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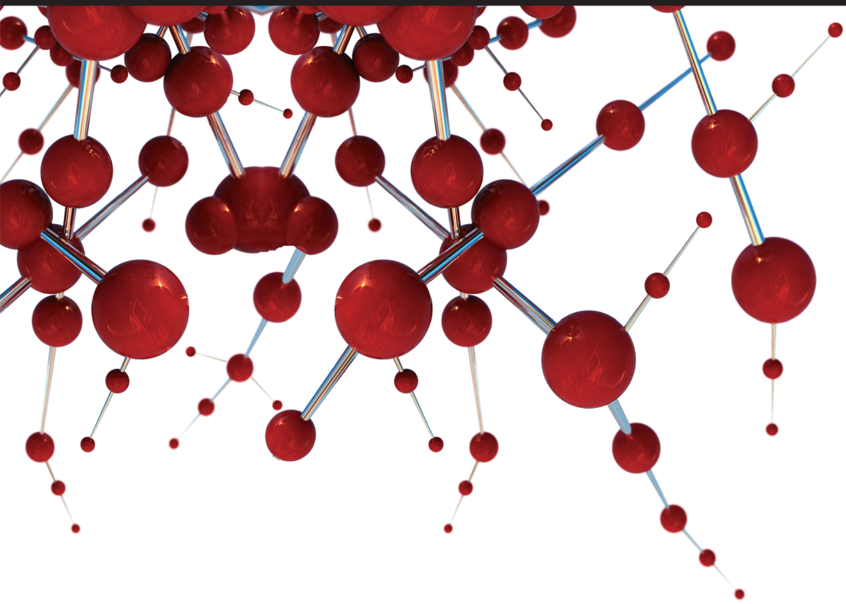

Antti Sand

On Adding Haptic Feedback to Interaction with Unconventional Display Devices

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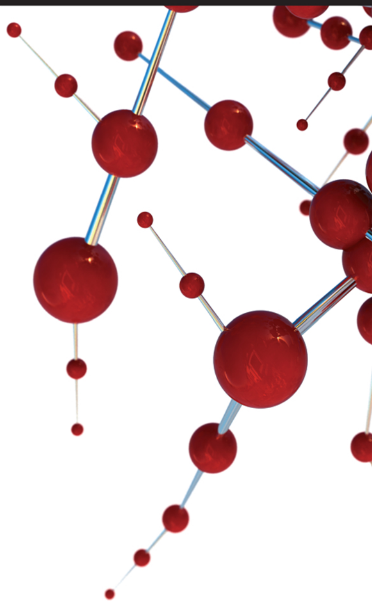

Intangible user interfaces presented via VR headsets or permeable screens may become noticeable parts of human-technology interaction. The sense of touch is important to human interaction as well as for interacting with our surroundings. Touch and tactile feedback are essential also when interacting with digital technology. This thesis investigated methods of adding haptic feedback to interaction with these unconventional display devices. Measurements such as error rates and task completion times were employed, in addition to subjective rating scales and free-form user comments.

The findings indicated that haptic feedback provided in mid-air using phased acoustic transducers or locally using wearable vibrotactile actuators is most beneficial for user experience rather than productivity. Further, the addition of haptic feedback to interaction with intangible user interfaces is significantly preferred by the users. The results of the current work can partly help in motivating attempts to introduce more expressive and effective haptic feedback to interaction with unconventional displays, which eventually results in the case that devices currently classified as unconventional will one day become mainstream.

Antti Sand

On Adding Haptic Feedback to Interaction with Unconventional Display Devices

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ACADEMIC DISSERTATION
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Abstract

The sense of touch is important to human interaction as well as for interacting with our surroundings. Touch and tactile feedback are essential also when interacting with digital technology. The present doctoral thesis aimed to discover a profound understanding of how touch sensations could be added to unconventional display devices that do not inherently provide tactile feedback. Novel and less explored devices and use cases were studied in five carefully controlled studies.

Study I introduced a novel lightweight, environment sensing limitedly volumetric permeable display. It could be interacted with by swiping the display in mid-air to, for example, reveal slices of medical magnetic resonance images. The results of this study consisted of the introduction of a novel interactive display device and use cases for it.

Studies II and III investigated the use of ultrasonic mid-air haptic feedback with unconventional displays. In both studies, the participants were to enter numbers by tapping virtual buttons. Their hands were tracked, and the tasks were repeated with and without haptic feedback. In study II, the user interface was presented using a permeable display formed of flowing light-scattering particles. In study III, the user interface was presented using a head-mounted virtual reality display. The results showed that ultrasonic mid-air haptics can be a suitable method for tactile feedback in intangible user interfaces. In terms of task completion times and error rates, there were no statistically significant differences in entering the numbers with or without tactile feedback. On the other hand, the addition of ultrasonic feedback was uniformly preferred by the users.

Study IV investigated the effect of adding vibrotactile actuation to gestural interaction with a large permeable display. Tapping and dwell-based interactions were supplemented with feedback from a custom-built wireless wearable actuation device in addition to audio-visual feedback. The experiments were repeated with and without the haptic device. The results showed that while tapping on a target was more efficient than dwelling over it, limitations in tracking quality made the use of dwell-based selection methods more robust, as is often the case. Vibrotactile feedback was preferred by the users in dwell-based interaction over audio-visual feedback alone.

The aim of study V was to investigate the differentiation of six ultrasonic tactile stimulations that were varied by form (i.e., square and circle) and timing (i.e., movement speed and duration, and the frequency of tactile phases within a stimulus). In a stimulus familiarization task, participants were introduced to all stimuli in a specific order (1 to 6) and repeated four times. After this, participants were to identify the stimuli presented in random order by pressing the number key corresponding to the stimulus index used in the familiarization task. The results showed that stimuli formed of repetitive 400ms pulses were easier and more reliably identified than those with a shorter duration regardless of the number of repetitions. Post-experiment interviews revealed that the changes in form were not noticed.

In conclusion, the results showed that ultrasonic mid-air haptic stimuli are a well-suited method for feedback delivery in permeable and virtual displays. Further, the results showed that users uniformly preferred the addition of haptic feedback to interaction with intangible user interfaces. In addition, the results showed that mid-air tactile stimuli can be designed so that they were reliably identifiable after minimal familiarization and hence can be utilized for efficient information transfer on tactile displays. Taken together, the findings of this thesis suggest functional solutions for adding haptic feedback in interaction with displays that currently are classified as unconventional but will become more mainstream technologies in the future.

Acknowledgements

First, I would like to thank Dr. Ismo Rakkolainen, a calm visionary with an unquenchable thirst for knowledge. His inventions and ideas have been imperative to the studies presented in this thesis. I also thank Professor Veikko Surakka for all his tireless efforts trying to make a writer out of me, as well as for his no-nonsense guidance and feedback. You both have helped me grow. Thank you Dr. Diego Martinez Plasencia and Associate Professor Eve Hoggan for your expert feedback for this thesis. I would also like to thank Professor Roope Raisamo for my employment as well as for all you have done for the people of TAUCHI making it a great place to work.

I would like to thank all my coauthors in the publications in this thesis for all your valuable input. Especially Professor Karri Palovuori for his electronic constructions and Professor Stephen Brewster for letting me visit his group in Glasgow. Thank you Drs Sumita Sharma, Toni Pakkanen, and Jari Kangas, as well as Juho Hella and Jobin James for all the fun conversations over the years. Thank you, Hanna Venesvirta and Jani Lylykangas, for your help with the intricacies of SPSS. Additionally, I thank the financial support from the Faculty of Information Technology and Communication Sciences. Further, I thank Paula Pajamäki for her support when it was needed.

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Kangasala, January 19, 2021

Antti Sand

Contents

List of Publications

This dissertation is composed of a summary and the following original publications, reproduced here by permission.

I. Sand, A., & Rakkolainen, I. (2014). A Hand-held Immaterial Volumetric Display. In *Proceedings of SPIE - The International Society for Optical Engineering* (Vol. 9011, p. 90110Q). https://doi.org/10.1117/12.2035280 97

II. Sand, A., Rakkolainen, I., Isokoski, P., Raisamo, R., & Palovuori, K. (2015). Light-weight Immaterial Particle Displays with Mid-air Tactile Feedback. In *2015 IEEE International Symposium on Haptic, Audio and Visual Environments and Games, HAVE 2015 - Proceedings*. https://doi.org/10.1109/HAVE.2015.7359448 107

III. Sand, A., Rakkolainen, I., Isokoski, P., Kangas, J., Raisamo, R., & Palovuori, K. (2015). Head-mounted Display with Mid-air Tactile Feedback. In *Proceedings of the 21st ACM Symposium on Virtual Reality Software and Technology - VRST '15* (pp. 51–58). https://doi.org/10.1145/2821592.2821593 115

IV. Sand, A., Remizova, V., MacKenzie, I. S., Spakov, O., Nieminen, K., Rakkolainen, I., Kylliäinen, A., Surakka, V., & Kuosmanen, J. (2020). Tactile Feedback on Mid-Air Gestural Interaction with a Large Fogscreen. In *Proceedings of the 23rd International Conference on Academic Mindtrek* (pp. 161–164). New York, NY, USA: Association for Computing Machinery. https://doi.org/10.1145/3377290.3377316 125

V. Sand A., Rakkolainen I., Surakka V., Raisamo R., & Brewster S. (2020). Evaluating Ultrasonic Tactile Feedback Stimuli. In: Nisky I., Hartcher-O'Brien J., Wiertlewski M., Smeets J. (eds) *Haptics: Science, Technology, Applications*. EuroHaptics 2020. Lecture Notes in Computer Science, vol 12272. Springer, Cham. https://doi.org/10.1007/978-3-030-58147-3_28 131

The Author's Contribution to the Publications

All of the papers presented in this dissertation were co-authored with at least one other author. The following details the current author's contribution to each of the publications included in this doctoral thesis.

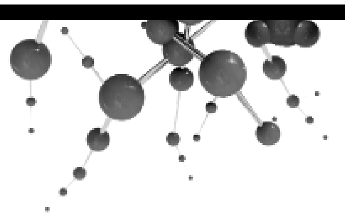
In the first publication, the novel display device came from Ismo Rakkolainen. The novel interaction was designed together with the present author. The present author had the main responsibility for designing and implementing the interaction, while the publication writing was a joint effort with Ismo Rakkolainen.

In the second publication, the novel display device was provided by Ismo Rakkolainen and the ultrasonic transducer array was provided by Karri Palovuori. The present author was responsible for designing and implementing the interaction, designing and conducting the experiment, and data analysis. The publication writing was a joint effort with Ismo Rakkolainen. Poika Isokoski and Roope Raisamo gave feedback on the publication writing.

In the third publication, the ultrasonic transducer array was provided by Karri Palovuori. The present author was responsible for designing and implementing the interaction, designing and conducting the experiment, and data analysis. The writing of the publication was a joint effort between the present author and Ismo Rakkolainen. Poika Isokoski helped with the data analysis. Jari Kangas and Roope Raisamo gave feedback on the publication writing.

In the fourth publication, the present author published a part of a larger, multi-author experiment. The design of the experiment was a joint effort, with clear roles so that Vera Remizova was responsible for designing the gestural interaction and the present author was responsible for the tactile feedback. Both took part in designing and conducting the experiment. The present author was also responsible for data analysis and writing the publication presented here.

In publication five, Ismo Rakkolainen, Roope Raisamo, Veikko Surakka, and Stephen Brewster provided comments on the article draft. Stephen Brewster had a supervisory role in the experiment. The present author was responsible for implementing the user experiment, carrying out the data analysis, and writing the publication.



1 Introduction

Human-technology interaction is entering a new era as novel displays and methods of manipulation of displayed data are emerging. Mobile computing and internet-of-things (IoT) devices call for the next evolutionary step, the next generation of user interfaces. With small device sizes, sparse screen estate, and new use contexts, new ideas for user interfaces are needed. The evolution of computers goes hand in hand with significant advances in display technologies. Higher definition resolutions, 3D displays, head-mounted virtual reality displays, and permeable displays all could benefit from and in some cases require new user interface paradigms.

Displays are the most visible element of most computer applications and the part we spend the most time looking at. The traditional paradigm of a monitor and a pointing device has dominated the field of computer user interfaces (UI) for decades. In the 1960s, a shift from the then traditional terminal computers used primarily by typing on a keyboard was set in motion: Bill English's prototype device constructed from Douglas Engelbart's sketches was presented as a "mouse" in the 1965 report *Computer-Aided Display Control* (Engelbart, English, & Huddart, 1965). The offspring of their design remained the dominant pointing device until the mass acceptance of touchscreen devices.

Being able to point and select icons and other user interface elements by simply touching the screen with a finger was novel to most users. Fundamentally it was similar in that the elements presented were ultimately still two-dimensional representations on a tangible surface. In Human-Technology Interaction (HTI) the concept of tangibility also encompasses aspects like shape and texture. Throughout this thesis, the term will be used to refer to palpable objects.

The advent of intangible display screens and user interfaces presented in virtual environments has perhaps been a more substantial paradigm shift. No longer are the elements tangible or confined to a flat physical surface separate from real-world objects.

A "holographic" display floating in thin air has been (a sort of) a holy grail for scientists, researchers, and all-around tinkerers for centuries. Similar end results have been attempted since at least the 15th century. One of the first patented solutions was Just's *Ornamental fountain* from 1899 (Just, 1899) and the development has led now to the emergence of various 3D displays able to create an illusion of a 3D image. The image is still often confined inside a physical, tangible display device unlike the mid-air permeable holograms seen in some science-fiction movies.

Ubiquitous and mobile computing calls for novel, unconventional solutions for presenting user interfaces. Common examples of these unconventional displays include head-mounted displays, (HMD), and projection screens formed of flowing light-scattering particles, like the FogScreen (See Section 2). Head-mounted displays can be further categorized into virtual reality devices, such as Oculus Rift and HTC Vive, augmented reality devices, such as Microsoft HoloLens, and head-mounted projected displays (e.g., Sand & Rakkolainen, 2013), etc. Virtual reality devices can be used with wearable controllers, but they support also gestural interaction without wearable controllers through different methods of, for example, visual hand tracking. Flowing particle screens could be used with a mouse or other pointing device, but in the context of this thesis, they will be used with gestural interaction.

We are used to the traditional tools that provide us natural tactile stimuli. User interfaces presented with these novel display devices share an inherent permeability and are not tangible. So, with these unconventional displays, the tactile sensation is inherently missing. Thus, adding tactile feedback to them is a must.

The sense of touch is important to humans. It serves several purposes for human behavior. It can provide information about the structure and form of objects or the texture of surfaces. It can serve as a trigger to regulate behavior, such as withdrawing the hand from hot surfaces or sharp objects. When touching another person or a pet it can also mediate emotional information. All in all, the sense of touch is a profound means of interaction.

In the realm of human-technology interaction, the potential of utilizing the sense of touch has only recently been ascertained and appreciated. In this realm, the term "haptic(s)" refers to technology-mediated haptic sensations, often, but not exclusively, touch.

While interacting with technology it is typical to feel haptic sensations. When we type on a mobile phone, we expect to feel a short, sharp vibration to confirm our input. When our phones are on silent mode, we expect a longer pattern of vibrations to inform us of incoming calls or the alarm clock going off. A smartwatch may alert us with vibration when we have been sedentary for an unhealthy period. All these examples could be, and often are, substituted or complemented with auditory output. However, in socially delicate situations, or situations where vision and hearing cannot be used, such as in noisy environments, vibration can be preferred. Indeed, haptics can be used in a multitude of devices and contexts, whether it is mobile phones or smartwatches, video gaming, or driving.

This has not been the case for very long. In fact, interaction devices have traditionally relied heavily and almost exclusively on visual and auditory senses, even when the cognitive processing of such information is problematic due to limitations in human mental capacity (Oulasvirta, Tamminen, Roto, & Kuorelahti, 2005). Even though the sense of touch is so commonplace in our day to day lives, it is only recently that researchers have started studying and developing haptic features in computers and mobile devices to actively support the human-technology interaction.

Prior to wearable or mid-air haptics, meaningful touch-based interaction was limited to touch detection and tactile sensation through the touched surface. This can be enabled by the inherent tangibility or through a haptic actuator, such as a vibration motor. To mediate the sense of touch on an intangible user interface element, new technological devices are needed. For example, the user could wear tactile data gloves (e.g., Ku et al., 2003) or other wearable tactile actuators, or the stimulation could be provided mid-air without the need for physical touch. The most commonsensical approach has been to include a tactile actuator, often they have been vibration motors such as those used on mobile phones that are in direct contact with the users' hand(s). This way the tactile stimulation can be presented when needed to give the illusion of a tangible surface or to transfer information by encoding it into the tactile stimuli. For the unconventional displays introduced in this dissertation, haptic feedback was presented using several techniques and technologies, from wearable actuators to mid-air haptics.

The present doctoral thesis aimed to discover profound understanding of how touch sensations could be added to unconventional display devices that do not inherently provide tactile feedback. Novel and less explored devices and use cases were studied in five carefully controlled studies.

2 Unconventional Displays

The term unconventional display is used in this thesis to distinguish such display devices that are intangible or permeable. In the case of virtual reality headsets, the display device itself is very much tangible, but any user interface presented with such technology would appear permeable. Further, these displays will be categorized into virtual displays and physical permeable displays. Strictly speaking, neither clause is accurate, but both terms are widely accepted.

Hinckley (1997) divides the evolution of user interfaces into generations. The first generation was the batch input of punch-cards. The main concern of administrating extremely expensive computer mainframes was to optimize their utilization time and the human specialists operating them had to adapt to their UI limitations. The second was the command-line interface, which improved the utilization time of the computers by allowing for multi-user operating systems. Their alphanumeric displays were able to provide the users with context-sensitive UIs. With improved graphical capabilities and new input devices - mainly the computer mouse - came the third, and arguably the most common today, generation of user interfaces. This generation is denoted by acronyms graphical user interface (GUI) and windows, icons, menus, and pointing device (WIMP).

The WIMP GUI uses the haptic channel for input and the human visual channel for output (Rakkolainen, 2008b). Graphical user interfaces and WIMP made the use of computers intuitive and easy enough for even the laypeople to use. The personal computer (PC) became pervasive, something not out of the ordinary even in homes. If we think of computers only as machines for text input, a glorified electrical typewriter of sorts, then this UI serves the purpose well. But as computers are increasingly used for tasks other than plain writing, be that entertainment, navigation, or information retrieval, the traditional user interface techniques, such as WIMP or desktop metaphor will not scale well to diverse factors, locations, and uses of the pervasive and ubiquitous future computers (Rakkolainen, 2008b).

Weiser's (1999) "ubiquitous computing" stated that the traditional computer is disappearing. As processors keep getting smaller, require less power, become more powerful, and cheaper, the users end up increasingly more surrounded by numerous embedded processors. Weiser's vision presents displays in various forms and sizes. Hand-held devices, tablet devices, desktop devices, and large public displays all have different form factors and different use cases. Displays can be everywhere and nowhere, it all depends on the application, context, and environment (Rakkolainen, 2008b). E Ink displays are low-powered and cheap enough to be incorporated in magazines or coffee mugs. Similarly, the user interface can adjust to the use case and availability of displays, and in some cases, it might not be needed at all. It is also likely that there will never be a universal display type for all possible purposes (Rakkolainen, 2008b). Overall, novel display technologies can bring advanced features that in some cases end up competing with traditional lower cost displays if the added value or demand surpasses the added expense. For example, 3D display devices may be valuable tools for architects or medical professionals, as well as certain researchers and data analysts.

There are many display innovations that at first sight were thought as unconventional, but currently are taken as conventional. For example, wrist and cell phone displays at one end and optical camouflage displays that can render armored vehicles seem invisible on the battlefield at the other extreme. Permeable displays are current technologies that can be regarded as unconventional ones.

2.1 PERMEABLE DISPLAYS

Mid-air and holographic displays have dominated the display imagery in science fiction movies for decades. Ranging from Star Wars (1977-) to Minority Report and Iron Man, they have captivated the general public's and media's attention. But the idea has intrigued people for centuries before the advent of movies.

Volumetric, autostereoscopic, and other 3D displays, as well as partially transparent screens, can be used to create the illusion of elements floating in a three-dimensional space, but these are still impervious sheets of glass or plastic keeping the images behind them out of reach (Benzie et al., 2007; Rakkolainen, 2008b), or displayed within a very short distance from the display, limiting their applicability.

A "holographic", permeable display floating in thin air has been seen as a sort of a pinnacle of display technology (Shedroff & Noessel, 2012). Attempts to create one have been made for centuries, at least from Wheatstone's stereoscopic images (see Section 2.2) in the early 1830s, to the introduction of various 3D displays. Most such displays are not truly mid-air or penetrable. If they could break free from the constraints of physical displays, it would, for example, bring the augmented reality information closer to the object. This could work to shorten the mental and physical gap between the real object and the displayed augmented information, giving a more coherent user experience (Sand & Rakkolainen, 2014).

The term "permeable display" is used here to refer to a display surface consisting of tiny, flowing, light scattering particles, such as dust, smoke, or fog. In the case of fog, small layers of water vapor are translucent and seem to disappear when lights are dimmed. If the flow is non-turbulent and the particles are illuminated, they can form a crisp image floating in mid-air.

The idea of permeable displays is not novel. Images have been projected to various kinds of water, smoke, haze, or fog screen since at least the 15th century. The concept gained popularity and birthed commercial viewings in which attendees would sit in a darkened room occupied by flying demons, hellish scenery, and appropriate audio effects (See **Figure 1**). Belgian inventor Étienne-Gaspard Robert coined a term *fantascope* for these "magic" lanterns used to project the images. The macabre atmosphere in the post-revolutionary city of Paris combined with the novelty of moving mid-air projections made Robert the best-known phantasmagoria showman. (Barber, 1989)

Figure 1. Fantasmagorie de Robertson at Cour des Capucines in 1797.

P. C. Just (1899) was perhaps the first to be awarded a patent for an apparatus for a mid-air projection screen. Common particle mediums were smoke, water, haze, and smoke. Smoke, however, is opaque and usually darker, requiring more illumination and resulting in less than optimal contrast. Often the screens made from water and fog are wet or use thick particle flows that are unable to reproduce sharp images unless they are viewed from afar and directly towards the projector. Chemicals, such as those used in fog machines in concerts, can also be used to create fine particles. The use of chemicals can, however, have adverse effects in humans after prolonged use in enclosed spaces. They also create fairly permanent, accumulating haze, which may float around for long periods.

In the experiments introduced in this thesis different versions of the FogScreen were used when a permeable display was required. The FogScreen (See **Figure 2**) was invented and developed by Ismo Rakkolainen and Karri Palovuori of the Tampere University of Technology (now Tampere University) and was first published in 2002 (Rakkolainen & Palovuori, 2002).

Figure 2. A large fogscreen hanging from the ceiling showing a projected image on a thin layer of fog.

The fogscreen is the optimal method to create a light scattering particle screen in terms of high-quality images in mid-air. It is a permeable projection screen, consisting of a thick non-turbulent airflow of around 1 m/s, with a thin, non-turbulent fog flow as a part of it. The tiny fog particles cannot be felt, and the screen feels just like air to the hand. The fog particles are also dry to touch. The light scattering fog particles serve as a rear-projected screen with the unconventional feature, that the user can unobtrusively interact with the screen, or walk or reach right through it. Created this way, the fog screen is an internal part of the laminar airflow and remains thin, crisp, and turbulent free. (Rakkolainen & Palovuori, 2002; Sand, Rakkolainen, Isokoski, Raisamo, & Palovuori, 2015)

The mid-air screen opens new use cases as it cannot be broken - it recovers automatically and instantly when penetrated. This allows for spectacles, such as driving a car through the display in car shows, entertainment, such as a rollercoaster driving through the screen in amusement parks, and augmented reality with intersecting objects getting augmented information projected around it. It also has advantages over traditional large touchscreens in public spaces, such as shopping malls. It stays clean and hygienic as there is no permanent surface for dirt, bacteria, and viruses to transfer, which can be invaluable in times of global pandemics or local outbreaks. It also enables two-sided content, where the two sides do not interfere with each other (Rakkolainen, 2008a), which can add value in multi-user scenarios.

Fogscreen technology can create screens of different sizes and orientations. A small, hand-held fogscreen, in which the fog moves vertically upwards, was used in Publication I (Sand & Rakkolainen, 2014). A mid-sized desktop version where the fog moves vertically upwards was used in Publication II (Sand, Rakkolainen, Isokoski, Raisamo, et al., 2015), and a large, ceiling-mounted version was used in Publication IV (Sand, Remizova, et al., 2020).

A hand-held fogscreen with extra sensors can track its location in three dimensions. As the display device is relatively lightweight, it can be interacted with by moving the display itself. To demonstrate this, the display was held and swept across mid-air to reveal 2D slices of volumetric data sets, such as magnetic resonance imaging (MRI) or computer tomography (CT) scan datasets in Publication I. Light weight and a novel fogscreen flow construction, which enables to turn the screen to any orientation, allow ease of movement to reveal the desired slices of the volumetric data. Flowing particle screens can also be used for teaching and collaboration as augmented reality displays because they are inherently permeable. This allows for physical objects to share space with the screen surface, that is, they can be placed within or moved through the screen surface and the screen surface can encompass the object. This allows for the physical object of interest to have a tight bond with the augmented information.

Currently, augmented reality is often viewed through a smartphone, a tablet, or a special head-mounted display (see section 2.2). By adding an Arduino board paired with an XBee shield for radio frequency identification (RFID) reading, the display could power any close by passive RFID tags to read their identification codes. This allows for object detection of predefined objects and the creation of augmented information when an object of interest intersects the display surface.

Several kinds of volumetric displays have been reported. These display objects and send light from their actual 3-dimensional position (e.g., Benzie et al., 2007). The most common implementation of a volumetric display produces the images in a confined space with rotating or solid screens (e.g., Favalora, Dorval, Hall, Giovinco, & Napoli, 2001; Jones, McDowall, Yamada, Bolas, & Debevec, 2007; Traub, 1967). The limitation of this approach is that these do not allow for touch or for physical objects to intersect the display volume. Various types of slicing displays (Cassinelli & Ishikawa, 2009; Issartel, Gueniat, & Ammi, 2014; Konieczny, Shimizu, Meyer, & Colucci, 2006; Leung, Lee, Wong, & Chang, 2010; Sullivan, 2003) can be used to view volumetric slices on a movable tablet or diffuse plastic sheet, although in a limited range. However, the solid sheet/tablet may be too cumbersome to use for augmented reality with delicate physical objects, possibly harming them, as proximity with the screen is required. As solid screens cannot intersect with physical objects, unnecessary separation of the physical objects and the related virtual information is formed.

A hand-held fogscreen can be created with ultralight materials, such as carbon fiber, allowing it to be lifted and swiped in the air with ease. The prototype hand-held fogscreen used in Publication I weighs 271 grams, excluding the projector, which is light enough to be accessible, but not light enough for comfortable extended use. This size allows for a display width of 200mm. As gravitation has a non-existing role on the travel of the fog particles, and the device is so light, it can be easily turned into any orientation.

With the addition of hand-tracking, a stationary desktop fogscreen can be used as a mid-air, permeable touchscreen. As physical interaction with a fogscreen has been shown to increase motivation in children (Jumisko-Pyykkö, Weitzel, & Rakkolainen, 2009), its use could be beneficial in education.

Figure 3 illustrates two educational applications created for the desktop fogscreen using hand-tracking for gestural interaction. The figure on the left shows a space-themed math learning application, in which the user explores cartoonish planets that have solutions to simple arithmetic problems presented in the lower part of the screen by breaking them by pushing their finger through them. The figure on the right shows a visualization of an atomic model. The user can rotate and resize the model freely by moving their fingers in front of it.

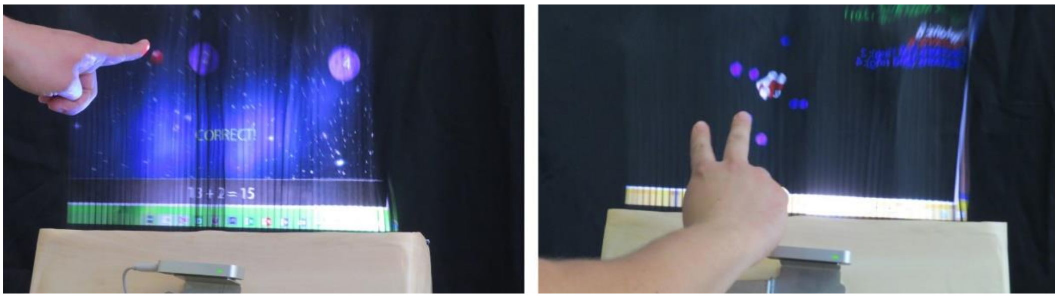


Figure 3. Left: an interactive math learning application on a 17″ desktop fogscreen with hand tracking. Right: an atomic model visualizer with gestural interaction.

Stationary fogscreens with hand tracking seemed like interesting devices, but the lack of tactile feedback when interacting with them seemed like a drawback that could be alleviated. Mid-air tactile feedback was added to a desktop fogscreen in Publication II. Large fogscreens are a good medium for public displays, and also for head-mounted projection displays. However, most current mid-air tactile feedback technologies are designed for smaller screens. A large fogscreen was used with wearable haptics in Publication IV.

Head-mounted projection displays (HMPD) have been presented (e.g., Stanton, 2003) but commonly require retro-reflective materials in the projection surfaces and typically produce images visible only to the wearer of the device. Such a need for preparation of the environment before use limits their applicability. A non-stereoscopic head-mounted pico projector (HMPP) that does not require for retroreflective material to be placed in the environment (Sand & Rakkolainen, 2013) is a fairly little-explored display concept.

A HMPP can be used to project augmented information onto unprepared surfaces in the real world. It cannot be used to create immersive worlds or to block the real world out with projected elements due to the limitations in the amplitude and dimensions of the projected image. It can, however, be used to integrate augmented information with the real world whilst leaving the user's hands-free for interaction with the real world and projected objects. (Palovuori & Rakkolainen, 2018)

The information displayed with a HMPP can be shared with multiple participants. Using a HMPP with a large fogscreen (Rakkolainen, Sand & Palovuori, 2014) allows for multi-user content sharing, where the participants can occupy either side of the screen and move between the sides through the screen without occluding the projection. **Figure 4** shows this in action.

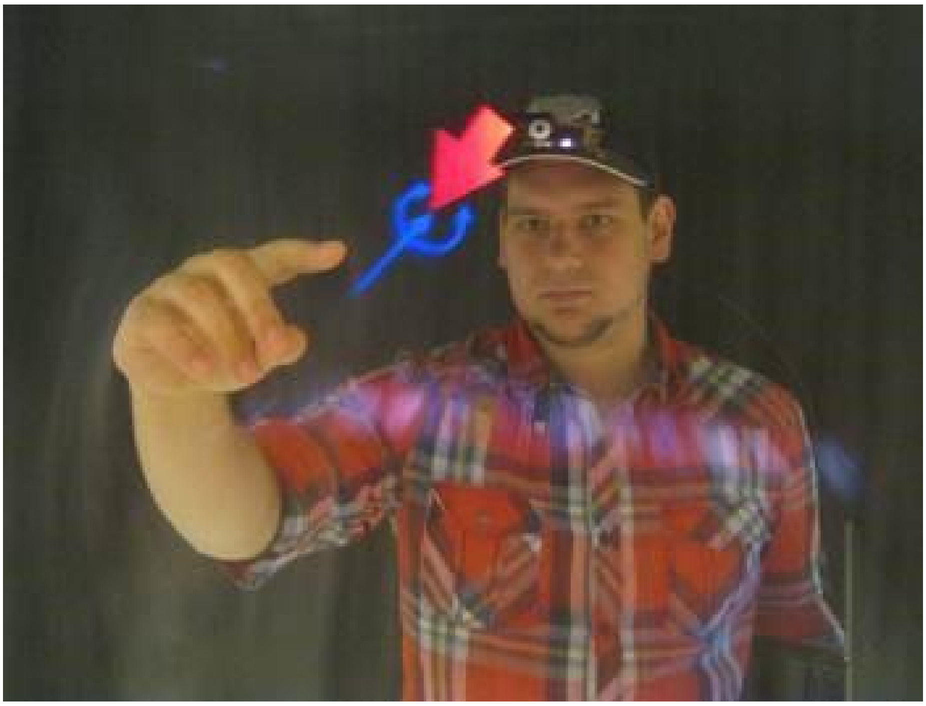


Figure 4. HMPP on a large fogscreen allows for multi-user content sharing without participants obstructing the projection.

