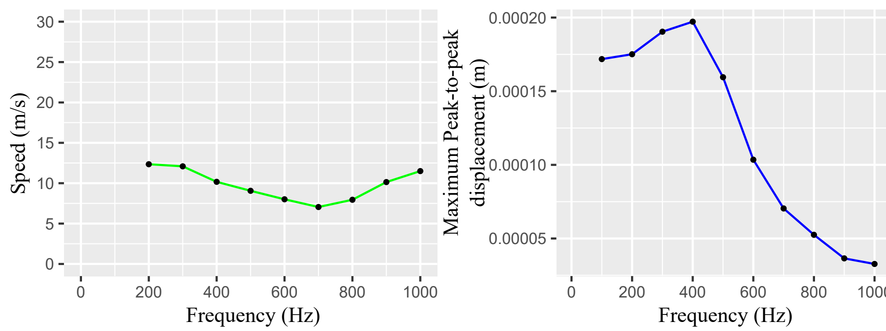

Figure 5.3: Surface wave propagation speed and resonant frequency Left – Measured propagation speed. Right – Measured frequency response, one can see the 400Hz resonant frequency.

geometry. Further, measurements were carried in an anechoic room and band-pass filtered to remove the ultrasonic 40 kHz carrier frequency and remaining noise, where the low cut-off was at 50 Hz and the high cut-off frequency at 1 kHz. Finally, to be able to work with displacement data, we applied a time integral on the velocity data, hence obtaining the variation of displacement over time rather than the variation of velocity over time. We describe how we used the displacement data, according to the information we wanted to extract, in sections 5.2.2 and 5.2.3.

5.2.2 Preliminary Measurement

Our study focuses on the displacement induced by the spatiotemporally modulated patterns and their associated surface waves. However, surface waves propagate differently on different media, hence our first step was to characterise the surface wave propagation on the silicone we were using. To that end, we generated a focal point at the centre of the silicone slab and measured how induced surface waves propagated away from the position stimulated. As the silicone is a dispersive medium, surface waves with different frequencies travel at different speeds. To measure this, we modulated the focal point at known frequencies ranging from 200 Hz to 1 kHz with 100 Hz steps. We assumed the silicone to be a homogeneous and isotropic medium, and therefore focus our measurements on a single line going from the silicone slab centre towards the edge (17.5 cm long in total). From the measurements data, we extracted the surface wave propagation speed and the frequency response of the silicone.

Surface wave propagation speed

To extract the surface wave propagation speed across the silicone, we calculated the speed at which wavefronts of surface waves propagated along the measured direction and took the average of repeated measurements of the speed. As predicted, the surface wave propagation speed varied with the frequency (see Figure 5.3) but

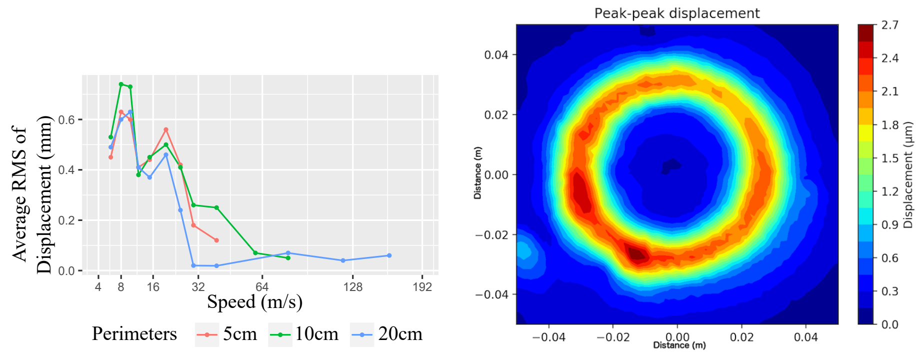

Figure 5.4: Displacement measurement. Left: Average root-mean-square of displacement as function of speed for circular patterns with different perimeters. Right: Example of the measurement obtained for the root-mean-squared displacement of a circular pattern.

remains in the interval of $7\,\mathrm{m\,s^{-1}}$ to $13\,\mathrm{m\,s^{-1}}$, and has for average $10\,\mathrm{m\,s^{-1}}$. The average propagation speed is slightly greater than the one measured by Manfredi et al. [147] on the fingertip, but the general trend is similar. Therefore, we assume the difference in mechanical behaviour between the two media to be responsible for the differences observed.

Frequency response

To extract the frequency response of the silicone, we analysed the maximum peak-to-peak displacement at the focal point position and repeated over the frequency range. We found that the peak-to-peak displacement was also varying with frequency (see Figure 5.3) and was maximum at 400 Hz. This result suggests that the silicone slab has a resonant frequency at 400 Hz. It is sometimes suggested that human skin also possess a resonant frequency around 200 Hz [147]. Once again, we assume the differences in material properties to be responsible for the difference in the measured resonant frequency.

Overall, we can see that the silicone measurement shows similar behaviour to the skin even though the exact values differ.

5.2.3 Spatiotemporally Modulated Patterns

After characterising the surface wave propagation speed on the silicone and the silicone frequency response, we undertook to investigate the effect of surface waves on the displacement that spatiotemporal patterns induced. To that end, we generated a spatiotemporally modulated circular pattern, with its centre matching the silicone centre (equivalent to Figure 5.1). We chose a circular pattern for its numerous properties (continuous, periodic, without self-crossing points), which limits possible pattern-specific artefacts. We then used the LDV to measure a square area of the surface encompassing the pattern (see Figure 5.4). As defined in the introduction, knowing the pattern length (here the circle perimeters), one can go from the focal point speed to the spatiotemporal modulation frequency as follow: $FP_{\text{speed}} = F_{\text{STM}} \times perimeter$. To compare the different effects of FP_{speed} and F_{STM} individually, we repeated the measurement while varying the perimeter and FP_{speed} each in turn. In our data set, we had 3 different circle perimeters of $5\,\mathrm{cm}$, $10\,\mathrm{cm}$, and $20\,\mathrm{cm}$ of perimeter. We chose these circle sizes as they could fit the user's palm that is $7.5\,\mathrm{cm}$-$9.5\,\mathrm{cm}$ wide on average [152]. We picked 8 speeds around the measured average surface wave propagation speed and 4 additional speeds that match to 4 frequencies around the measured resonant frequency. Yet, for certain perimeter lengths, some speed values overlapped, making for somewhere between 9 and 12 distinct speeds measured per perimeter. In total 32 area measurements were taken. For each measurement, we computed the root-mean-square value for peak-to-peak displacement and extracted the average value along the measured circular path (see Figure 5.4).

5.2.4 Results

In Figure 5.4, we plotted the measured average root-mean-square values of peak-to-peak displacement induced by focused ultrasound on circular patterns with different perimeters, for which spatiotemporal modulation is run at different speeds. These results show that the quantity of displacement varies with the focal point speed but remains similar across circle perimeters. Moreover, the displacement is maximum for speed between 8 and $10\,\mathrm{m\,s^{-1}}$, which corresponds to the average of the surface wave propagation speed measured previously. Therefore, the results seem to support our hypothesis about a constructive interference between spatiotemporally modulated patterns and the wave surfaces they produced, when the focal point speed matches the speed of the surface waves propagation. Additionally, the results show a second maximum appearing at a focal point speed of $20\,\mathrm{m\,s^{-1}}$, which corresponds to twice the propagation speed of the surface waves. This behaviour that could be anticipated from the periodic property of the studied pattern is reminiscent of the kind of behaviour governed by "harmonics" often found in acoustics. Finally, the data does not show any evidence of a resonating mode, which should appear at 20, 40 and 80 $\mathrm{m\,s^{-1}}$ for the perimeters 5, 10 and 20 cm, respectively.