Near-to-eye displays, such as virtual reality headsets can be used for a private viewing of virtual information, characteristically involving isolation and exclusion. Mid-air screens and HMPPs, on the other hand, can be used for sharing views with groups and on top of real objects, characterizable by accessibility and inclusion. HMPPs allows for the merging of the virtual and physical worlds. A suitable use case for a HMPP is, for example, a classroom situation, in which the teacher is on the opposite side of the screen than the students. The teacher can share and annotate images on a permeable mid-air particle screen while facing the students. Mid-air projection could be useful for situations that could benefit from information sharing, such as meeting rooms and other social, collaborative, or teamwork situations. Compared to multi-user touchscreens, interactive fogscreens also have the added benefit of remaining hygienic and not being able to transmit bacteria or viruses.

2.2 HEAD-MOUNTED DISPLAYS

Dioramas and stereoscopic image pairs have immersed the general public into scenes since the early 19th century. One of the first examples of the core concepts behind head-mounted displays was presented by Charles Wheatstone in 1838. He used stereoscopic images that were viewable through a device called a stereoscope (See **Figure 5** Left). This rather simple device was placed in front of the eyes of the user, had a slit at the back for a picture card, and a divider in the middle ensuring that each eye only saw one side of the card where two drawings were printed.

Attempts at photography have been made since at least the 11th century, but the first practical photographic process came only after Wheatstone's introduction, so initially, only drawings were used. These drawings were done with a slight offset in perspective to mimic that offset of the human eyes. Seeing these two different two-dimensional drawings, the human brain processed them into a single three-dimensional image. With the slight offset in the images and with each eye only seeing one of them, the users experienced a sense of depth and with it, in other words, experienced *immersion*.

In 1849 David Brewster improved on Wheatstone's contraption by suggesting the use of lenses for uniting the dissimilar pictures, which allowed for a reduction in device size (**Figure 5** Right). This simple device was then refined into the well-known View-Master by William Gruber in 1939 (Kallioniemi, 2018). Simple, low-budget head-mounted displays that use smartphones as their display, such as Google's Cardboard, used this very same design principle almost 200 years after Wheatstone's invention.

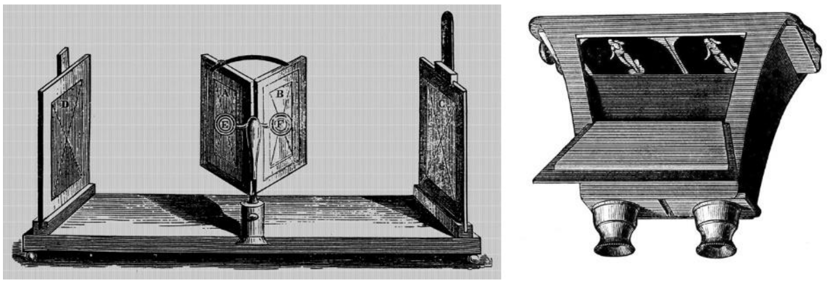


Figure 5. Left: Charles Wheatstone's stereoscope. Right: David Brewster's stereoscope.

One type of head-mounted viewing apparatus was designed during the Great War to safely peer from the trenches over the no man's land. Albert Pratt's design merged the more common periscope with a steel helmet (Pratt, 1915).

The concept of a head-mounted display has been discussed as early as the 1930s. Hugo Gernsback, editor and publisher of the *Amazing Stories*, an American science fiction magazine, had the idea of "teleyeglasses" in 1936. Light-weight television eyeglasses were built around small cathode-ray tubes running on low-voltage current from tiny batteries. Gernsback, the father of the term *science fiction*, had his invention presented in Life magazine feature in July 1963. Gernsback himself is still honored today with the *Hugo* awards for the best science fiction or fantasy work, but his invention was before its time and did not see financial success. Also in the 1930s was Pygmalion's Spectacles, a story by science fiction writer Stanley G. Weinbaum. In the story, a pair of goggles allowed their wearer to experience a fictional world through holographics, smell, taste, and touch.

A head-mounted stereoscopic TV viewer was later patented by cinematographer Morton Heilig. The patent named "Stereoscopic-television apparatus for individual use" (Heilig, 1960) was awarded in 1960.

In 1961 Comeau and Bryan created the first head-mounted display. This *Headsight,* as it was called, had two video screens, as well as a magnetic tracking device, making it also the first head movement tracking device ever created. Headsight allowed the moving of a remote camera, thus letting the user look around dangerous environments without physically being there (Comeau & Bryan, 1961).

The first HMD featuring 3D graphics and head tracking was implemented by Harvard professor Ivan Sutherland in 1968 (Sutherland, 1968). As the contraption was suspended from the ceiling, it was aptly named 'The Sword of Damocles'. It is worth noting that the 3D graphics of that time consisted mostly of wireframe rooms and objects.

Virtual reality, as a concept, not the term, was made known to popular culture perhaps the most by the 1982 movie *Tron*, in which the protagonists were immersed in a fully virtual environment simulating a video game. The term *virtual reality* came later, in 1987 when commercial VR products started emerging. VPL Research introduced the EyePhone, the first-ever commercial HMD in 1989 (Haller, Billinghurst, & Thomas, 2006). Companies, such as Sega and Nintendo, also released their own VR headsets for gaming purposes, but none saw commercial success. This deterred commercial interest for decades. Virtual reality devices disappeared from stores, but academic interest remained. Immersion and the transfer of spatial ability continued to be prominent subjects of research. Recent advances in mobile technology and the increase of computational power and graphical capabilities in home computers and entertainment systems have brought VR back to the mainstream.

Today, head-mounted displays take many shapes. They are often categorized into augmented reality and virtual reality devices. Virtual reality displays transfer the user into a virtual environment, with computer-generated scenery. Recently, as processing power has increased, this can also include cinematic, spherical 360°x180° video, commonly referred to as 360° video. Augmented reality displays, as the name suggests, augment virtual elements to what we see physically. Augmented reality displays can be used to view real objects or places and overlay virtual information, such as navigation directions onto the users' view. Some HMDs can serve both functions. For example, the Varjo XR-1[1] HMD can provide a high-quality stereoscopic video feed of the surroundings onto the display and the level

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[1] https://varjo.com/products/xr-1/

of augmentation can be anything from plain physical surroundings with no artificial objects to completely artificial virtual environments.

While these near-to-eye displays are the most common, an HMD can also be for example an environment tracking projector-based system that detects physical objects and projects the augmentations next to them (Sand & Rakkolainen, 2013). The line between the virtual and physical worlds is also shifting. Remote 360° video can be fed to virtual reality glasses and virtual pointing of objects in the video can be projected back to the physical world (Kangas et al., 2018).

Virtual reality displays are used to display purely virtual environments for the purposes of training and simulation, or entertainment. In training use for highly skilled professionals, virtual reality displays provide numerous advantages. Foremost, training applications can be simulated without exposing these professionals, or the devices they operate, to the harm of real-life consequences of injury or death due to poor performance or mistakes due to low skill levels. Professionals, such as pilots, astronauts, surgeons, and soldiers, can train in simulation safely without worry about their or other participants' well-being. Since knowledge transfers between virtual environments and the real world (e.g., Witmer, Bailey, Knerr, & Parsons, 1996), virtual reality has been used extensively for therapy and simulated training.

Terminologically, *virtual reality* refers to the technology or the building blocks for *virtual environments*, whereas *virtual environments* are three-dimensional spatial representations created with *virtual reality* technology (Kallioniemi, 2018; Mikropoulos & Bellou, 2010). Mikropoulos and Bellou also list immersion, as well as multimodal and intuitive interaction as important characteristics of virtual reality.

Overall, hundreds of commercial and military HMDs, academic prototype devices, and do-it-yourself devices by enthusiasts have been presented in various designs (e.g., Cakmakci & Rolland, 2006; Kress & Starner, 2013). HMDs are currently under intense developments by some of the largest ICT companies, including Microsoft, Facebook, Google, Sony, HTC, and many others.

Field of view (FOV), resolution, latency, weight, and price are among the many important parameters that make a good HMD. Many of these parameters need to be well balanced; for example, wide field of view and resolution are contradictory goals, as wide FOV stretches the available pixels to a wider angle, thus making them more apparent (Rakkolainen, Raisamo, Turk, Höllerer, & Palovuori, 2017).

Usually, these setups include at least sensors to provide the user's head orientation back to the system for virtual camera alteration. Simple, standalone HMDs can consist of only lenses, orientation sensor(s), and housing with straps and can use a mobile phone as the display and processing device. Samsung Gear VR (**Figure 6** Right) and Google's Cardboard were examples of such devices.

The opposite of a standalone HMD uses a dedicated processing machine, such as a personal computer for all the heavy calculations, and includes the display device in the housing, for example, the HTC Vive (**Figure 6** Left). These often also include a head tracking system via separate beacons for location information, allowing the user to traverse in the virtual environment in addition to just looking around stationary. Both types of HMDs usually come with a separate controller or controllers for virtual interaction, but gestural interaction can also be used with special hardware.

While standalone HMDs can be used untethered, the lack of tracking beacons limits the benefits of freedom of movement. Limitations of both computational power and battery capacity can also hinder the experience. Similarly, tethered HMDs have better locational tracking thanks to the separate beacons, but the tethers can limit the benefits of freedom of movement. These, however, are flaws that can relatively easily be remedied with wireless image transfer and wireless peripherals.

Figure 6. Head-mounted displays. On the left is an HTC Vive HMD; on the right is a Samsung Gear VR HMD.

Virtual reality displays have some inherent design challenges. As the display device is very close to the eyes of the user and is enhanced even further with lenses, the display device is required to have a very high resolution to keep the seen image from appearing pixelated. This, in turn, pushes the boundaries of graphical processing power. Technology has however taken rapid leaps forward in this area and modern mobile phones are capable of producing high pixel density images with moderate framerates. Human foveal vision (area of precision) is just a few degrees wide. Moving the gaze can, however, make us perceive it as if it were larger than it is. Most of the time we view towards the front and do not focus on our peripheral vision, so the issue of insufficient resolution can also be remedied by simply having relatively small areas of high resolution, as long as those areas are positioned where we are looking at. The aforementioned Varjo XR-1 achieves human-eye resolution using separate small high-resolution displays at the foveal vision with the larger screen being of lower resolution.

The spatial resolution also tends to be limited in comparison to the natural stereoscopic FOV of about 120 degrees. Current popular HMDs have limited fields of view, for example, Oculus Rift ~80°x90° (horizontal x vertical), HTC Vive ~100°x110°, and Microsoft Hololens ~30°x17° (Rakkolainen et al., 2017).

Another inherent challenge with virtual objects is that they are intangible and cannot provide natural haptic feedback. While grabbing a virtual stone, the visual feedback can mimic a hand holding a stone, but nothing stops the user from making a fist and feeling that the hand is still empty. Similarly, touching any surface may seem to stop the virtual hands' movement, but kinesthesia and proprioception tell us that something is wrong.

Usually, when designing virtual reality content, immersion is more important than reality. The virtual world can differ greatly from the real world. There is no need for the same laws of physics to apply or for recognizable environments, but for the user to truly feel like being in the virtual world, immersion is vital. Many aspects of the design can affect immersion, but for the scope of this dissertation, the focus will be on the inherent lack of haptic feedback.

While using a near-to-eye display and interacting with virtual objects, often only vision- or audio-based affirmation for the interaction is provided. This can be remedied with the use of data gloves or wearable haptics hardware that can provide tangible sensations, but often these solutions are tethered or obtrusive. The lack of tangible elements in feedback when interacting with virtual objects can feel unreal, thus breaking the immersion, or can lead to uncertainty about whether the action was registered. For example, when pressing a button, the user might be left wondering if the finger was pushed far enough, or were they just waving their hand in front of it, not quite connecting with the gesture. Tactile feedback can make the experience feel more natural, immersive, and reassure the user that a selection was indeed made.

Mid-air haptic devices can create the sensation of touch at distance without actually touching any tangible surface or wearing any devices on one's person. They can help bring tactile interaction to virtual interfaces. One such device is an ultrasonic tactile actuator that can incur vibration with modulated waves of ultrasound. Such a device can be fitted on the front of an HMD (See **Figure 7**) to allow for mid-air haptic feedback to be provided on the users' hands (Sand, Rakkolainen, Isokoski, Kangas, et al., 2015).

Figure 7. An ultrasonic mid-air haptics device attached to a head-mounted display always keeps the feedback oriented to facing direction. The hand tracking sensor on top of the matrix allows the focal point to be directed at the fingertip.

2.3 TACTILE DISPLAYS

A device presenting tactile information can be called a tactile display. A tactile display is a human-computer interface that can as closely as possible mimic the tactile parameters of an object (Chouvardas, Miliou, & Hatalis, 2008). Today, many devices incorporate some form of a tactile display from mobile phones to smartwatches to game controllers in addition, or instead of, visual or auditory feedback. They originate from a device that translated speech into touch sensations for people with hearing impairments (Gault, 1925, 1927). Traditionally, people with visual or hearing impairments have been a significant user group for tactile displays (Kaczmarek & Bach-Y-Rita, 1995) with Braille being probably the most widely-known form of encoding information into touch (See **Figure 8**). While tactile displays can be used to present information encoded as Braille (e.g., Rantala et al., 2009), other codecs can also be used.

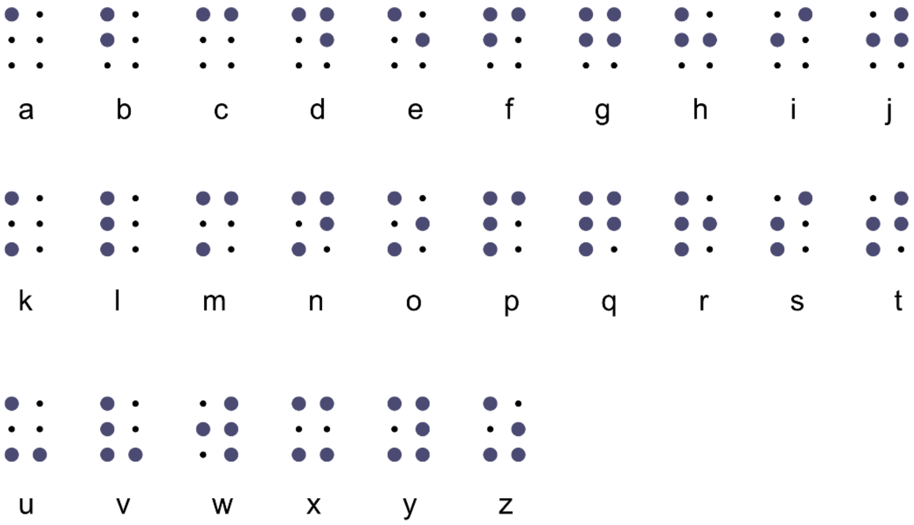


Figure 8. Braille is a form of tactile communication.

The first tactile language, *Vibratese,* consisting of 45 variations of amplitude, duration, and location, was presented by Geldard in 1957 (Geldard, 1957). Since then, tactile displays have been employed in, for example, navigation, notifications, and action feedback (Jones & Sarter, 2008), interpersonal communication (Huisman, Darriba Frederiks, Van Dijk, Hevlen, & Krose, 2013), rehabilitation after a physical trauma (Kapur et al., 2009), and education for the impaired (Toennies, Burgner, Withrow, & Webster, 2011).

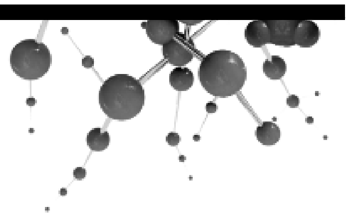
Research around tactile information presentation has experienced a surge driven by both need and opportunity. Users in work domains facing visual and auditory data overload need increasing amounts of complex data presented via tactile displays. And users of virtual environments want immersion. The opportunity emerged from tactile displays becoming less intrusive, more sophisticated, effective, and acceptable to users (Jones & Sarter, 2008).

Tactile sensations, tactile feedback, and tactile devices will be covered in more detail in chapters 3 and 4. In the experiments introduced in this thesis, tactile displays were supporting feedback methods in experiments 2 – 4, while experiment 5 used a tactile display as the only method of presenting information to the user.

2.4 SUMMARY

This Chapter introduced the evolution and previous research on permeable particle screens and head-mounted displays. Flowing light-scattering particle screens could be useful when it is required or convenient for the display surface to be present only sporadically. Particle screens could also be used as extensions to other displays when more screen real estate is occasionally needed, like with household appliances. Attaching hand or gesture tracking to particle screens turns them into gesturally interactive displays. Further, wearable or mid-air tactile actuation can help mitigate their inherent lack of tactile feedback. Large walk-through screens could make engaging public displays and their inability to transfer dirt, bacteria, or viruses make them hygienic and ideal in times of epidemics. This makes them also ideal for places with strict hygienic needs, such as operating rooms in hospitals, and places where hands tend to be dirty, such as factories or bakeries. Some small, hand-held particle screens can be viewed in any orientation.

Head-mounted displays can be used in training, simulation, treatment, education, and entertainment. Virtual reality glasses are a type of HMD and can isolate and immerse their wearer. Virtual reality HMDs can support embodied interaction with hand-tracking devices. Using one's hands to interact with virtual environments can be immersive, but the lack of cutaneous stimulation is not. Technology can be used to mediate artificial touch sensations by stimulating the human sensory system.



3 Sense of Touch

The human sense of touch has several functions. It provides us with information about physical objects that we are in contact with. It also provides us information about ambient conditions, such as wind, temperature, and humidity. Our sense of touch serves as a means to experience, explore, and interact with our surroundings.

The human mechanism to react to tactile stimulation is among the first to develop. This can be seen as the palmar grasp reflex of a fetus (Jakobovits, 2009). The skin is our largest sensory organ and also the first sense organ to develop. The fetus, while suspended in amniotic fluid, receives tactile stimulation through the mother's abdominal wall (Field, 2001). Later, the caregiving touch is essential for growth and development and calms infants in pain and discomfort (Bellieni et al., 2007). The importance of the sense of touch can also be seen as the ability to respond to tactile stimulation even when the person is unresponsive to other external events like visual and auditory stimulations (Dolce & Sazbon, 2002). Touch has positive physiological and biochemical effects, such as decrease in blood pressure, heart rate, and cortisol (stress hormone) levels, as well as increased oxytocin ("love hormone") levels (Heinrichs, Baumgartner, Kirschbaum, & Ehlert, 2003; Henricson, Berglund, Määttä, Ekman, & Segesten, 2008).

So, the sense of touch is an important part of our interaction with people and objects. Our ability to explore contours, textures, shapes, and densities in nature with the sense of touch can also be utilized in human-technology interaction with the use of actuators that stimulate our somatosensory nervous system.

3.1 SOMATOSENSORY NERVOUS SYSTEM

The somatosensory nervous system is centrally the basis of the sense of touch. It provides sensations from the peripheral and inner parts of the body. This system is divided into several sub-modalities. These sub-modalities allow us to distinguish shapes, weights, and textures of objects, feel pressure, vibrations, temperature, pain, and the position and movement of body parts (Kalat, 1998).

In the context of HTI, the term *haptics* is often used to mean somatosensory sub-modalities. These modalities are further divided into kinesthesia (i.e., sensation or perception of motion), proprioception (i.e., the perception of the position and posture of the body), and cutaneous (i.e., stimulations of the skin) perception (van Erp et al., 2010). By definition, haptics refers to *the sensory and motor activity based on the skin, muscles, joints, and tendons* (ISO 9241-910, 2009), so it includes kinesthesia and proprioception, as well as the many cutaneous perception sub-modalities. **Figure 9** illustrates these somatosensory sub-modalities.

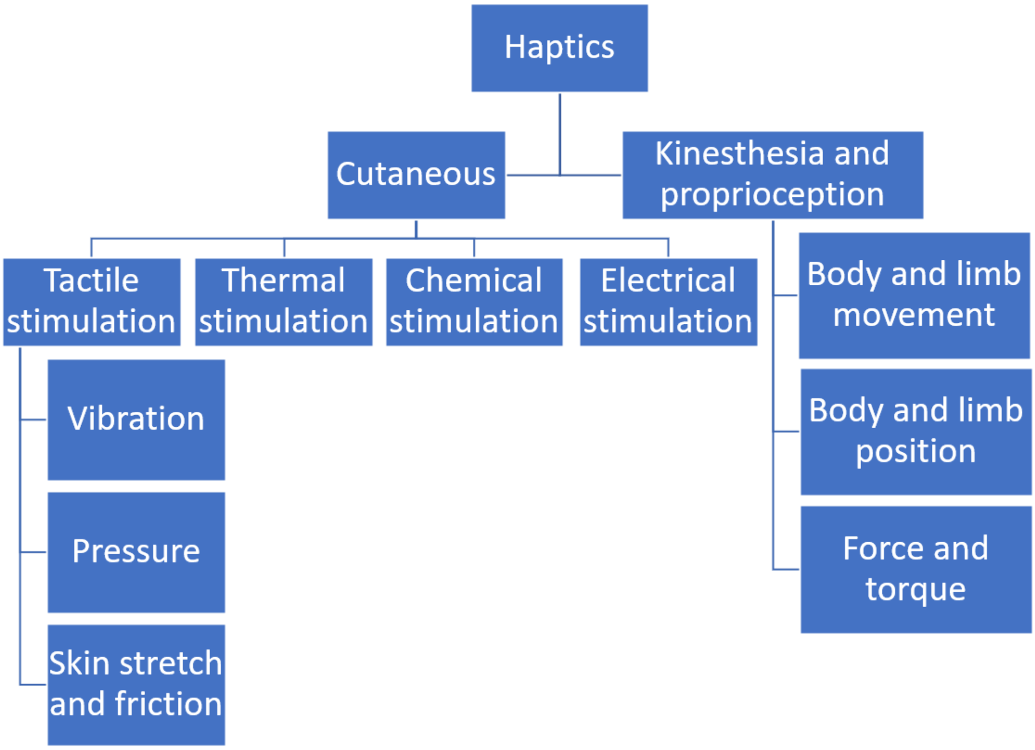


Figure 9. The main components of the haptic sensation (excluding pain). Adapted and redrawn from van Erp et al. (2010) and Goldstein (1999).

Inputs for kinesthesia and proprioception mainly come from within our bodies. These inputs are the result of movement, position, and force dynamics of muscles, tendons, and joints. Cutaneous perception, on the other hand, responds to external stimuli presented on the skin surface. In the context of HTI, example input for kinesthesia and proprioception could be a force feedback steering wheel that transmits torques to gamer’s hands.

An example of cutaneous input could be simply the vibration alarm of a mobile phone.

The human haptic system reacts to haptic stimuli. Cutaneous perception employs several sensory neurons that respond to, for example, varying temperatures (thermoreceptors), changes in spatial parameters of limbs and other body parts (proprioceptors), potentially damaging stimuli (nociceptors), and mechanical forces (mechanoreceptors).

3.2 MECHANORECEPTORS

Skin is our biggest sensory organ at around 2 m^2 in an average adult male. Anatomically it is divided into three layers. The outermost of the three layers is the *epidermis* followed by the *dermis* and *hypodermis*. Each layer contains cutaneous sensory receptors, such as free nerve endings, but also four main types of touch-sensitive receptors, *mechanoreceptors*, each specialized to respond to different types of mechanical stimulations. Mechanoreceptors and their location in the epidermis, dermis, and hypodermis are illustrated in **Figure 10**.

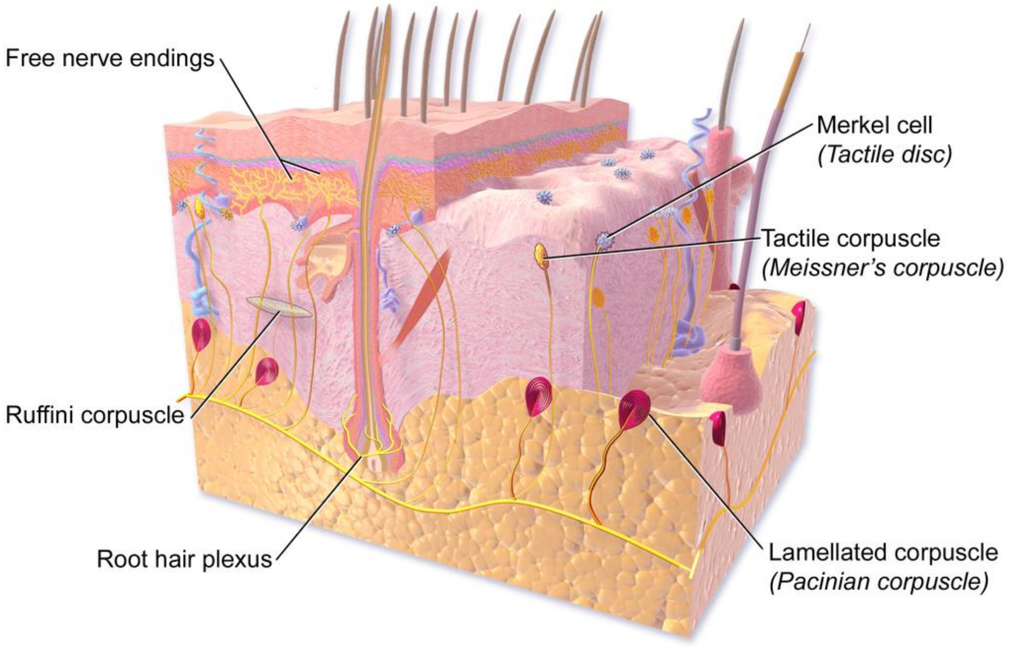


Figure 10. Mechanoreceptors in epidermis, dermis, and hypodermis. Blausen.com staff (2014). "Medical gallery of Blausen Medical 2014". WikiJournal of Medicine 1 (2). DOI:10.15347/wjm/2014.010. ISSN 2002-4436. CC BY 3.0.

Merkel receptors are located on the border of dermis and epidermis and are specialized to respond to pressure. Nerve fibers associated with Merkel receptors fire continuously, as long as the stimulus is on. For this, they are called slowly adapting (SA) fibers. Merkel receptors can be used to explore shapes, as well as fine details and texture. As SA fibers fire continuously, we can, for example, press our finger against a spherical object and perceive its curvature as the number of Merkel receptors activating.

Meissner's corpuscles are located in the dermal ridges and are specialized to respond to low-frequency vibration of around 50 Hz. Nerve fibers associated with Meissner's corpuscles fire to onset and offset of the stimulus. For this, they are called rapidly adapting (RA) fibers. They can be used to perceive motion across the skin and in handgrip control.

Ruffini endings are located in the dermis and are specialized to respond to skin stretch. Nerve fibers associated with them are slowly adapting, so they fire to continuous stimulus.

Pacinian corpuscles are the deepest located mechanoreceptors in the hypodermis layer and are specialized to respond to vibrations around 10 - 500 Hz (Goldstein, 1999). The nerve fibers associated with them are rapidly adapting, making them fire to the onset and offset of the stimulation. Pacinian corpuscles can also be used to percept fine texture by moving the fingers on a surface.

Pacinian corpuscles and Meissner's corpuscles are especially important for sensing vibrations (Gallace & Spence, 2014), which is the most common way of providing haptic feedback in human-technology interaction. However, the perception of tactile stimuli often involves the coordinated activity of different types of neurons working together (Goldstein, 1999). **Table 1** summarizes the key features of the four mechanoreceptors.

Receptor	Skin type	Responds to	Receptive field	Location in skin
Merkel receptors	Glabrous and hairy skin	Pressure	Small	Border of dermis and epidermis
Ruffini endings	Glabrous and hairy skin	Stretch	Large	Dermis
Meissner's corpuscles	Glabrous skin	Stroke and flutter, vibration (50 Hz)	Small	Dermal ridges
Pacinian corpuscles	Glabrous and hairy skin	Vibration (10-500 Hz)	Large	Hypodermis

Table 1. The general mechanoreceptor types and their main characteristics. Adapted from Kalat (1998) and Vallbo and Johansson (1984).

Mechanoreceptors differ from each other with respect to the size of a receptive field on the skin surface. A cutaneous receptive field is the area of skin which, when stimulated, influences the firing of the neuron (Goldstein, 1999). The Merkel receptor and the Meissner's corpuscle are located close to the surface of the skin, near the epidermis, and therefore have small receptive fields, whereas the Ruffini endings and Pacinian corpuscles are located deeper in the skin and have larger receptive fields. Smaller receptive fields result in better spatial resolution than larger receptive fields. Because of this, a vibrating stimulus cannot be perceived with as much spatial resolution as, for example, a poking needle.

Upon detecting a stimulus exceeding the sensory threshold, nerve fibers are used by the sensory nervous system to transfer information from the receptors to the brain (See **Figure 11**). These nerve fibers conduct the neural stimuli through three pathways: the medial lemniscus in the spinal cord, the anterolateral system, and the somatosensory pathways to the cerebellum (Gallace & Spence, 2014). Of these, the medial lemniscus transfers tactile, vibratory, and proprioceptive information. Ultimately these are projected onto different parts of the somatosensory cortex for further processing. (Goldstein, 1999).

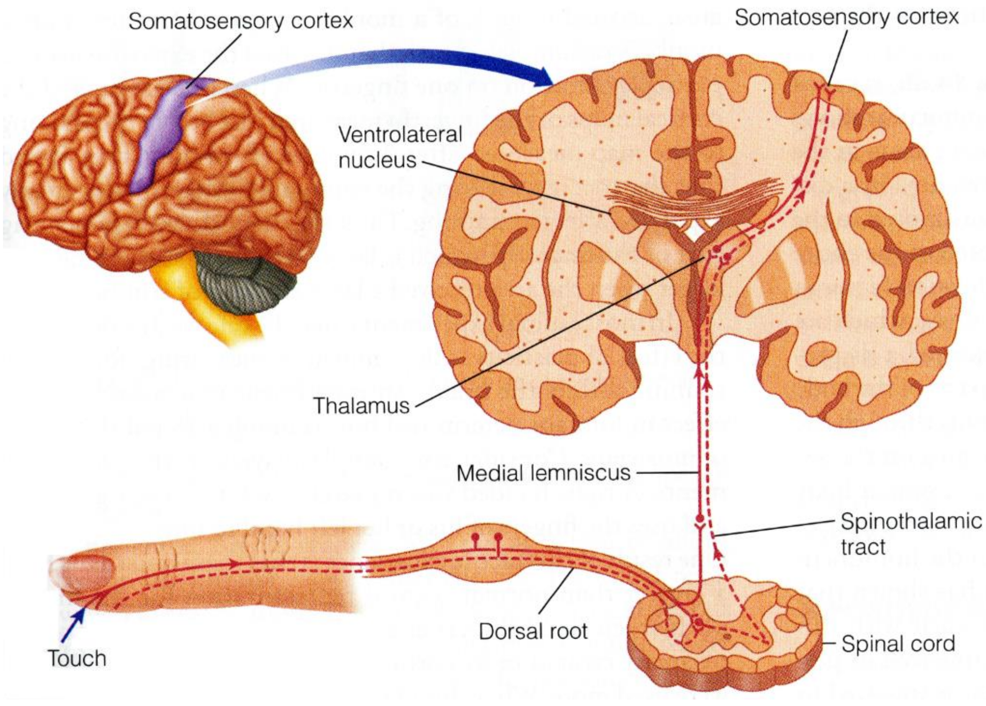


Figure 11. The pathway from receptors in the skin to the somatosensory receiving area of the cortex. Cengage Learning Inc. Reproduced by permission. www.cengage.com/permissions

Due to the structure and properties of the mechanoreceptors, their capability to sample various tactile information differs. To create meaningful tactile sensations, artificially applied physical signals need to be optimized in such a way that they can be effectively absorbed by the receiving mechanism. Physical parameters of the applied haptic signal must remain within the bandwidth of absorption of the receptors. For example, the Pacinian corpuscles are sensitive only to a certain range of vibration frequencies, thus limiting the use of vibration frequency as a haptic signal parameter. Further, mechanoreceptors exist in different densities in different parts of the body, limiting the use of spatial location as a parameter. Finally, the type of skin has a role in stimulation perception. A great majority of the skin on a human body contains hair follicles. In these areas of the skin, hair follicle receptors respond to the movement of body hair. Most mammals, to varying degrees, also have some skin areas without natural hair, called glabrous skin. On the human body, glabrous skin is found on the ventral portion of the fingers, palms, soles of feet, lips, etc. (Freberg, 2010). Glabrous skin is more sensitive to tactile stimulation without the dampening effect of hair follicles, although the hair follicle receptors can also be used to mediate tactile stimuli. This limits further the use of spatial location as a haptic signal parameter with the most common actuation technologies.