The conclusion of the current vibrometry study was finally that varying the spatiotemporal modulation speed has a large effect on the indentation of the silicone along circular patterns. Because silicone Ecoflex-0010 possesses numerous similarities with human skin, it is likely that equivalent amplification phenomenon could be observed on human skin, but it is difficult to predict to what extent. However, repeating the above measurement on human skin will not inform us about the consequences on the haptics of such spatiotemporally modulated patterns as they will be influenced by perceptual effects beyond simple displacement. To investigate the perceptual implications and especially the patterns perceived strength, we decided to run a user study with similar spatiotemporally modulated patterns. We hypothesise that there will be an effect of speed on the haptic stimulus perceived strength, although the nature of the interaction with haptics and whether it is detectable is not immediately clear.

5.3 User Study

In this user study, we assessed the perceived intensity of haptic circles of different sizes and speeds. To this end, users rated the intensity of 39 different circles: 3 sizes (i.e. perimeter of $5\,\mathrm{cm}$, $10\,\mathrm{cm}$, and $15\,\mathrm{cm}$) and 13 speeds (i.e. from $2\,\mathrm{m\,s^{-1}}$ to $20\,\mathrm{m\,s^{-1}}$ with gaps of $1.5\,\mathrm{m\,s^{-1}}$). The different conditions (i.e. sizes and velocities) were fixed after pilot testing involving 15 people. Users rated each condition 3 times, giving a total of 117 trials (i.e. 39×3).

Study set-up and procedure

First, users were given an oral introduction to the study and the software used, before signing a consent form. They were invited to sit comfortably on a chair in front of a computer screen and asked to place their left-hand on a custom-made armrest that was built as a box integrating the mid-air haptic device. Users would then put their left palm above an opening, so that they can perceive the haptic stimulus from below. They were then invited to wear headphones playing white-noise to remove auditory cues and were given two trials to familiarize themselves with the haptic set-up and the software. Users were asked not to move the left hand during the experiment and used the mouse with their right hand to answer the questions displayed on the screen between stimuli.

The study itself involved a succession of 117 trials. In order to avoid any order effects, trials were pseudo-randomized. To move to the next trial, users were instructed to click on a next button on the screen in front of them. Then, a four-second countdown was displayed and the haptic stimulus was then played for five seconds. After each stimulus, the users were asked on screen if they perceived it. If so, they were invited to rate the intensity of the haptic pattern using a ratio scaling method of magnitude estimation, which can be used to find the optimal parameters of a device [153]. This approach is composed of 2 steps: (1) ask participants to rate the intensity of the stimulus on an arbitrary scale chosen by the participant and (2) normalize the values of each participant. No discrimination nor other qualitative information were asked during the experiment.

A combination of two software parts was used in the study: `C++` for programming the mid-air haptic device, and `C#` for presenting questions.

We recruited 16 users (mean age 30.0 ± 4.5, 3 female). Users had no touch, or auditory impairments. The experiment lasted on average 35 minutes. An ethics approval was obtained in advance.

		Perimeter			
		5		10	
		p	cor	p	cor
Perimeter	10	<0.001	0.901	∅	∅
	15	<0.001	0.856	**<0.001**	0.960

Table 5.1: Correlation matrix of the intensities ratings for the 5,10 and 15cm perimeter.

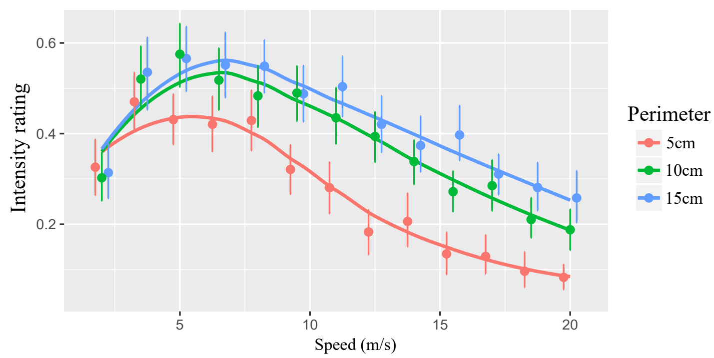

Figure 5.5: A plot of the intensity ratings of the haptic feedback by perimeter size.

Results

The data collected was normalized between 0 and 1 for each participant. Non-felt stimuli were set at 0. In order to assess if the speed of the point was driving the intensity felt by participants, we separated the data into 3 groups, depending on the perimeter of the circle used for the feedback (see Figure 5.5). We then averaged the data for each speed and computed the Pearson correlation coefficients between the different pairs of perimeter sizes. The results are summarized in Table 5.1. The very high coefficient of correlation of intensity between the three perimeters shows that the haptic feedback strength is independent from the perimeter and dependant of the speed.

5.4 Discussion

The vibrometry study showed that the variation in silicone displacement, caused by spatiotemporally modulated patterns, is function of the spatiotemporal modulation speed. Moreover, the displacement seems independent of the circle perimeter and is maximised when the focal point speed equals the surface wave propagation speed. These results suggest that there is constructive interference occurring between spatiotemporal modulated patterns and the surface waves they induce, which leads to an amplification of the silicone displacement.

$$F_{\mathrm{STM}_1} = FP_{\mathrm{speed}} \div P_1$$

Figure 5.6

However, the results show no relation between silicone resonant frequency and displacement, even though the patterns studied were periodic. One could argue that variations in medium mechanical properties will lead to different results. Hence, future work will investigate the effect of spatiotemporal modulation on silicone slabs of different mechanical properties. Ultimately, measurement on human skin would more conclusively prove the amplification phenomenon existence we describe. Yet, such measurements on human skin could be proved challenging.

The user study showed that the tactile pattern perceived strength is also function of the spatiotemporal modulation speed. Moreover, the results showed that user perceived stronger the circles that are drawn around 5 and $8\,\mathrm{m\,s^{-1}}$, which is close to the surface wave propagation speed measured by Manfredi et al. on human fingertips [147]. The similarities between the vibrometry results and the user study results suggest that the increase in displacement measured in the vibrometry study is responsible for the increase in perceived strength in the user study. Therefore, one could conclude that matching spatiotemporal modulation speed with surface waves propagation speed ensures the maximum perceived strength for human participants experiencing the tactile patterns. One could argue that an individual mechanoreceptor, along the stimulation path, perceives a periodic signal with a given frequency. Therefore, to optimise the perceived strength, the stimulation frequency should match the mechanoreceptor frequency response. Yet, no relation between pattern frequency and pattern perceived strength were found.

Therefore, in the current study, the effect related to spatiotemporal modulation speed prevail over any effect related to the mechanoreceptors' frequency response. Additionally, the user study shows, in a lesser extent, that perceived strength is function of circles perimeters. The $5\,\mathrm{cm}$ perimeters are perceived weaker than those with 10 and $15\,\mathrm{cm}$ perimeters. We believe this effect might be resulting from the fact that the $5\,\mathrm{cm}$ circle covers less surface area than the other two circles sizes, and therefore involve spatial summation [29].