The main sensory organs for the other senses, vision, hearing, olfaction, and taste are localized in one area (head) and are all close to the brain. In contrast, tactile receptors are distributed all over the body. Following this, cutaneous signals can take considerably more transmission time than, for example, perception of auditory signals. For example, the transmission time of the stimulus from a toe to the brain takes approximately 35 milliseconds, but only about 5 milliseconds from the nose to the brain (Vroomen & Keetels, 2010). Also, touch perception is interpreted for its semantic meaning based on the interpretation context (Nukarinen, 2019). This can happen either consciously or subconsciously, ultimately leading to positive or negative emotions, action or inhibition of action, or indifference. Most of the processing taking place in the somatosensory system happens subconsciously employing the innate and previously learned skills and knowledge (Naumann et al., 2007), since while the somatosensory system can transfer approximately one million bits per second, we can consciously process this data around five bits per second (Zimmermann, 1989). In conclusion, many things affect how we perceive tactile stimuli. Cultural backgrounds (San Roque et al., 2015), age (Verrillo, 1979; Wickremaratchi & Llewelyn, 2006), and gender (Karuei et al., 2011; Neely & Burström, 2006) can all affect how we perceive haptic interaction. The sense of touch can also be temporarily or permanently lost.

Overall, the inclusion of haptic feedback has been shown by meta-analyses to improve human performance in many types of environments. (Burke et al., 2006; Prewett, Elliott, Walvoord, & Coovert, 2012).

3.3 VIBROTACTILE FEEDBACK

There are many ways to induce tactile sensations through technology. Vibrotactile actuation has been the most frequently used technology to enable technology-mediated tactile stimulation. There are certain advantages in choosing vibration over pressure or skin stretch, one of them being the fact that vibrations can be generated with very simple low powered mechanical actuators. These require only simple electronics and hence can be made to be reliable and portable, and are cheap.

Vibrotactile feedback has been researched as a viable method of stimulating encoded information since the late 1970s (Rothenberg, Verrillo, Zahorian, Brachman, & Bolanowski, 1977; Sherrick, 1985). In the 1990s, the general public was introduced to vibration technology through pager devices. We are accustomed to vibrotactile feedback when using our smartphones, but its application in mobile devices was not very popular until the early 2000s. Vibrotactile feedback was used primarily to engage the user's visual attention. It was only when mobile phones had transitioned far enough into pocket PC territory that feedback modalities had to be rethought. As input and output had taken a more general role, number keys were replaced by touchscreen keyboards, and the inherent tactile sensation was replaced by the solid, featureless glass, creating the need for technology-generated haptics.

Still, vibrotactile feedback has remained surprisingly simple amidst other technological evolutions. A state-of-the-art smartphone might still only have a single vibration motor. And this motor will vibrate the entire device, not just the point of contact. Since devices rarely take into account the materials that the haptic signal is mediated through, the signal that reaches the skin contact is rarely the signal that was technically originated.

When interacting with technology, we typically employ visual, auditory, and haptic modalities. When selecting UI elements on a mobile device, we use visual modality to guide our fingers onto the target elements. Kinesthetic modality aids our visual modality in providing information on how far we need to extrude our finger and tactile modality confirms that the finger is touching the screen. The UI can then further inform us that the selection has been registered via visual, auditory, and/or vibrotactile feedback. When typing on a mobile device's virtual keyboard, visual, auditory, and vibrotactile feedback are commonly combined to mimic the functionality of a traditional keyboard. Studies have found that incorporating vibrotactile feedback to touchscreen improves the typing speed, accuracy, and the subjective experience of the user (e.g., Fukumoto & Sugimura, 2001; Hoggan, Brewster, & Johnston, 2008).

Tactile feedback can support auditory and visual feedback, but it can also, to some extent, substitute them. Vision can be overloaded in very bright conditions and audio can be muffled in very noisy environments. The use of audio may also be distracting in many delicate social settings. People may also have sensory deficits rendering vision or hearing not suitable for information delivery. Vibrotactile technology has been used for deaf and hard of hearing people for decades before the use of digitized vibrotactile stimulation for interaction purposes.

Haptic sensations are commonly induced in direct skin contact with actuators based on static pressure, skin stretch, friction (Choi & Kuchenbecker, 2013), electrical muscle stimulation (Farbiz, Yu, Manders, & Ahmad, 2007; Lopes, You, Cheng, Marwecki, & Baudisch, 2017), or vibration. These are often called wearable tactile actuators, as they need to have the actuator in direct skin contact with the user. Another approach is delivering haptic sensations without direct skin contact, in mid-air, using, for example, air pressure, or ultrasonic vibrations.

3.4 CONVEYING INFORMATION WITH VIBROTACTILE FEEDBACK

When transferring information, there usually happens a process of encoding and decoding. A simple example is a vibration alert on a mobile phone. The information of "notice, something took place" is encoded as a short burst of vibration that activates mechanoreceptors, makes its way through neural pathways, arrives in different parts of the somatosensory cortex where it is decoded and interpreted.

This example of a vibration alert is simple in the extent of its information content. The same haptic pattern can have multiple information contents. It can be a notification of an email arriving. Or it can be a notification, that you have reached a corner where you need to turn to another direction while navigating. The context can give meaning to the encoded information, while in this example, it could have just as well been an incoming email. Some other systems, a sports watch, for example, can encode information such as "you have reached your optimal heartbeat rate for this exercise", or "you need to slow down", or "you need to speed up" as different, distinctive haptic patterns (Lylykangas et al., 2009). This can be seen as the level of expressiveness of an information conveying system, or as the size of their lexicon.

When designing vibrotactile feedback, we must take into account the type of information that the human nervous system can process effectively. To mediate meaningful vibrotactile information, we must consider different parameters for its encoding. The most common stimulus parameters used to encode vibrotactile information include waveform, frequency, amplitude, location, duration, and rhythm (e.g., Cheung, van Erp, & Cholewiak, 2008; Jones & Sarter, 2008). To be able to create stimuli that has varying information content, alteration of at least one of these parameters is often necessary.

Waveform represents the shape of the signal. This can be for example a sine wave, a square wave, or a sawtooth wave. A sine wave is a common choice as most actuators can produce it. Altering the shape of the signal can affect the perceived roughness of the stimulus (Brown, Brewster, & Purchase, 2005).

Frequency is the number of times a waveform signal repeats per unit of time. Frequency can be altered to produce different sensations and to activate different receptors. The range of the skin's vibrotactile frequency response if roughly 20 – 1000 Hz, but sensitivity changes based on frequency, with maximal sensitivity occurring around 200 – 250 Hz (e.g., Gunther & O'Modhrain, 2003) where it stimulates mainly the Pacinian corpuscles. The skin is relatively poor at frequency discrimination with ranges broadly divided into 8 to 10 discrete steps perceptible over a range of 70 to 800 Hz, with just 3 - 5 of them being reliably differentiated (Sherrick, 1985). Frequencies of 100 to 300 Hz are commonly described as smooth vibration (Tan, Durlach, Reed, & Rabinowitz, 1999) and are considered as optimal for all body locations by many researchers (Jones & Sarter, 2008). Further, it is found that the human sense of touch in fingers and palms is the most sensitive to the vibration of 150 – 250 Hz (Ryu & Jonghyun, 2010).

Amplitude refers to the magnitude or intensity of the vibration. It defines the strength of the waveform signal and is often measured in either volts or decibels. The range of stimulus values for this parameter should be kept between the detection threshold and the pain threshold for most use cases. The shape, frequency, and amplitude of the stimulus are known as spectral parameters.

As for location, the fingers, the palm, and the facial area are particularly sensitive to tactile stimulation (Weinstein, 1968). These areas are covered with glabrous skin or have relatively small hair follicles, thus not obstructing the stimulus. The same intensity of stimulus applied to different spatial locations creates sensations that are perceived differently (Jones & Sarter, 2008). Still, it must be noted that the location of the actuator on the skin does not precisely dictate the location of the stimulus, as the stimulus can travel for many centimeters as circular waves (Cholewiak, Brill, & Schwab, 2004).

Finally, the temporal parameters, duration and rhythm. Duration has relatively distant bounds of acceptable values as the skin is sensitive to detecting even very brief stimuli. Vibrotactile feedback with a duration of only 20 milliseconds has been successfully used (Kangas et al., 2014). As discussed previously, there is an upper limit to duration however, as the potential amount of information transferred decreases as the stimulus duration increases (Nukarinen, 2019). In addition to this, people have perceived durations of over 200 milliseconds as annoying when used in event notifications (Kaaresoja & Linjama, 2015).

In comparison to other stimulus parameters, rhythm enables encoding more information. This is due to humans having high discrimination and recognition abilities. Humans can distinguish time gaps of only five milliseconds in successive pulses (Gescheider, Wright, & Verrillo, 2008), making the temporal sensitivity to touch worse than that for hearing (0.01ms), but better than that for vision (25ms) (Jones & Lederman, 2007). This allows for the encoding of relatively large amounts of information with rhythmic on/off pulses. Further, as the stimulus duration increases, it becomes easier to identify differences in tactile rhythm patterns (Nukarinen, 2019).

Spectral and temporal parameters can be used to create *tactons* (Brewster & Brown, 2004) or tactile icons. They are structured, abstract messages that can be used to communicate complex concepts to users non-visually via the sense of touch. Tactons can be used to represent complex interface concepts, objects, and actions concisely. The idea follows Shneiderman's (1987) definition of an icon being "an image, picture or symbol representing a concept". An icon can convey complex information in a very small amount of screen space, much smaller than its written counterpart. Presenting information in speech or text is slow because of their serial nature – to assimilate information many words may have to be comprehended before the message can be understood (Brewster & Brown, 2004). Icons can share the same message more rapidly. A similar comparison can be made between Braille and tactons. A high-frequency, intensifying pulse could represent a 'Create' command, and a lower frequency pulse that decreases in intensity could represent a 'Delete' command. The mapping is abstract as there is no intuitive link between the stimulus and concept it represents (Brewster & Brown, 2004).

Another dimension in which tactile stimulation has been studied relates to emotional experiences evoked by tactile stimulations. There is some evidence that through varying different parameters of haptic stimulations also emotion-related responses can be evoked. Arousal, valence, dominance, happiness, sadness, anger, and fear can be effectively communicated through haptic stimulation by altering the stimulus parameters (Eid & Al Osman, 2016; Obrist, Subramanian, Gatti, Long, & Carter, 2015; Salminen et al., 2008, 2009). For example, continuous forward-backward rotating stimuli were rated as significantly more unpleasant than discontinuous forward rotation (Salminen et al., 2008). The other way around, there is also evidence that technology-mediated haptics can also modify the receiving participants' emotional state (Gatti, Caruso, Bordegoni, & Spence, 2013).

One limitation that all vibrotactile actuators share is that a single wearable actuator usually has a fixed location on the body. It can be attached to the user's finger, worn as a ring or a bracelet, or embedded in eyewear, for example. Hence, multiple feedback locations usually require multiple actuators at fixed locations.

Ultrasonic phased arrays can circumvent this limitation to a degree. They focus acoustic pressure to points in space (known as focal points), in which the pressure can slightly deflect human skin and induce tactile sensation (Frier et al., 2018). The location of the focal point can be updated rapidly. This enables multiple feedback locations with a single actuation device.

With ultrasonic phased arrays, a cluster of focal points can also be created to render patterns or volumetric shapes (Frier et al., 2018). The use of multiple simultaneous focal points, however, means that the acoustic power produced by the device is divided between them. Following this, each focal point becomes weaker, and ultimately focal points can no longer be perceived. Spatiotemporal modulation has been used to remedy this issue (Frier et al., 2018). It updates the position of a single focal point rapidly and repeatedly, thus creating a sensation of a pattern, while the ultrasound output intensity remains at its maximum (Frier et al., 2018). The temporal resolution of perception is relatively low; the exact value may range from 2ms to 40ms (Loomis, 1981), allowing the focal point to complete its trajectory faster than the temporal resolution and allowing the user to perceive the resulting stimulation as a single tactile pattern rather than a succession of tactile points (Sand, Rakkolainen, Surakka, Raisamo, & Brewster, 2020). Rendering tactile patterns and volumetric shapes is another way to encode information into haptic feedback.

For tactile information encoding to be a viable communication method, the sensations need to be differentiable. If we wish to communicate something, we need to use suitable vocabulary to do so. Similarly, tactile communication can fail if the meaning of the messages is confused. Altering the stimulus parameters slightly can create a vast vocabulary, but if the user can not differentiate between the tactons, the language loses its power to express semantic meaning.

A common strategy in conveying information with vibrotactile feedback has been to design a group of unique vibration patters that are within human skin sensitivity and are easily distinguished from each other. Certain information is then assigned to each of them and once the receiver detects and identifies them, they can then decode the vibration pattern to receive the information. When the user has a chance to concentrate on the sensation and the vocabulary is small enough to be manageable, this approach can be very useful for information transfer (Tan, Reed, & Durlach, 2010).

While these made up patterns work well when dealing with abstract questions (what does it feel like to receive a text message?), virtual environments can take a different approach. For example, when touching a virtual rock surface, it is appropriate that the vibrotactile feedback tries to mimic a physical rock surface. This process of mimicking physical touch sensations aims at inducing haptic imagination (Loomis & Lederman, 1986). Since the user might already be immersed in the virtual environment through visual and auditory senses, even partial tactile information related to the environment can induce powerful haptic imagination (Intraub, Morelli, & Gagnier, 2015; Lacey & Lawson, 2014).

The semantic meaning of tactile stimuli is a little-explored domain. There might not be many inherent interpersonal semantic associations to tactile stimuli. It has, however, been shown, that communicating through mid-air haptics is not entirely arbitrary and that people can express and recognize tactile stimulation to convey emotional meanings (Obrist et al., 2015).

Rutten *et al.* (2019) have experimented with how identifiable mid-air haptic shapes are and found out that there might not be much of a learning effect, that is, the participants were as accurate at identifying different mid-air haptic shapes the first time they felt them, as they were the fifth time they felt them. They also found out that the age of the participants had a strong negative correlation to the proportion of correct identifications. The performance of male and female participants was equal. It was also shown that it was significantly easier to identify shapes like horizontal and vertical lines than it was to identify shapes such as circle and square.

3.5 SUMMARY

This Chapter presented theoretical perspectives into touch perception. It introduced various mechanoreceptors and gave an overview of the human somatosensory system. A special focus was given to cutaneous receptors and especially the Pacinian corpuscles, as these are the receptors most targeted by many common tactile feedback methods. While tactile sensations can be created with many different devices and through many different receptors, it is often done with simple vibrating actuators more described in the next chapter.

To stimulate the Pacinian corpuscles, a vibration of 200 Hz is a suitable frequency. In addition to this, the stimulus must be modulated so that the receptors do not get desensitized to it. Different waveforms, breaks, or spatial movement can be used to keep the stimulation up. Tactile icons, tactons, can be formed by altering these parameters.

Tactile sensations are also linked to our emotions. Some stimuli can be annoying, while others can convey feelings of, for example, anger, joy, or fear. When designing tactile stimulations, subjective ratings, such as arousal, valence, and dominance can be considered. Also, our ability to discriminate between stimuli is limited. It can be important to design stimuli in such a way that important and insignificant information encoded into tactile sensations feel distinctively different.

Finally, it is important to note, that previous experiences, other senses, conscious and subconscious processing, physical properties, such as age and gender, as well as the situation and our emotions, can all have a part in how we perceive a touch.

The next chapter will introduce different devices for producing technology-mediated haptic feedback from applying torque to wearable actuators to methods of producing haptic sensations in mid-air.

4 Technology-Mediated Haptic Feedback

This Chapter provides an overview of the different types of technology-mediated haptic feedback used in the studies of this dissertation, as well as an overview of a selected list of haptic and vibrotactile feedback devices. While many technologies exist for creating and mediating haptic sensations, this thesis will focus on kinesthetic haptic feedback devices, cutaneous vibrotactile actuators, and cutaneous ultrasonic mid-air haptics.

4.1 HAPTIC FEEDBACK DEVICES

Haptic feedback devices discussed in this subsection fall into the category of kinesthetic feedback. These devices can exert force and torque onto the users' limbs, traditionally on the hands and arms. Other devices can act as resistors to the forces extruded by the user to give the illusion of virtual surfaces. Commonly these devices require the user to hold on to some part that mediates forces created via motors.

A common example of the first type of haptic feedback device is a force feedback gaming controller such as a steering wheel for driving simulators or a joystick for flight simulators. The motors can be programmatically activated to exert forces onto the user's hands. The devices are commonly fastened to a surface via clamps or suction cups to allow for torque transfer. Another common category is a haptic feedback device like a 3D Systems Touch X device[2] (See **Figure 12**). These can be used to explore virtual surface textures and material properties when designing new hardware.

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[2] https://www.3dsystems.com/haptics-devices/touch-x

For example, an automotive gear shift lever can be modeled, and the engineers and designers can experience its use before manufacturing it to gain insight beforehand on how it would feel to operate. These devices use motors to resist the forces extruded by the user to give the illusion of surface density.

Figure 12. A 3D Systems Touch X haptic device.

4.2 WEARABLE VIBROTACTILE ACTUATOR TECHNOLOGIES

Most consumer technologies that offer technology-mediated tactile stimuli utilize vibration stimulations. Vibration technology is affordable and technically simple to implement. Vibrotactile actuators most commonly fall into three main categories, eccentric rotating mass motors (ERM), linear resonant actuators (LRA), and piezoelectric actuators.

Probably the earliest technology used to generate vibrational stimulation for information delivery is the eccentric rotating mass actuator. Its components and its operating idea are simple. A direct current motor is attached to a shaft which in turn is attached to an eccentric, unbalanced weight. These parts are illustrated in **Figure 13**. As the motor turns, the unbalanced mass moves and generates vibration much like an unbalanced load on a washing machine. This somewhat crude design is simple to construct thus making it inexpensive. Operating such an actuator is also simple as one can simply adjust the voltage given to the motor. It does, however, have a significant downside due to its construct. A motor requires time to accelerate and to decelerate, thus making it less than precise as to when the actuation starts and stops (Choi & Kuchenbecker, 2013). Further, the frequency and amplitude of the stimulation usually go hand in hand, making it impossible to control these parameters individually in ERMs unlike with LRAs (Jones & Sarter, 2008). And as with most mechanically moving parts, it generates some noise and heat limiting its use to some extent. In many use-cases these flaws can be tolerated, making the ERMs widely used in devices like mobile phones and vibrating video game controllers.

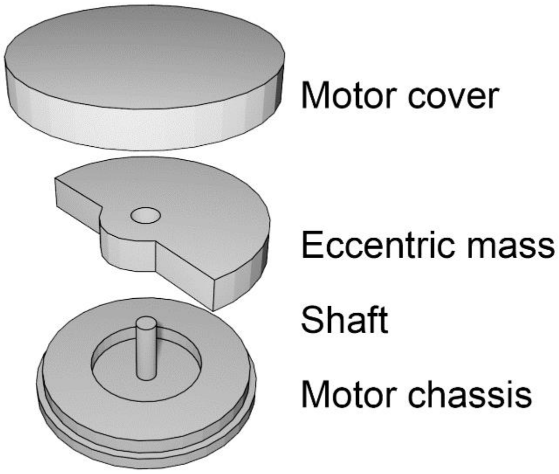

Figure 13. A simplified schematic of the main components of an ERM-type vibrotactile actuator.

ERMs can be constructed in varying shapes and sizes, commonly as either rod-shaped actuators or so-called pancake actuators, in which all the moving parts are concealed inside a small pancake-like disc. LRAs are less mechanical than ERMs. Their operating principle is similar to a loudspeaker, in which an alternating current is applied to a coil of wire suspended between the poles of a permanent magnet thus forcing it to move rapidly back and forth. These parts are illustrated in **Figure 14**. LRAs are often referred to as voice coils. When the coil moves a contact-plate placed directly against the skin vibration is sensed. As there are no mechanically moving parts, there is also less delay accelerating or decelerating the motion and less noise and heat generated. This allows for more precise timing of the stimulation and a more accurate waveform. The biggest advantages of LRAs over ERMs are shorter delay and better control of stimulus parameters, such as duration, frequency, amplitude, and waveform (Choi & Kuchenbecker, 2013). They are more expensive than ERMs, but the price difference is not great. Often, they achieve the same level of vibration at a slightly smaller size.

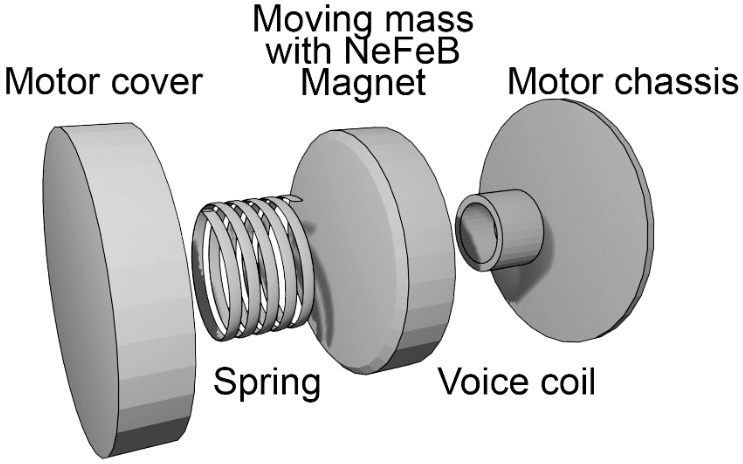

Figure 14. A simplified schematic of the main components of an LRA-type vibrotactile actuator.

Piezoelectric actuators (See **Figure 15**) generate vibrations by moving a plate linearly upon receiving electricity. These actuators allow for more precise control of stimulus parameters than ERMs and LRAs (Tikka & Laitinen, 2006). This technology does less work, so its power consumption is also more efficient and with fewer parts, its size can be reduced. Downsides to using piezoelectrical actuators are its low stimulus intensity and a requirement for high activation voltage, which can be problematic when used in direct skin contact (Pasquero et al., 2007). Piezoelectric actuators can be used for touch surfaces making just the surface vibrate rather than the whole device around it.

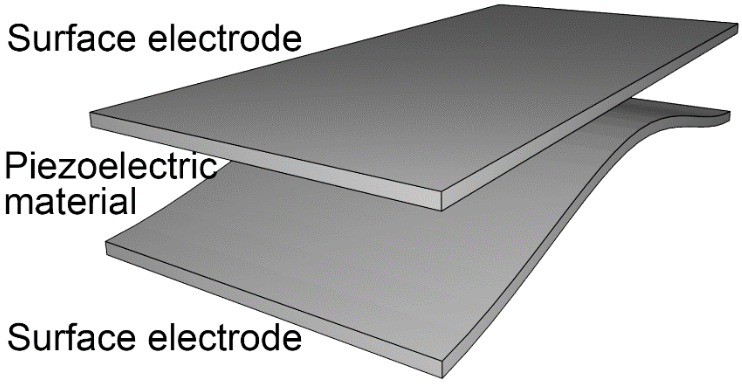

Figure 15. A simplified schematic of the main components of a piezoelectric actuator.

4.3 MID-AIR HAPTIC FEEDBACK TECHNOLOGIES

Wearable vibrotactile actuators and data gloves are simple and effective, but as a significant downside, require the user to wear extra devices on their body. Further, a high spatial resolution requires the use of many actuators. Another option is to mediate the sensation in mid-air, without the need for wearable, often tethered, and therefore movement confining devices.

Any interface that relies on the user's hand touching virtual objects through hand tracking and without tangible surfaces has the potential to benefit from mid-air tactile feedback. Potential usage situations include virtual user interface controls (e.g., buttons, switches, sliders), sensing of ephemeral elements such as wind or rain, touching objects to feel the surface texture, density, or weight, move or deform them, feedback from a collision, etc.

Prior to the emergence of mid-air haptics, meaningful touch-based interaction was limited to touch detection and tactile sensation through the touched surface, or to the usage of wearable tactile actuators, such as data gloves (e.g., Ku et al., 2003) or other wearable haptics hardware (Sand, Rakkolainen, Isokoski, Kangas, et al., 2015). A comparison of various ways of providing tactile feedback without touching the device has been published recently (Freeman, Brewster, & Lantz, 2014), listing a great number of different solutions to this problem.

Mid-air haptics is a group of technologies that allow for tactile feedback on touchless interaction. Within cutaneous interaction, in addition to tactile stimulation, pain and temperature can also be used. Often, the classification inside cutaneous interaction cannot be exact. For example, many vibrational feedback devices can also cause skin stretch or rising of temperature.

Different techniques can be used to create mid-air tactile sensations. At very short distances, femtosecond lasers can be used to generate touch perception (Ochiai et al., 2016). A high-intensity laser can excite physical matter to emit light at an arbitrary 3D location. The femtosecond laser can also be used to induce plasma. When a user's finger comes into contact with the glowing plasma voxels, shock waves are generated by the plasma. The user feels an impulse on the finger as if the light has a physical substance. The holograms and workspace of mid-air feedback of the system proposed by Ochiai et al. occupy a volume of up to 1 cm^3; however, the size is scalable depending on the devices and setup. Further, plasma can be harmful to humans. The femtosecond pulse used in the setup by Ochai et al. is an ultrashort pulse, which might not damage human skin seriously. The temptingly glowing very small floating image created by the plasma can, however, still pose a threat to the retina, making it only suitable to be used by trained persons or with protective equipment covering eyes.

Very short distance feedback can also be generated via electrical discharge. A high-voltage resonant transformer may be used through electromagnetic induction and transformed into several kilovolts at low current. When the potential difference to ground surpasses the dielectric strength of air (~3 kV/mm), the electric current ionizes the air around the output terminal and causes a plasma discharge (Spelmezan, Sahoo, & Subramanian, 2016). High-voltage electric arcs have very high temperatures and can burn the skin. With clever design, the arcs can be made safe to touch, and instead of feeling like electrostatic shock, they can be associated with barely perceivable sensations, ticking, pulsing, or hot (Spelmezan et al., 2016).

Human body hair can be augmented with passive magnetic materials to be actuated by external magnetic fields for contactless near full-body tactile stimulation of hair follicle receptors (Boldu, Jain, Cortes, Zhang, & Nanayakkara, 2019).

In mid-air tactile feedback devices, the tactile sensation is often generated via focused air or sound pressure. As the pressure is focused on a single location in space, it can become strong enough to slightly indent the human skin and become detectable by mechanoreceptors.

Mid-air tactile stimuli created with targeted air jets or vortex launchers (Gupta, Morris, Patel, & Tan, 2013; Sodhi, Poupyrev, Glisson, & Israr, 2013) can be used to provide tactile stimulations in mid-air. In these designs, the actuating device needs to track the users' hands and rotate itself mechanically to accurately provide the stimuli towards the hand. With this mechanical alignment, they are relatively slow for real-time interaction. This is further emphasized by the fact that the focal point of the feedback pulse takes a longer time to reach its target as distance increases. Air pressure can be increased to mitigate this effect, but this, in turn, can make the feedback pulse harmful at closer distances. As air pressure dissipates rapidly over distance, the interaction volume is somewhat limited. Also, as the generated pressure wave is relatively large, the stimuli can feel coarse.

To circumvent the need for mechanical orienting, several systems of focused acoustic air pressure for providing mid-air tactile feedback have been reported recently (Carter, Seah, Long, Drinkwater, & Subramanian, 2013; Hasegawa & Shinoda, 2013; Hoshi, Abe, & Shinoda, 2009; Inoue et al., 2014; Iwamoto, Tatezono, & Shinoda, 2008; Long, Seah, Carter, & Subramanian, 2014; Monnai et al., 2014; Palovuori, Rakkolainen, & Sand, 2014; Takahashi & Shinoda, 2010; Wilson et al., 2014).

Systems of focused acoustic air pressure can provide mid-air haptic sensations without mechanically moving parts and with much greater speed and precision. A phased ultrasonic transmitter array is essentially a device that can be used to focus ultrasound signals to one or several focal points. As an ultrasonic actuator matrix can remain at a distance and requires no tethering on the user, this approach is unobtrusive, maintaining the user's freedom to move in the target area.

Focused airborne acoustic air pressure produced by ultrasonic phased arrays is particularly good at generating a range of tactile stimuli on the user's palm or fingertips (Sand, Rakkolainen, et al., 2020). They use a matrix of small ultrasonic speaker components that produce inaudible sound waves, typically at 40 kHz (Iwamoto et al., 2008) or 70 kHz (Ito, Wakuda, Inoue, Makino, & Shinoda, 2016). Spatial resolution of individual focal point is limited by the wavelength - about 8.58 mm for 40 kHz and about 4.9 mm for 70 kHz in 20°C. For this reason, the focal point cannot be fully singular, although higher frequencies would provide narrower wavelengths. There will also always be some grating lobes, that is, secondary peaks of intensity, but these are weaker than the main focal point. Different frequencies can also be combined to benefit of both the better spatial resolution of 70 kHz and lesser attenuation in the air of 40 kHz (Ito, Wakuda, Makino, & Shinoda, 2018). While it is possible to perceive unmodulated ultrasound fields, as demonstrated by Inoue *et al.* (Inoue, Makino, & Shinoda, 2015), the human hand cannot feel vibrations at 40 kHz, requiring for the emitted ultrasound to be modulated to a lower frequency (Rakkolainen, Sand, & Raisamo, 2019).

The image sequence in **Figure 16** illustrates the principle of an ultrasonic phased transducer array. The device times and focuses the sound waves in such a way that they form a focal point in the 3D space above the phased array.

Figure 16. Illustrative image sequence demonstrating the principle of focusing ultrasound from a phased array of eight transducers. The phase of each wave is offset such that they arrive at the desired focal point at the same time.

Measurements of perception of ultrasonic tactile feedback have been reported (Ryu & Jonghyun, 2010; Wilson et al., 2014; Yoshino, Hasegawa, & Shinoda, 2012) and it has been found that this type of stimulation suits well for the palmar side of hands. As the human sense of touch in fingers and palms is the most sensitive to the vibration of 150 – 250 Hz (Ryu & Jonghyun, 2010), common frequency modulation for focused airborne acoustic air pressure is around 200 Hz.

An instinctively fitting form of mid-air tactile feedback for a button click has been reported as a single burst of 200 Hz modulated ultrasound with a duration of 200 milliseconds (Palovuori et al., 2014). With these parameters, all test subjects described it to be an "unmistakable" and confirming response functionally equivalent to a physical click of a button.

Since the mechanoreceptors most sensitive to vibration can quickly become desensitized to the stimulus, the acoustic pressure must change. A common method for this is amplitude modulation (AM), where the amplitude (signal strength) is varied. Recently it has also been reported that repetitive lateral movement (LM) of mid-air ultrasound focus can create stronger tactile stimulation than amplitude modulation (Takahashi, Hasegawa, & Shinoda, 2019; Ryoko Takahashi, Hasegawa, & Shinoda, 2018).

The focal point generated by ultrasonic actuation can be rapidly updated within the interaction volume. Multiple focal points can also be rendered to create volumetric shapes. But for the most common hardware types, rendering multiple focal points simultaneously makes each point feel weaker. If the ultrasonic transducer array consists of, for example, 256 pieces of 40 kHz transducers arranged as a 16x16 matrix (which is the case for the UltraHaptics [now Ultraleap] UHEV1[3], see **Figure 17**), most of the 256 transducers can focus their effort on a single focal point, but the creation of several simultaneous points decreases each point's intensity. Rendering complex volumetric shapes would quickly become increasingly difficult to feel and then impossible. Similarly, a matrix with a low number of transducers can result in weaker signals. On the opposite, a very large transducer array will not result in a stronger signal by default, as it can be very difficult to employ it fully for a single focal point due to the directivity of the transducer signals.

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[3] http://www.ultraleap.com

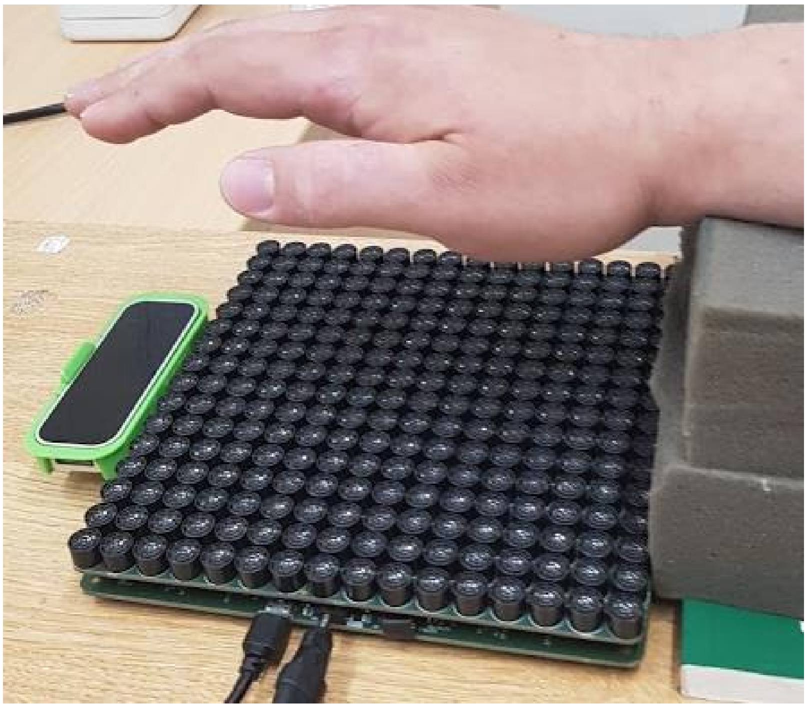


Figure 17. An UltraHaptics UHEV1 ultrasonic mid-air haptics device with 256 pieces of 40 kHz transducers.

The temporal resolution of the touch perception of a few milliseconds (Loomis, 1981) is relatively poor compared with the speed of the ultrasonic waves. This means that the human sensory system is fine-tuned to prefer change detection over constant stimuli. If a stimulus stays constant for a duration, the signal is suppressed. Also, if a stimulus repeats in quick successions, it is perceived as constant. If the location of a focal point is rapidly and repeatedly updated, the fast-moving single point can be used to create the sensation of an entire shape being rendered at once. This technique, called spatiotemporal modulation (Frier et al., 2018), can be used to create the sensation of complex volumetric shapes while still employing the maximum number of transducers available for each individual focal point.

The overall sensation strength achievable with current generation ultrasonic actuators is relatively weak, especially when compared with wearable actuators. Users have likened the sensation to the feeling of a “gentle breeze” focused upon the skin (Obrist, Seah, & Subramanian, 2013).

As pressure dissipates over distance, mid-air tactile feedback through focused acoustic air pressure is not suitable for large distances, of several meters away from the transducers, as that would require massive ultrasonic arrays. But when the transducers remain close to the area of the natural operation of a user’s hands, mid-air tactile feedback can provide an unobtrusive method of feedback delivery. Users do not need to be tethered to the systems and their freedom of movement is not restricted by wires.

Mid-air tactile feedback systems can benefit traditional displays, be used as tactile displays (Sand, Rakkolainen, et al., 2020), and be merged with display devices such as 3D monitors or mid-air reach-through particle displays (Hoshi et al., 2009; Inoue et al., 2014; Long et al., 2014; Monnai et al., 2014; Sand, Rakkolainen, Isokoski, Raisamo, et al., 2015). These are stationary ultrasonic arrays, requiring the user to stay close to the array to receive the tactile feedback. The transducer arrays can also be fitted on head-mounted display devices, making it more likely that the transducer array remains close to the area of the natural operation of the user's hands (Sand, Rakkolainen, Isokoski, Kangas, et al., 2015). While using head-mounted displays, the interaction volume remains small naturally, as we tend to look at the elements we are interacting with and we cannot extend our hand very far away from our face. Mounting the ultrasonic array on the front of the HMD ensures that it is always pointing at the active field of view of the user, thus somewhat circumventing the issue of limited interaction volume. For this reason, head-mounted displays seem to be a natural match with mid-air tactile feedback. Compared to wearable vibrotactile actuators, ultrasonic mid-air haptics has some clear benefits. It does not require any wearable actuators or for the user to be tethered to the device. It has spatial freedom – the focal point can be translated quickly inside the interaction volume. It can be used to create volumetric shapes and surfaces and to present surface textures (e.g., Freeman, Anderson, Williamson, Wilson, & Brewster, 2017). It can feel like magic to the user.

The freedom of touchless interaction can be beneficial in many use cases. Mid-air haptics can provide haptic feedback to above-device gestural interaction in hospitals, where touchless interaction prevents the transfer of bacteria. It can be used with messy hands in factories or bakeries. And it keeps public information displays hygienic. Mid-air haptics can also help create multisensory art experiences. When adding mid-air haptics to an art exhibition, the visitors reported feeling more immersed and uplifted (Vi, Ablart, Gatti, Velasco, & Obrist, 2017).

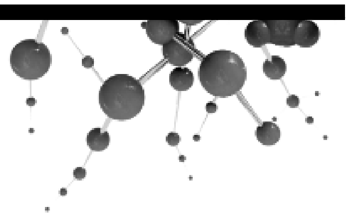
Recently, ultrasonic mid-air haptics has received academic interest (Rakkolainen, Freeman, Sand, Raisamo, & Brewster, 2020; Rakkolainen, Sand, & Raisamo, 2019), stimming especially from the automotive industry. Comparing a traditional in-vehicle touchscreen with a virtual mid-air gestural interface with ultrasound haptics has shown that haptifying gestures with ultrasound effectively reduced the visual demand and increased performance associated with continuous tasks (Large, Harrington, Burnett, & Georgiou, 2019). Further, mid-air ultrasonic feedback can reduce eyes-off-the-road time when using gestural interaction in vehicles (Shakeri, Williamson, & Brewster, 2018).

Other uses of phased ultrasound arrays include also acoustic levitation of light objects (e.g., Freeman, Anderson, Andersson, Williamson, & Brewster, 2017). Further, ultrasound-driven Bessel beams can be used to transfer particles, such as smoke or fog (Keisuke Hasegawa, Qiu, Noda, Inoue, & Shinoda, 2017), and fragrance (Qiu, Hasegawa, Makino, & Shinoda, 2016). They can also be used to deliver a cooling sensation remotely (Nakajima, Hasegawa, Makino, & Shinoda, 2018) and, for example, to blow out a candle in an inhospitable environment not suitable for human presence. A phased ultrasound array has even been proposed as a non-contact method of stirring for hygienic preparation of food (Sato et al., 2017), although the 16mN force extruded by the presented device might only be enough for stirring fluids with low viscosity. Van den Bogaerd, Geerts, and Rutten (2019) have reported 54 applications of mid-air haptics in the home from their ideation workshop. These were further categorized with thematic analysis into 5 main use categories: guidance, confirmation, information, warning, and changing status.

4.4 SUMMARY

In gestural interaction tethers and wearable devices can be limiting and cumbersome. Many different methods of providing tactile stimulations in mid-air have been presented, but many of them have obvious limitations in reach, resolution, strength, or safety. Acoustic pressure from phased ultrasonic transducer arrays is a viable option of contactless stimulation of cutaneous receptors. The strength of the feedback can be rather weak, but experiments have been made with larger matrices of transducers, different frequencies, and different types of modulation. Perhaps its greatest selling point is its ability to produce a sensation of multiple simultaneous focal points while providing maximum intensity for each. Spatiotemporal modulation can be used to fool the human somatosensory system into perceiving multiple simultaneous points with a single rapidly updating focal point.

All the experiments introduced in this thesis explored the transfer of haptic information in varying degrees, from informing the user of a detected interaction to stimulus suitability for a specific use. Experiments in Publications II – IV provided haptic information as a part of selection actions. It is, hence, important to look at the common conventions of human-technology interaction research of studying and evaluating different target selection methods next.



5 Interaction Measurement and Evaluation in Human-Technology Interaction

To better understand the motivation behind some of the experiment setups introduced in this thesis, it can be beneficial to explore some of the core concepts of interaction study in human-technology interaction.

5.1 INTRODUCTION TO HUMAN-TECHNOLOGY INTERACTION

Our history of interacting with information technology devices is relatively short. Human-Computer Interaction (HCI) as a field of research started in the early 1980s alongside the emergence of personal computers in the homes and workplaces of laypeople. Before that, computers were mainly present in large companies and institutions and were operated by specially trained information technology professionals (MacKenzie, 2012).

As the general population started using computers at the turn of the 1970s and the 1980s, human factors needed to be included in the multidisciplinary academic research of HCI. Presently, the field combines many disciplines, among other hardware and software engineering, psychology, usability, and user experience (UX) engineering.

As computers are becoming more ubiquitous and are more embedded in various consumer devices, the term human-computer interaction seems slightly misleading, evoking mental images of a personal computer in its traditional sense. Since the publications in this doctoral study focus less on the traditional PC and more on the novel technological devices that are used to interact with the PC or other devices, it seemed natural to use the term human-technology interaction (HTI) in the current work to describe the chosen context.

This is not to say that both humans and technology should be seen as equal actors in the interaction process. To illustrate this point, we can look at a common human-technology interaction scenario, where a mobile phone vibrates to inform the user of an incoming call. In this example, technology is merely a tool working in the background, enhancing human capabilities, rather than an equal individual entity. For this reason, technology can be seen as an environmental extension to the human nervous system, at least in the context of haptic interaction and in the scope of this dissertation.

5.2 RESEARCH METHODS IN HUMAN-TECHNOLOGY INTERACTION

Experimental research methods in HTI are derived largely from those used in experimental psychology. These include objective measurements of participants' behavior and performance as well as their subjective experiences of the interaction presented in the experimental study. Objective measurements are factually obtained and quantifiable data. Examples of such data are the time it takes to complete a given task or the number of errors made in completing it. Subjective, self-reported measures, on the other hand, can give insight into the participants' personal experience and thoughts about, for example, the pleasantness of haptic feedback. Subjective ratings can reveal information about how the user felt when using the technology, which types of interaction or feedback modalities they preferred, etc. This information can be difficult to obtain via objective methods.

Typical examples of objective metrics in HTI research measure the performance and behavior of the test subject while completing a task. These are directly observable and can be measured with special instruments. On a target selection task, the quantifiable measurements could be the time it takes to make a selection, the total time it takes to make all of the selections, and the number of errors the user made while making the selections. Throughput can be calculated based on speed and accuracy and different user interfaces as well as different input and output modalities can be compared based on their average throughput.

Reaction time (RT), commonly defined as the time it took from the onset of the stimulus to the participants' reaction (Pachella, 1973), is a typical example of quantifiable measurement.

Subjective metrics have been adopted to HTI research from psychology, where they have a long history as research tools. They are typically obtained via questionnaires and interviews. The participant can be asked to rate, for example, pleasantness of the given feedback, or how easy or difficult was the task. Typically, if the experiment exposes the user to two or more alternative independent variables, like auditory feedback, visual feedback, and tactile feedback, participants can be asked to rank the alternatives in order of preference. Post-experimental interviews and open-ended questions can allow the participants to express reasons and explanations relating to their ratings and rankings (Tullis & Albert, 2008).

Typical questionnaires usually mix *Likert scale* ratings, often formed as a statement (e.g., "The pace of the task felt hurried" or "The pace of the task felt relaxed") with a rating on a 5, 7, or 9-point scale, pairs of bipolar adjectives, such as unpleasant/pleasant at the negative and positive ends of the scale, and open-ended questions. Bipolar adjective pair question could be for example "How mentally difficult the technique was?", and the rating scale could be a nine-point scale with -4 = Very difficult, 0 = Neither difficult nor easy, and 4 = Very easy (Tullis & Albert, 2008).

Human-technology interaction focuses on the human aspect. This makes interaction with technology centrally associated with human emotions. Gross (2010) presents human emotional response with three main components: physiological reactions, behavioral expressions, and subjective experiences. Schlosberg (1954) and Wundt (1907) conceptualize human emotions as a continuum instead of separate categories in their model referred to as the *dimensional theory of emotions.* This dimensional model is utilized in human-technology interaction research to track users' feelings when interacting with technology. Albert Mehrabian and James A. Russell (Mehrabian, 1980) created the pleasure, arousal, dominance (PAD) model. It is used to give emotion-related ratings by dimensions of *valence, arousal,* and *dominance*. Valence, or pleasantness, describes how pleasant the stimulus feels on a scale from unpleasant to pleasant. Arousal describes how arousing the stimulus feels on a scale from calming to arousing. The dominance scale describes how dominant the stimulus felt like on a scale from submissive to dominant. A gentle stroke might feel pleasant and calming, but perhaps not very dominant. A sudden slap might feel very arousing and dominant as well as somewhat unpleasant. Brave and Nass (2003) map the spectrum of conscious emotional experiences to valence and arousal. These dimensions can be reflected in bipolar rating scales as unpleasant/pleasant and relaxed/aroused.

These subjective ratings can be used to design tactile feedback for specific use cases. When creating tools to help hyperactive users to calm down, a high level of valence and low level of arousal might be preferred. And when designing a horror game, a high level of arousal and low level of valence might be desired. But when the task is more universal, for example when designing a vibrotactile pattern used as a vibrational mobile phone call notification, the user's preference of arousal and valence can differ. Some users might not want to miss any calls and want a vibrational notification that is demanding and relentless. Other users might be so stressed about the constant flow of information and irritants that they want the notification to be subtle and calming.

Another aspect of evaluating human-technology interaction has to do with estimating cognitive load. When driving a car, for example, the level of cognitive load of adjusting onboard systems can have a fatal difference. Cognitive load evaluation strategies are commonly divided into three categories: performance evaluation, subjective methods, and physiological measurements (Haavisto & Oksama, 2007).

Performance evaluation focuses usually on the participants' speed and accuracy of the main task. Cognitive load cannot, however, be derived directly from how well the participant performed on the main task. Usually, participants try to maintain a consistent level of performance on the main task even when the cognitive load fluctuates. As the main task's level of demand increases or decreases, the participants' level of effort tends to increase or decrease accordingly to compensate for it. For this reason, a secondary task can be used to evaluate the level of excess capability left over from the main task. This can be achieved by, for example, making the participant do periodical math tasks, reaction time tasks, or memory-related tasks while focusing on the primary task.

Several methods for the evaluation of cognitive load have been developed. Some of the most frequently used ones are the NASA-Task Load Index (NASA-TLX), The Subjective Workload Assessment Technique (SWAT), and Workload Profile (WP) (Haavisto & Oksama, 2007). They are subjective ratings collected between, or immediately after, tasks. They consist of scales validated by comparing different situations and the burdening parts of them. The data must be gathered quickly after the task, as the cognitive load cannot usually be accurately recalled after a while.

Physiological measurements are usually heart rate, eye movement, skin conductivity, or ECG measurements. These can provide insight into what areas of the main task induced increases or decreases in cognitive load.

Overall, task analysis can reveal some otherwise difficult to notice but cognitively challenging and overall essential subtasks. These can include, for example, spatial design tasks done in short-term memory. In HTI, task analysis can help identify issues with user interfaces.

In the publications presented in this thesis, several of these research methods were used. The NASA-TLX was used in Publications II, III, and IV. Arousal and valence were collected in Publications IV and V. Likert scales, bipolar scales, and preference ratings were used in Publications II-V.

5.3 TARGET SELECTION RESEARCH IN HTI

When novel interaction modalities arise, it is important to ask whether they are useful. Some might be useful in very specific conditions, for example, in aiding the blind or paralyzed persons to accomplish a certain task. Nevertheless, we need to evaluate their usefulness with predefined metrics. These metrics can be numerous and far apart, some focusing on the subjective emotional parameters of the receiver, such as how pleasant or unpleasant some sensation is, and some focusing on empirically observing and measuring objective gains.

To allow for the evaluation of new interaction techniques objectively for their gains and flaws they need to be tested against some other well-known interaction technique (Surakka, Illi, & Isokoski, 2004). Commonly novel pointing modalities are compared to the mouse, usually by comparing the mean pointing task times (i.e., pointing at a target and selecting it) and the number of pointing errors between the techniques (Surakka et al., 2004). This, however, is not always suitable, as some interaction methods are novel and cannot be directly compared with existing methods. For example, in gestural interaction it is common to dwell the pointing hand or finger on top of the target object for a duration of a certain time interval to select it, making it impossible to "click" outside any target. It is hence moot to calculate the number of selections that missed the target objects altogether - something that is plausible with a computer mouse.

One common method used for evaluating pointing devices is through the use of empirical experiments based on Fitts' law (Fitts, 1954). Fitts' law states that there is a relationship between the time it takes to point and the difficulty of the pointing task. In this relationship, the difficulty is denoted and quantified by the index of difficulty (ID). This can be derived from the following formula.

$$ID = log_2\left(\frac{A}{(W+1)}\right)$$

In the formula, A is the distance of the movement and W is the target area width (Fitts, 1954). To paraphrase, Fitts' law dictates that selecting targets that are bigger in size and closer together is easier than selecting those that are smaller in size and farther apart. It is quite common to use circles as the objects to select, as this helps avoid complications that might arise from the angle of approach (MacKenzie, 1995). The relationship between the pointing time and the index of difficulty is linear, allowing it to be described with the following linear regression equation.

$$MT = a + b\, ID$$

In the equation, MT denotes the movement time while a and b denote the regression coefficients. The equation was in the beginning evaluated against data from tasks in which objects were manipulated with hands directly in a reciprocating pattern (Surakka et al., 2004). Since then, further research has proven Fitts' law holding when pointing with a mouse and other computer pointing devices (e.g., Carol, English, & Burr, 1978; MacKenzie, 1995).

An index of performance (IP) can be calculated by the reciprocal of b (i.e., $1/b$). The IP can be used to compare two different input devices or modalities (e.g., Carol et al., 1978; MacKenzie, 1995; Miniotas & Darius, 2000). If the IP is low, making the task more difficult has a more significant effect on the movement time than when the IP is high. For this reason, devices and modalities with higher IP can be considered better. It is, however, important to note that when comparing these IP values, one should have knowledge of the experimental and computational methods used in their acquiring (Douglas, Kirkpatrick, & MacKenzie, 1999; MacKenzie, 1992; Surakka et al., 2004).

Another thing to note in comparing target selection methods is a speed-accuracy trade-off. If there is no requirement for accuracy, one can complete the task with an emphasis on speed. Likewise, if one takes an unlimited amount of time for completing a task, the likelihood of making errors gets smaller. The basic Fitts' law experimental setup does not take into account this issue (Surakka et al., 2004). Participants can be advised to complete the task as fast and as accurately as possible, but ultimately all participants are merely assumed to have the same level of speed-accuracy balance in their performance, when individual characteristics may introduce variations to this. It can be, that some of the participants take the instructions with different emphasis, choosing different strategies for the speed-accuracy tradeoff. The error rate can be normalized in the data analysis phase to counter this problem.

MacKenzie (1995) suggests using an effective target width rather than the presented target width when doing the Fitts' law calculations. The effective target width can be calculated by multiplying the standard deviation of the pointing coordinates by a factor of 4.133 (Surakka et al., 2004). In case the pointing coordinates follow a normal distribution, this operation normalizes the error rate to 4% (Surakka et al., 2004). Then, the ID can be calculated based on the effective target width *We* rather than the presented target width *W*. Hence, the Fitts' law formula takes the following form (MacKenzie, 1995).

$$MT = a + b\ log_2\left(\frac{A}{(W_e + 1)}\right)$$

When using the Fitts' law model to compare the effectiveness of novel interaction techniques, it is worth noting that the new tracing devices can have significantly more tracking errors than a trusty old mouse. It is then vital to consider whether we are measuring a novel concept or early technological implementations. Do we want to make a fair comparison against the mouse with the technology that is currently available or with the technology that could be once it matured? For example, pointing time can increase and the effective target width can grow simply due to a poorly performing tracking device. This can make the new technique look bad in comparison. There is a tradeoff between observing the new technique under ideal conditions by excluding such erroneous tasks and using all the data making a comparison against the mouse fairer. Neither way might give the answer one was looking for. One emphasizes what the interaction could be like once the technology matures, the other suffers from technological limitations not really part of the interaction method.

5.4 TAPPING AND TOUCHING AS TARGET SELECTION MODALITIES

Interaction techniques that are based on the use of hands for pointing rather than for controlling a pointing device have some promising benefits. It is natural for humans to look at objects while simultaneously performing tasks with their hands; eye movement requires little conscious effort and it is normal for humans to look spontaneously at objects of interest, whether in real life or when interacting with computers (Sibert & Jacob, 2000). Eyesight is a modality which people use naturally when seeking information (Sibert & Jacob, 2000). When using a dedicated pointing device, such as a computer mouse or a game controller, subjects must first locate the object of interest by fixing their gaze on it before the virtual pointer can be manually translated over it.

The difference between using a pointing device and using hands for pointing comes from the pointing devices normally operating in two-dimensional planes - whether a mousepad or an imaginary plane in the case of handheld game controllers - and hand operating in (physically limited) three-dimensional space. Humans can move their eyes very fast. Saccadic eye movements, for example, can be as fast as 500 degrees per second (Rayner, 1998). But once the target has been acquired by gaze, the subject must then also seek the position of the virtual pointer to guide its path to the target.

On the other hand, when using hands for pointing, we normally tend not to look at our hands traveling towards the target, but rather rely on our sense of proprioception for that task, thus allowing us to keep our eyes fixed on the target (Just & Carpenter, 1976). When we get closer to the target, whether with the virtual pointer or with our hands, pointing with hands still has an advantage as our finger presses down on the z-axis where the virtual pointer travels in x and y axes, thus making it inherently easier to track the pointer even with our peripheral vision at the same offset distance. Finger at a 5 cm distance from the target in the z-axis is better in line with our vision than the virtual pointer at 5 cm distance from the target in x and/or y-axes.

When we tap or touch an icon on a mobile phone or a tablet screen, we feel the inherent tangible surface signaling us that the touch itself has connected with the device. Often this is not enough as touchscreen devices can sometimes be occupied with something else and the touch may not be immediately detected. Or the resistive touchscreen might not have received enough pressure on top of the sensor to trigger the event in the first place or there might be something blocking the conductivity between a finger and a capacitive touchscreen. This is one of the reasons many users prefer the device to vibrate to acknowledge the user that the action has been noted. It has been shown, that when using haptic feedback while typing on a touchscreen keyboard users entered significantly more text, made fewer errors, and corrected more errors than without haptic feedback (Brewster, Chohan, & Brown, 2007).

When using touching or tapping in virtual reality scenes, with permeable displays, or when using mid-air gestures, there are still some tradeoffs due to technological limitations. It can be difficult to tap on a virtual target in such a uniform way that it can be reliably recognized by the system between gestures and users. To make gesture recognition more reliable, many systems opt for dwelling the pointing finger or hand on top of the target for a duration. This can help eliminate unintentional selections but is often much slower and more tiring for the user (van de Camp, Schick, & Stiefelhagen, 2013; Yoo, Parker, Kay, & Tomitsch, 2015).

Many technological challenges can be alleviated with good design, others require less than optimal interaction methods. One of the most prominent technological challenges related to mid-air gesturing is commonly known as the Midas touch (Kjeldsen & Hartman, 2001). Because the user is constantly being tracked for gestures by the gesture tracking technology, there can often be a disparity in what the system detects as a gesture and what the user intends as one. This can lead to constant unintentional selections and make the use of the system a very frustrating endeavor. The user might be communicating to another person and, perhaps subconsciously, moving their hands, or engaging in other physical tasks in the tracking system's interaction space (Walter, Bailly, Valkanova, & Müller, 2014). This issue is not limited to just gestural interaction but is prominent in most interaction methods that rely on continuous tracking, for example, in using eye gaze to select targets in gaze-based interfaces (Vrzakova & Bednarik, 2013).

The Midas touch phenomenon is worsened by the inherent lack of tactile feedback associated with permeable and virtual displays, as well as mid-air gestural interaction. Traditional physical input devices come with haptic feedback built in – a button can only be pressed so far, and a knob can only be turned one way or the other.

On the other hand, permeable screens such as the different versions of the FogScreen used in the experiments introduced in this thesis, make the mid-air gestural interaction significantly easier, as the user has a visual reference on roughly where the interaction should take place, for example, how far they need to reach to make a tap gesture. This allows for the system to only regard gestures made in a shallow depth volume and frees the user to move and gesture at will without having to worry about unintentional selections. Yet, fog and other common light-reflecting particles reduce the tracking accuracy of many common tracking methods, such as time-of-flight sensors and depth cameras. Moreover, users may be wary of gestural interfaces, at least initially, worrying if the system is working or not, and haptic feedback could work to reassure the user that the system is indeed tracking the selections reliably.

Common remedies for the Midas touch problem include the use of extra actions. In whole-body interaction the user might be required to take a special body pose, such as a "teapot" (Walter, Bailly, & Müller, 2013), meaning that the user must place their hands on their hips to indicate to the tracking system that they wish to begin the interaction. When using just pointing and tapping, the user might, for example, be required to make a fist or other special gesture to confirm the selection of the pointed object. This can, however, result in the virtual cursor moving away from the intended target as the hand tends to move slightly as the gesture is being made.

Technological limitations can also be alleviated with more technology. The system can analyze in addition to the gestures the user's posture and gaze to guess when the user wants their movements to be considered as interacting with the system (Schwarz, Marais, Leyvand, Hudson, & Mankoff, 2014).

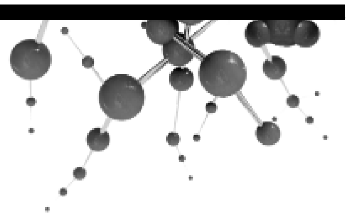
While the dwell-based selection method has clear drawbacks (time consumption and physical strain) it might still require more technical advances before simple pointing and tapping becomes reliable enough to surpass the need for such clutch actions.

5.5 SUMMARY

This Chapter introduced the common research methods used to test and evaluate the different target selection methods in human-technology interaction. It also discussed the human and technological difficulties of some embodied interaction methods, namely the challenges related to pointing at objects from distance.

Interactions can be evaluated objectively through performance (e.g., characters entered per unit of time, numbers of errors made). Fitts' law is a framework for comparing different pointing techniques to one another. But the needs and use cases can differ. While it can be more accurate to digitally sign with a stylus rather than with a finger, pointing and gestures can still be appropriate for other tasks. Different questionnaires can be used to collect subjective data about, for example, different types of demand associated with a certain interaction task, or preference of one method over another.

The previous chapters have given a succinct introduction to the different aspects explored in the experiments presented in this thesis. The next chapter will introduce the five publications made from these experiments and discuss how they relate to one another. A further discussion of the results and limitations of the experiments is reserved for Chapter 7.



6 Introduction to the Publications

The primary goal of the studies presented in this thesis was to introduce and evaluate methods for providing haptic feedback to interaction with such unconventional displays that do not provide inherent touch sensations.

The following introduces the experiments, starting with their aims and the methods used. Further, it will present the main results and consider their implications briefly. The purpose of this chapter is to provide an overview of each experiment. The next chapter will discuss the findings and limitations at a higher level to address the research questions presented in this dissertation.

6.1 PUBLICATION I: A HAND-HELD IMMATERIAL VOLUMETRIC DISPLAY

Objectives and Methods

Augmented reality displays could benefit from breaking free from the constraints of physical displays. This would allow delicate objects of interest to safely be enveloped by the display surface, bringing the AR information closer to the object. If the display would be tracked in three dimensions, it could, for example, be swiped in mid-air to reveal slices of volumetric data. In the publication I the aim was to introduce such a novel device prototype. The requirements of the device were as follows. It needed to be light enough for easy operation, it needed to track its environment for interaction, and it needed to be permeable.

A small hand-held permeable display was created first. It used flowing light-scattering fog particles for information visualization. The laminar airflow allowed for a free orientation of the display device as gravity has a negligible effect on the fog particles. An attached pico projector was used to project the information onto the fog and a camera was added for environment sensing. As the device senses its surroundings by tracking visual markers with the camera, moving the device can be used as an input method. For example, swiping the display device in mid-air can be used to reveal individual slices of a volumetric dataset, such as computer tomography data. **Figure 18** presents a slice of volumetric data of a human knee. The resulting projected image is sharper when viewed in person.

The process in this study was exploratory so that the device was iteratively constructed and prototyped mostly from custom-built hardware and software components. Then it was pilot tested and developed further until the prototype was functional enough.

Figure 18. Mid-air visualization of volumetric objects.

Results and Discussion

This publication presented a light-weight hand-held volumetric flowing particle display with the ability to track its location. It was a new concept and also the first hand-held FogScreen display device. The device successfully rendered mid-air volumetric slicing images based on the position of the display relative to its surroundings in any orientation, for example, upside down, sideways, etc. Its range is not as limited as with other projector-based systems, as the projector is in a fixed position relative to the screen and moves with the screen.

It is also well suited for AR visualizations, as a physical object can share the same space with the display surface: the particle flow fills out any gaps left by intersecting objects maintaining solidness of the surface.

This publication presented the development of a novel display device. Further, the publication discusses possible use cases that could benefit from the device's ability of physical objects sharing space with the display surface. It served also as an inspiration to explore the domain further and led to the next publication.

6.2 PUBLICATION II: LIGHT-WEIGHT IMMATERIAL PARTICLE DISPLAY WITH MID-AIR TACTILE FEEDBACK

Objectives and Methods

The idea presented in Publication I was taken further with the aim of enabling tactile interaction with the flowing particle screen.

A phased ultrasonic transducer array was constructed and integrated with a 17″ desktop fogscreen, illustrated in **Figure 19**. A LeapMotion controller was added for hand tracking, effectively transforming the permeable display into a reach-through touchscreen with mid-air haptic feedback. The ultrasonic feedback device consisted of 128 pieces of 40 kHz transmitters organized onto a 16x8 array that provided a 200ms tactile burst of 200 Hz modulated ultrasound.

The hand tracker was placed in front of the laminar flow with the phased actuator array placed on the far side of the fog and tilted at an angle. These placements were chosen due to the impact of the light-scattering particles on the hand tracker as well as to achieve an optimal distance from the phased array. Also, the tilted orientation allows the signal to reach the sensitive glabrous skin on the palmar side of the fingers. The laminar flow did not have a noticeable effect on the ultrasonic signal, nor did the ultrasonic signal have a noticeable effect on the flowing particles.

The interaction consisted of touching and pressing the projected number keys in the present order. Touching the number target gave visual feedback in the form of highlighted color. Pressing on it, thus intersecting with the screen, made the number target move backward with the finger. Tactile feedback was given in counterbalanced tasks when the finger was touching the target.

Participants (N=12) were to interact with the display with and without the tactile feedback in a key pressing task. They were asked to enter a sequence of three random numbers on a virtual Numpad by tapping the corresponding icon. There were two blocks of tasks, one with and one without haptic feedback. A block consisted of 15 tasks of entering 3 random numbers, which were randomized for each task and participant. In both blocks the speed of entering characters per second and error rate were automatically recorded. Subjective ratings were collected between blocks via NASA-TLX ratings. Finally, preference ratings were collected, in which the participants chose whether they rather used the system with or without haptic feedback.

Figure 19. From front left to back right: Leap Motion controller, FogScreen, phased ultrasonic 16x8 array, and projector (masked with an R2D2 printout).