However, additional investigations would be required to confirm the supposition and identify a relation between the two.

$$x^n + y^n = z^n$$

Our results have implications for the design of mid-air tactile stimuli, highlighting the focal point speed importance as a parameter in the tactile patterns perception. To scale up or down a given tactile pattern, the spatiotemporal modulation frequency must be scaled accordingly, to maintain the spatiotemporal modulation speed constant, and hence insuring a similar perceived strength of the tactile pattern. For instance, let's consider a circular pattern of perimeter P_1, our study show that the pattern should be driven at a rate

$$F_{\mathrm{STM}_1} = FP_{\mathrm{speed}} \div P_1$$

where FP_{speed} produces the desired perceived strength. To scale that circle such as

$$P_2 = 2 \times P_1$$

then, the spatiotemporal modulation frequency will need to be updated such as

$$F_{\mathrm{STM}_2} = 2 * F_{\mathrm{STM}_1}$$

. Being able to scale up and down a given pattern is particularly useful when rendering 3D-volumetric shapes [18]. Adapting our results to more complex and abstract patterns could prove challenging and would certainly require further investigations.

5.5 Conclusion

The current study showed that the vibrations generated in silicone with mid-air tactile patterns can be increased when selecting an appropriate speed for spatiotemporal modulation. The outcome of the user study complements this result and show a clear peak in the perceived intensity occurring around $5 - 8\,\mathrm{m\,s^{-1}}$ across three different circle sizes. However, further vibrometry measurements should be made to ascertain what the actual displacement on the hand is and concluded on the relation between perceived strength of sensation and stimulus speed.

Chapter 6

Using Ultrasonic Mid-air Haptic Patterns in Multi-Modal User Experience

William Frier, Damien Ablart, Jamie Chilles, Benjamin Long, Marcello Giordano, Marianna Obrist, and Sriram Subramanian. Published in the Proceedings of the 2018 IEEE International Conference on Human Haptic Sensing and Touch Enabled Computer Applications (EuroHaptics), pp.270–281 (2018). [3]

Ultrasonic mid-air tactile displays offer a unique combination of high spatial and temporal resolution and can stimulate a wide range of tactile frequencies. Leveraging those features, a new modulation technique producing spatially distributed tactile sensations has recently been introduced. This new approach, referred to as Spatiotemporal Modulation (STM), draws lines, curves and shapes on users' palm by moving a mid-air tactile point rapidly and repeatedly along the path. STM parameters and their impact on tactile perception are yet to be studied systematically. In this work, we first study how varying the draw frequency and the size of a simple shape affects the participants perception of texture and their emotional responses. In the second part of our study, we used the most salient tactile patterns of the first study to extend the results within a multimodal context. We found that tactile patterns' perception was consistent within both studies. We also found instances when the tactile patterns could alter the perception of the audio and visual stimuli. Finally, we discuss the benefits of our findings and conclude with implications for future work.

6.1 Introduction

Mid-air haptics is a growing research field with the advantage that users do not need to hold or wear any attachments to feel tactile feedback while interacting with video games [14], movies [2], art pieces [1], and is therefore an emerging new Human Machine Interface (HMI) [154]. Moreover, mid-air haptics has the opportunity to compliment current media and create more compelling and realistic experiences. However, as with many new HMIs, how mid-air haptics stimulation impacts media perception is still not fully understood and merits further investigation.

In this paper, we focus on ultrasonic mid-air haptics to produce mid-air tactile stimuli. Following, a method introduced in 2008 [16], the mechanical properties of sound wave can be leveraged to create tactile feedback in mid-air. A set of ultrasonic transducers, if synchronised, can focus acoustic pressure at a desired location in space hence creating a pressure point in mid-air referred as a focal point. This focal point is able to indent the human skin, however the high frequency used by the ultrasonic transducers (in most cases around $40\,\mathrm{kHz}$) is too high to be felt by human mechanoreceptors (the skin can feel vibrations up to $500\,\mathrm{Hz}$ [29]). To alleviate this and cause a tactile sensation, the common approach is to modulate the amplitude of the signal at frequencies from 20 Hz to 250 Hz. This approach, referred as Amplitude Modulation (AM), has been used in several work, to create emotional textures [20] or to augment short film content [2]. However, the AM patterns are localised and limited to just a few focal points, thus limiting the spatial information that can be conveyed.

With the aim to convey more complex patterns, a new approach has been produced referred to as Spatiotemporal Modulation (STM), where the focal point location is modulated instead of its amplitude [3]. With this technique, the amplitude of the point is maintained at a constant intensity, but its location is varying quickly alongside a desired curve (e.g. a circle). The focal point motion causes perceivable vibrations on the skin surface. The frequency of this vibration is mainly dominated by the number of times the point repeats the curve per second. In a first exploration, Frier et al. [3] showed that the perceived intensity of STM mid-air haptic feedback with a circle-shaped pattern was directly related to its speed (i.e. *frequency*× *perimeter of the circle*) and not its frequency as in AM. In a second study, Frier et al. [53] showed that the perceived intensity of the feedback was further dependent on the number of sample positions along the curve.

In this paper, we expand the previous works by the authors by exploring how STM parameters and patterns (i.e. frequency and size) impact people's tactile experience alone and within a multimodal context. Here, tactile experience refers to five variables used to assess how participants perceive the tactile patterns. These five variables are: a) intensity, b) roughness, c) regularity, d) roundness, and e) valence. To that end, we conducted and report on two perceptual studies. In the first study, we started by exploring a large set of mid-air haptic patterns to find any relationship between parameter space and the different perceptual dimensions assessed and construct associations – links between parameter space and perceptual space. Then, we ran a second and larger perceptual study using a subset of the first study with mid-air haptic stimuli in combination with audio and visual stimuli from a standardised database [32]. Our goal was twofold: (1) confirm that mid-air haptic parameters like frequency and pattern size can strongly affect tactile experience, and (2) assess how the perception of audio and visual stimuli is affected by mid-air haptic stimuli. Specifically, we choose to limit the investigations to mid-air haptic stimuli covering different perceptual spaces (e.g. soft and rough), while the combination of media and haptics was allowed to either be congruent or incongruent. The results of the first study showed that varying pattern size and frequency could indeed change the intensity, roughness, regularity, and roundness ratings. The results of the second study confirmed those results even in the presence of auditory and visual stimuli. Furthermore, the tactile patterns could successfully sway the perception of the auditory and visual content one way or another thus suggesting the possibility of haptic augmentation [155].

In summary, this paper presents a first exploration of STM ultrasonic mid-air haptics to create different tactile experiences in a multimodal setting. Namely, we applied those different patterns alongside standardised auditory and visual stimuli to understand how these other senses could be influenced. Our results present opportunities for new applications using mid-air haptic stimuli, especially in enriching and enhancing media content.

6.2 Apparatus and Setup

The ultrasonic tactile sensation was produced by an Ultrahaptics Evaluation Kit (UHEV1[1]) [17]. This device is composed of a 16×16 array of ultrasonic speakers controlled via a C# SDK (version 2.5). The device was updated at the highest rate possible with this SDK (i.e. $16\,\mathrm{kHz}$) using the time point streaming method, assuring the smoothest curve as possible for each pattern.