Results and Discussion

The results showed small differences. Pairwise t-tests showed no statistically significant differences between the interaction modes in terms of speed of characters entered and the error rates. The NASA-TLX ratings between the interaction modes showed no statistically significant differences either. The preference ratings showed that 8 out of 12 preferred to have the tactile feedback.

Publication II presented a prototype of a lightweight interactive fogscreen with mid-air tactile feedback. Tactile mid-air displays blur the boundaries between real and virtual worlds. For this reason, mid-air tactile feedback matches well with the intangible fogscreen, as it enables the user to touch and feel virtual objects in thin air in an unobtrusive way.

The idea of using ultrasonic tactile feedback in intangible user interfaces can be widened to other user interfaces that would benefit from tactile feedback. Head-mounted virtual reality displays are one such example that could be used to present virtual UIs and with the addition of hand tracking the user could use their hands to touch the virtual objects. The solution presented with particle screens was transformed into use with HMDs and presented in the next publication.

6.3 PUBLICATION III: HEAD-MOUNTED DISPLAY WITH MID-AIR TACTILE FEEDBACK

Objectives and Methods

One of the problems with gestural interaction in virtual environments is that touching virtual objects does not generate touch sensations. This can lessen experienced immersion as well as create uncertainty when interacting with virtual user interfaces. This can be remedied with the use of wearable actuators or by holding a controller with vibration motors. But to have the hands completely free for interaction, another solution is needed. For the purpose, a mid-air tactile feedback system for head-mounted displays was created. The focusing of a modulated ultrasonic phased array was used for unobtrusive mid-air tactile feedback generation.

The ultrasonic feedback device was the same 16x8 transducer array used in Publication II. The feedback was again a 200ms tactile burst of 200 Hz modulated ultrasound. The participant's hands were tracked with a LeapMotion controller attached to the HMD to allow for hands-free interaction. As the array is mounted on the front of the HMD facing outwards, its optimal focal area will always be directed along the direction of the users' face. The limited optimal interaction volume of the ultrasonic phased array is overcome with this novel arrangement. The forward-facing hand-tracking sensor was used to direct the acoustic pressure focal point at the users' fingers. **Figure 20** shows the prototype device.

Figure 20. A modulated ultrasonic phased array integrated into a head-mounted display can provide tactile feedback in mid-air. A LeapMotion hand tracker is attached on top of the array.

To evaluate the tactile feedback together with visuals on an HMD, we had participants (N=13) do a simple target selection task with and without tactile feedback. The task was essentially the same as that in Publication II but presented in virtual reality.

Results and Discussion

Pairwise t-tests showed no statistically significant differences between different modes of interaction in terms of speed and error rates. NASA-TLX ratings showed that the perceived temporal, physical, and mental demand, as well as perceived effort, decreased with the addition of tactile feedback. However, according to t-tests, only temporal demand had statistically significant differences: the participants reported smaller temporal demand with the haptic feedback than without it (t_{12}=2.38, p=0.00009).

Preference, on the other hand, showed more clear results, with eleven out of the thirteen participants reporting that they preferred the addition of haptic feedback. The experimental setup did not reveal objective effects of mid-air tactile feedback in this kind of use, but subjectively the solution was very well received by the users.

One limitation of current ultrasonic phased arrays is their rather weak amplitude. The next experiment explores interaction with permeable displays replacing the feedback based on acoustic pressure with more traditional vibrotactile actuators.

6.4 PUBLICATION IV: TACTILE FEEDBACK ON MID-AIR GESTURAL INTERACTION WITH A LARGE FOGSCREEN

Objectives and Methods

Projected walk-through fogscreens can be used to render permeable user interfaces on a large scale. Different content can be projected on each side catering to multiple users. As seen in some trade shows, a car can drive through the display only to have the surface realign itself practically instantaneously. However, with their lack of inherent tactile feedback, the user experience can deteriorate. The user might be left wondering did the touch connect and was the gesture recognized or were they simply waving their hands in vain.

Visual feedback alone may be insufficient. The intersecting finger can cause slight turbulence in the fog, which in turn can blur the projected graphics. The finger may also occlude the projected graphics altogether depending on the line of sight. Adding tactile feedback to permeable screens might make them more user-friendly and pleasurable to use.

Study IV investigated the effect of adding vibrotactile actuation to gestural interaction with a large permeable display. Participants (N=20) were to interact with the screen using tapping and dwell-based interactions. The interactions were supplemented with feedback from a custom-built wireless wearable actuation device in addition to audio-visual feedback. The experiments were repeated with and without the haptic device. The device (illustrated in **Figure 21**) was designed around an Arduino Nano microcontroller with an HC-05 Bluetooth chip for communication with the experiment computer providing the projected graphics and driving the Fitts′ test software. Participants' gestures were tracked via a Microsoft Kinect for Windows V2 sensor. Vibrotactile feedback was generated by an ERM motor controlled by a Texas Instruments DRV2605L haptic motor driver chip. Battery operation was made possible by a Pololu 5V stepper voltage regulator drawing power from two AA batteries also housed in the wrist-mount Velcro baseplate.

We used the Fitts' law framework, where the targets are presented along a circular path with varying sizes and distances from the center. After selecting a target another one appears on the opposite side of the circle.

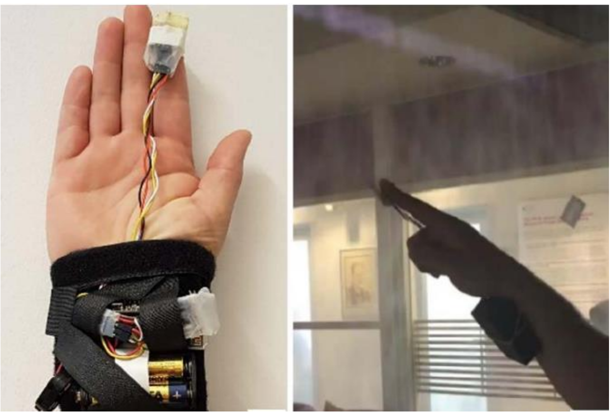


Figure 21. A wrist-worn wireless vibrotactile device producing haptic feedback on the tip of the index finger.

Results and Discussion

The results showed that while tapping on a target was more efficient than dwelling over it, limitations in tracking quality made the use of dwell-based selection methods more robust, as is often the case. Vibrotactile feedback was preferred by the users in dwell-based interaction over audio-visual feedback alone. Tapping was the fastest method of selection and it was also rated as the most preferred by the participants.

The overall preference for tapping is likely explained by the perceived delay of the dwell-based selection method. Previous research (e.g., van de Camp, Schick, & Stiefelhagen, 2013; Yoo, Parker, Kay, & Tomitsch, 2015) has shown that while dwell-based selections can be slower and more tiring – hence also less preferred – they are still practical when and if the recognition quality of other gestures is poor. Pointing in mid-air can be both more difficult to recognize by the system and more difficult to perform uniformly by the participant if they cannot feel any tangible surface on which to press. These results showed that when using the dwell-based selection method, haptic feedback was significantly preferred by the participants.

6.5 PUBLICATION V: EVALUATING ULTRASONIC TACTILE FEEDBACK STIMULI

Objectives and Methods

Ultrasonic tactile stimulation can give the user contactless tactile feedback in a variety of human-computer interfaces. It could strongly compliment mid-air gestural interaction giving the needed tactile affirmation to pressing a button or touching other seemingly tangible virtual or mid-air projected surfaces. It has limited ability to generate shapes, textures, objects, and surfaces for us to explore through touch and can help take the immersion of virtual reality to a whole new level.

Technology-mediated tactile sensations can be used to convey information. Common tacton design parameters, such as duration, rhythm, and intensity, have been explored to encode information into tactile sensations. The ability of transducer arrays to rapidly update the focal point location to create the sensation of movement and shapes opens new possibilities to tactile information transfer.

The aim was to better understand the technical and human limitations of ultrasonic haptic information transfer. For this, a study was conducted to investigate the differentiation of six ultrasonic tactile stimulations that were varied by form (i.e., square and circle) and timing (i.e., movement speed and duration, and the frequency of tactile phases within a stimulus). An UltraHaptics UHEV1 ultrasonic transducer array with 256 pieces of 40 kHz transducers (see **Figure 22**) was used as a tactile display.

In a stimulus familiarization task, participants (N=16) were introduced to all stimuli in a specific order (1 to 6) and repeated four times. After this, participants were to identify the stimuli presented in random order by pressing the number key corresponding to the stimulus index used in the familiarization task.

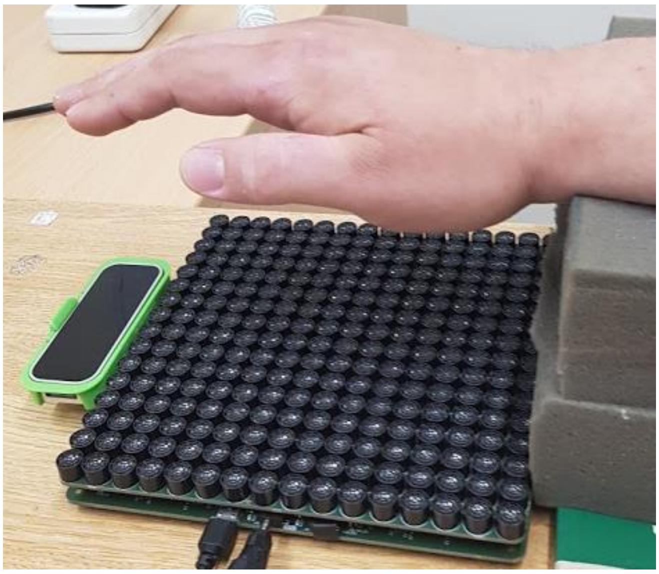


Figure 22. A modulated ultrasonic phased array providing tactile feedback in mid-air.

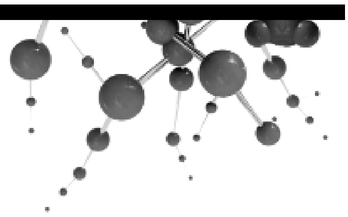
Results and Discussion

The identification times were analyzed using one-way repeated-measures analysis of variance (ANOVA) and Bonferroni corrected t-tests were used for pairwise post hoc comparison of the 15 pairs. Bonferroni corrected t-tests at the .05 level were used for pairwise post hoc comparisons of the 15 pairs.

Error rate, in this experiment the number of incorrect identifications, as well as subjective ratings, such as valence, arousal, and stimulus suitability for predefined use cases, were first analyzed with Friedman tests and then Bonferroni corrected Wilcoxon Signed Ranks Test was used for their post hoc comparisons.

The results showed that stimuli formed of repetitive 400ms pulses were easier and more reliably identified than those with a shorter duration regardless of the number of repetitions. Post-experiment interviews revealed that the changes in form were not noticed.

As the experiment explored a set of varying stimuli with multiple parameters, the results cannot give precise answers as to what independent variables have the strongest effect on dependent variables, but rather serves to shed some light on the effects of a small set of parameters.



7 Discussion

The present doctoral thesis aimed at discovering profound understanding of how touch sensations could be added to unconventional display devices. Novel and less explored devices and use cases were studied in five studies.

Study I introduced a novel lightweight, limitedly volumetric permeable display. Because of its environment tracking camera, it could be interacted with by swiping the display in mid-air to, for example, reveal slices of volumetric magnetic resonance images. This way the volumetric point cloud looked like floating in the room invisibly and the display could be used to create a window into the unseen. Moving the planar display around in the volumetric point cloud revealed individual slices.

Various types of slicing displays have been reported earlier (Cassinelli & Ishikawa, 2009; Issartel et al., 2014; Konieczny et al., 2006; Leung et al., 2010; Sullivan, 2003). These can be used to view volumetric slices on a movable tablet or diffuse plastic sheet, although in a limited range. Compared with these, the hand-held display presented in study I allowed greater freedom of movement and a larger interaction area.

Several kinds of volumetric displays have also been reported. These display objects and send light from their actual 3-dimensional position (e.g., Benzie et al., 2007). The most common implementation of a volumetric display produces the images in a confined space with rotating or solid screens (e.g., Favalora, Dorval, Hall, Giovinco, & Napoli, 2001; Jones, McDowall, Yamada, Bolas, & Debevec, 2007; Traub, 1967). The limitation of this approach is that these do not allow touch or physical objects to intersect the display volume.

Augmented reality use can also benefit from the permeable display, as the display medium can envelop physical objects, thus bringing the augmented information close to the object of interest. Solid displays and tablets may be too cumbersome to use for augmented reality with delicate physical objects, possibly harming them, as proximity with the screen is required. In contrast to the permeable fogscreen, solid screens cannot intersect with physical objects. This creates unnecessary separation of the physical objects and the related virtual information. If an object intersects the particle flow, it creates an upward turbulent flow that does not significantly exceed its width, leaving the remaining display surface intact. The object may also occlude part of the projection, but usually, most of the screen nearby can still be used. Permeable AR displays can be used near delicate objects as there is less worry of damaging the objects compared with traditional solid displays.

The particle display can be enticing, especially in dim ambient lighting, when the light-scattering particles appear to be glowing. Further, it is safe to use, as the display surface recovers instantaneously from intersecting objects. This allows also the display surface to appear only when needed. Such displays could be integrated with many appliances and objects to provide a display on cue. The display can also be turned into a reach-through touchscreen if the user's hands are tracked for input.

Study II investigated the use of hand tracking and ultrasonic mid-air haptic feedback with a permeable fogscreen to create such a reach-through touchscreen. This solution retained the benefits of permeable screens but allowed the interactivity of more traditional touchscreens, such as tablets. Gestural interfaces let people interact with devices using hand gestures. Since the display in study II was permeable, interaction with it was similar than with gestural interfaces. With such interfaces, effective feedback can be useful to help the users in avoiding uncertainty about gesture performance. This is often achieved using visual or auditory feedback, but also haptic feedback.

Before the emergence of mid-air haptics, meaningful touch-based interaction was limited to touch detection and tactile sensation through the touched surface. Tactile feedback required tactile data gloves (Ku et al., 2003) or other wearable haptics hardware (Freeman et al., 2014), but often the devices were tethered and obtrusive or the interaction was indirect. Targeted air jets (Sodhi et al., 2013) and vortex launching (Gupta et al., 2013) have been used to deliver mid-air tactile feedback, but they can be relatively coarse and slow for real-time interaction. Ultrasonic mid-air tactile feedback devices could be a natural match with permeable particle screens. Further, since neither require touching physical surfaces, the combination could be one solution for hygienic interfaces in times on pandemics.

Previous research suggests that a tactile sensation can affirm the user that a selection has been made while making gestures above a display (Freeman et al., 2014), thus giving a more coherent user experience. In study II, most test persons found mid-air tactile feedback engaging and intriguing.

However, the evaluation did not reveal any measurable interaction efficiency benefits of the tactile feedback, nor did it degrade the performance of the users. There can be several reasons for this. For example, the ultrasonic feedback device used in this study had relatively few transducers. Larger arrays with more transducers can produce stronger feedback. Also, the tactile sensitivity of human hand varies widely on various parts of the skin (Pont, Kappers, & Koenderink, 1997). Palmar side of the hand is fairly sensitive, but the dorsal side of the hand and other body parts are significantly less sensitive. This means that any tracking errors causing the roughly 8mm wide focal point missing the relatively thin fingertip could result in the stimulus landing on an insensitive area. Further, the novelty of the mid-air tactile feedback and the permeable flowing particle screen may also have distracted the participants from the task that they were asked to perform. Curiosity and novelty may lead users to try to maximize their interaction with the devices rather than optimizing their performance in the task. It might be that after prolonged use the novelty of the feedback and display would wear off and better concentration on the task could lead to better utilization of the tactile feedback and thus to improved performance. On the other hand, the novel feedback method might be reviewed more favorably because it is new (Rutten & Geerts, 2020).

Tactile mid-air displays blur the boundaries between real and virtual worlds and ultrasonic mid-air haptics is one good match with the permeable fogscreen. It enables the user to touch and feel virtual objects in the air in an unobtrusive way and it could improve interaction and sense of presence.

Study III investigated the use of ultrasonic mid-air haptic feedback on interaction with a virtual user interface presented on a head-mounted display. Many kinds of 3D user interfaces (Bowman, Kruijff, LaViola, & Poupyrev, 2004) and devices could benefit from mid-air tactile feedback. Any interface that relies on the user's hand touching objects in VR has the potential to benefit from mid-air tactile feedback. Potential usage situations include interaction with UI elements (as in Study III), sensing of ephemeral elements, such as wind or rain, touching objects to feel, move or deform them, feedback from controlling abstract data visualizations, etc.

Currently, users of head-mounted displays cannot have unobtrusive tactile feedback while touching virtual objects. Hand-held controllers housing vibrotactile actuators are included with most HMDs, but hands-free interaction suffers from the lack of tactile stimulation. For this, a modulated ultrasonic phased array was integrated into a head-mounted display to provide tactile feedback in mid-air. As far as we know, there were no earlier implementations of ultrasonic arrays embedded into head-mounted displays. The user could see their hands in the virtual environment, could use their hands to touch virtual objects, and could receive tactile feedback while doing so. And what was truly different from common solutions, it did not require the user to wear any extra devices, such as data gloves, controllers, or actuators, on their hands. As people tend to look at, and hence turn their heads to face what they are touching (M. A. Just & Carpenter, 1976), the placement of the phased ultrasonic array allowed the interaction volume to be covered with a single device.

Current ultrasonic mid-air tactile feedback devices are most suitable for distances up to 25 - 30 cm. The stimuli from the device used in Studies II and III started to dissipate quickly at the distance of about 30 cm. The interaction volume of the array matches well with the width and height of the FOV and the practical interaction volume of the hands. Only peripheral areas remain outside of coverage, limiting suitable interaction volume in the lateral dimensions. Lately, a solution has been proposed in the form of rotating the array around the pan and tilt axes (Howard, Marchal, Lécuyer, & Pacchierotti, 2020). This solution, however, may share some of the same limitations seen on directable vortex launchers, that is, repositioning speed, positional accuracy, and increased complexity. To be able to provide mid-air tactile feedback on the user's hands without limiting their freedom of movement, the ultrasonic transducer array as well as the hand tracker were mounted on the front surface of the head-mounted display, facing away from the user. Being able to dynamically focus the feedback to a point where the fingers are in contact with the virtual objects is important. However, there are several reasons why the volume in which the feedback is needed can be made small in practical implementations. First, the comfortable depth range of touching with the hand is naturally limited by the length of the arm. Secondly, working very close to one's face does not feel comfortable. Thirdly, the HMD itself limits the shortest possible distance. Furthermore, scaling the virtual content so that full arm extensions and interaction close to the face do not happen can further reduce the needed range.

The results of Study III showed that the mid-air tactile feedback did not enhance or degrade the performance of the participants. However, it was heavily preferred by the users. This result, together with a similar result from study II, suggests that the best use of mid-air haptic feedback could be in situations emphasizing user experience. Entertainment technology, games, and other user interfaces that are used for fun could potentially be even more fun with mid-air haptics, whereas in productivity applications the measurable performance benefits may turn out to be small. At least amplifying an art exhibition with ultrasonic haptics left the visitors feeling more immersed and uplifted (Vi et al., 2017). The biggest perceived differences found in study III were found on the effort and temporal demand. It seems that the users felt that introducing the mid-air tactile feedback made the task feel more relaxed and perhaps required less effort. Even though the actual delays did not change, the tactile feedback made the pace seem slower according to the participants' feedback. It could be that the tactile feedback made the task cognitively easier and that the reduced workload might have made the pace feel more relaxed.

The relatively low intensity achievable with the small transducer array might have affected the results negatively. Further, the issue of targeting the small focal point on the small, moving fingertip discussed with study II might have resulted in the stimulus not landing on sensitive parts of the skin. Studies II and III both provided the user with visual feedback. It might be that mid-air haptics is more pivotal when visual feedback is not provided or when the visual attention of the user is required elsewhere - for example, in gestural interaction with in-vehicle systems while driving (Georgiou et al., 2017). There is evidence that mid-air haptics reduced visual demand (Large et al., 2019) and decreased eyes-off-the-road time (Shakeri et al., 2018) while driving on a driving simulator compared with gestural interaction without haptic feedback.

Study IV investigated the effect of adding vibrotactile actuation to gestural interaction with a large permeable display. A large permeable display can be an enticing walk-through screen, but with hand tracking, it can also be turned into a large touchscreen. As such, it can be a viable option for an engaging multi-user public display as it can be interacted with from both sides, it remains hygienic and the display cannot be broken even by stepping through it.

Often gestural interaction on large displays can suffer from the Midas touch issue, where the system detects unintentional selection gestures (Kjeldsen & Hartman, 2001). The illuminated particle flow offers the user some reference as to what the interaction depth for the gestures is, possibly alleviating the Midas touch issue. Still, the exact point of contact with the fog layer can be difficult to estimate visually without touch sensation. To aid in this, tapping and dwell-based interactions were supplemented with feedback from a custom-built wireless wearable actuation device in addition to audio-visual feedback.

Both tapping and dwelling are common gestures for gestural interaction with large screens and both have pros and cons. The speed at which targets can be selected using dwell-based gestures is heavily influenced by the dwell time duration. This could favor the faster tapping gesture. The prolonged gesturing of the dwell time-based gesture can also lead to physical fatigue (Hincapié-Ramos, Guo, Moghadasian, & Irani, 2014; Jang, Stuerzlinger, Ambike, & Ramani, 2017). However, when assessing the intuitiveness of several mid-air target selection gestures, the dwell time-based gesture was found to be the most intuitive (Hespanhol, Tomitsch, Grace, Collins, & Kay, 2012). Further, Walter et al. (2014) reported that people would commonly point and dwell at interactive elements if no explicit onscreen instructions were provided. However, Yoo et al. (2015)

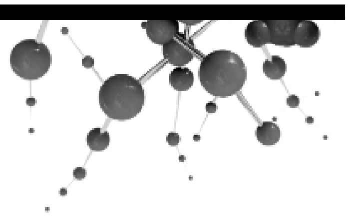
reported contradictory results where participants preferred the push gesture over dwelling for selecting items. Nevertheless, dwell-based gestures are often used if the recognition quality of the gesture-tracking equipment is poor (van de Camp et al., 2013; Yoo et al., 2015).

The experiment was repeated for both gestures, tapping and dwelling with and without the haptic device. The results showed that the vibrotactile feedback was preferred by the users in dwell-based interaction over audio-visual feedback alone. Overall, it seems that our device contributed more to improved user experience than raw performance, which remained about the same with and without the haptic feedback.

The aim of study V was to investigate the differentiation of six ultrasonic tactile stimulations that were varied by form (i.e., square and circle) and timing (i.e., movement speed and duration, and the frequency of tactile phases within a stimulus). Previous research indicates that while wearable tactile patterns can be very differentiable - up to 99% identification accuracy of 24 tactile patterns after 40 minutes of training (Lee & Starner, 2010) – ultrasonic feedback stimuli can be difficult to differentiate even when visual representations are provided (Rutten, Van Den Bogaert, Frier, & Geerts, 2019). Lee and Starner (2010) found that out of the four parameters they tested (i.e., intensity, starting point, temporal pattern, and direction), the temporal pattern was the easiest to identify, with the intensity being the worst-performing parameter. Hence, the stimuli used in study V were designed around the rhythm. The form was varied to see if changes in it would be noticed.

The results showed that stimuli formed of repetitive 400ms pulses were easier and more reliably identified than those with a shorter duration regardless of the number of repetitions. Post-experiment interviews revealed that the changes in form were not noticed. Based on the results of the post-experiment interviews, it seems unlikely that the ability of the ultrasonic transducer arrays to create shapes and spatial displacement could be used to encode a vast vocabulary of haptic icons. Instead, these results, combined with those from Rutten et al. (2019), seem to suggest that different shapes might only be differentiable in the most prominent cases (e.g., lines versus crosses). This would limit the size of a possible haptic icon vocabulary formed of shapes to a handful of symbols.

Overall, the types of haptics used in the studies introduced in this dissertation seem most beneficial when used in conjunction with other modalities, such as visual, or auditory feedback. Their impact on task performance depends on the use case, but people’s preference to include haptic feedback, and hence its positive effect on user experience, is clear.



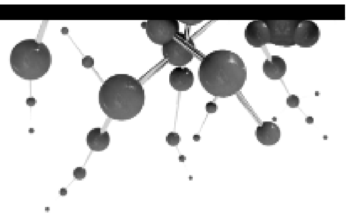
8 Conclusions

In conclusion, the results showed that ultrasonic mid-air haptic stimuli are a well-suited method for feedback delivery in permeable and virtual displays, but that the biggest advantage seems to come from improved user experience rather than improved productivity. Further, the results showed that users uniformly preferred the addition of haptic feedback to interaction with intangible user interfaces. In addition, the results showed that mid-air tactile stimuli can be designed so that they were reliably identifiable after minimal familiarization and hence can be utilized for efficient information transfer on tactile displays. Taken together, the findings of this thesis suggest functional solutions for adding haptic feedback in interaction with displays that currently are classified as unconventional but will become more mainstream technologies in the future.

This work was positioned at the intersection of various research fields. These include HTI, user interface research, haptics, and engineering. Currently, touch is used in HTI as an input relying on the inherent tactile nature of the touch surface, such as a smartphone or a trackpad. The present research indicates that multiple use cases require the touch sensation to be artificially generated. This can have a direct impact on how pleasant or demanding it is to use embodied interaction with permeable displays. The main outcomes of this research were the demonstrations of several methods, apparatus, and use cases for technology-mediated touch sensation with unconventional, permeable displays. Ultimately, the wider acceptance and adoption of these technologies rely on how meaningful and effortless the interaction can become.

Overall, haptic feedback can be an important factor in human-technology interaction. Several unconventional displays allow the user to touch at virtual objects but do not provide a touch sensation possibly leading to confusion, uncertainty, and lack of immersion. The cutaneous receptors responsible for touch sensations can be stimulated with technology-mediated stimuli, either wearable or from a distance. The constructive research introduced in this thesis explored some of the ways of doing this.

The results of the current work can partly help in motivating attempts to introduce more expressive and effective haptic feedback to interaction with unconventional displays, which eventually results in the case that devices currently classified as unconventional will one day become mainstream.



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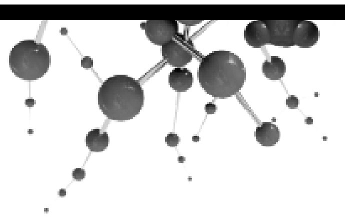

Paper I

Sand, A., & Rakkolainen, I. (2014). A hand-held immaterial volumetric display. In *Proceedings of SPIE – The International Society for Optical Engineering* (Vol. 9011, p. 90110Q).

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A Hand-held Immaterial Volumetric Display

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ABSTRACT

We have created an ultralight, movable, “immaterial” fogscreen. It is based on the fogscreen mid-air imaging technology. The hand-held unit is roughly the size and weight of an ordinary toaster. If the screen is tracked, it can be swept in the air to create mid-air slices of volumetric objects, or to show augmented reality (AR) content on top of real objects.

Interfacing devices and methodologies, such as hand and gesture trackers, camera-based trackers and object recognition, can make the screen interactive. The user can easily interact with any physical object or virtual information, as the screen is permeable. Any real objects can be seen through the screen, instead of e.g., through a video-based augmented reality screen. It creates a mixed reality setup where both the real world object and the augmented reality content can be viewed and interacted with simultaneously. The hand-held mid-air screen can be used e.g., as a novel collaborating or classroom tool for individual students or small groups.

Keywords: Fog screen, display technology, volumetric, walk-through screen, mixed reality

1. INTRODUCTION

Augmented reality displays would benefit from breaking free from the constraints of physical displays. This would allow the objects of interest to be enveloped by the display surface, bringing the augmented reality information closer to the object. This would shorten the mental and physical gap between the real object and the displayed augmented information, giving a more coherent user experience.

We have created a movable, ultralight “immaterial” display, which is inherently free from the aforementioned limitations. It creates a dense but confined screen of fog onto which the desired image can be projected. Our solution allows the user to reach through the screen and interact with the projection screen or with the real object behind the screen.

If the hand-held fogscreen is tracked in three dimensions, it can be used as a limitedly volumetric slicing display, which can be swept across mid-air to create slices of volumetric objects. It can also be used to create augmented reality on top of physical objects. The screen and its projected images can flow around and intersect with the real objects.

Our immaterial display medium can create added value in some use-case scenarios. Our novel display could be used for scientific work, such as analyzing volumetric data, e.g., magnetic resonance imaging (MRI) or computer tomography (CT) scan datasets in a natural and intuitive manner. The display can easily be moved to reveal the desired slices of the volumetric data. It could also be used for teaching and collaboration as an augmented reality display. The display is inherently “immaterial”, i.e., physical objects can be placed within or move through the display surface, making the display curve over and encompass the object. This creates a tighter bond with the augmented information and the physical object of interest.

2. RELATED WORK

There are several kinds of volumetric displays [1], which display objects and send light from their actual 3D position. Usually volumetric displays produce the images in a confined space with rotating or solid screens [e.g., 2, 3, 4, 5, 6], which do not allow touch and do not allow to place real objects into the display volume. Various kinds of volume slicing displays [e.g., 7, 8, 9, 10] enable volumetric slices on a movable diffuse plastic sheet in a very limited range. However, the solid sheet may be too cumbersome or it may harm delicate physical objects when used for augmented reality, as it requires proximity of the screen. Solid screens cannot intersect with physical objects, thus unnecessarily separating the real objects from the related virtual information.

Images have been projected to various kinds of water, smoke or fog screens for over 100 years [11]. They may produce impressive nightly shows e.g., in theme parks [12, 13], but usually they use wet projection surfaces, or alternatively they use thick particle (fog, smoke) flows as screens, which are not capable of creating sharp images, except when viewed from afar and directly towards the projector. The FogScreen [14, 15, 16] consists of a thick non-turbulent airflow, within which there is a thin, non-turbulent fog flow. The resulting fogscreen enables high-quality projected images in mid-air. It is also dry, so walking through the image is possible.

The previous fogscreen installations have been heavy, fixed setups with a width of a few meters. We have recently created proof-of-concept prototypes of ultralight, movable fogscreens. They can be expanded to volumetric slicing displays or “immaterial” augmented reality screens.

3. THE ULTRALIGHT FOGSCREEN

We have constructed a proof-of-concept ultralight immaterial display based on the FogScreen technology. It is the first mobile, hand-held fogscreen. The fogscreen flow unit, pico projector, and a smartphone (for tracking and rendering) are all merged to a light-weight hand-held unit, and only the fog is generated in a separate container. Figure 1 shows the ultralight fogscreen prototype construction. It has roughly the same dimensions and weight as a small toaster, making it light enough for convenient one-handed operation.

Figure 1: The hand-held fogscreen prototype construction.

The device can be lifted and swiped with the fitted handle fairly easily and can be held for a moderate duration of time. Holding the current prototype with one hand can, however, be strenuous in longer sessions. The device can be made smaller and lighter, allowing operation for longer durations of time with less strain to the user's hand. Future versions could also have more ergonomic and aesthetic design.

We employed a Microvision ShowWX+ pico projector, which can accept video from multiple sources through standard micro-HDMI port or VGA input. It can also be attached to Apple's mobile devices. It is a very small and light laser projector, but not very bright at 15 ANSI lumens. The projector is eye-safe for our (and most other) applications.

In our setup the viewer looks always roughly towards the projector, which produces higher brightness due to the high anisotropy of Mie scattering of light from the fog [17] and high resolution, as the neighboring pixels do not blend visually together [17]. It is not advisable to place the projector very off axis, as this would reduce apparent brightness and resolution. The slightly annoying hotspot of the projector can be removed with user tracking and proper rendering [18].

4. MOBILE SCREEN WITH TRACKING

In order to use the hand-held display as a volumetric or augmented reality display, it needs to be tracked. Initially we used visual AR markers for tracking. A marker-less solution would be more elegant, but for the prototype construction this was not essential. Modern smartphones have sufficient cameras and processing power for real-time movement tracking based on visual markers. The AR markers can, in addition to the position and orientation tracking, be used for object identification, but that was not implemented for the prototype device. Figure 2 illustrates the components and their positions.

The smartphone also serves as an image source for the pico projector. Volumetric image datasets in modest resolution can easily be rendered with relatively cheap smartphones. The high-end smartphone models or personal computers have enough graphics processing power to render moving and complex 3D graphics content if that is desired.

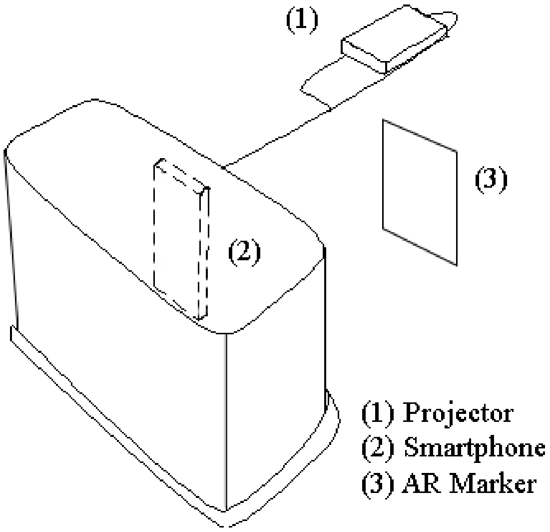

Figure 2: AR marker tracking components and their positions

Our prototype system requires at least one visual marker in a predefined location and orientation. More markers can expand the tracking volume. The software first tracks visual markers using the camera of the smartphone. The tracking software identifies the marker and acquires relative positions of its corners. From the corner point positions, we can estimate the delta of the distance to the camera as well as get the rotation of the device. By knowing the delta of the movement, we can render the desired slices of the volumetric dataset based on the sweeping motion of the hand-held display. Chart 1 illustrates the flow of information on volumetric slice rendering using AR markers and figure 3 shows the actual volumetric slicing prototype at work.

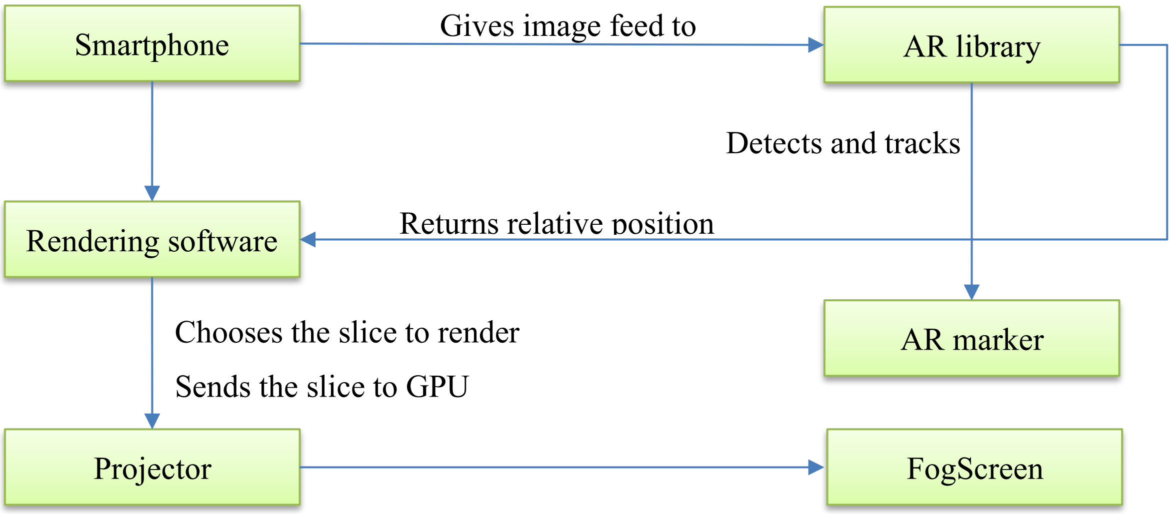

Chart 1: Flow chart of volumetric slice rendering using AR marker tracking

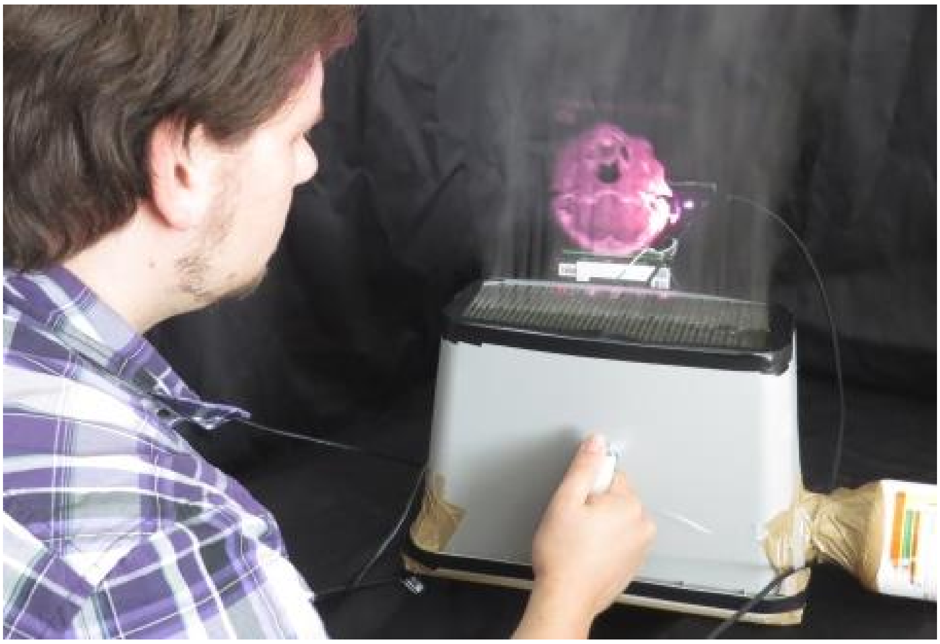

Figure 3: Mid-air visualization of volumetric objects.

We initially used js-aruco library [19] (a JavaScript port of the OpenCV based ArUco library) for the AR marker tracking. Advanced marker-less tracking is for future work. The prototype was built using standard HTML5 and JavaScript.

Instead of a hand-held unit, an alternative construction would be to use a desktop FogScreen, which would move the fogscreen plane back and forth automatically or manually, thus creating a reach-through slicing display volume with no strain on hands.

For this purpose, we tested a Leap Motion device [20] for tracking the user's hands and for displaying the volumetric slices based on the user's hand motion. Leap Motion or similar trackers enable to extend the range or type of interaction methods available and to create different kinds of software and user interfaces. We did also some preliminary testing by adding an RFID reader to the device to detect and identify the objects of interest and to display the desired augmented reality information corresponding to the identified object.

Our prototype can visualize three-dimensional objects in thin air. Several students can study together the visualized or augmented content and manipulate it, and thus understand better the phenomena or mechanisms behind it. AR seems to be a promising tool for collaborative learning and for providing learning experiences which integrate abstract and informative learning contents.

5. RESULTS

The device can render mid-air volumetric slicing images and it can be used in any orientation, e.g., upside down, sideways, etc. It also suits well for some AR visualizations. The display medium flows around real world objects and fills out any gaps left by intersecting objects. This allows for the object to be moved relatively quickly around and across the display surface without breaking solidness of the surface. There is however some turbulence occurring on the screen behind the object, if the object and the flowing screen intersect.

With the prototype and the visual AR marker we tested visualization of some medical datasets. The user can see the individual volumetric slices by just moving the apparatus in mid-air. We also tested some input hardware such as the Leap Motion tracker to create selection methodologies by pointing and grabbing. Leap Motion was also used for tracking the user's palm position to select a three-component value, such as the RGB color value, using the three axes of the 3D coordinate system.

The Microvision ShowWX+ projector outputs 15 ANSI lumens making the image brightness acceptable for the small screen size even in normal office lighting. This can be improved by using a brighter pocket projector, and pico projectors will improve further in the future. The maximum resolution of our projector is just 848 x 480 pixels, but as the viewing distance is short and the display surface is relatively small, the resolution still gives quite good results.

The hand-held proof-of-concept display is not as limited to physical constraints as many other volumetric slicing displays as objects can pass through it without touching. It provides an easy way to visualize volumetric objects in mid-air and its range is not as limited as with other projector-based systems, as the projector is in a fixed position relative to the screen and moves with the screen.

6. FUTURE WORK

Our proof-of-concept construction is still very crude and big, but the device can be made smaller and lighter, taking also ergonomics and design into account. We are working on improving the physical construction and image quality. The work is ongoing and user testing will be conducted in the near future.

A small depth camera can be added to improve the tracking or for interaction on the display volume. Also some of the sensors of modern smartphones (e.g., inertial sensor, gyroscope) can be used to further improve the tracking and interaction with the device. It is for example difficult to estimate slight rotation or tilt with just using the AR marker tracking, so a gyroscope can provide more accurate tracking when used in conjunction with them.

Continuous improvements on pico projectors (e.g., price, size, brightness) will help to make a hand-held fogscreen feasible in the near future. Smartphones have somewhat limited processing and rendering capabilities. We also made a version for standard personal computers, which enables more image processing and visualization power. Marker-less tracking, object recognition and complex rendering can require heavy processing from the smartphones, but eventually they become more powerful, and they may be suitable for complex signal processing operations in the near future.

As the smartphone is attached to the screen device in our prototype, the haptic feedback capabilities of the smartphone cannot be fully utilized. Additional haptic actuators and other feedback modalities could be included on the handle.

The fog in our prototype is created in a separate container, but it is possible to imagine a self-contained, truly mobile solution in the future. Such a device with smaller dimensions and weight could be carried with the user much like the office projectors of today.

7. CONCLUSIONS

Usually volumetric displays produce images in a confined space, which does not allow touch. These displays unnecessarily separate the real object and the augmented reality content. Various kinds of volume slicing displays enable volumetric slices on a diffuse plastic sheet, but in a very limited range and requiring a solid display surface, which cannot intersect with real objects making them less suitable for use with delicate objects.

We have created a movable, limitedly volumetric “immaterial” display. It is a new concept and also the first hand-held fogscreen. The proof-of-concept display can show e.g., slices of volumetric objects when swept across mid-air. It can also pass through real objects without touching them, being thus suitable for e.g., augmented reality in proximity of real objects. Applications for the display include mixed reality, mid-air 3D user interfaces [21], visualizations in mid-air [22], etc.

The work on the hand-held fogscreen is in the early phases and continues. In future revisions we hope to create a smaller and lighter device as well as create educational software applications for it to be tested with. Additional devices, such as trackers and actuators can be included in the future constructions.

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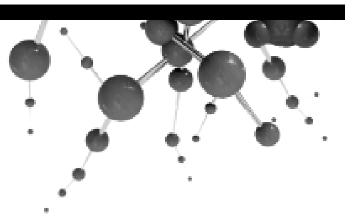

Paper II

Sand, A., Rakkolainen, I., Isokoski, P., Raisamo, R., & Palovuori, K. (2015). Light-weight immaterial particle displays with mid-air tactile feedback. In *2015 IEEE International Symposium on Haptic, Audio and Visual Environments and Games, HAVE 2015 – Proceedings.*

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Light-Weight Immaterial Particle Displays with Mid-Air Tactile Feedback

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Abstract— **Immaterial mid-air displays formed of flowing light-scattering particles are becoming feasible for displaying information in thin air and interacting with it. With light-weight desktop fogscreens and low-cost hand tracking, the user can easily and unobtrusively interact with virtual information. Any real objects can be seen or reached through the screen, as it is permeable and almost intangible. However, no tactile feedback can be perceived when interacting with a mid-air display.**

Our contribution in this paper is the construction of an interactive mid-air fogscreen employing ultrasonic phased arrays in order to create mid-air tactile feedback. The feedback is suitable for small desktop-sized fogscreens. This creates a mixed reality setup where real objects and e.g., augmented reality content can be brought closer together conceptually and physically. In an experimental evaluation of the mid-air tactile feedback for the fogscreen we found no significant difference in performance, but the mid-air tactile feedback was slightly preferred over no tactile feedback by the users. The tactile feedback is more engaging.

Keywords— Immaterial display; tactile feedback; mixed reality

I. INTRODUCTION

A “holographic” display in thin air has been pursued for centuries, starting from Wheatstone’s stereoscopic images in the 1830’s, to the emergence of various 3D displays [1]. Most 3D images are not truly mid-air or penetrable, but they only create an illusion of a 3D image. If they could break free from the constraints of physical displays, it would shorten the conceptual and physical gap between the real object and the augmented information.

The FogScreen [2] is a permeable projection screen. It consists of a thick non-turbulent airflow (~1 m/s), with a thin, non-turbulent fog flow as a part of it. The screen feels just like air to the hand. The planar dry-to-touch light scattering particles serve as a rear-projected screen with the unusual feature that the user can unobtrusively interact with the screen, or walk or reach through it.

Tactile mid-air feedback has recently been created by utilizing focused ultrasonic transducers. This is not feasible for large fog-screens, as distances of several meters would require very large ultrasonic arrays, but it can be used for smaller screens. The mid-air tactile feedback on the screen makes virtual objects tangible.

Our contributions in this paper are the construction of light-weight fogscreens, and employing ultrasonic phased arrays to create mid-air tactile feedback for them. We have created several prototypes of portable, light-weight “immaterial” displays with mid-air tactile feedback to explore the new opportunities. We have also made initial user tests of the tactile fogscreens to measure the user’s per-formance and subjective impressions.

In this paper we first describe related work. We then present the light-weight interactive fogscreens, and how to create mid-air tactile feedback for them. Finally we present the results of our user test and conclusions.

II. RELATED WORK

Volumetric displays render objects and send light from the actual 3D position. Usually they produce images in a confined space with rotating or solid screens, which do not allow to touch or the placement of real objects into the display volume. Images have also been projected to various kinds of water, smoke or fog screens for over 100 years [3]. Usually the water and fog screens are wet or use thick particle flows as screens, which cannot reproduce sharp images, except when viewed from afar and directly towards the projector. The FogScreen is the optimal method to create a particle screen in terms of high-quality images in mid-air. Previous installations have been heavy setups with a screen width of a few meters.

Gestural interfaces let people interact with devices using hand gestures. Effective feedback helps users in avoiding uncertainty about gesture performance. Visual or auditory feedback is often used, but also various ways of haptic feedback [4] are possible.

Targeted air jets or vortex launching [5, 6] can deliver mid-air tactile feedback, but they are relatively coarse and slow for real-time interaction. Several aerial tactile feedback systems employing acoustic radiation pressure have been reported [7, 8, 9, 10, 11, 12]. Some of them have also been merged with display devices to augment the visual feedback. Small mid-air reach-through particle displays would be a natural match with the mid-air tactile feedback.

III. Light-Weight FogScreens

One contribution of our work is a proof-of-concept light-weight fogscreen construction where the fog is generated in a separate container and then directed through a flexible pipe to the flow unit, which then shapes the fog and air flows to laminar form. This enables small, movable, even hand-held fog dispenser units, which can be used e.g., as an augmented reality (AR) display. It is inherently "immaterial", i.e., physical objects can be placed within or move through the screen.

The challenge with a fogscreen of any size is to create proper structures for the laminar flow. Uniform flow is easier to create for small size screens, as the flow does not have to stay laminar for as long a distance as with the bigger screens. Also lower projector flux can be used for small screen area. Nevertheless, just scaling down every part will not do. Essential parts of the design are the inner flow structures, flow speed and an ideal honeycomb structure. We tested several honeycombs and 3D printed designs for our prototypes.

Our first hand-held fogscreen prototype [13] weighed 1069 g (Fig. 1, at left) and had a screen width of 250 mm. 3D printing helped to optimize many components. A lighter prototype (Fig. 1, at right) dimensions are 210 x 100 x 70 mm and a weight of 271 grams not including the projector. The screen is 200 x140 mm.

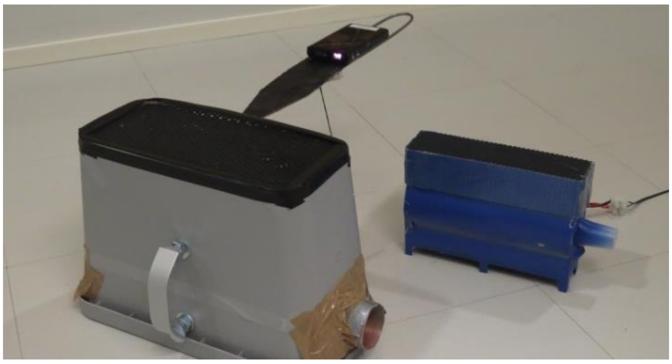

Fig. 1. Light-weight fogscreen prototypes. The bigger one has an integrated projector on an extruding arm.

The ultralight fogscreen can be used as a desktop device, it can be embedded into a desk, or optionally it can be used as a hand-held fog dispenser unit. Gravitation has no role on the travel of fog. The fog dispenser can be used in any orientation, e.g., upside down, sideways, etc. If the flow unit is moved or tilted, it takes about 0.2 sec. for the screen of fog to stabilize.

Hand-held fog dispensers (~size and weight of a small hair dryer) can be used as pseudo-volumetric or AR screens [13, 14]. However, a small desktop fogscreen unit can be used for most applications and purposes, which prevents hand fatigue on extended usage. A hand-held unit is needed mainly for some special applications such as pseudo-volumetric 2D slicing or some types of AR.

If an object intersects the flowing screen, there is some turbulence occurring on the screen flow behind the object, but the flow immediately restores the screen when the object is removed. The intersecting object creates an upward turbulent flow that does not significantly exceed its width, leaving the rest of the display surface on its sides intact. The object may also occlude part of the projection, but usually most of the screen nearby can still be used.

The fog is generated from pure water with ultrasonic atomization in a stationary container. The fog droplets are so tiny (~10 µm) that they do not impact or wet the intersecting object.

The noise consists mainly of three fans each generating 7 to 20 dBA (depending on the fan diameter and operating voltage). The device and the projector are practically silent. Also the pressure exerted by the flow of fog is very low.

We used Microvision ShowWX+ and Optoma ML750 pico projectors. Microvision is small (122 g) but not very bright (15 ANSI lumens). Optoma has 700 ANSI lumens, but it is heavier (380 g). It has also high contrast, which is good for fogscreen applications.

In our setup the viewer looks always roughly towards the projector, which produces high brightness due to the anisotropy of Mie scattering of light from the fog [15] and high resolution, as the neighboring pixels do not blend visually together. The thickness of the display medium in our prototypes is roughly 10 mm. The image is clearly visible up to 45° angle around the actual projection direction [15]. The slightly annoying hotspot of the projector (i.e. the bright projector light seen through the projected image) could be removed with user tracking and proper rendering [16].

IV. Mid-air Tactile Feedback

We constructed a phased ultrasonic transmitter array and merged it with a 17" desktop fogscreen. Mid-air tactile feedback is suitable for small screens, but not for large screens, as distance of several meters from the transducers would require massive ultrasonic arrays. The location of the phased array must be close enough to the screen area, it must not obstruct the fog flow and it should not block light from the projector. Also the user's freedom of movement must be maintained. In our user tests we used half of the screen to maximize the tactile effect. The array was 9-12 cm from the keys on the screen. Fig. 2 shows our prototype.

Fig. 2. A user is pressing keys on a particle screen with finger tracking and tactile feedback. From front left to back right: Leap Motion Controller, FogScreen, phased ultrasonic 16x8 array and projector (masked with an R2D2 printout).

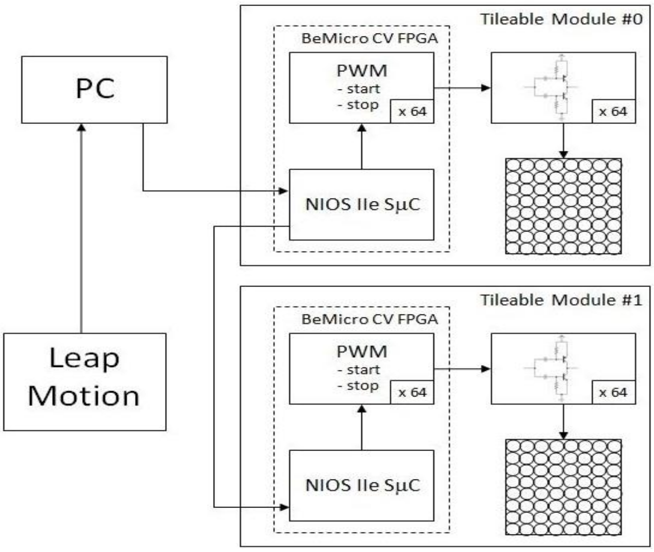

Fig. 3. Ultrasonic transducer array structure and its control.

The acoustic radiation pressure has a small visible interference with the fog layer in some cases, but in general the turbulence causes much bigger effect on the screen. While the sound pressure for the focused ultrasound is impressive (calculated to be of the order of 150 dB), the particle displacement in air is still minuscule. The observable disturbance to the image is further reduced by the fact that the ultrasound is emitted only when tactile feedback is needed. The finger is partially blocking the visibility of the area of the display, which is slightly disturbed by the intersecting finger and by the ultrasound focus area.

The ultrasonic 2D-array consists of two infinitely tileable array modules (64 transducers each), thus the whole array has 128 transducers. The system is connected via a USB serial port to a PC, which controls the generation of the tactile feedback effects. Finger or hand is tracked with a Leap Motion Controller[1]. Fig. 3 shows the ultrasonic transducer array structure and its control system. Fig. 4 shows the constructed ultrasonic 2D-array.

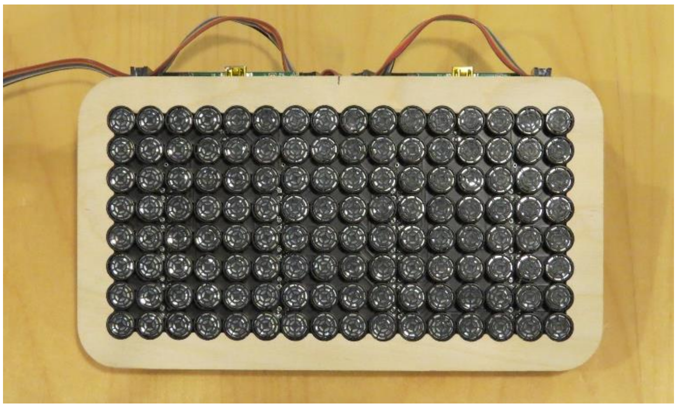

Fig. 4. The 16x8 phased ultrasonic transducer array.

Each ultrasonic array module consists of 64 low-cost 40 kHz transmitters with 64 dedicated, local, discrete transistor amplifiers and an FPGA board with 64 high-resolution pulse-width modulation (PWM) generators marshalled by a NIOS IIe soft processor. We used Multicomp MCUST10P40 B07RO transducers and integrated the custom voltage amplifier directly below each transducer, being thus able to dispense with the multitude of cables and amplifier boards typical for these kinds of systems. We stacked an FPGA board below the transducer board, which makes each module self-contained, requiring only a power supply and high level commands from the application.

The 64 ultrasound channels are generated by 64 PWM circuits, which are controlled by individually selectable pulse start and stop times. The timing is relative to a 10-bit counter running at 40.96 MHz resulting in a constant 40 kHz pulse frequency. The amplitude of each ultrasound channel is controlled by its pulse width and the phase by its pulse phase. The amplitude A of the relevant 40 kHz sine component of the harmonic content of a 40 kHz pulse wave depends on the pulse width W non-linearly as

$$A = A_0 \frac{2}{\pi} \sin\left(\pi \frac{W}{T}\right), \qquad (1)$$

where A_0 is the pulse wave amplitude and T is the cycle time i.e. 25 μs. Thus the amplitude changes from 0 to the maximum of $A_0 \frac{2}{\pi}$ as the pulse duty cycle increases from 0 % to 50 % and similarly returns to 0 as the duty cycle increases to 100 %. Due to this mirroring, there are 9 bits of actual amplitude control while full 10 bits of phase control for each ultrasound channel. Since the steepest slope for the non-linear amplitude response is $\pm \frac{\pi}{2}$ (at 0 % and 100 %) i.e. less than 2, the worst case local resolution of the amplitude is still better than 8 bits. If this worst case is used to quantify the amplitude levels, the result is approximately 326 levels, which coincidentally happens to be very close to the 320 reported in [17].

To create a single ultrasonic focal point, it is only necessary to adjust the phases of the channels to coincide at that point. This requires calculating the distance to each transducer and compensating the transmission delay by advancing the phase accordingly. To create a more complex pattern, e.g. consisting of multiple foci and/or nulls or even an arbitrary force field, the optimal set of phases and amplitudes need to be solved. This was reported to be computationally challenging for real time response [18], but we found a reasonable approximation to be within the reach of the modest NIOS IIe. Of course, with an FPGA, the calculations could ultimately be assisted in hardware, too.

Since the human sense of touching fingers and palms is found to be the most sensitive to vibration of 150 – 250 Hz [19], we provided an option to hardware modulate the 40 kHz ultrasound carrier on and off at 200 Hz to create a strong tactile vibrating signal. To avoid generating audible 200 Hz noise as a side-effect, every other channel was turned off by setting it to 0 and every other to 1. This approach is advisable in normal

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

operation, too, by using the pulse widths of 0 - 50 % for the odd and 50 – 100 % for the even transducers to balance the total array DC component. While the transducers are very resonant, having a Q of about 40, audible frequencies are still easily converted to noticeable sound, due to the high overall signal level. The high Q also limits the modulation rate to 1 kHz, which is not a significant restriction, but results in an additional 1 ms delay to the system response time.

The maximum power requirement is 700 mA/24V for the array, and 200 mA/5V for the FPGA board. The 10 mm diameter transducers are placed in a 16x8 matrix (160x80 mm) to obtain high packing density and a simple structure for the driving electronics. The array depth is 29 mm and weight 253 g without cables.

The system can achieve a positional resolution of 2 mm and an active focus size of 10 mm at 100 mm distance. The response time is about 2 ms, dominated by the phased array transducer response time (1 ms) and the sound travel time (~34 cm/ms).

The tracking data is interpreted into screen space within and nearby the screen area. The fog did not affect the tracking, as both the Leap Motion and the hand are in front of the fogscreen. The tracking data updates the tactile focus to desired position on the screen, such as buttons on the user interface (UI), thus affirming the user that it was actually pressed.

The prototype used a fairly small ultrasonic array but even with this size the effect was clearly noticeable up to around 30 cm distance. The focal width is determined by the wavelength and the F-number. The F-number is increased with larger array, resulting in tighter focus. Larger or tighter arrays would produce a stronger and more focused sensation, and our system is infinitely tileable.

The tactile sensitivity of human hand varies widely on various parts of the skin [20]. Fingertips are the most sensitive for vibration caused by ultrasonic pulses. Also palmar side of the hand is fairly sensitive, but the dorsal side of the hand and other body parts are significantly less sensitive. Thus orientation of the hand (and location of the array) has an effect on the tactile feedback.

Safety is one important issue concerning the use of focused ultrasonic feedback, especially as in our case it is directed towards the user's head. Ultrasound at 40 kHz is not audible, but it might potentially have some effects on ears [21]. While we have not yet measured the sound field generated by the array in detail, there are several reasons why it can be considered safe. First, as the ultrasound is focused, we estimate that even a dislocation of 10 cm away from the focus would reduce the volume by 20 dB (1/100th of the power). Secondly, user's head is typically 20-50 cm away from the focus area (the screen). According to Lenhardt [22] "detectability and the potential for damage to hearing are related," and our system is not audible. He recommended 145dB maximum exposure at 40 kHz, which is extremely loud. In our applications the power is lower and pulse duration is very short.

V. USER TEST

In order to evaluate the tacto-visual display, we compared it with and without the tactile feedback in a key pressing task. 12 participants (4 female, 8 male; from 27 to 59 years old) participated in the experiment.

We ran a simple 3x2 numerical keyboard task (see Fig. 2) in two different conditions. The independent variable was the presence of tactile feedback. The visual feedback was identical in both conditions. The dependent variables were measures of tapping performance (text entry rate and error rate) and subjective ratings of workload. The actual pressing of a button was made with a slight push towards the screen. The pressing was affirmed with a 0.2 s visual flash (key changed its color) and in the tactile case also with a 0.2 s tactile burst of 200 Hz modulated ultrasound aimed at the location of the button being pressed. Whatever part of the hand was on the location received the feedback.

A block of number entry consisted of 15 tasks of entering 3 random numbers, which were randomized for each task and participant. Each participant first completed training blocks in each condition and the results from the second blocks are reported below. The order of tactile vs. no tactile conditions was balanced between participants. Touching wrong numbers caused the same feedback as touching correct numbers. The system recorded the entered values and their timestamps, from which we calculated the entry speed and error rate. After each block the participant filled in a TLX questionnaire [23] on paper and indicated whether he or she preferred to have the tactile feedback or not.

The **results** showed small differences. Numbers were entered at the rate of 0.97 characters per second (cps) without tactile feedback and at 0.74 cps with tactile feedback. The error rate without tactile feedback was 14% and 17% with it. However, these differences were not statistically significant according to paired samples t-tests. The differences in **TLX ratings** were also not statistically significant. Finally, **preference ratings** continue the same trend, while 8 out of 12 preferred to have the tactile feedback, according to the binomial distribution this result will happen 19.4% of cases if the participants answer randomly. More user tests are needed in our future work.

VI. DISCUSSION AND CONCLUSIONS

We have presented a prototype of light-weight interactive fogscreens with mid-air tactile feedback. As tactile feedback is feasible mainly for small screen sizes, it required a new kind of fogscreen construction and 3D printed parts. While dwelling over an UI element, mid-air tactile feedback can make the mid-air image feel more natural and tangible. Tactile sensation can also affirm the user that a selection has been made while making pushing or other gestures [4], giving a more coherent user experience.

The tactile feedback is more engaging than without it. However, our preliminary evaluation did not show measurable benefits of the tactile feedback. There can be multiple reasons for this. The implementation can be improved with a larger ultrasonic array that produces stronger feedback. Any tracking errors would impact the effect as the pointing finger is relatively thin. The novelty of the mid-air tactile feedback may also have distracted the participants from the task that they were asked to perform. Curiosity may lead new users to trying to maximize their interaction with the tactile feedback rather than optimizing their performance in the task. In a longer experiment the novelty would wear off and better concentration on the task could lead to better utilization of the tactile feedback to improve performance.

The work on the tactile desktop fogscreen is in the early phases and will continue. Our proof-of-concept fogscreen prototypes are still crude and big, but the device can be made significantly better and smaller, with also having more ergonomic and aesthetic design. Depth cameras and other trackers could improve interaction.

Tactile mid-air displays blur the boundaries between real and virtual worlds. Mid-air tactile feedback matches well with the "immaterial" fogscreen, as it enables the user to touch and feel virtual objects in thin air in an unobtrusive way. It seems to be an important interaction element and improve sense of presence.

Light-weight mid-air screens are versatile and they can become fairly low-cost devices, thus eventually enabling their wider adoption. Applications for the mid-air tactile particle display include mixed reality, mid-air 3D UIs [14], remote haptic collaboration, telepresence, engineering prototyping, visualizations in mid-air, etc. However, as any display technology, these screens have their advantages, uses and limitations.