The ultrasonic board was embedded in an acrylic laser-cut black box to hide it from participants view. A hole of size $10 \times 10\,\mathrm{cm}$ was left open on the top of the box to allow the device to stimulate the participant's palm and feel the tactile sensations. This setup allowed a precise control of the distance from the board to the participant's hands ($16\,\mathrm{cm}$). Moreover, to avoid overheating, the bottom part of the box utilised a standard laptop cooler (see Figure 6.1).

The software and procedures used in this work was written in C# using Visual Studio 2017. The user study questionnaires were presented on-screen through a simple interface where only a mouse was required (only buttons and sliders). The auditory and visual stimuli were controlled by the same software, enabling smooth synchronisation and allowing a accurate control of the display time of each media.

[1]https://www.ultrahaptics.com/

In addition to the tactile feedback, participants used headphones with pink noise to cover the ambient noise and a 24 inches screen to display the questionnaires to the participants.

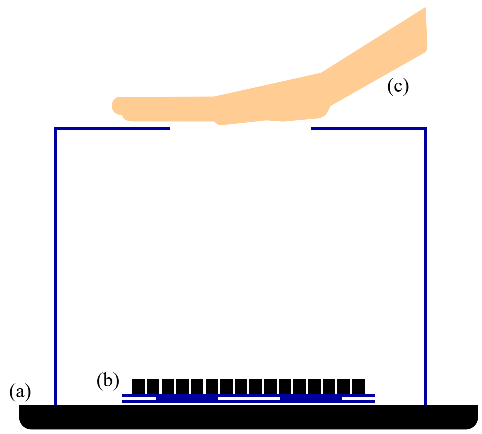

Figure 6.1: The laser-cut acrylic box used for the study (a) a laptop cooling pad placed below the ultrasonic mid-air board device to avoid overheating, (b) the ultrasonic mid-air board, and (c) the participant hand above the box, with their palm centred above the hole to which the ultrasonic waves are directed.

6.3 First Study: Haptic Perceptions

In this a first study, we sought to understand how different parameters of STM patterns affect the perceived experience. Since, there is no prior work studying the feelings and user experience resulting from STM mid-air haptics, this first exploratory study covers a wide range of stimuli to unveil any trends or differences. However, to keep the study scope focused, we limit the stimuli variability to two parameters: the pattern size (i.e. the length of the pattern's path), and the pattern frequency (i.e. how many times the pattern is drawn on the hand per second). In the section we report the design of the study, the procedure and the results.

6.3.1 Study Design

To keep the design consistent with previous studies that use STM, all the tactile patterns used here where in the shape of a circle as it provides a perfectly regular shape (i.e. the geometric update to draw the circle is always the same). We also kept the same three sizes (5 cm, 10 cm and 20 cm) [3] and 20 frequencies from 5 Hz to 100 Hz with a 5 Hz step, for a total of 60 tactile circles.

For each tactile pattern, five questions were asked to assess (1) the strength of the circle, (2) some tactile properties and (3) associated emotion (see Table 6.1). To assess the strength of the tactile feedback, question one (Q1) used a ratio scaling method of magnitude estimation scale. To assess the tactile properties, three questions (Q2-Q4) were presented to the participants about the roughness (i.e. does the pattern feels soft or rough) and the regularity (i.e. does the stimulus feel constant over time or not), and the roundness (i.e. does the pattern feels like round) Finally, Q5 rated the induced emotion through a sad/happy scale using valence pictures of the self-assessment manikin [25].

ID	Questions
Q1	Intensity rating on a magnitude estimation scale
Q2	Roughness rating on a Likert scale (1-9 from soft to rough)
Q3	Regularity rating on a Likert scale (1-9 from regular to irregular)
Q4	Shape recognition rating on a Likert scale (1-9 from not at all to very much)
Q5	Emotion rating on a Likert scale (1-9) with SAM Valence pictures

Table 6.1: The five questions asked in the first study and the scales used.

6.3.2 Procedure

After reading the information sheet and signing the consent form, participants were comfortably seated in front of a computer screen with a mouse. The ultrasonic haptic box was placed under their left armrest with their palm adjusted and rested above the hole.

They were then introduced to the purpose of the study, including a description of the different scales used during the study. They were then invited to ask any questions related to safety of the collected data, the procedure of the experiment and the right to withdraw from the experiment at any time. After this, the users were presented with the different patterns, each for a duration of 5 s, and asked to rate them on the different scales.

6.3.3 Users

We recruited a total of 11 users (mean age 27.3$\pm$4.2, 3 females). Users reported no impairments to their sense of touch. The experiment lasted on average 30 minutes and was rewarded with £5 ($\approx$\$6.5). This study has been approved by the ethics committee of the university.

6.3.4 Results

This first study was aimed at giving a first insight on how the different parameters of the STM might influence the perception and experience of different tactile patterns. In order to see any trends in the data, we plotted the mean data of questions Q1 to Q5 (see Figure 6.2). By analysing the Figure 6.2, we draw the following observations:

- Q1: the intensity follows and confirms the findings of [3], where the intensity rating is a result of the frequency by the size (i.e. the speed). For instance, the 5 cm circle reaches a plateau at 50 Hz (speed of 2.5 $\mathrm{m\,s^{-1}}$) and grows slowly to peak at 100 Hz (speed of 5 $\mathrm{m\,s^{-1}}$). Also, the 20 cm circle peaks at 25 Hz (speed of 5 $\mathrm{m\,s^{-1}}$) and decrease after 60 Hz (speed of 12 $\mathrm{m\,s^{-1}}$).

- Q2: for all the circle sizes, the roughness rating reached the highest value for a frequency value of around 25 Hz, with the 5 cm circle peaking at 3.75, 10 cm at 5.6 and the 20 cm at 6.8 on a 1 to 9 scale.
- Q3: the three circle patterns received are distinguishably different in terms of regularity for frequencies below 30 Hz, with the 5 cm circle peaking at 4.5, 10 cm at 5.2 and the 20 cm at 6.4 on a 1 to 9 scale, but then merge and are reported as being irregular.
- Q4: the roundness ratings seem to correlate positively with the size of the pattern. The 5 cm circle ratings are around 2, the 10 cm circle around 3 and the 20 cm circle around 6 on a scale from 1 to 9.
- Q5: the valence does not seem to follow any clear patterns, as standard error is wide and overlap each other, however the larger circle appears to be associated with higher valence for all frequencies tested.

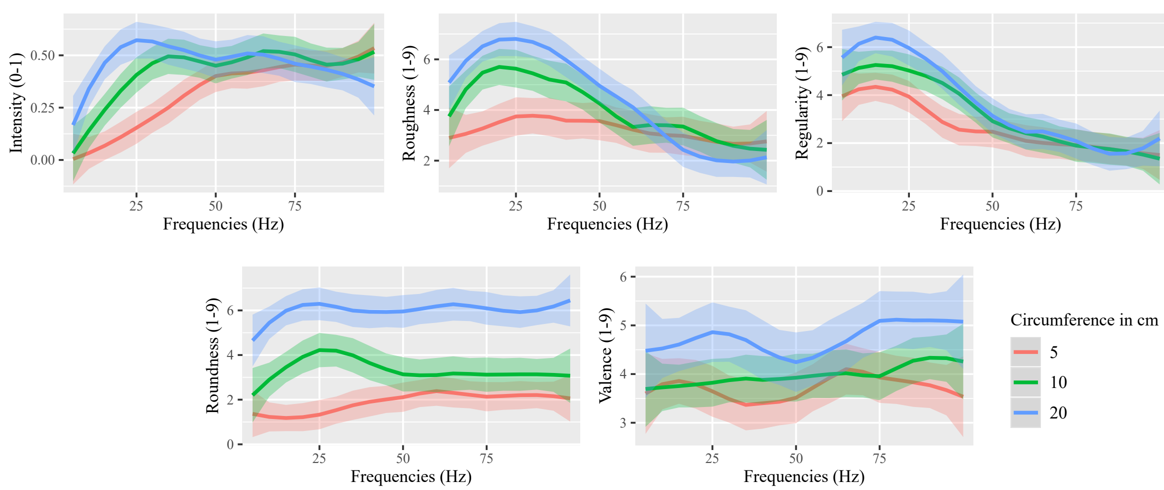

Figure 6.2: Average ratings and standard error of the first study Results are displayed as function of pattern repetition frequency ranging between 5 Hz to 100 Hz, in increments of 5 Hz. Each panel corresponds to Q1-Q5, and plots the reported rating for a circle tactile pattern of perimeter 5 cm, 10 cm and 20 cm (red, green, blue curves), respectively.

6.3.5 Intermediary Discussion and Hypothesis

The results presented in this exploratory study give a first glimpse on how STM parameters could impact the tactile patterns experience.

The intensity's ratings are in line with previous studies, where the speed (*perimeter* $\times$ *frequency*) is the leading factor, with an optimal speed around 5 $\mathrm{m\,s^{-1}}$ to 10 $\mathrm{m\,s^{-1}}$. The roughness and the regularity present similar features with a maximal rating reached at frequencies around 25 Hz. Finally, both the roundness and valence ratings strongly depend on the pattern size while being impervious to pattern repetition frequency.

The above preliminary conclusions of the first study are now re-phrased as three hypotheses:

- Hypothesis 1: 25 Hz provides a significantly higher roughness than 75 Hz, especially when displaying a 20 cm circle.
- Hypothesis 2: 25 Hz provides a significantly higher regularity than 75 Hz, especially when displaying a 20 cm circle.
- Hypothesis 3: Larger circle size conveys a better sense of roundness irrespective of frequency.

6.4 Second Study: Multimodal Perception

We used the results from the first user study to shape our second and larger study. Specifically, we are interested in the interplay of STM haptic patterns and audio-visual stimuli as used in recent works [2, 1, 20, 81]. For instance, can mid-air haptics have a significant effect on the 5 perceptual dimensions we tested (intensity, roughness, regularity, roundness, and valence) when displayed in conjunction with different audio and visual stimuli? To that end, we selected 4 tactile patterns from the previous study in combination with 4 audio stimuli and 4 visual stimuli from an emotional database [32]. The total number of selected stimuli is therefore 44; 12 individual stimuli (4 tactile, 4 visual and 4 audio stimuli), 16 pairs of tactile+audio, and 16 pairs of tactile+visual. Each pattern and each combination pair of tactile+audio and tactile+visual was rated on the same 5 perceptual dimensions as those used in the first user study.

6.4.1 Tactile Stimuli

To focus our results, we choose 4 tactile patterns from the first study of this paper. Namely, these 4 patterns where chosen such that we could test the hypothesis made in the previous section. The parameters chosen were:

- P1: 75 Hz & 20 cm
- P2: 75 Hz & 5 cm
- P3: 25 Hz & 20 cm
- P4: 25 Hz & 5 cm

6.4.2 Audio Visual Stimuli

We selected the audio-visual stimuli from a standardised stimuli database [32] that is composed of:

- 10 pictures from the IAPS [156]
- 10 abstract art paintings
- 10 audio files for the IADS [157]
- 10 music extract from instrumental pieces

In order to reduce the number of audio-visual stimuli, we focused on getting 8 stimuli that fit the following four criteria: (1) four audio (2 music, 2 abstract sound) and four visual (2 pictures, 2 abstract) stimuli, (2) not distressful (e.g. avoiding dead bodies from IAPS), (3) cover different range of valence and roughness (with a low standard deviation), (4) no obvious link with scales used (removed round pictures). The chosen stimuli are presented in Table 6.2.

Media ID	Referred to as	Duration	Valence (0-100)	Arousal (0-100)
4	Music calm	45 s	69.17	58.32
6	Music fast	30 s	49.81	72.4
12	Sound bees	6 s	26.80	61.85
13	Sound waves	6 s	71.00	47.80
21	Abst. wave	5 s	56.66	31.78
25	Abst. art	5 s	60.96	47.35
32	Picture dog	5 s	24.91	62.75
37	Picture sunset	5 s	78.89	50.43

Table 6.2: List of audio and visual stimuli. The Media ID column refers to the ID from the original database [32].

6.4.3 Study Design

We selected 4 tactile patterns from the first study, 4 visual and 4 auditory stimuli from an emotional database and asked participants to rate them when presented alone (i.e. unimodal conditions) and alongside mid-air haptic stimuli (i.e. multimodal conditions: tactile + audio or tactile + visual).

The five questions asked were the same as in the first study and it was explained to the users how to interpret the scales. Intensity and valence were mapped to the emotional response of users to the stimuli. The regularity corresponded to the changes over time (e.g. tempo, intensity, colours, style). The roughness was described as a scale going from smooth to rough. Finally, the roundness for the visual stimuli was interpreted as any association that could be made with a round shape. Similarly, for music it was left to users' preference to interpret and make an association between music and roundness.

Tactile Stimulus	Intensity		Roughness		Regularity	
	mean	sd	mean	sd	mean	sd
75 Hz & 20 cm (P1)	0.441	0.233	3.444	1.874	3.311	1.862
75 Hz & 5 cm (P2)	0.413	0.235	3.263	1.880	3.022	1.760
25 Hz & 20 cm (P3)	0.536	0.273	5.333	1.820	5.025	1.864
25 Hz & 5 cm (P4)	0.296	0.221	3.370	1.925	3.450	1.842

Tactile Stimulus	Roundness		Valence	
	mean	sd	mean	sd
75 Hz & 20 cm (P1)	4.400	2.248	4.233	1.547
75 Hz & 5 cm (P2)	3.153	2.033	4.200	1.372
25 Hz & 20 cm (P3)	4.061	2.273	3.830	1.684
25 Hz & 5 cm (P4)	3.083	2.074	4.181	1.489

Table 6.3: List of the mean score and standard deviation of the different variable Includes the 4 touch conditions (i.e. 4 touch patterns) and the 8 media condition (i.e. 4 pictures and 4 music).

6.4.4 Procedure

Users rated all stimuli alone (unimodal), as well as for each combination pair of tactile patterns and audio-visual stimuli (multimodal), giving a total of 44 unique stimuli. The unimodal conditions were used as based line for the multimodal conditions.

6.4.5 Users

We recruited a total of 20 users (mean age 28.25$\pm$3.21, 7 females). Users reported no touch, vision, or auditory impairments. The experiment lasted on average 45 minutes and was rewarded with £5 ($\approx$\$6.5). This study has been approved by the ethics committee of the university.

6.4.6 Results

In this section, we report all the results of the analysis described in the previous section relating to the second study. Data were tested for violation of normality using a Shapiro-Wilk test. Result showed that the data were significant significantly different from a parametric distribution ($p < 0.001$). Therefore, we used only non-parametric tests in this section.