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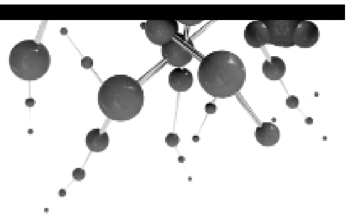

Paper III

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Head-Mounted Display with Mid-Air Tactile Feedback

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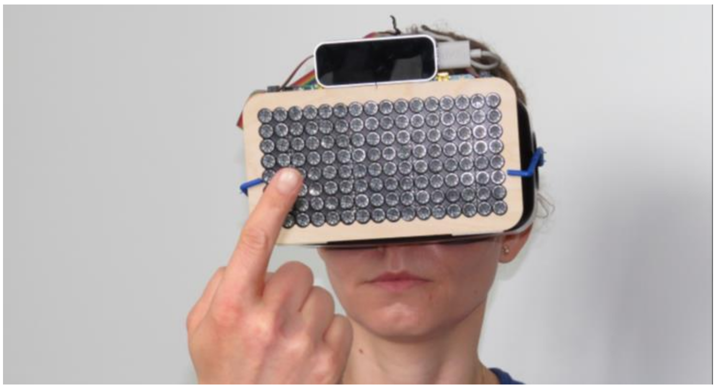

Figure 1: *A modulated ultrasonic phased array integrated to a head-mounted display can provide tactile feedback in mid-air.*

Abstract

Virtual and physical worlds are merging. Currently users of head-mounted displays cannot have unobtrusive tactile feedback while touching virtual objects. We present a mid-air tactile feedback system for head-mounted displays. Our prototype uses the focus of a modulated ultrasonic phased array for unobtrusive mid-air tactile feedback generation. The array and the hand position sensor are mounted on the front surface of a head-mounted virtual reality display. The presented system can enhance 3D user interfaces and virtual reality in a new way.

To evaluate the tactile feedback together with visuals on an Oculus Rift VR headset, we had 13 participants do a simple virtual keypad tapping task with and without tactile feedback. The results indicate that while the measured speed and accuracy differed only a little, the subjects were nearly unanimous in that they preferred to use the tactile feedback. The "raw" NASA TLX questionnaires conducted after use revealed that the participants felt slightly less mental, physical and temporal demand with the tactile feedback. The participants' self-assessment of their performance was also higher with the tactile feedback.

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1 Introduction

The first head-mounted display (HMD) employing 3D graphics and head tracking was envisioned already 50 years ago [Sutherland 1965] and implemented in 1968 [Sutherland 1968]. Recent HMDs can be categorized to *immersive* HMDs, optical *see-through glasses* and *peripheral displays*. Immersive HMDs (e.g., Oculus Rift) block out reality and replace it with a synthetic one. See-through glasses (e.g., Meta Pro) have a form factor of eyeglasses and they show synthetic objects on top of real ones. *Peripheral* near-to-eye displays cover only a small area of the human visual field at the edges. They are typically monocular and small.

Hand gestures are a natural and intuitive way of pointing or selecting with HMDs [Billinghurst et al. 1998]. Modern gestural sensors such as the Leap Motion Controller[1] or small depth cameras can be mounted on or embedded in HMDs to let users interact through mid-air hand gestures. Mid-air gestures, however, suffer from the lack of tactile feedback that is an important part of the feedback mechanism when interacting with physical objects.

When an HMD is used, often only vision- or audio-based affirmation for the interaction with virtual objects is provided. Data gloves or desktop or wearable haptic hardware can provide tangible sensation [Freeman et al. 2014], but often the devices are

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

tethered, obtrusive or the interaction is indirect. In all fairness, the same can be claimed also about HMDs.

Interaction in virtual reality (VR) without tactile feedback may feel unreal and can lead to uncertainty. The user may wonder: “did the action register”, or “am I pressing a button or just waving my hand in front of it”. Mid-air tactile feedback can make the experience feel more natural and reassure the user that the hand was indeed in contact with the virtual object.

Our contribution in this paper is to demonstrate a mid-air tactile feedback system that can be built into the front surface of an HMD (Figure 1). We also conducted a small experiment to measure the performance and subjective impressions on tactile feedback when using the tacto-visual HMD. We utilized a self-constructed proof-of-concept prototype of an ultrasonic transmitter array with 128 transducers. It enables tactile interaction with virtual objects. In addition to the experiment with the Oculus Rift DK2[2] HMD, we informally tested the prototype with a Homido[3] HMD for smart phones to enhance virtual objects with mid-air tactile feedback. As discussed later in this paper, the system has interesting implications for 3D UIs, VR and other 3D applications.

In this paper we first discuss previous work and then present our mid-air tactile hardware implementation and how it is merged with HMDs such as Oculus and Homido. We describe and discuss the results of user tests and finally give conclusions.

2 Previous Work

Many kinds of 3D user interfaces [Bowman et al. 2004] and devices can benefit from mid-air tactile feedback. Any interface that relies on the user's hand touching objects in VR has potential to benefit from mid-air tactile feedback. Potential usage situation include keyboard use (as in our experiment), sensing of ephemeral elements such as wind or rain, touching objects to feel, move or deform them, feedback from controlling abstract data visualizations, etc.

Prior to the emergence of mid-air haptics, meaningful touch-based interaction was limited to touch detection and tactile sensation through the touched surface. Wider-range tactile feedback required tactile data gloves [e.g., Ku et al. 2003] or other wearable haptics hardware. A comparison of various ways of providing tactile feedback without touching the device has been published recently [Freeman et al. 2014].

Mid-air tactile stimuli mechanisms with air jets or vortex launching [Gupta et al. 2013; Sodhi et al. 2013] can give tactile feedback, but they are coarse and relatively slow for real-time interaction.

Recently several systems of focused acoustic air pressure for providing aerial tactile feedback have been reported [e.g., Carter et al. 2013; Hasegawa and Shinoda 2013; Hoshi et al. 2009; Inoue et al. 2014; Iwamoto et al. 2008; Long et al. 2014; Monnai et al. 2014; Palovuori et al. 2014; Sand et al. 2015; Takahashi and Shinoda 2010; Wilson et al. 2014]. The phased ultrasonic transmitter array focuses the ultrasound signals to one or several focal points. Mid-air tactile feedback is not suitable for large distances of several meters from the transducers, as that would require massive ultrasonic arrays. Mid-air tactile feedback is unobtrusive and maintains the user’s freedom of movement in the target area.

Some mid-air tactile feedback systems [Hoshi et al. 2009; Inoue et al. 2014; Long et al. 2014; Monnai et al. 2014; Sand et al. 2015] have also been merged with display devices such as 3D monitors or mid-air reach-through particle displays. All of them used *stationary* ultrasonic arrays so that the user needed to stay close to the array in order to receive the tactile feedback.

Several works on measuring perception of ultrasonic tactile feedback have been published [Ryu et al. 2010; Wilson et al. 2014; Yoshino et al. 2012]. The human sense of touch in fingers and palms is found to be the most sensitive to vibration of 150 – 250 Hz [Ryu et al. 2010]. A good form of mid-air tactile feedback for a button click has been reported as a single 0.2 s burst of 200 Hz modulated ultrasound [Palovuori et al. 2014], where all test subjects described it to be an 'unmistakable' and confirming response functionally equivalent to a physical button click.

3 Mid-Air Tactile Feedback Array

Head-mounted displays seem to be a natural match with mid-air tactile feedback, as the tactile actuator can be attached to the HMD and thus it can be moved freely with the user. The head mounted ultrasonic array is always pointing to the active field of view of the user.

We created a 2D ultrasonic array, which consists of two infinitely tileable ultrasonic array modules (64 transducers each), thus the whole array has 128 transducers. The system is connected via a USB serial port to a PC, which controls the generation of the tactile feedback effects. Finger or hand is tracked with Leap Motion controller. Figure 2 shows the structure of the transducer array and its control system.

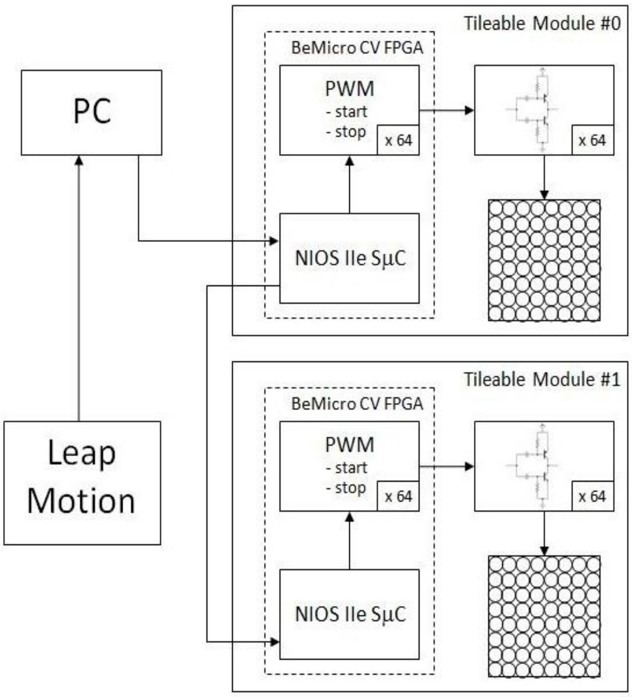

Figure 2: *The ultrasonic transducer array and its control.*

Each ultrasonic array module consists of 64 low-cost 40 kHz transmitters with 64 dedicated, local discrete transistor amplifiers

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[2] https://www.oculus.com/

[3] http://www.homido.com/

and a FPGA board with 64 high-resolution pulse-width modulation (PWM) generators marshalled by a NIOS IIe soft processor. We used Multicomp MCUST10P40 B07RO ultrasound transducers.

We integrated a custom voltage amplifier directly below each transducer, being thus able to dispense with the multitude of cables and amplifier boards typical for these kinds of systems. The phase and amplitude of each of the transducers is controlled with 1024 and 512 steps, respectively. The modulation signal is generated directly by the FPGA boards and does not require real-time external control. The modulation frequency can be set freely from 0 Hz to 400 Hz, although at these limits the effect becomes unnoticeable.

We stacked a FPGA board below the transducer board, which makes each module self-contained, requiring only a power supply and high level commands from the application. Figure 3 shows the ultrasonic transducer array for HMD.

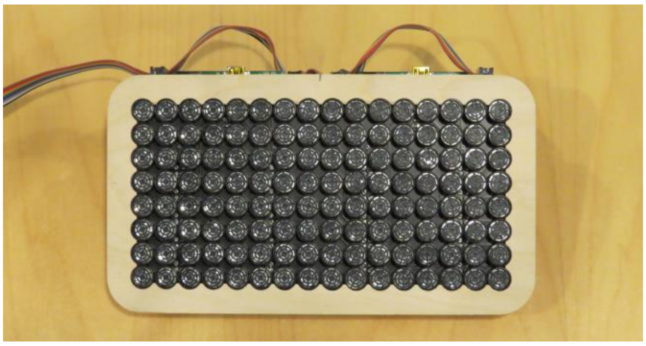

Figure 3: *The 16x8 phased ultrasonic transducer array.*

The 64 ultrasound channels are generated by 64 PWM circuits, which are controlled by individually selectable pulse start and stop times. The timing is relative to a 10-bit counter running at 40.96 MHz resulting in a constant 40 kHz pulse frequency. The amplitude of each ultrasound channel is controlled by its pulse width and the phase by its pulse phase. The amplitude A of the relevant 40 kHz sine component of the harmonic content of a 40 kHz pulse wave depends on the pulse width W non-linearly as

$$A = A_0 \frac{2}{\pi} \sin\left(\pi \frac{W}{T}\right), \qquad (1)$$

where A_0 is the pulse wave amplitude and T is the cycle time, i.e., 25 µs. Thus, the amplitude changes from 0 to the maximum of $A_0 \frac{2}{\pi}$ as the pulse duty cycle increases from 0 % to 50 % and similarly returns to 0 as the duty cycle increases to 100 %. Due to this mirroring, there are 9 bits of actual amplitude control while full 10 bits of phase control for each ultrasound channel. Since the steepest slope for the non-linear amplitude response is $\pm\frac{\pi}{2}$ (at 0 % and 100 %), i.e., less than 2, the worst case local resolution of the amplitude is still better than 8 bits. If this worst case is used to quantify the amplitude levels, the result is approximately 326 levels, which coincidentally happens to be very close to the 320 reported in [Hasegawa and Shinoda 2013].

To create a single ultrasonic focal point, it is only necessary to adjust the phases of the channels to coincide at that point. This requires calculating the distance to each transducer and compensating the transmission delay by advancing the phase accordingly. To create a more complex pattern, e.g. consisting of multiple foci and/or nulls or even an arbitrary force field, the optimal set of phases and amplitudes need to be solved. This was reported to be computationally challenging for real time response [Wilson et al. 2014], but we found a sufficient approximation to be within the reach of the modest NIOS IIe for real-time response. Of course, with a FPGA, the calculations could ultimately be assisted in hardware, too.

Since the human sense of touching fingers and palms is found to be the most sensitive to vibration of 150 – 250 Hz [Ryu et al. 2010], we provided an option to hardware modulate the 40 kHz ultrasound carrier on and off at 200 Hz to create a strong tactile vibrating signal. To avoid generating audible 200 Hz noise as a side-effect, every other channel was turned off by setting it to 0 and every other to 1. In other words, the gross DC signal level of the entire array is kept at 50% at all times. This approach is advisable in normal operation, too, by using the pulse widths of 0 - 50 % for the odd and 50 – 100 % for the even transducers to balance the total array DC component. While the transducers are very resonant, having a Q of about 40, audible frequencies are still easily converted to noticeable sound, due to the high overall signal level. The high Q also limits the modulation rate to 1 kHz, which is not a significant restriction, but results in an additional 1 ms delay to the system response time.

The maximum power requirement is 700 mA / 24 V for the array, and 200 mA / 5V for the FPGA board. Instead of the power cable, a rechargeable battery could be used for the array for light to modest use, especially in case of smartphone-based HMDs such as Homido, which don't have any cables attached (unlike Oculus).

The 10 mm diameter transducers were placed in a 16x8 matrix (160x80 mm, roughly the same as the front plate of Oculus Rift and similar HMDs) to obtain high packing density and a simple and ordered structure for the driving electronics. Maximum depth of the array is 29 mm. The weight of our ultrasound array without cables is 253 g.

The ultrasonic focal point can be created to a desired three-dimensional location in front of the array. The focal point can also be beyond the matrix area, but the further the focus point is projected, the weaker the tactile effect becomes. The system automatically phases each of the transducers in the array to produce a coherent focus of the 40 kHz carrier at the intended point of feedback. The very strong local ultrasound pressure gives rise to radiation pressure pushing the skin slightly. When the ultrasound is modulated (i.e. turned on and off repeatedly), it creates stronger vibration to the skin, and thus the touch becomes much clearer and more noticeable than without modulation.

The phased array is able to generate a clear and tactile focal point with an active spot size of about 10 mm at 100 mm distance. This is close to the Visio-Tactile Threshold reported in [Yoshino et al. 2012]. The typical response time of the system is about 2 ms, dominated by the phased array transducer response time (1 ms) and the sound travel time (~30 cm/ms).

4 HMD with Mid-Air Tactile Feedback

The Leap Motion controller and the ultrasonic transducer array were mounted on the front surface of the Oculus Rift DK2 HMD. The Leap Motion tracked user's finger and hand, and detected when the interactive VR objects and the tip of the index finger of the hand model intersected. The haptic and visual feedback was then given. The feedbacks were played to their full duration of 0.2

seconds regardless of what happened to the intersection during the feedback. The ultrasound was focused onto the center of the pressed key.

As far as we know, there are no earlier implementations of ultrasonic arrays embedded into head-mounted displays. We also made a version for Homido HMD, but that was not used in the user tests.

Figures 1 and 4 show a person wearing our tactile Oculus Rift DK2 prototype. While it is important to be able to dynamically focus the feedback to a point where the fingers are in contact with the virtual model, the volume in which the feedback is needed can be made fairly small in practical implementations. First of all, the comfortable depth range of touching with the hand is limited by the length of the arm. Secondly, working very close to one's own face does not feel comfortable. Furthermore, the HMD limits the shortest possible distance. The needed range can be further reduced by scaling the virtual space so that full arm extensions and interactions very close to the face do not happen.

Figure 4: *Mid-air tactile feedback can focus ultrasound waves to user's finger or palm, which are here tracked with Leap Motion. The system can be used with any HMD, here with Oculus Rift.*

Also, people generally tend to turn their heads so that they face the area where they are looking at [Foulsham et al. 2011]. Thus, the effective volume of our array covers a very large percentage of the interaction situations.

If the point of interaction is known in advance, as is the case for the push buttons in our user study, all the necessary calculations can be computed and tabulated beforehand. For larger or more freeform interaction, these calculations may increase the response time. Still, for a single focal point anywhere within the effective volume, the calculations are easily performed by a low-end microcontroller in real time.

In informal tests with the prototype we found that the user can get a reasonably strong tactile sensation up to 30 cm from the ultrasound array. Adding the thickness of the display and the array, the maximum distance from the face is almost 50 cm. The focus point is best felt if the hand is slightly moving and not stationary. Longer range sensation beyond 30 cm is still perceptible but rather weak. By using more ultrasonic transducers, a tighter focus with much higher intensity can be produced. At some point, however, the size of the array becomes impractical for head-mounted use. We found the 128 transducer array a reasonable compromise between sensation intensity and array size.

The tactile sensitivity of human hand varies widely in different parts of the skin [Pont et al. 1997]. Fingertips and the palmar side of the hand are the most sensitive for vibration caused by ultrasonic pulses. The dorsal side of the hand and most other body parts are significantly less sensitive – in fact the persons that tested it could feel only very weak effect or nothing at all on the dorsal side. Thus hand orientation has an effect for the use of the tactile HMD. Dorsal push gesture (back of the hand pointing towards and moving away from the user and HMD) is ergonomically a little easier to execute, but a pull gesture with the palm facing the array is required for sensing the tactile effect. The user should be guided to orient the hand so that the use the palmar side faces the ultrasonic array in order to gain the maximum tactile effect.

There are several built-in near-infrared LEDs on the front plate (and on all the sides) of the Oculus Rift HMD. Oculus Rift DK2 has an external IR camera which tracks the LEDs and they are used for positional tracking. Our ultrasonic array hides many of the LEDs and thus positional tracking may not be as reliable as normally. This is not an inherent problem in our design. It would be easy to embed both the ultrasonic array and the infrared LEDs to the Oculus front plate. Furthermore, most smart phone-based HMDs such as the Homido do not have IR LEDs, as their tracking is based solely on the sensors embedded in the smartphone.

As the Leap Motion controller and the phased array are attached to the Oculus HMD pointing at the perceived viewing direction, both the hand tracking and tactile feedback occur naturally in front of the eyes no matter which way the user is looking at. As the user can see a representation of the tracked hand in the virtual environment, it is easy to actually point at and feel the virtual UI elements. The tactile effect can cover the field of view of the HMD at the distance of 30 cm.

5 User Tests

In order to evaluate the HMD-based tacto-visual display, we compared it with and without the tactile feedback in an object touching task. The goal of this initial user test was to get insight in performance, usability, and preference.

Participants
We recruited 13 participants (2 female, 11 male; from 23 to 47 years old, with a mean age of 32) from the laboratory staff and students. None of the participants had previous experience with mid-air ultrasonic haptics.

Recruiting "in house" participants may lead to a bias, but recruiting random people might also lead to a bias because the HMD and ultrasonic tactile stimulation are "pretty cool" to a layman. We hoped the technology savvy participants would be more objective and critical. However, we have no data to support this hope and our results should be read with caution given the convenience sampling method we employed for participant recruitment. A key for collecting reliable user experience data would be to do long term studies to get past the initial positive reaction. These were, however, beyond our means at this time.

Apparatus
The test hardware consisted of the mid-air tactile HMD built around the Oculus Rift DK2 as explained above. We also created a semitransparent virtual 3x2 numerical keyboard, which appeared to be about 30 cm away from the user. The keyboard followed

head movement, i.e., it was always in the same position in front of the user. This eliminated the problems that covering the frontal LEDs in the Oculus HMD might have caused with motion tracking.

Figure 5 shows the virtual environment with number keys to be touched. Key “2” has become red for 0.2 seconds as it is being touched. The Figure also shows how the task is directed by giving the next numbers to be touched on the upper area of the scene. When a number is entered, the current number is surrounded with angled parentheses (see number “1” in the Figure).

Figure 5: *View of the virtual test environment with numerical keyboard. It shows also the skeletal representation of the user’s hand touching a key and the key “2” in the red state that lasted for 0.2 seconds.*

Design

To test the effect of the tactile feedback, we ran a simple keyboard task in two different conditions. The independent variable was the presence of tactile feedback. The visual feedback was identical in both conditions.

The dependent variables were measures of tapping performance (text entry rate (based on the times between pressing 1st and 2nd key and pressing 2nd and 3rd key) and error rate) and subjective ratings of workload. Timing of the first keypress was not comparable to keys 2 and 3 because the starting point of the action could not be clearly determined. For keys 2 and 3 the timing started from the previous key press. At the end of the experiment we also asked whether the participants preferred to have tactile feedback or not and why.

Procedure

Upon entering the laboratory the participants read and signed an informed consent sheet. It was emphasized that they may interrupt the experiment for any reason if they so wish and were told to interrupt immediately if they sensed any signs of simulator sickness, which is a real possibility in experiments with immersive VR. We instructed the participants to use the hand palm towards the array to standardize the experiments, but we had no other strict controls regarding the technique of completing the task.

The users were seated on a chair and fitted with the HMD. In addition to the headset the participants wore over-the-ear hearing protectors. This was to block the slight buzzing sound that the ultrasonic array may create when operating. In this experiment we wanted to measure the effect of tactile feedback only.

A block of number entry consisted of 15 tasks (with or without tactile feedback). Each task consisted of entering 3 random numbers, which were randomized for each task and participant. Each participant first completed training and practice blocks with a tutor in each condition. The results from the actual testing blocks are reported below.

The order of tactile vs. no tactile was balanced between participants. After the training, the next two blocks were completed in the same order as the training blocks. Generally there was clear improvement in performance between the training blocks and the recorded blocks indicating that learning might further improve performance, but this is a topic for further work.

Pressing a key was indicated with a 0.2 second visual flash on the key (see Figure 5). When tactile feedback was active, also a single focal point was projected in front of the key for the same 0.2 s. Whatever part of the hand or fingers was on the location received the feedback. In other words, the feedback was given based on the key locations, not based on the hand location and shape.

For each block the users entered 15 sequences of 3 numbers. The numbers were presented in a virtual environment as shown in Figure 5. The participants were asked to memorize the 3 numbers before they started entering them. Recording started when the first key was pressed. Timing was possible only for the two latter numbers because the starting time of the first key press was unclear. However, all errors, including those made when pressing the first key, were recorded.

All pressed keys were registered but only correct numbers were accepted by the system. Touching wrong numbers caused the same feedback (visual and tactile) as touching correct numbers except for that the task display (the three number sequence) did not change for incorrect presses.

After each non-practice block the participant took off the headset and filled in also a TLX questionnaire on paper. To simplify the participant’s task, we used the so called “raw” TLX without the weighting portion [Hart 2006].

After all 4 blocks were completed, the participant answered a question on whether he or she preferred to have the tactile feedback or not. A typical completion time for the experiment was 10 minutes.

6 Results

The system recorded automatically the entered values and their timestamps. From those we calculated the entry speed (in characters per second (CPS)) and error rate. The error bars in Figure 6 and Figure 7 show the standard deviation.

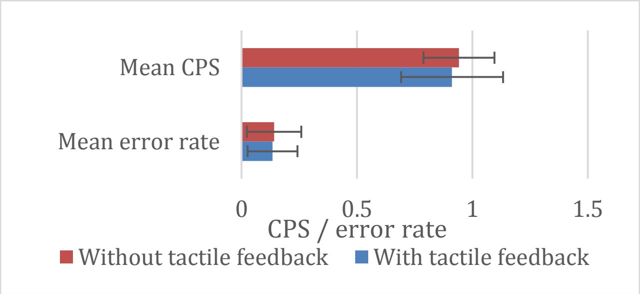

Figure 6: *Characters per second and error rate on both sets with and without the tactile feedback.*

TLX

The TLX had a scale of 0 (very low) to 21 (very high) on mental, physical and temporal demand, perceived performance, perceived effort and frustration. Figure 7 shows the average responses with and without tactile feedback.

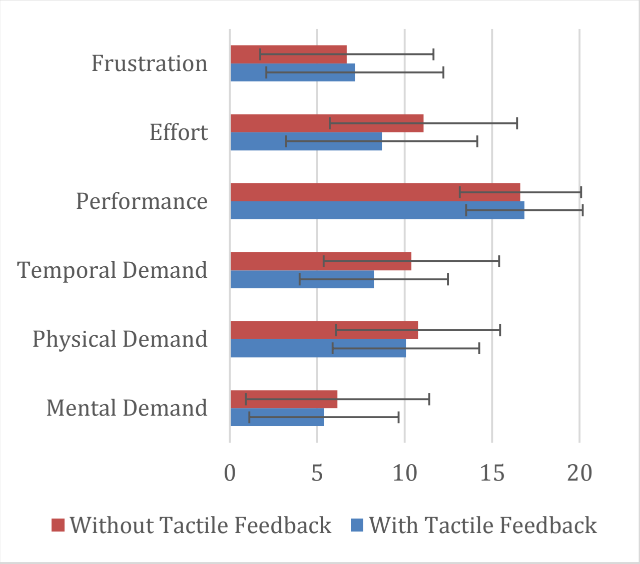

Figure 7: *TLX averages with and without tactile feedback (smaller is better, except in performance, where larger is better).*

Figure 7 illustrates that the perceived demand (temporal, physical and mental) and effort were ranked slightly lower and the perceived performance was ranked higher when using the tactile feedback. Frustration was rated slightly higher with tactile feedback than without it. However, according to t-tests, only the difference in temporal demand was statistically significant (t_{12}=4.38, p=0.0009).

Preference

The responses to the preference question showed a clear preference for the tactile feedback. 11 participants preferred to have it. One participant could not tell because he claimed that he did not feel any tactile stimulation. One participant preferred not to have tactile feedback. She said that this was her preference regarding all vibro-tactile stimulation in all situations.

7 Discussion

From our preliminary results, it appears that the mid-air tactile feedback did not enhance or degrade performance, but was heavily preferred by users. If such results turn out to be replicable, this would suggest that the best use of mid-air haptic feedback is perhaps in situations where user experience is the key issue. Entertainment technology and user interfaces that are used for fun could potentially be even more fun with mid-air haptics, whereas in productivity applications the measurable performance benefits may turn out to be small or non-existent.

The biggest perceived differences were found on the effort and temporal demand. It seems that the users felt that introducing the mid-air tactile feedback made the task feel more relaxed and perhaps require less effort. Based on the feedback from the participants, the tactile feedback made the pace seem lower (while the actual delays didn't change). Perhaps the tactile feedback makes the task cognitively easier. The reduced workload may have made the pace feel more relaxed, although objectively the task completion rate was almost the same for both conditions.

There are several details that can be improved in our implementation. For example, our prototype used a fairly small ultrasonic array, which can easily be integrated into the display. Even with this array size the effect was clearly noticeable up to the distance of around 30 cm. The anatomically possible maximum distance of touching measured from the eyes is about 50 cm for most persons. However, the normal and natural working range is typically about 20-30 cm, and a distance of up to 30-40 cm from the front plate of an HMD would cover all but the most extreme hand positions. The ultrasonic transducers could be packed a little tighter together into a diamond shape, instead of a rectangular array. Another option to stretch the distance would be to add the number of transducers, in which case they would overflow to a wider area than the front plate of the HMDs that we used. We presume that a 256-element array would be fully sufficient for the practical working volume for an HMD.

The fact that one of our participants did not feel the tactile stimulation was to be expected. Sensitivity of the hands varies in a wide range. Because air is soft and gaseous, mid-air tactile feedback can never be as precise and clear as tactile sensation against a rigid object. Whether it is possible to generate stimulation that is sufficient for giving benefits for most users was one of the main reasons for this research. Based on the preliminary results the answer to this question is positive, but more work is needed to confirm this.

A significant limitation of our prototype and ultrasonic mid-air haptics technique in general is that the tactile stimulation was not strong enough to produce sensations in all parts of the hand. The need to construct user interfaces so that objects are touched with the palm facing the ultrasonic array is a major hindrance. Alone this haptic feedback technology will work only in those applications that can adjust to this limitation. Stronger ultrasonic arrays and supplementary arrays in the environment may improve the situation. However, the difference in sensitivity between the fingertips and most other body parts will remain despite improved technology.

There can be different types of tactile signals (e.g., constant, short or long pulses, Morse code, etc.) for different types of actions. Which methods are better and more suitable for various purposes is an open question and invites further research. Gaze tracking, audio and other multimodal techniques could be used e.g., to further extend the user interface possibilities.

Because ultrasound cannot be heard, there is a possibility that unlike with audible sound, dangerous exposure could go unnoticed. Some animals may be sensitive to 40 kHz sounds and the powerful signal in the focal point and its lower harmonics may even be dangerous for human ears. While we have not yet measured the sound field generated by the array in detail, there are several reasons why it can be considered safe. First, as the ultrasound is focused, we estimate that even a dislocation of 10 cm away from the focus would reduce the volume by 20 dB (1/100th of the power). Secondly, user's head is typically 20-50 cm away from the focus area and the sound is always directed away from the user.

According to Lenhardt [2008] "Current exposure standards are based on the concept that detectability and the potential for damage to hearing are related." Apart from the barely audible low-frequency buzz, operation of the array was not detectable by hearing or other human senses outside the focus area. Lenhardt recommended 145dB maximum exposure at 40 kHz, which is extremely loud. Based on other studies (e.g. [Smagowska and Pawlaczyk-Łuszczyńska 2015]) that discuss the safety of ultrasound it seems that even extreme airborne ultrasound noise is well tolerated in industrial settings. In VR headset applications the power is lower and pulse duration is very short.

To block the audible by-product of the ultrasound generation the participants in our experiment wore hearing protection. An added benefit was that even a catastrophic equipment malfunction could not have caused danger to hearing.

Despite all this evidence suggesting that the tactile ultrasonic stimulation is safe, it is better to err on the side of caution and test possible products utilizing this technology fully to ensure that they conform to ultrasound exposure safety guidelines.

8 Conclusions

We have presented a mid-air tactile feedback system for head-mounted displays. As far as we know, our prototype is the first mid-air tactile headset. Ultrasonic tactile feedback suits well for HMDs, as it enables the user to touch virtual objects in an unobtrusive way, and the tactile feedback is always directed to the working visual area of the user.

User tests affirm that our system provides a means of interacting in an intuitive and easy-to-use manner. According to our tests, it seems that the users prefer it very much over no tactile feedback, even though its measured added effectiveness is small. The presented concept seems to be useful and easy to use.

Mid-air tactile feedback for HMDs can enhance the user experience and it may have implications also for 3D UIs and VR. While dwelling over an UI element (such as a button), tactile feedback can enhance the otherwise non-tangible button and affirm the user that a selection has been made when making a gesture. It can also deliver an enhanced tactile warning over the air to the user. The tactile effect cannot simulate a fully natural and realistic touching of an object, but nevertheless it gives some tactile feedback for the user.

The benefits of embedding ultrasonic actuators to HMD instead of embedding them to the environment include mobility, economy (small actuator panel is needed, instead of the walls and ceiling of a room to be covered), better tolerance for obstructions in the space, and safety (signal is directed away from the user). The shortcomings include limited possible size (and power) of the ultrasonic array, the added weight, the ability to stimulate only the palm facing towards it, and the fact that interaction with objects outside of the user's field-of-view isn't possible. Combining head-mounted panels with external panels would enable full coverage from all angles. Naturally also alternative methods of haptic and multimodal interaction can be merged with the system.

We conclude that mid-air tactile feedback is a viable and intriguing option for HMDs if the hand is oriented suitably. We will continue developing the ultrasonic transducer hardware system and gestural user interaction with it to test these issues further.

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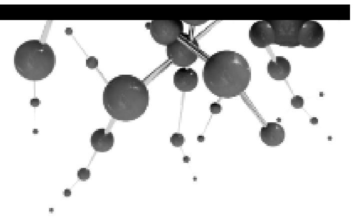

Paper IV

Sand, A., Remizova, V., MacKenzie, I. S., Spakov, O., Nieminen, K., Rakkolainen, I., ylliäinen, A., Surakka, V., & Kuosmanen, J. (2020). Tactile Feedback on Mid-Air Gestural Interaction with a Large Fogscreen. In *Proceedings of the 23rd International Conference on Academic Mindtrek* (pp. 161-164). New York, NY, USA: Association for Computing Machinery.