Unimodal Results

We first analysed the ratings of the different tactile patterns P1-P4, to see whether it was in line with the results from the first study. To do so, we stacked the data for each of the 4 tactile patterns used (i.e. consider both unimodal and multimodal conditions) and ran a Friedman's ANOVA test followed by a Kruskal-Wallis post-hoc test to see if there was any effect between each pair of patterns. The Friedman's ANOVA for the ratings for the tactile patterns were significantly different for the intensity $\chi^2(5) = 234.56$, the Valence $\chi^2(5) = 28.063$, the regularity $\chi^2(5) = 28.519$, the roughness $\chi^2(5) = 21.077$ and the roundness $\chi^2(5) = 26.777$. In all cases the p-values were less than 0.001.

The post-hoc test comparison results are summarised in Table 6.4 with the mean and standard deviation summarised in Table 6.3.

Comp.	Q1	Q2	Q3	Q4	Q5
P1 - P2	43.5	18.0	24.0	105.0*	4.5
P1 - P3	149.5*	253*	227.0*	45.5	105.0*
P1 - P4	214.0*	26.5	41.0	119.5*	3.5
P2 - P3	193.0*	235.5*	251.0*	59.5	109.5*
P2 - P4	170.5*	8.5	65.0*	14.5	8.0
P3 - P4	363.5*	227.0*	186.0*	74.0*	101.5*

Table 6.4: Kruskal-Wallis Post-hoc test results for the different haptic pair patterns. The critical difference is set to 64.62 and significant results are highlighted with an *.

Multimodal Results

We then explored how much the different patterns influenced the ratings when combined with the different media. To do so, we stacked the data for the 32 different multimodal combination pairs. For each of them, we plotted in Figure 6.3 the shifted normalised difference of each rating relative to the unimodal audio or visual baseline taken from [32]. Thus, this metric captures the mean influence of adding mid-air haptic patterns (P1-P4) to different types of non-haptic media.

6.5 Second Study: Discussion of Results

In this section, we will first discuss the different patterns used in the second study and compare our results with the hypothesis made at the end of the first study (Section 6.3.5). We then examine how the tactile patterns have impacted the multimodal stimuli ratings.

6.5.1 Mid-Air Tactile Patterns

Intensity

The results shown in Table 6.4 are in line with the previous study and previous work [3]. P3 is the strongest feedback with an optimal speed of $5\,\mathrm{m\,s^{-1}}$. P1 is above the optimal speed ($15\,\mathrm{m\,s^{-1}}$) where P2 and P4 are below ($3.25\,\mathrm{m\,s^{-1}}$ and $1.25\,\mathrm{m\,s^{-1}}$).

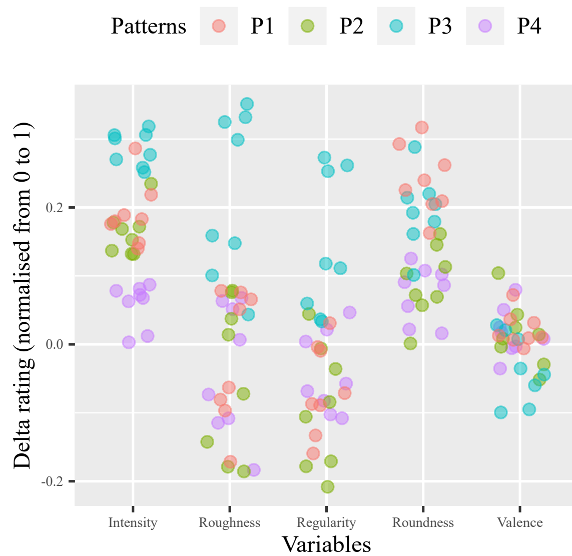

Figure 6.3: Graphical representation of the effect of the tactile patterns on the media. The x axis shows the 5 perceptual dimensions asked to participants and the y axis represents the difference of the ratings of the media alone and the haptics+media conditions. For each perceptual dimension, 4x8 colourful points are plotted representing the 4 tactile patters (P1-P4) and their effect on the 8 chosen non-haptic media (4 audio and 4 visual).

Roughness

Hypothesis 1: 25 Hz provides a significantly higher roughness than 75 Hz, especially when displaying a 20 cm circle. Table 6.4 shows a significant difference in the post-hoc test for the pattern P3 compared to all other patterns. It seems that a perimeter of 20 cm and a frequency of 25 Hz is optimal for a high roughness feedback. This is in line with the first study, where the roughness ratings were peeking for those value and therefore com firm the first hypothesis.

Regularity

Hypothesis 2: 25 Hz provides a significantly higher regularity than 75 Hz, especially when displaying a 20 cm circle. Table 6.4 has similar results for regularity than for roughness. Indeed, it seems that a perimeter of 20 cm and a frequency of 25 Hz is optimal for a low regularity feedback. This is also in line with the first study, where the regularity ratings was peeking for those value and therefore confirm the second hypothesis.

Roundness

Hypothesis 3: Larger circle size conveys a better sense of roundness irrespective of frequency. Table 6.4 demonstrates that the post-hoc test gave a significant difference for each frequency (i.e. P1-P2 and P3-P4). For a frequency of $25\,\mathrm{Hz}$, the roundness rating of the $20\,\mathrm{cm}$ circle is 0.98 points higher than the $5\,\mathrm{cm}$ circle. And for $75\,\mathrm{Hz}$, the $20\,\mathrm{cm}$ circle is 1.25 points higher than the $5\,\mathrm{cm}$ circle.

Valence

The post-hoc test was significant for the pattern P3, which is the highest roughness and irregularity pattern. The mean score shows a slightly lower valence for this pattern (0.3 to 0.4 lower than other patterns), which might be indicating that roughness and irregular patterns can lead to a lower valence. But the mean difference seems too weak and further validation is required.

6.5.2 Multimodal Experiences

The Figure 6.3 shows how the different patterns influence the ratings of the audio and visual stimuli by comparing them with their baseline ratings.

The intensity rating showing that all four selected patterns P1-P4 have a positive impact on multimodal stimuli. Generally, P1 and P3 seem to have the strongest effect ranging from 15% to 25% increase.

The roughness and regularity ratings demonstrate both a positive and negative shift when mid-air haptics are applied to the benchmark media. Specifically, P3 resulted in higher rating of 10% to 30%, where the other patterns resulted in either no effect or lower ratings. This could signify that it is possible to change the texture perception of audio-visual-haptic content by selecting specific pairs of patterns.

The roundness rating presents similar features, showing an overall positive impact on the ratings. This was expected as we only used the circle STM pattern. Moreover, the patterns P1 and P3 seems to have overall higher ratings, which is likely to be linked to their bigger size.

Finally, the valence ratings did not show much of a change, as most ratings lie within a $\pm$ 10%. It is therefore unclear if haptic feedback can significantly influence the valence of audio-visual content. Further investigations are needed.

6.6 Conclusion

Spatiotemporal modulation (STM) is a recent technique for producing mid-air ultrasonic tactile patterns. Previous work showed that speed and sampling rate can impact the perceived haptic feedback intensity [3, 53]. Building upon these works, we have conducted and reported on two user studies that showed that the pattern frequency and size can also affect the perceptual dimensions of roughness, regularity, and roundness. Moreover, we have showed that those tactile patterns could also influence the perception of auditory and visual media according to these same perceptual dimensions.

Our findings can help UX designers tailor STM parameters to deliver richer tactile and multimodal experiences that better reflect the desired effect. This would have direct applicability, as mid-air haptics could complement user experiences in gaming, movies, and interactive art installations.

The current work investigated the effect of two STM parameters on user experience, both in unimodal and multimodal scenarios. However, mid-air tactile patterns displayed using STM technique can be further tuned with additional parameters, as recent work [53] showed that device sampling rate, could change the perception of intensity for low frequency pattern. Future work could therefore investigate additional STM parameters and their impact on multisensory experiences and in particular their correlated effects and valence ratings.

Chapter 7

Conclusion and Future Work

"There are always flowers for those who want to see them."

– Henri Matisse

UMH feedback is an emerging technology and we are only starting to understand its opportunities for designing interactive applications and creating novel haptic experiences. The overall aim of this thesis was to investigate the design space around UMHs through combining field and laboratory explorations. We first started with an integration of mid-air haptics feedback in a real-world application scenario to augment art experiences in a art gallery. Based on the lessons learned from this initial exploration, we studied mid-air haptics experience design in controlled laboratory environments in order to better determine its added value to users' experiences and also to better understand the different design parameters. Finally, we ran two exploratory projects to expand the available range of sensations provided by UMHs.

This chapter first summarises our key contributions derived from these explorations, linked to each of the four driving research questions. It then closes the thesis with a conclusion and several openings for future work with UMHs.

7.1 Discussion and Contributions

Over the last decade, we could observe an increased attention beyond audio-visual interaction design within the HCI field, and see a proliferation of novel haptic technologies and devices [158]. More recently, multi-sensory HCI research and design [130] has gained momentum and enriches the design space through novel explorations into not only touch, but also taste and smell interaction and interfaces. Within this thesis, we particularly aimed to make a contribution to the understanding of UMHs technology and devices. Hence, the first research question of this thesis was: What are the challenges of designing an art multisensory experience involving mid-air haptics?

At this time, no guidelines and no specific rules were provided on how to use UMHs. There was some initial work by Obrist et al. [19, 20] providing us with an initial vocabulary on how to talk about mid-air haptic experiences and how they can be mapped towards emotional dimensions including valence and arousal. However, at the point of starting my thesis and still to date, there are no guidelines on how to integrate mid-air haptic feedback with other sensory modalities.

The Tate Sensorium project provided not only a great initial platform to explore the potentials of UMHs in a specific use case scenario, but also allowed us to iteratively design and integrate the touch experience in collaboration with a sound design expert. The main challenge during this collaboration was to enable the sound designer to create an experience involving touch without having to learn programming. To tackle this problem, we designed a tool that allowed him to express his creativity by controlling the haptic device through tools he was already using (i.e. MIDI inputs).

This approach worked well and resulted in a successful exhibition in the Tate Britain. But it took time and resources: a haptic specialist needs to support the creation process by both explaining the technology and delivering the curated tool. In the future, this approach could be generalised and simplified but the core of it need to stay the same: the media creators need to be informed and guided from the beginning and then be provided with tools that fit the specific need of the creators (e.g. live performance, museum exhibition, or multisensory movie).

Inspired by the massive positive feedback from over 2500 people and over 4000 visitors of the Tate Sensorium exhibition, we defined a second experiment in a controlled laboratory environment aiming to answer the second research question: Can mid-air haptics support the viewing of traditional audio-visual content?

To make it more ecological valid, not having art pieces at hand, which would also be difficult to compare, we used short films as research object in this second step of exploring the mid-air haptics design space. This time, to design the mid-air haptic experience, we used user's physiological responses as input. More specifically, we measured participants' skin conductance response while watching a set of short movies. We analysed and used the physiological data as input for the design of the haptic experience. The chosen content format (60 seconds narrative) allowed us to create an automated experience for each movie. To answer our second research question, the design of the study was comparing the following conditions: specifically designed haptics (sync), generically designed haptics (not sync), and no haptics (off).

The results showed that when the haptic condition was on (sync and not sync) the arousal was higher. This effect was again found two weeks later when the participants participated a second time to the experiment. This is a very encouraging result, showing the potential of mid-air haptics to enhance the arousal of participants, but it also shows that synchronising the haptic feedback based on the SCR data was not successful. Despite the additional value provided by the mid-air haptics through arousal, the lack of understanding about the tactile sensation on user's emotions was a limitation.

These first two initial explorations in the field and lab context allowed us to better understand the challenges but also the opportunities for UMH. What was however becoming clear is that a richer understanding of the design parameters facilitated through this technology are needed in order to full exploit the UMH possibilities. Hence, in the following steps within this thesis we tackled the third research question: Can we broaden the range of mid-air ultrasonic tactile possibilities?

As the thesis progressed, the uptake of mid-air haptic technology within the HCI community increased and the company producing the ultrasonic mid-air haptics devices innovated on the stimulation approaches, which is mainly based on AM technique. While prior work used AM techniques to improve the quality of the tactile perception [20, 1, 2, 78], it was our aim to explore novel methods that would expand the design space even further and make the creation of more tactile sensations possible. We introduced the STM technique that uses the location of the focal point to display and modulate the haptic feedback.

The AM technique changes the intensity of the focal points over time to create a frequency. The STM technique does not change the intensity over time, but instead moves the point alongside a curve several times per seconds, creating the frequency. The STM technique introduce one new key parameter: the speed of the focal point. Therefore, we focused on understanding how the speed could impact the strength of the haptic feedback. We ran two separate experiments, the first one relied on vibrometry and the second one was a user study involving 15 participants.

Both studies had aligned results: the speed is the determinant factor for the strength of the feedback when using STM, not the frequency. The peak strength is achieved with a speed of around $5\,\mathrm{m\,s^{-1}}$ to $8\,\mathrm{m\,s^{-1}}$.

While there is more to be investigated in the direction of new interaction techniques, we were eager to apply our STM method to link it back to our original aim to create new experiences and understand what difference mid-air haptics can make. Hence, in our last research step included in this thesis we addressed the question: Can the ultrasonic mid-air haptic parameters impact users' perceptual and emotional responses?

To answer this question, the first study of the last project explored a wide range of sizes and frequencies of STM patterns through five perceptual questions about intensity, roundness, roughness, regularity and valence. This exploration brought to light several correlations between the parameters of the STM pattern and its tactile properties. In a second user study, we used the most salient patterns from the first study in conjunction with audio and visual stimuli taken from a standardised database [32]. This helped us to understand how UMH feedback could change the experiences of other sensory channels (i.e. vision and hearing) when displayed simultaneously.

The results from this study provided a first correlation between the 5 studied scales and some parameters of the STM patterns (i.e. the frequency and size). This is only the first step towards a systematic exploration of the STM technique, but it is a proof of concept that the parameters have an impact on the tactile sensation and should therefore be chosen carefully by the creator.

7.2 Conclusion

When this thesis started in 2015, the ultrasonic mid-air haptic field was in its infancy and its availability was very limited. At this point, the Sussex Computer-Human Interaction (SCHI /skʌi/) Lab was one of the three laboratories world-wide to have access to the new mid-air haptics device developed by Ultrahaptics. Carrying out my PhD in the SCHI Lab allowed me to be an early adopter and explorer of this new haptic technology. This was both thrilling and challenging, as we set foot onto an uncharted field. We initially set the goals of both integrating it in multisensory experiences and broadening the available tactile sensations provided by the device.