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Tactile Feedback on Mid-Air Gestural Interaction with a Large Fogscreen

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ABSTRACT

Projected walk-through fogscreens can be used to render user interfaces, but lack inherent tactile feedback, thus hindering the user experience. This study examines this by investigating wireless wearable vibrotactile feedback on mid-air hand gesture interaction with a large fogscreen. Participants (n = 20) selected objects from a fogscreen by tapping and dwell-based gestural techniques. The results showed that the participants preferred the tactile feedback. Further, while tapping was the most effective selection gesture, dwell-based target selection required haptic feedback to feel natural.

CCS CONCEPTS

• **Human-centered computing → Pointing**; • **Hardware →** *Displays and imagers*; *Haptic devices.*

KEYWORDS

Touchless user interface, mid-air hand gestures, fogscreen, haptic feedback

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1 INTRODUCTION

Intangible projected mid-air displays employing flowing light-scattering particles bring new possibilities to displaying information. An interactive *fogscreen* is such a walk-through, semi-transparent display to which interactive objects are projected.

The fogscreens are permeable, visible and allow physical interaction. They can be used as touch screens and as interactive public displays while tracking and sensing user interaction. However, no tactile feedback can be perceived when interacting with fogscreens.

We investigated the potential of wearable vibrotactile feedback for mid-air gestural interaction with a large fogscreen. We investigated two gestures for physical interaction with the fog, *tapping* and *dwell-based selection* gestures, with and without tactile feedback. In fog tapping, hand movement imitates a conventional physical tap on a vertical screen. Dwell-based selection implies that a finger dwells in the fog over an object for one second to select. The difference between the gestures is that dwell-based selection gesture does not require removing the user's hand from the fog between selections. The user may continuously point and select targets while their hand travels from one target to another in the fog. Fog tapping requires the hand to leave the fog to register a target selection.

Visual feedback alone may be insufficient for this type of interaction, due to slight turbulence in the fog caused by the intersecting finger. This can blur the projected graphics. Furthermore, previous studies revealed the need for tactile feedback [5]. We tested the two gestures with two feedback modalities (auditory + visual, auditory + visual + haptic) when interacting with a large fogscreen to understand the effect of tactile feedback on user preference and performance. Haptic feedback was produced by a custom-built light-weight wireless vibrotactile actuating devices on the user's hand.

The contribution of this work quantifies the subjective experience and the effects of haptic feedback on user performance. We carried out a user study to objectively measure and compare performance and overall subjective user preference. Our findings can inform the design of haptic feedback with mid-air gestural interaction on large projected particle screens.

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2 RELATED WORK

2.1 Particle displays

Images have been projected on water, smoke, or fog for more than 100 years [9]. Modern fogscreens are concise, thin-particle-projection systems producing image quality superior to previous methods [2]. The fogscreen we used consists of a non-turbulent fog flowing inside a wider non-turbulent airflow [13]. Small movements of the fog are possible, which in turn causes a slight movement in the projected graphics. The screen is permeable, dry, and cool to touch, so it is possible to physically reach or walk through the image. Fogscreens can be very engaging when the audience can directly interact and play with them.

2.2 Mid-air interaction techniques

The advent of depth-sensing methods that track 2/3D position of the hand has enabled mid-air hand interaction for large screens. Mid-air hand gestures with large conventional projector displays have been widely researched over the last decade. Several hand selection gestures were evaluated for their intuitiveness and effectiveness. These include push [4, 18], AirTap [4, 17], dwell [4, 16, 18, 19], or thumb trigger [4, 16, 17]. Point-and-dwell selection techniques are commonly used [19], intuitive [18], and easy to detect [4].

Palovuori et al. [11] improved Microsoft Kinect tracking for the fogscreen and demonstrated the potential of fogscreens as an interaction medium. Martinez et al. [10] merged an interactive tabletop screen with a vertical fogscreen in their MisTable system. Sand et al. [15] experimented with a small fogscreen with ultrasonic mid-air tactile feedback and found that participants preferred tactile feedback when selecting objects on the fog. Similar conclusions about the preference of tactile feedback in gestural interaction have been made with other touchless user interfaces [5], but large fogscreens have not been extensively studied.

3 EXPERIMENT SYSTEM DESIGN

3.1 Screen, projection and tracking

Our interaction solution utilizes a large fogscreen coupled with depth-sensing Microsoft Kinect Sensor V2 for Windows. The Kinect device was placed behind the fog screen and monitored the area in front of the screen. It tracked skeletal data of the user's hand while our software analyzed hand gestures.

We used an early prototype of the fogscreen [8, 14]. It has a 1.55 × 1.05 m area available for interaction. We used an Optoma ML750e mini LED projector, which produces 700 ANSI lumens at a contrast of 15000:1. The projector faces the user on the other side of the fog. In this configuration, the image is brighter than when projecting from the user's side and the user cannot block the projector's light with their body.

3.2 Haptic device

To provide the user with haptic feedback, we designed a lightweight wireless wearable vibrotactile actuation device. The design uses an Arduino Nano microcontroller board combined with an HC-05 serial Bluetooth radio and a Texas Instruments DRV2605L haptic motor controller with an eccentric rotating mass (ERM) vibration motor. The choice of a Bluetooth connection over a WiFi connection was made during extensive piloting, which revealed erratic WiFi signal delays due to interference. We powered it with two AA batteries regulated to 5V through a Pololu S7V8A stepper voltage regulator.

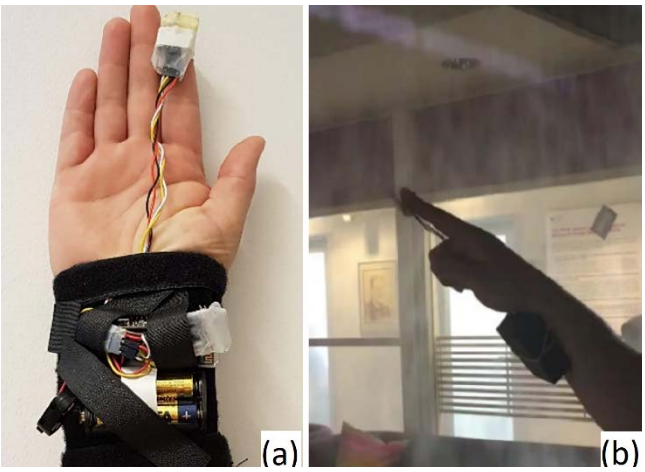

Figure 1: (a) Haptic device, (b) device in the experiment.

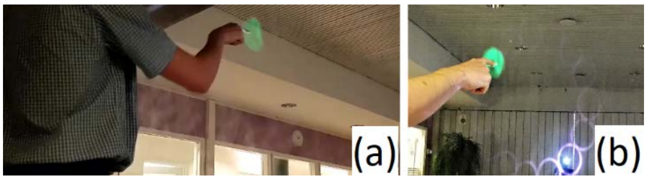

Figure 2: (a) User tapping to select a target, (b) user holding their finger over the target for dwell-based selection.

The bulk of the device is worn around the user's wrist with the motor controller and the coin-cell ERM motor taped to the user's dominant hand's index finger in the palmar side (See Figure 1). Earlier studies found that the placement of the actuator (on the finger or on the wrist) might not affect user's performance [5]. However, placing it on the finger is preferred by users [5, 12]. Also, it was found that user responses are faster when a vibrotactile stimulus is applied to the hand used for target selection [12].

3.3 Interaction and feedback

The targets for selection are blue circles on a black background arranged in a circular layout, with only one target visible at a time. The background effectively attenuates the bright spot of the projector, which might otherwise be uneasy for the user's eyes (see Figure 2). Selecting one target makes it disappear and a new target is presented on the other side of the circle rotating clockwise.

A successful selection of the tapping gesture required the finger to exit the fog within the borders of the target's current position. After this, the target disappears, a clicking sound is played, and a new target appears. A special error sound is played if the finger incorrectly leaves the fog. This informs the user that their tapping gesture was not executed correctly.

In the target acquisition state of the dwell-based gesture, a rotating animation of a green arc is rendered on the target to visualize the dwell progress. After the dwell time is reached, target selection is registered, wherein the target disappears. A click sound is played and a new target appears in a new location of the fog. If the finger leaves the target during the dwell, the dwell counter is reset. A small white cursor is visible as help for target selection.

In fog tapping with haptic feedback, the user feels an instantaneous distinct vibrotactile feedback pattern in the fingertip as the finger enters the fog. After the finger returns to its initial position, the user feels a clicking haptic pattern that confirms a successful target selection. No clicking pattern is provided in case of an erroneous fog tapping gesture.

In dwell-based selection, the haptic feedback begins immediately when the user touches the target. The user then feels a continuous vibration, indicating the progress of the dwell interval. Upon the selection, a clicking pattern is presented via haptic feedback similar to that of tapping.

To generate recognizable tactile cues, we used well-known characteristics of tactile-cue design: frequency, duration, rhythm, waveform, and location [1, 3]. Vibrotactile stimulation patterns were empirically selected in the range of 150 - 300 Hz. This range was shown [6, 7] to stimulate the Pacinian corpuscles in both glabrous and hairy skin areas, which results in good perception and recognition of haptic sensations. We empirically selected short pulses of 60 ms at 200 Hz to form a clicking sensation.

For dwell-based gesture, we used a long stimulus of 1000 ms divided into four waveforms of 250 ms where the frequency rapidly ramped up from 0 Hz to 200 Hz and back to 0 Hz at the end of each sequence, to create rhythm in the waveform. No participant reported the intensity of the tactile feedback as lacking, but one participant said it felt too intense.

We measured the movement time between targets and counted target re-entries. We assumed that the user moves to the next target more quickly if they received a haptic confirmation that the previous selection was completed. In dwell-based selections, the assumption was that haptic feedback during dwelling could reduce the number of target re-entries.

4 EXPERIMENT

The large, open experiment room had no direct sunlight. We dimmed the lighting to improve the projected image so that it was still comfortable to read and answer the questionnaire.

Twenty healthy university students and staff members attended the tests. Ages ranged from 20 to 66 years (mean = 35.3, *SD* = 12.9). Some of the participants had prior experiences with mid-air gesturing or with projected particle screens (e.g., they had seen fogscreens in shopping malls or in research demonstrations), bun none had first-hand experience interacting with a fogscreen.

4.1 Procedure

Upon arriving at the laboratory the participants read an information sheet, gave informed consent, and completed a background form. The first gestural technique was explained and they watched a video of the selection method in question. The gesture was explained and demonstrated, followed by enough practice trials for the participant to feel comfortable with the interaction.

The participants were instructed to make selections as fast and accurately as possible. The four conditions (tapping, dwell-based, with and without haptic feedback) were presented in a counterbalanced order to offset learning effects.

After the experiment, a final rating scale and a free-form questionnaire about the interaction with the fogscreen was provided. We asked participants to rank the four conditions in order of preferences from the most (1) to least (4) preferred.

4.2 Design

The experiment was a within-subjects study. Each participant was presented with four conditions: two selection gestures with and without haptic feedback. Each condition consisted of 540 selections of targets. After each selection, the target disappeared and a new target appeared on the opposite side of the circle, rotating clockwise. Targets were divided into sets of 15, with each set having a different combination of target amplitude (the distance from the origin of the circular layout, 100, 350, 600 pixels) and target width (40, 70, 100 pixels).

A 2 selection methods × 2 feedback modes within-subjects analysis of variances (ANOVA) was performed on the data combined for all amplitudes and widths. Bonferroni corrected t-tests were used for pairwise *post hoc* comparisons.

We used a Friedman test to compare the subjective ratings for statistical significancy, a Wilcoxon signed-ranked test with Bonferroni corrections was conducted for pairwise comparisons, resulting in significance level set at $p < .008$.

5 RESULTS

Analyses revealed some anomalous behaviours that resulted in outliers. In fog tapping, selections where the selection coordinate was greater than 3× the radius from the target centre were removed (96 selections). In dwell-based interaction, selections that took more than 10 seconds were removed (48 selections). The total number of outlier selections was 96 + 48 = 144, or 1.3% of the original 10,800 selections. All analyses below are with outliers removed.

The addition of haptic feedback affected the movement time slightly – in fog-tapping the inclusion of haptic feedback increased the movement time and in dwell-based selection it reduced the movement time. These differences were subtle and not statistically significant ($F_{1,19} = 0.3$, $p > .05$).

Similarly, the addition of haptic feedback lessened the target re-entries, most notably in dwell-based selections, but these differences were not statistically significant ($F_{1,19} = 2.18$, $p > .05$).

These effects are illustrated in Figure 3.

After testing, participants ranked their preferences among the four conditions (2 selection methods × 2 feedback modes). The means of the responses are shown in Figure 4. A lower score is better. Friedman tests showed a statistically significant effect for participants' preference of interaction gesture, $\chi^2(3) = 7.980$, $p = .046$.

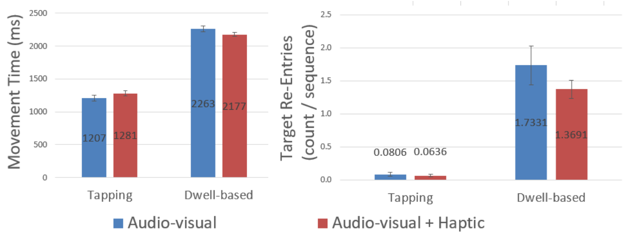

Figure 3: Mean values by selection method and feedback mode. Error bars are standard error of the means (SEMs).

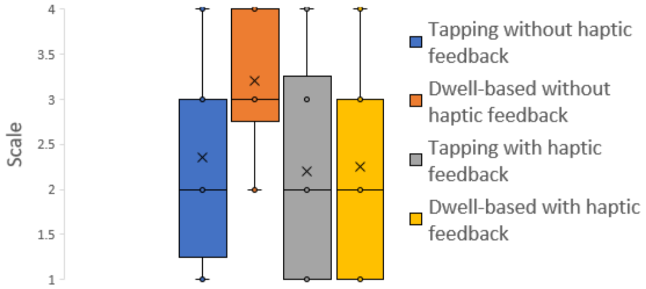

Figure 4: Mean of participants' preference ratings by selection method. A lower score is better.

Post hoc pairwise comparisons with Wilcoxon signed-rank tests showed that dwell-based selection with haptic feedback was significantly preferred over that without haptic feedback, Z = -2.879, p = .004.

6 DISCUSSION

The users ranked tapping without haptic feedback as the most preferred interaction method but also ranked the dwell-based selection with haptic feedback as the second most preferred interaction method. Overall, subjectively, no method was rated significantly worse than the others. The overall preference for tapping is likely explained by the perceived delay when using dwell-based gestures, as it required participants to hold their hand still for 1 second. As found in previous research [4, 19], dwell-based gestures are tiring but practical if recognition quality of other gestures is poor.

The inclusion of haptic feedback did not affect the measured performance of the participants, but in the subjective ratings the participants somewhat preferred the inclusion of haptic feedback. In the experiment, the haptic feedback was reactive – it gave affirmation to the user in much the same way as the visual and auditory feedback. This could have affected the measured performance. However, these results show that haptic feedback has its use in gestural interaction with large fogscreens. Further studies will be conducted to measure objective gains.

7 CONCLUSIONS

We studied the effects of vibrotactile feedback in gestural interaction with a large projected particle screen. Fog tapping and dwell-based selection were compared, both with and without vibrotactile feedback. Vibrotactile feedback yielded a statistically significant difference when used with dwell-based gestures, but not with tapping. Subjective ratings reflected these findings. Tapping without haptic feedback was the most preferred interaction, but dwell-based gestures with haptic feedback were preferred over dwell-based gestures without haptic feedback.

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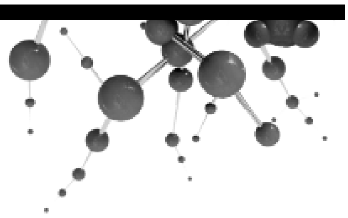

Paper V

Sand, A., Rakkolainen, I., Surakka, V., Raisamo, R., & Brewster, S. (2020). Evaluating Ultrasonic Tactile Feedback Stimuli. In: Nisky I., Hartcher-O’Brien J., Wiertlewski M., Smeets J. (eds) *Haptics: Science, Technology, Applications.* EuroHaptics 2020. Lecture Notes in Computer Science, vol 12272. Springer, Cham.

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Evaluating Ultrasonic Tactile Feedback Stimuli

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Abstract. Ultrasonic tactile stimulation can give the user contactless tactile feedback in a variety of human-computer interfaces. Parameters, such as duration, rhythm, and intensity, can be used to encode information into tactile sensation. The present aim was to investigate the differentiation of six ultrasonic tactile stimulations that were varied by form (i.e., square and circle) and timing (i.e., movement speed and duration, and the number of repetitions). Following a stimulus familiarization task participants ($N = 16$) were to identify the stimuli presented in the same order as in the familiarization phase. Overall, the results showed that it was significantly easier to identify stimuli that were rendered at a slower pace (i.e., longer duration) regardless of the number of repetitions. Thus, for ultrasonic haptics, rendering time was one important factor for easy identification.

Keywords: Ultrasonic haptics · Mid-air haptics · Stimuli design · User study

1 Introduction

Haptic feedback is commonly used in mobile phones, but so far the feedback has required physical contact with a device or the use of wearable actuators. Ultrasound tactile actuation [7] is a new approach for providing tactile feedback. It removes the limitation of contact and creates true mid-air haptic sensations.

Parameters such as duration, rhythm, and intensity, can be used to encode information into tactile sensation. Yet, it is unclear how to combine these for easy identification of stimuli. The ability of transducer arrays to rapidly update focal point location to create movement and shapes opens up new possibilities as to how much and what kind of information can be encoded into haptic feedback. However, this brings with it new open questions about how to best design haptic cues to convey information.

To better understand the technical and human limitations of ultrasonic haptic information transfer, we conducted a study to evaluate six different haptic feedback stimuli in terms of how quickly and accurately they could be identified and how well they would work as mobile phone notifications (e.g., receiving a phone call or a notification).

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2 Related Work

Mid-air haptics can be made with a number of technologies that allow for tactile feedback on touchless interaction. Tactile sensations can be rendered to interactive spaces in 3D. Technologies such as pressurized air jets [16] or air vortex rings [18] can provide strong but rough feedback with some inherent time lag. Lasers [8,11] or electric arcs [17] are possible for very precise short range feedback.

Focused airborne acoustic air pressure produced by ultrasonic phased arrays [2,6,7] is particularly good at generating a range of tactile stimuli on the user's palm or fingertips. This technology allows for fast rendering of single points or multiple simultaneous ones for patterns such as volumetric shapes [9].

These inaudible sound waves (typically 40 kHz [7] or 70 kHz [6]) can be focused into a single location in space. As the human hand can not feel vibrations at 40 kHz, the emitted ultrasound is modulated at the focal point to a frequency of around 200 Hz. This frequency is detectable by mechanoreceptors sensitive to vibration and pressure [5]. At a focal point, the acoustic pressure becomes strong enough to slightly indent the human skin and stimulate the Pacinian corpuscles, thus generating a touch sensation.

For the most common hardware types, rendering multiple focal points simultaneously makes each point feel weaker as there are less transducers used for each point. The temporal resolution of touch perception is only a few milliseconds [10]. Hence, fast moving single points, through spatiotemporal modulation [4], can be used to create the sensation of an entire shape being rendered at once.

Tactons [1], or tactile icons, have been used to communicate messages non-visually to users through ultrasonic actuation [3] and have been used with immaterial [15] and virtual screens [14].

Previous work on identifiability of mid-air haptic shapes [13] found that users are better at identifying shapes with a single focal point or shapes organized in straight lines compared to circular shapes. However, there has been little research into the range of parameters that can be used in ultrasound haptics to find out what makes the most effective tactile cues. Therefore, we designed a study to find out what parameters can make the stimuli more identifiable.

3 Methods

Sixteen voluntary participants (11 male), aged 20 to 42 years (median age 29 years, SD 6.07) with normal sense of touch by their own report, took part in the study. Seven of them had no previous experience using ultrasonic haptics and the rest had experienced it once or multiple times.

3.1 Pattern Design

Preliminary testing indicated that stimuli using variation in duration and rhythm resulted in more reliable identification of six different haptic stimuli than variations in shape. Pretesting also suggested that a 3 × 3 cm stimulation area

Table 1. Haptic stimuli parameters used in the experiment.

Stimulus id	Total duration (ms)	Pulse duration (ms)	Repetitions	Breaks (ms)	Shape
1	400	400	1	0	Square
2	1100	400	2	300	Square
3	1800	400	3	300, 300	Square
4	1100	1100	1	0	Circle
5	500	100	2	300	Square
6	900	100	3	300, 300	Square

Fig. 1. Rendered shapes and repetitions. In stimuli 1 to 4, the focal point movement can be perceived, as shown by the arrow. Stimuli 5 and 6 use spatiotemporal modulation, making the entire shape concurrently perceivable.

provided stronger and clearer stimulus perception than larger areas and was therefore selected for the experiment.

Based on above the following six stimuli were designed. Each stimulus consisted of a rhythm formed by either one, two or three pulses, followed by a 300 ms break. Stimuli 1 to 3 had a 400 ms pulse duration, stimulus 4 had a single long pulse, and stimuli 5 and 6 had short, 100 ms pulses. Stimuli 5 and 6 used spatiotemporal modulation in which the focal point was rapidly and repeatedly updated to create a sensation of a single tactile shape.

Stimulus 4 had a circular shape, while the other stimuli had a square shape. It was also rendered in counterclockwise direction with the others rendered clockwise to see if the change in direction could be reliably noticed. Stimuli used in this experiment are described in Table 1 and visualized in Fig. 1.

3.2 Procedure

The UltraHaptics UHEV1 ultrasonic transducer array with 256 40 kHz transducers was used (see Fig. 1) to deliver haptic feedback.

Participants were to rest the wrist of their dominant hand comfortably on a foam pad with their palm facing down about 10 cm above the centre of the array. All participants used their right hand. They were instructed to keep their hand in the same position throughout the experiment. Near their left hand they had a keypad for input. No visual feedback was provided.

The experiment started with a written and verbal introduction and instructions, followed by a short training period, where the participants experienced each stimulus in a specific order (1 to 6), and repeated four times. They were instructed to try to remember the order number. In the experiment, the same stimuli were presented randomly, with each occurring three times (for a total 18 of stimuli). The participants wore headphones playing white noise to mask any audible noise from the array.

After each stimulus, a 500 ms audio sample was played as a cue for action. The participants were instructed to identify the stimulus by pressing a corresponding numeric key on the keypad in front of them as fast and accurately as possible.

Response times from the onset of the audio cue to the key press, as well as the key selected, were automatically logged in the database. Timing started after the stimulus had ended so that the stimulus duration would not affect the identification times. After an answer was given the experiment proceeded to the next stimulus and continued until all the stimuli were presented.

After the identification task, the participants were given the same stimuli again and they rated them on scales of *valence* (−4, unpleasant to 4, pleasant) and *arousal* (−4, calming to 4, arousing). They also rated the functionality of the stimuli as potential mobile phone notifications and incoming call notifications using a scale from 0 = does not suit at all to 7 = suits very well. At the end of the experiment, they were asked to freely describe their perceptions of the stimuli to see if the change in shape or drawing direction were detected.

The identification times were analyzed using one-way repeated measures analysis of variance (ANOVA). Bonferroni corrected t-tests at the .05 level were used for pairwise post hoc comparisons of the 15 pairs. The number of incorrect identifications, the valence and arousal ratings, and the stimulus suitability for mobile phone notifications ratings were first analyzed with Friedman tests and Bonferroni corrected Wilcoxon Signed Ranks tests were used for post hoc comparisons.

4 Results

One participant had trouble in sensing any of the stimuli. Therefore, this data was removed from the data set.

The ANOVA for the identification times showed a statistically significant effect of the haptic stimulus (F(5,75) = 5.824, $p < 0.01$). Post hoc tests showed that identification times were statistically significantly different between stimuli 1 and 3 (MD = 949.193, p = 0.019), 3 and 5 (MD = 1235.229, p = 0.003), and 3 and 6 (MD = 551.813, p = 0.029). Comparing just the duration, stimuli 2 and 3 were on average 500 ms and 700 ms quicker to identify than stimuli 5 and 6 respectively (See Fig. 2).

The Friedman test for the number of incorrect identifications showed a statistically significant effect of the haptic stimulus $X^2 = 18.673$, $p = 0.02$. Post hoc pairwise comparisons were not statistically significant.

Figure 2 shows the percentage of incorrect identifications made for each stimulus. Accuracy rate across all stimuli was 66%.

Three participants were able to identify each stimulus without errors. Stimulus 5 saw an 118% greater error rate compared with stimulus 2 and stimulus 6

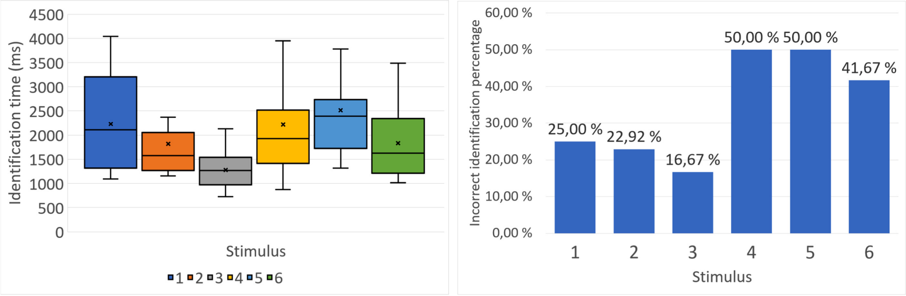


Fig. 2. Left: identification time distributions in ms from the start of the audio cue. Right: percentage of incorrect identifications for each stimulus.

saw an 150% increase compared with stimulus 3, which were those with the same rhythm. Stimulus 3 was the quickest and most accurate to identify. There were large differences in accuracy across the tested stimuli. When drawing a square shape at a lower speed for one, two or three repetitions, the accuracy was 78%. With stimulus 3 the accuracy rose to 83%, with 11 participants not mistaking once in all of the 48 identifications.

The confusion matrix for the stimuli is shown in Fig. 3. Correct identifications are on the main diagonal and the rhythmically similar options have a solid border. 100% correct identification would give a score of 48. Stimulus 3 is the best performing cue, with 5 the worst.

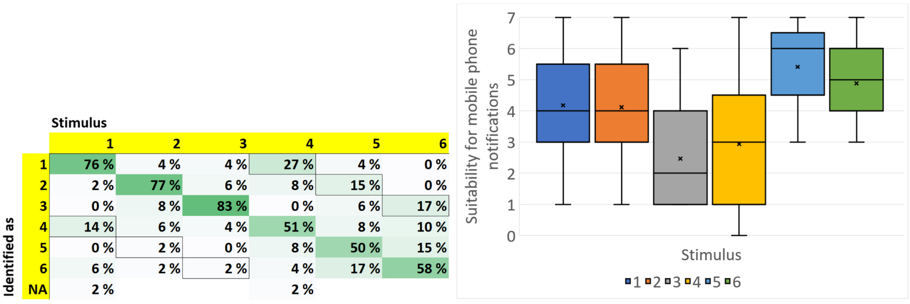
Stimulus 4 was often mistaken as stimulus 1, but not the other way around. Stimuli 5 and 6 were as likely to be confused with each other, as they were with those with the same rhythm, stimuli 2 and 3.

Ratings of stimulus suitability for mobile phone notifications (Fig. 3) showed a significant effect $X^2 = 28.114$, $p < 0.001$. Pairwise comparisons showed significant difference between stimuli 3 and 5 (Z = 3.307, p < 0.01), and 3 and 6 (Z = 3.311, p < 0.01). Stimulus 6 seems well suited for a general notification.

The ratings of arousal and stimulus suitability for a notification of an incoming phone call (Fig. 3) showed a statistically significant effect of the haptic stimulus $X^2 = 13.577$, $p = 0.019$. and $X^2 = 14.071$, $p = 0.015$, respectively. Post hoc pairwise comparisons were not statistically significant.

No statistically significant effect of stimulus were found on valence ($X^2 = 1.484$, $p = 0.915$). Overall, participants regarded all stimuli as quite pleasant with an average rating of 1.41 (SD 1.83).

Participants' descriptions of sensations failed to accurately identify differences in shape and direction, and the shapes were often incorrectly identified as being for example lines, crosses, vortexes or just random pokes. For the square shaped stimuli, there were 26 answers suggesting either a square shape, a line or a cross and 34 answers suggesting an oval, a vortex, a point, or a fluttering of points. For the circular shaped stimuli, there were 4 answers suggesting an oval, an infinity sign or a circle and 7 answers suggesting a linear movement or a



Identified as \ Stimulus	1	2	3	4	5	6
1	76 %	4 %	4 %	27 %	4 %	0 %
2	2 %	77 %	6 %	8 %	15 %	0 %
3	0 %	8 %	83 %	0 %	6 %	17 %
4	14 %	6 %	4 %	51 %	8 %	10 %
5	0 %	2 %	0 %	8 %	50 %	15 %
6	6 %	2 %	2 %	4 %	17 %	58 %
NA	2 %			2 %		

Fig. 3. Left: confusion matrix for the stimuli. Stimuli (horizontal axis) and what they were identified as (vertical axis). Right: stimulus rating distribution on suitability for mobile phone notifications on a scale of 0 (does not suit at all) to 7 (suits very well).

fluttering of points. This suggests that shape and direction are not good options for cue design in this case.

5 Discussion

The results of the study showed that stimulus number 3 (See Table 1) was the fastest and most accurate to identify. It consisted of three 400 ms pulses forming a square pattern rendered at a slow rate. As the stimuli with lower rate were identified better than the ones with faster rate it seems that the duration had a greater effect than rhythm. However, as the experiment had multiple variables, isolation of the effect of one parameter is not viable.

The tested stimuli formed pairs of similarities. Stimuli 1 and 4 consisted of a single pulse, stimuli 2 and 5 had two pulses, and stimuli 3 and 6 had three pulses. In stimuli 1 to 3 the shape was drawn at a slower pace than in stimuli 5 and 6 so that the shape was completed in 400 ms.

The average identification time as well as the error rate of the stimuli 1 to 3 decreased as the number of pulses increased. A similar trend was seen for stimuli 5 and 6 so that adding the third pulse seemed to decrease the identification time and decrease the number of errors. Nevertheless, for the stimuli 4 to 6 there were considerably more errors than for the stimuli 1 to 3. Probably this is due to the very short duration of the pulse or due to the use of spatiotemporal modulation or both.

The results suggest that the longer duration of the stimulus led to a quicker and more accurate identification when the rhythm was two or three repetitions.

Palovuori *et al.* [12] reported that a 200 ms burst of ultrasound was an ‘unmistakable’ stimulus being functionally equivalent to a physical button click. However, in our experiment shortening the duration of the stimulus to 100 ms resulted in more incorrect identifications than prolonging the duration to 400 ms.

Stimulus 4, which had the longest duration to complete one shape had the highest number of errors and took a long time to identify. Increasing stimulus duration to 1100 ms did not make identification easier. However, it is unclear whether the shape drawn, or its drawing direction affected the identification. Considering that the participants couldn't reliably identify any shape or direction, it is assumed that it had very little effect, but further study is required.

Rutten *et al.* reported 44% identification rate when the participants were provided with visual representations of the stimuli [13]. Our stimuli formed pairs of similarity, thus identification by chance is 50%. However, some stimuli were considerably more accurate to identify. Our results seem to indicate that identifying any ultrasonic haptic shape is difficult, but that stimuli can be identified with the right parameters for which rendering time is a key factor.

6 Conclusions and Future Work

The present work reported an experiment that compared six different ultrasound haptic stimuli to see how fast and accurately they could be identified. Statistically significant differences were found for identification times, number of incorrect identifications and subjective ratings. With a rhythm of three repetitions, a 400 ms pulse duration made the cue quicker and easier to identify than with a pulse duration of 100 ms.

Further, using short pulse duration, when the shape was drawn rapidly and repeatedly, the identification time and errors increased. This could be either due to the pulse duration or due to the use of spatiotemporal modulation.

Subtle changes in shape or direction of draw seem to go unnoticed by the users. Building a vocabulary based on direction or complex shapes is not a viable method of information encoding. These results may help in designing easy to identify ultrasonic stimuli.

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