I believe this thesis brought the field of UMHs forward, but there is still a lot of work to be done. In order to bring it to the next level, and make UMHs mainstream, there is a crucial need for tools for both research teams and creators. Over the course of my PhD, I had several encounters with creators that were interested and eager to work with UMHs, but could not because of the lack of appropriate and accessible tools. Artists are creative and open for novel explorations, but the programming interaction using c++ to create new tactile sensations was a stumbling block. I became, especially in the first project presented in this thesis, a human translator between the technology and the creators. This translation is less needed now as the device is now offered alongside a sensation editor. While this is a great step forward, the tool is still limited to a subset of the sensations and therefore more explorations into toolkits, widgets, plugins of the existing audio-visual ecosystem such as Unity, Photoshop, or Audicity are needed.

While my PhD journey has come to an end, there is plenty of room for others to continue, and I provide below several openings towards future works.

7.3 Limitations and Future Work

As many innovations, research works bring not only answers but also open new areas to be explored (e.g. a new technique [3, 54] or a new multisensory integration process [2]). Those concepts require a careful examination in order to understand their potential and limitations. This section summarises the open questions associated with UMHs around three challenges.

The first challenge is to extend the range of possible sensations. This can be achieved by introducing new techniques to the existing ones (i.e. AM, LM, STM). It would also be possible to optimise the current ones by exploring how a careful use of the parameters could improve the quality of the feedback [53].

The second challenge is to continue the exploration of multisensory experiences using UMHs. The area of haptic-audio-visual interaction has been part of the HCI community for the past two decades [159], and UMHs has the potential to contribute to it.

Finally, the last challenge results directly from the two previous ones. As the number of technical and design possibilities is growing, working with UMH gets more complex. Indeed, the designer needs to understand the strengths and weaknesses of each of the different techniques. Therefore, there is a need to simplify the use of UMHs for designers and non-technical people. It could be done either by creating guidelines, tutorials or by developing tools that could hide the technical side. This challenge is a requirement if UMHs are to get mainstream.

In the following sections, we dive into those three challenges and present several directions that could help the future research.

7.3.1 Systematic Exploration of UMH Possibilities

Since its introduction in 2008 [16], UMHs have constantly been improved: displaying multiple points [17], displaying shapes [18], STM technique [3], LM technique [54], or the optimisation of the STM technique by using different sampling rates [53].

Improving UMH techniques and tactile sensations is usually done through a careful exploration of its parameters and some measurements done either through vibrometry [3], sound measurement [17], or user testing [4].

The first opportunity would be to explore in more details the freshly introduced STM and LM techniques. For instance, the four main parameters (i.e. intensity, frequency, curve length and sampling rate) are still to be explored with different shapes, either simple like a square or a triangle or complex ones like fractals or Lissajous curves. Also, the STM technique could use two points instead of one, which could double the frequency (i.e. each point of the curve is travelled twice more often) at the same speed. Knowing that the speed and frequencies are linked and have both interesting properties, it could open new possibilities.

AM, LM and STM techniques have only been used separately, and there might be potential to explore how they could be used at the same time. The first application would be to facilitate the shift of one technique to another, which could prove useful in some situations, for instance when shrinking a STM circle into an AM point. Moreover, it could create a new range of experiences and textures, knowing that each technique has its own tactile properties.

The results given in this thesis allow to control the intensity and modulate some properties like the roughness or regularity. A systematic exploration of the textures and their link to the different haptic parameters is yet to be done. Also, a link might exist between the roughness and valence [4], this needs to be further explored.

7.3.2 New Experiences to Explore

In this thesis, we presented two ways to create mid-air haptic experiences. The first one automated haptic feedback created from physiological data while the second one was made by hand by a haptician and a sound designer. Both approaches could be improved in several ways.

The automated approach only relied on the physiological data, and we could improve it by getting more information through automatic extraction of relevant data through sound and images. For instance, there is a growing interest in the music information retrieval field [160], allowing getting contextual information: mood, tempo, semantic etc. Combined with the toolbox approach [22], it could automatically match semantic patterns to the audio channel. It could also take into consideration the interpersonal differences. The way people use touch and how they perceived haptic feedback is unique. A screening and the creation of user profiles could be one approach to tackle this. Maybe association between similar users could also help (e.g. people that get excited by actions vs people that get scared). Also, in this work, we focused on the skin conductance response, but it could be extended to other measurements like the heart rate.

The creative approach taken in [1] was based on the semantic space: the two patterns used were matching the shape of the painting (i.e. a circle) and its texture (i.e. drops of spray paint). Moreover, the tactile creation was synchronised with the sound. This is a common approach to mirror the content of the media [23, 22], but it might be interesting to take a different approach, where the haptic experience is not only mirroring the other channels but bringing its own creativity. For instance, by using the haptic channel to build up some tension, could relief the user after a scary scene, or a totally creative approach where the haptics has its own meaning.

7.3.3 Tools and Toolkits

Both approaches to create haptic tools (toolbox [12, 22] and creative [62, 63]) have interesting points for designers. But at the current state of the art of UMH, there is no such tool available for the designers. It is therefore mandatory to involve the participation of haptic practitioners. For instance, Vi et al. [1] presents a unique case where a haptician and a sound designer created a unique multisensory experience.

In the future, it would be necessary to give modular and scalable solutions. Such project would start by working with haptic practitioners to gather the needs and the interfaces that could match their needs. For instance, a live performance would have different needs from a movie where the haptic experience could be made in post-production. Those challenges are beyond mid-air haptics alone but represent one of the big obstacles that needs to be addressed before haptic becomes mainstream. Below are some ideas of what such tools could look like.

With the toolbox approach, one could create a set of patterns from the AM, LM and STM techniques and assess them through a user study. Like in the work from Seifi et al. [63], a multimodal interface would be preferable. Some ideas would be:

- Raw parameters: a window addressed to advanced users, where it would be possible to see the basic parameters (e.g. sampling rate, frequency, or intensity) and which technique is used (i.e. AM, LM, and STM).
- Semantic space: What the pattern could be associated with (e.g. heartbeat, speed, texture etc.).
- Emotional space: using the finding from the literature [20, 2, 4], it would display information about the arousal of the pattern, and maybe the associated valence.

On the other hand, following the creative approach, the first challenge encountered with UMH would be to be able to work in 3D [18]. The interface could propose two modes: (1) the first one in 2D where the tactile pattern would follow users' palm, iterating on previous work [62] and (2) the second one in 3D where the user could load simple shapes from a library or import 3D models and customise them (e.g. give them surfaces, density etc.). If possible, the interface could be multimodal, and features such as roughness or intensity could be computed in real time using our findings [4], giving some insight to the creator about what his creation would feel, even before testing it.

It's hard to predict what ultrasonic mid-air experiences will look like in the future, as both the research and the technology are moving fast. Earlier this month, (Nov. 2019) as this thesis is finishing, Hirayama and colleagues [161] introduced a brand-new technique that integrates visuals and sound directly into UMHs. There is not doubt that this technology will grow in the near future and change the way we interact with technology, our environment and maybe with other people.

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